INTRODUCTION TO CONSERVATION BIOLOGY



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Introduction to Conservation Biology

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TABLE OF CONTENTS

Licensing

1: What is Conservation Biology?

- 1.1: Introduction to What is Conservation Biology?
- 1.2: Conservation Biology is Still Evolving
- 1.3: A Multidisciplinary Approach
- 1.4: History of US Conservation
- 1.5: Environmental Ethics
- 1.6: Summary
- 1.7: Topics for Discussion
- 1.9: Bibliography

2: The Process of Science

- 2.1: What is Science?
- 2.2: The Scientific Method
- 2.3: Scientific Papers
- 2.4: Basic and Applied Science
- 2.5: Data Dive- California Wildfires
- 2.6: Review

3: Population Ecology

- 3.1: Introduction to Population Ecology
- 3.2: Populations
  - 3.2.1: Population Dispersion
  - 3.2.2: Population Size
  - 3.2.3: Population Growth and Regulation
  - 3.2.4: Life History
  - 3.2.5: Data Dive- Wildlife Corridors
  - 3.2.6: Section Review
- 3.3: The Human Population
  - 3.3.1: The Human Population
  - 3.3.2: History of Human Population Growth
  - 3.3.3: The Rate of Human Population Growth
  - 3.3.4: Looking Ahead
  - 3.3.5: Human Impact on the Environment
  - 3.3.6: Data Dive- World Population Densities
  - 3.3.7: Section Review

4: Community Ecology

- 4.1: Biotic Interactions
  - 4.1.1: Trophic Interactions
    - 4.1.1.1: Predation
    - 4.1.1.2: Herbivory

        - 4.1.1.3: Parasitism
        - 4.1.1.4: Food Chains and Food Webs
    - 4.1.2: Competition
    - 4.1.3: Facilitation
    - 4.1.4: Symbiosis
- 4.2: Community Structure and Dynamics
- 4.3: Data Dive- Bison Impacts In Prairies
- 4.4: Section Review

5: Ecosystems

- 5.1: Ecosystem Types and Dynamics
- 5.2: Matter
- 5.3: Biogeochemical Cycles
- 5.4: Fresh Water Supply and the Water Cycle
    - 5.4.1: Water Usage
    - 5.4.2: Water Scarcity and Solutions
- 5.5: Soils
- 5.6: Soil Degradation
- 5.7: Data Dive- Beaver Impacts on Wetlands
- 5.8: Review

6: Biomes

- 6.1: Climate and Biomes
- 6.2: Terrestrial Biomes
- 6.3: Aquatic Biomes
- 6.4: Data Dive- Biome Carbon Storage
- 6.5: Review

7: What is Biodiversity?

- 7.1: Introduction to What is Biodiversity?
- 7.2: Classification of Earth's Species
- 7.3: Origin of Biodiversity
- 7.4: Species Diversity
- 7.5: Genetic Diversity
- 7.6: Ecosystem Diversity and Services
- 7.7: Patterns of Biodiversity
    - 7.7.1: Species Distribution
- 7.8: Summary
- 7.9: Topics for Discussion
- 7.11: Bibliography

8: Importance of Biodiversity

- 8.1: Introduction to the Importance of Biodiversity
- 8.2: Material Contributions
- 8.3: Regulating Services
- 8.4: Nonmaterial Contributions
- 8.5: Option Values

- 8.6: Environmental Economics
- 8.7: Summary
- 8.8: Topics for Discussion
- 8.9: Bibliography

9: Habitat Destruction and Fragmentation

- 9.1: Introduction to Habitat Destruction and Fragmentation
- 9.2: Habitat Loss Overview
- 9.3: What is Habitat Loss?
- 9.4: Habitat Loss' Impact on Select Ecosystems
- 9.5: Population Growth and Consumption
- 9.6: Summary
- 9.7: Topics for Discussion
- 9.9: Bibliography

10: Impacts of Climate Change

- 10.1: Introduction to the Impacts of Climate Change
- 10.2: Climate Change
  - 10.2.1: Climate vs. Weather
    - 10.2.1.1: The Greenhouse Effect and Climate Change
- 10.3: Drivers of Climate Change
- 10.5: The Impact of Climate Change
- 10.6: Beneficiaries of Climate Change
- 10.7: The Overall Impact of Climate Change
- 10.8: Summary
- 10.9: Topics for Discussion
- 10.11: Bibliography

11: Pollution, Overharvesting, Invasive Species, and Disease

- 11.1: Introduction to Pollution, Overharvesting, Invasive Species, and Disease
- 11.2: Pollution in Its Many Forms
  - 11.2.1: Water Pollutants and Their Sources
  - 11.2.2: Mitigating Water Pollution
  - 11.2.3: Air Pollution
    - 11.2.3.1: Acid Deposition
  - 11.2.4: Section Review
  - 11.2.5: Solid Waste Management
    - 11.2.5.1: Waste Generation
    - 11.2.5.2: Waste Disposal
    - 11.2.5.3: Solid Waste and Marine Life
    - 11.2.5.4: Data Dive- Plastic in World Oceans
    - 11.2.5.5: Waste Reduction
    - 11.2.5.6: Data Dive- "Flushable" Wipes
    - 11.2.5.7: Review
- 11.3: Impacts of Industrial Agriculture
- 11.4: Overharvesting
- 11.5: Persecution

- 11.6: Invasive Species and GMOs
  - 11.6.1: Overview of Invasive Species
- 11.7: Parasites and Diseases
- 11.8: Data Dive- Threats to Biodiversity
- 11.9: Summary
- 11.10: Topics for Discussion
- 11.12: Bibliography

12: Extinction

- 12.1: Introduction to Extinction
- 12.2: History of Extinction
- 12.3: Rates of Extinction
- 12.4: What is Extinction?
- 12.5: Which Species are at Risk of Extinction?
- 12.6: Characteristics of Threatened Species
- 12.7: Problems of Small Populations
- 12.8: Is De-extinction a Solution?
- 12.9: Summary
- 12.10: Topics for Discussion
- 12.12: Bibliography

13: Applied Population Biology

- 13.1: Introduction to Applied Population Biology
- 13.2: Monitoring Population Size
- 13.3: Estimating Extinction Risk
- 13.4: Data Dive- Island Fox Populations
- 13.5: Topics for Discussion
- 13.7: Bibliography
- 13.8: Summary

14: Conserving Ecosystems

- 14.1: Introduction to Conserving Ecosystems
- 14.2: Measures of Biodiversity Loss
- 14.3: Ecosystem Monitoring
- 14.4: Maintaining Complex and Adaptive Ecosystems
- 14.5: Restoring Damaged Ecosystems
- 14.6: Ecosystem Restoration
- 14.7: Combatting Climate Change Through Ecosystem Conservation
- 14.8: Summary
- 14.9: Topics for Discussion
- 14.11: Bibliography

15: Preventing Extinctions

- 15.1: Introduction to Preventing Extinctions
- 15.2: Species-level Conservation
- 15.3: Studying Species and Populations
- 15.4: Saving Species Through Translocations
- 15.5: Managing and Facilitating Movement Dynamics

- 15.6: Managing Species Sensitive to Climate Change
- 15.7: Ex Situ Conservation Strategies
- 15.8: Thoughts on Neglected Taxa
- 15.9: Summary
- 15.10: Topics for Discussion
- 15.12: Bibliography

16: Biodiversity and the Law

- 16.1: Introduction to Biodiversity and the Law
- 16.2: Identifying Legislative Priorities
- 16.3: Environmental Laws and Policies
- 16.4: National and State Laws
- 16.5: The Limits of Environmental Laws and Regulations
- 16.6: Conclusion
- 16.7: Summary
- 16.8: Topics for Discussion
- 16.10: Bibliography

17: The Importance of Protected Areas

- 17.1: Introduction to the Importance of Protected Areas
- 17.2: Establishing Protected Areas
- 17.3: Classification of Protected Areas
- 17.4: Government Protected Areas in the US
- 17.5: Non-profit Organizations
- 17.6: Prioritization - What Should be Protected?
- 17.7: Designing Protected Areas
- 17.8: Challenges for Protected Areas
- 17.9: Summary
- 17.10: Topics for Discussion
- 17.11: Bibliography

18: Conservation on Unprotected Lands

- 18.1: Introduction to Conservation on Unprotected Lands
- 18.2: Human-Dominated Landscapes
- 18.3: Sustainable Agriculture
- 18.4: Smarter Infrastructure
- 18.5: Confronting Human-Wildlife Conflict
- 18.6: Data Dive- Landslides and Ag Terraces
- 18.7: Summary
- 18.8: Topics for Discussion
- 18.10: Bibliography

19: An Agenda for the Future

- 19.1: Introduction to An Agenda for the Future
- 19.2: Individual Choices
- 19.3: Introduction to Sustainability
  - 19.3.1: History of Sustainability
- 19.4: Achieving Sustainable Development

- 19.4.1: Sustainable Cities
- 19.4.2: Sustainability and the Future
- 19.5: Dealing with Technological Advances
- 19.6: Funding Conservation Activities
  - 19.6.1: Data Dive- Sustainable Investments
- 19.7: Building Lasting Partnerships
- 19.8: Environmental Education and Leadership
- 19.9: Summary
- 19.10: Review
- 19.11: Topics for Discussion
- 19.13: Bibliography

Index

Glossary

Detailed Licensing

Licensing

*A detailed breakdown of this resource's licensing can be found in **Back Matter/Detailed Licensing**.*

CHAPTER OVERVIEW

1: What is Conservation Biology?

1.1: Introduction to What is Conservation Biology?
1.2: Conservation Biology is Still Evolving
1.3: A Multidisciplinary Approach
1.4: History of US Conservation
1.5: Environmental Ethics
1.6: Summary
1.7: Topics for Discussion
1.9: Bibliography

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1.1: Introduction to What is Conservation Biology?

Popular interest in protecting **biological diversity**—which describes the amazing range of species, **genetic diversity** within each species, and the multitude of Earth's complex **biological communities** with their associated **ecosystem processes**—has intensified during the past few decades. During this time, scientists and the public have recognized that biological diversity (often shortened to **biodiversity**) is being lost at increasing rates. Across the world, human activities are destroying ecological communities that have developed over millions of years. Over the next several decades, thousands of species and millions of **populations** will likely go **extinct**.



Figure 1.1: East Africa's great migration is one of the most famous wildlife spectacles on Earth. Each year, tens of thousands of tourists from around the world flock to the region to see the 1.7 million common wildebeest (*Connochaetes taurinus*, LC) and hundreds of thousands of other plains mammals make their way from Tanzania's Ngorongoro Conservation Area, through the Serengeti Plains, to Kenya's Maasai Mara National Reserve. Photograph by Daniel Rosengren, https://commons.wikimedia.org/wiki/File:Wildebeest_Migration_in_Serengeti_National_Park,_Tanzania.jpg, CC BY 4.0.

The fundamental driver of all the biodiversity losses we are currently witnessing is a rapidly expanding human population coupled with increased consumptive needs. In 1850, after roughly 300,000 years of *Homo sapiens* on the planet, there were around 1 billion people on Earth. By 1987, not even 140 years later, the world's human population had surpassed 5 billion. By 2022, there were 8 billion humans globally. With this many people, the human population grows by tens of millions of people each year, even with modest population growth (Figure 1.2). In many parts of the world, this is well beyond the ecological capacity of the region to support.

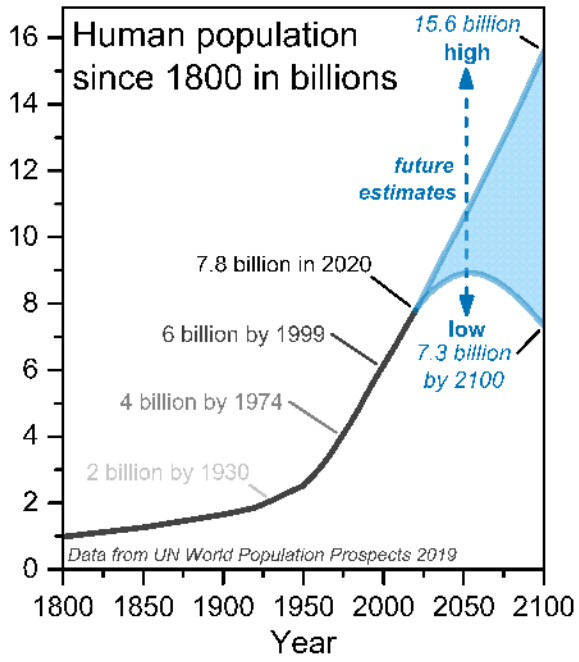


Figure 1.2: Human world population since 1800 with projections of future population (By Bdm25 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/inde...curid=89215845)

To survive and prosper, people use **natural resources**. They harvest and use oil, water, and wildlife products, and convert natural ecosystems for agriculture, cities, roads, and industrial activities. This consumption, which reduces natural **habitat** and the associated **wildlife** populations, is intensifying because of the demands of a rapidly increasing human population. Consumption of resources also increases as countries develop and industrialize: the average citizen of the USA uses five times more resources than the average global citizen, 11 times more than the average Chinese citizen, and 32 times more than the average Kenyan citizen (Worldwatch Institute, 2015). This growth in the number of humans, together with their ever-more-intensive use of natural resources, is the fundamental driver behind most current species extinctions.

For conservation biologists and other nature lovers, the widespread extinctions of species and destruction of natural ecosystems are incredibly discouraging. But it is possible, and indeed necessary, to find ways to ensure the persistence of biodiversity. Actions taken, or not taken, during the next few decades will determine how many species and natural areas will continue to survive. Someday, people will likely look back and say that this time—the first half of the 21st century—was an important and exciting time when people worked together, and acted locally and globally, to prevent the extinction of many species and ecosystems. Examples of successful conservation efforts are described throughout this textbook.

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1.2: Conservation Biology is Still Evolving

As a distinct scientific field, **conservation biology** is an integrated, multidisciplinary subject that developed in response to the challenge of preserving populations, species, ecosystems, and **biological interactions**. The main aim of conservation biology is to ensure the long-term preservation of biodiversity. To achieve its aim, conservation biology has set three goals:

- To document Earth's biological diversity.
- To investigate how humans influence species, **evolution**, and ecosystem processes.
- To investigate practical approaches to protect and restore biological communities, maintain genetic diversity, and prevent the extinction of species.

The first two goals describe typical scientific research investigating objective facts. The third goal, however, is a part of what makes conservation biology a **normative discipline**; that is, conservation biology incorporates human values, not just facts, to understand and achieve its value-laden goals (Lindenmayer and Hunter, 2010). In this sense, conservation biology is related to **environmentalism**, in which people aim to protect the natural environment for its own sake. However, conservation biology is at its core a **scientific discipline**; it is founded on scientific principles. This is not to say you must be a scientist to practice conservation biology; there are many people who are not scientists who apply the principles of conservation biology in their professional and personal lives.

The emergence of conservation biology as a distinct scientific field in the 1970s has given rise to the formation of various formal societies representing the field in a united voice. Most notable among these is the **Society for Conservation Biology (SCB**, Figure 1.2.1), which is a non-profit international professional organization with a mission to advance "the science and practice of conserving the Earth's biological diversity". To facilitate opportunities where like-minded people can share ideas locally, the SCB has regional branches which host regular conferences. In addition to the SCB, a great number of other local, national, and regional conservation organizations also exist and act as mouthpieces for grassroots movements and as custodians of nature. Many of these groups focus on specific animals or local protected areas. Others organically adapt their missions and visions in response to a specific need or threat.



Figure 1.2.1 The logo of the Society for Conservation Biology (SCB) has several layers of symbolism. Enclosed in the circle of life are ocean waves, representing change. The bird symbolizes beauty, and the leaves (the bird's wings) remind us of nature's productivity. Image courtesy of SCB, all rights reserved.

Conservation biology also has a history of adapting to new challenges. The very first conservation activities were geared towards securing the rights to valuable natural resources for people in powerful positions, such as kings and tribal chiefs, enforced through a strictly adherence to cultural norms and customary laws. But as a growing human population expanded its influence on the environment, and wildlife started to decline, earliest conservation models gradually shifted towards **fortress conservation** approaches (Wilshusen et al., 2002) which aimed to shield wildlife from people by setting aside protected areas where human activities were strictly controlled.

Today, however, as human populations are exploding, and consumption is increasing, even protected areas are increasingly unable to withstand the multitude of threats to biodiversity that ignore property boundaries and political borders. In response, fortress conservation approaches are beginning to make way for large-scale integrated activities that highlight the social and economic benefits of biodiversity conservation. To do this, new alliances are being formed and new agendas are being established, such as those that directly link human health with environmental health (Box 1.2.1). These **integrated conservation** philosophies that pursue strategies that benefit both humans and biodiversity show much promise because they focus on fundamental extinction

drivers, and advocate for more inclusive sustainable development. In this way, the practice of conservation has evolved from just a plan to save the environment to a vision that accomplishes its goals through sustainable development and social justice.

Yet, as we consider how to best invest limited conservation resources, some difficult questions arise. With seemingly more work to be done than can be accomplished, should we let some species go extinct (Bottrill et al., 2008)? Which species? Who decides? How can we even dare to think that we can play god? Such questions predictably bring about strongly opinionated and emotional debate (Soulé, 2013 vs. Marvier, 2014; Tallis and Lubchenco, 2014). Given the successful track record of fortress conservation initiatives in preventing extinctions despite limited budgets (Young et al., 2014), as well as the promising progress of more complex people-centerd initiatives (Pooley et al., 2014), it seems clear that conservation relies on some balance between these two conservation philosophies (Sodhi et al., 2011). Conservation biologists of tomorrow will be able to fine-tune the balance between these strategies by closely inspecting the successes and failures of our actions today.

Box 1.2.1 Conservation Through Public Health: A Case Study

Gladys Kalema-Zikusoka

Conservation Through Public Health, Kampala, Uganda.

http://www.ctph.org

Conservation Through Public Health (CTPH) is a grassroots non-governmental organization (NGO) and non-profit that promotes biodiversity conservation by enabling people, wildlife, and livestock to coexist. The organization was founded in 2003 after fatal scabies skin disease outbreaks in mountain gorillas (*Gorilla beringei beringei*, EN) were traced to people living around Bwindi Impenetrable National Park, Uganda, who had limited access to basic health services (Kalema-Zikusoka et al., 2002). Since then, CTPH has contributed to conservation and sustainable development in Africa by improving human and animal health and welfare in and around protected areas.

One of the main goals of CTPH is to reduce disease transfer between humans and gorillas. We accomplish this through an integrated population, health, and environment (PHE) program that was established in 2007 with funding from the US Agency for International Development (USAID). As a first step, piloted around Bwindi, CTPH held consultative meetings with local leaders, during which at least one Village Health and Conservation Team (VHCT) volunteer was selected from each village and two from each parish (consisting of 11 villages) to oversee distribution of family planning supplies. This initiative rapidly expanded into a sustainable social service delivery network that promotes family planning, hygiene, and sanitation. The network resulted in a 20% to 60% (national average is 30%) increase in new users to modern family planning, and a 10% to 60% increase in adoption of hand washing facilities at homes visited by VHCTs. VHCT volunteers also refer people suffering from infectious diseases and malnutrition to local health centres and promote more sustainable alternative livelihoods. Another group of community volunteers, the “Human and Gorilla Conflict Resolution” (HUGO) team, in turn collect gorilla faecal samples left on communal land to monitor their health (Figure 1.2.2), and visually monitor gorillas for clinical signs of disease inside and outside protected areas (Gaffikin and Kalema-Zikusoka, 2010). In the process, we have seen reduced disease incidences in the gorillas, reduced conflict between people and gorillas, and improved attitudes toward conservation. One unintended outcome has been increased gender equality: men are now more involved in family planning, and women are more involved in natural resource management.



Figure 1.2.2 A park ranger from the Uganda Wildlife Authority teaching HUGO community volunteers how to collect faecal samples from gorilla night nests during a CTPH training workshop. Photograph by CTPH, CC BY 4.0.

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1.3: A Multidisciplinary Approach

The field of conservation biology applies **scientific methods** to achieving its goals. Like the medical sciences, which apply principles from physiology, anatomy, and genetics to problems of human health, conservation biologists solve biodiversity problems using principles from fields, such as mathematics, veterinary medicine, social sciences, and several natural sciences (Figure 1.3.1). Conservation biology differs from these and other component disciplines in that its primary goal is the long-term preservation of biodiversity. Unlike many other scientific fields, conservation biology can also be described as a **crisis discipline** (Soulé, 1985; Kareiva and Marvier, 2012). That is, conservation biologists are often required to take creative steps to respond to imminent threats, typically without a complete knowledge of the systems requiring attention. Conservation scientists must also articulate long-term visions for conservation beyond solving immediate problems.

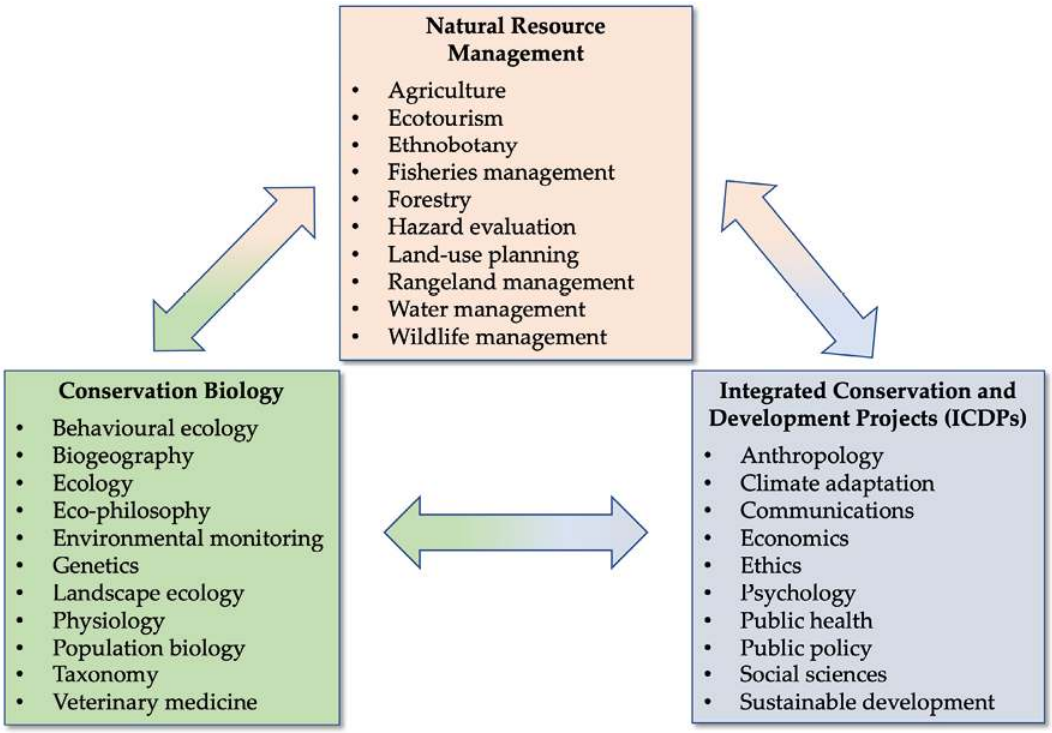


Figure 1.3.1 Conservation biology draws from many other sciences to protect biodiversity. It is closely related to natural resource management, which aims to manage biodiversity primarily for the benefit of humans. Integrated conservation and development projects (ICDP) are projects that manage nature for the benefit of both humans and biodiversity. After Kareiva and Marvier, 2012; Temple, 1991, CC BY 4.0.

To be effective, conservation biologists must demonstrate the relevance of their findings to a range of stakeholders. To be successful in this task, the importance of sound scientific principles cannot be over-emphasized. Nature is a complex network of many interdependent connections and **feedback loops**. Science is underpinned by principles that provide conservationists the necessary quantitative and qualitative tools to better measure and control for all these different aspects of biodiversity. Such measurements allow us to gain a better understanding of complex natural systems, and the consequences of human activities. Reliable, unbiased data obtained from sound and transparent scientific methods also facilitate policy making that is too often based on value judgments by non-experts who must balance many needs and different sources of information (Ntshotsho et al., 2015).

One of the cornerstones of modern science is to identify a hypothesis (a proposed explanation for a specific observation) to evaluate. The best hypotheses, often expressed as goals or objectives, are usually those that are SMART:

> Setting specific, measurable, realistic and timebound goals and objectives is essential for effective conservation.

Specific: not overly general;
Measurable: has both units and a method of measurement;
Attainable: realistic to achieve;
Relevant: related to what needs to be accomplished;
Time-bound: achievable within a specific timeframe.

Identifying SMART goals and objectives is an essential aspect of conservation biology. Without such benchmarks, practitioners cannot know whether their tasks were successful, or when management actions should be adjusted to achieve success. While this may seem obvious, many previous conservation projects have failed because biologists neglected to set SMART goals and objectives (Tear et al., 2005). While lofty, “We’re going to save all species” is not a SMART conservation goal because it is overly general, hard to measure, unrealistic, and not time bound. In contrast, “We want to protect 25% of our country’s wetlands within the next 10 years” is a SMART goal because it sets a very clear and measurable objective. In general, it is wise to set smaller short-term (e.g. quarterly), and medium-term (e.g. annual) goals as one works towards long-term (e.g. 5–10 years) objectives; this allows one to constantly assess progress, which in turn provides opportunities for celebrations and strategic adjustments as and when needed.

Biodiversity conservation, however, is not accomplished by simply setting SMART goals, measuring outcomes, and publishing results in scientific journals and reports. It is also important for conservation biologists to engage in **public outreach** activities, during which they can build on the public’s existing connection to nature, help them better understand the value of biodiversity in their local area, and enable them to actively contribute in conservation projects.

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1.4: History of US Conservation

Introduction

It is not uncommon to think of the sustainability paradigm as being a recent interpretation of environmental policy, one that was given credence by the United Nations report "Our Common Future" (the Brundtland Report) when it was first presented in 1987. However, it would be a mistake to conclude that sustainability as a mental construct and policy framework for envisioning the relationship of humans and nature came into being suddenly and at a single moment in time. Most environmental historians who have studied U.S. policy have discerned at least three distinct periods during which new concepts and ideas, scientific understandings, technological advances, political institutions, and laws and regulations came or were brought into being in order to understand and manage human impacts on the environment.

The American conservation movement: This 19th century movement had the main objective for conservation of American land and resources, it grew from opposite philosophies. On one side you had people like Gifford Pinchot (first head of the US National Forest Service) that were very pragmatic about their desire for conservation. For example, these people observed that policies for harvesting some resource (like lumber) were not sustainable, so they began conservation/sustainability research and new policies so the resource would not run out in the foreseeable future. On the other side were people like John Muir and Theodore Roosevelt that saw land/habitats/wildlife as intrinsic entities, meaning that had value in their own right (meaning nothing to do with money).



Figure 1.4.1: U.S. President Theodore Roosevelt (left) and nature preservationist John Muir, founder of the Sierra Club, on Glacier Point in Yosemite National Park. In the background: Upper and lower Yosemite Falls, 1903. (Public Domain, Wikimedia Commons)

The rise of environmental risk management as a basis for policy: The beginnings of environmental risk management can be traced to the fields of public health, industrial hygiene, and sanitary engineering, which came into prominence in the latter decades of the 19th century and beginning of the 20th. The spread of disease was a particularly troublesome problem as the country continued to urbanize. In addition, environmental scientists of the day were alarmed by the extent and degree of damage that they were documenting. The publication of *Silent Spring* in 1962 by Rachel Carson (1907-1964)(Figure 1.4.2), about the impact of the widespread and indiscriminate use of pesticides, was a watershed moment, bringing environmental concerns before a large portion of the American, and global, public. Carson, collected scientifically documented evidence on the effects of pesticides, particularly DDT, heptachlor, and dieldrin, on humans and mammals, and the systemic disruption they caused to ecosystems. *Silent Spring* is credited with bringing about a ban on the use of DDT in the United States, and setting in motion a chain of events that would ultimately result in the transformation of environmental public policy from one based on the problems and attitudes that brought about nineteenth century conservation, to one based on the management of risks from chemical toxins. The U.S. Environmental

Protection Agency was established in 1970, just eight years after the publication of *Silent Spring*. The same year Earth Day was created.



Figure 1.4.2: Rachel Carson, author of "The Sea Around Us" and "Silent Spring." She was a biologist for the US Fish and Wildlife Service and an author. Her book "Silent Spring" is credited with bringing environmental awareness to the forefront of the public. (Photo 1940 US FWS, Public Domain)

The integration of social and economic factors to create what we now refer to as the sustainability paradigm: Eventually, we (humanity) realized that in order to solve environmental issues (like ones identified by Rachel Carson), that the "human factors" (both social and economical) had to be accounted for. This is what defines the sustainability paradigm: environmental, social, and economic disciplines. Only Band-Aid solutions can be applied if we only take a one-minded approach.

History of Environmental Policy

Environmental policies are typically driven by problems of the day, real and perceived, that require systemic solutions. For example:

- Early conservationists were alarmed at the inefficiencies of human resource management and the encroachment of humans on unspoiled lands... Leading to conservation legislation.
- During the 20th century many groups (scientists, economists, politicians, and ordinary citizens) became alarmed and fearful of the consequences of toxic pollutant loads to the environment that included localized effects on human health and well-being... Leading to clean air and water legislation.
- As we proceed into the 21st century, an array of complex problems that have the potential to alter substantially the structure and well-being of large segments of human societies, calls for a renewal and reassessment of our approach to environmental policy.

This has, thus far, proven to be a difficult transition. Many of these complex problems have multiple causes and impacts, affect some groups of people more than others, are economically demanding, and are often not as visibly apparent to casual observers as previous impacts, nor are the benefits perceived to be commensurate with costs. Devising a regulatory strategy for such problems requires an adaptive and flexible approach that current laws do not foster.

Table 1.4.*a***:** Table illustrating evolution of environmental policy. Table by Sustainability: A Comprehensive Foundation in Openstax (CC-BY).

	1850-1920	1960-1990	1990-Present
Focus	Conservation/sanitation	Media/site/problem specific	Complex regional/ global problems
Outcome	Land preservation/efficiency/control of disease	Manage anthropocentric and ecological risk	Global sustainable development
Principal Activity	Resource management reform/simple contaminant controls	Compliance/remediation/technological emphasis on problem solving	Integration of social, economic, and technological information for holistic problem solving
Economic Focus	Profit maximization/public health	Cost minimization	Strategic investments/long-term societal well-being
Regulatory Activity	Low	Heavy	Adaptive and flexible
Conceptual Model	Expansion vs preservation	Command and control	Systems/life cycle approach
Disciplinary Approach	Disciplinary and insular	Multidisciplinary	Interdisciplinary/integrative

Table 1.4.*b***:** Table illustrating major environmental legislation, society, and organization conceptions. Table by Rachel Schleiger (CC-BY-NC).

Year	Policy/Society/Organization Conception
1899	Refuse Act
1905	National Forest Service
1916	National Park Service
1918	Migratory Bird Treaty Act
1930's	State Parks
1948	Federal Water Pollution Control Act
1950	The Nature Conservancy
1955	Air Pollution Control Act
1961	World Wildlife Federation
1963	Clean Air Act (1970, 1977, 1990 updates)
1965	Solid Waste Disposal Act (1976 update)
1965	Water Quality Act (1987 update)
1967	Air Quality Act
1969	National Environmental Policy Act
1970	Occupational Safety and Health Act
1970	Environmental Protection Agency
1971	Occupational Safety and Health Administration
1972	Consumer Product Safety Act
1972	Federal Insecticide, Fungicide, and Rodenticide Act
1972	Clean Water Act (1977 update)
1972	Noise Control Act
1973	Endangered Species Act
1974	Safe Drinking Water Act (1986, 1996 updates)
1975	Hazardous Materials Transportation Act
1976	Resource Conservation and Recovery Act
1976	Toxic Substances Control Act
1980	CERCLA (Superfund)
1984	Hazardous and Solid Waste Amendments
1986	Superfund Amendments and Reauthorization Act
1986	Emergency Wetlands Resources Act
1990	Oil Pollution Act
1993	North American Free Trade Agreement
2003	Healthy Forest Initiative

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1.5: Environmental Ethics

The concept of **ethics** involves standards of conduct. These standards help to distinguish between behavior that is considered right and that which is considered wrong. As we all know, it is not always easy to distinguish between right and wrong, as there is no universal code of ethics. For example, a poor farmer clears an area of rainforest in order to grow crops. Some would not oppose this action, because the act allows the farmer to provide a livelihood for his family. Others would oppose the action, claiming that the deforestation will contribute to soil erosion and global warming. Right and wrong are usually determined by an individual's morals, and to change the ethics of an entire society, it is necessary to change the individual ethics of a majority of the people in that society.

Moral extensionism defines how far a persons values extend outside of themselves (Figure 1.5.1). There are many variables that can influence where the limit lies for each individual person. For example: religion, culture, education, and personal interests (just to name a few).



Figure 1.5.1: Scope of consideration for moral extensionism. Image by Rachel Schleiger (CC-BY-NC).

Most human societies today aim to protect biodiversity through rules and regulations. An alternative approach is to change the fundamental materialistic values of modern society to values that prioritize genuine and lasting human well-being. This is the goal of **environmental ethics**, a discipline within philosophy that emphasizes the ethical values of biodiversity. The foundation of environmental ethics lies in the philosophical principle that every organism of Earth has a right to exist, regardless of its usefulness to humans, so any action that negatively impacts biodiversity would be considered unethical.

Because human quality of life is intricately linked to the ability of the natural world to prosper, the ethical arguments for biodiversity conservation hold even for people who value only human life. Or, in other words, respect for human life—even our instincts for self-preservation—should compel us to preserve biodiversity. In contrast, if we neglect our assumed responsibility to act as guardians of life on Earth, future generations will suffer with a lower quality of life. We can already see signs of this today: as species are lost and natural ecosystems replaced with sprawling cities, children are increasingly deprived of the wonderful experience of seeing a ‘new’ animal (Figure 1.4.1) or pretty flower. We can imagine that we are borrowing Earth from future generations, and that it is our responsibility to ensure that they receive it in good condition.



Figure 1.4.1 A ragged-tooth shark (*Carcharias taurus*, VU) fascinates two kids at the Two Oceans Aquarium, South Africa. People —and especially kids— enjoy seeing wildlife, as shown by the increased popularity of protected areas, zoos, and other institutions where biodiversity can be seen. Photograph by Karen Schermbrucker, courtesy of Two Oceans Aquarium, CC BY 4.0.

Because of this close link between nature and human well-being, the concept of nature preservation has permeated through the value systems of human cultures, philosophies, and religions throughout history. Often traditional societies have a deep connection with nature that is woven into their spiritual beliefs and customs (Figure 1.4.2). Our responsibility to protect animals is also explicitly described in Jewish, Christian, and Islamic traditions. Other major religions, including Hinduism, Buddhism, and Taoism also strongly support the preservation of non-human life. In light of accelerated biodiversity losses, faith-based groups have recently started playing a more active role in conservation, particularly among urbanized people. They do this by informing adherents that it is wrong to allow the destruction of nature, and that such destructive activities can have negative consequences for all people on Earth. These links between faith-based organizations and conservation have given rise to consortiums such as the Forum on Religion and Ecology (http://fore.yale.edu), the Alliance of Religions and Conservation (http://www.arcworld.org), and the SCB's Religion and Conservation Working Group (https://twitter.com/ReligionConBio), as well as the emerging field of spiritual ecology (Vaughan-Lee, 2016).



Figure 1.4.2 The spiritual connection between people and nature features strongly in ancient rock art made by Bushmen (also known as San, or First People) of Southern Africa, believed to be the oldest human population on Earth. Pictured here is a common eland (Tragelaphus oryx, LC), drawn by shamans to open the portals of the spiritual world. Photograph by Alan Manson, https://commons.wikimedia.org/wiki/File:Shaman_at_work_Game_Pass_2004_0522_121946AA.jpg, CC BY 4.0.

Environmental ethics has strong links to the **environmental justice** movement and has recently established strong ties to the social justice movement. Some of the most exciting developments in this direction involve initiatives that combine protection activities with community upliftment programs that improve the well-being of local peoples. These developments have shown that when poor and marginalized people are empowered to protect the environment, they may act as strong local guardians of forests, coastal areas, and other ecosystems that may have been destroyed otherwise.

1.4.1 Conservation biology's ethical principles

Conservation biology rests on a set of underlying ethical principles that is generally agreed upon (Soulé, 1985) and can be summarized as follows:

- *The diversity of species and biological communities should be preserved*: Most people appreciate biodiversity. Hundreds of millions of people visit national parks, game reserves, zoos, botanical gardens, and aquaria each year. They spend money and take actions to protect these places and species. People also recognize that biodiversity has economic value, whether through tourism, consumption, or other services.
- *The untimely extinction of populations and species should be prevented*: Throughout history, species have occasionally died off as a result of natural, non-human causes. The loss of a local population was generally temporary, until a new population established itself through dispersal. However, human activities have increased the rate at which species are going extinct by more than a hundredfold. Meanwhile, there is no similar increase in the rate at which new populations and species are being created.

- *Ecological complexity should be maintained*: In complex natural environments, biodiversity expresses many of its most valuable features and interactions. Although the biodiversity of species may be partially preserved in captivity, maintaining ecological complexity requires that natural areas be preserved.
- *Evolution should continue*: Evolution creates new species, increases biodiversity over time, and facilitates adaptation to changing environmental conditions. People can help preserve these evolutionary processes by maintaining genetic diversity in wild populations and allowing populations to exchange genetic material. In captivity, many natural evolutionary processes do not occur, which can hamper survival when species are **reintroduced** in the wild.
- *Biodiversity has intrinsic value*: The value of species, communities, and ecosystems does not depend on their utility to people. They are **intrinsically valuable** on their own, with unique evolutionary histories and ecological roles. There are certain iconic species that people simply want to have around, but other, lesser-known species or species seen as problematic to people are not less valuable.

  These principles are not absolute, nor are conservation biologists required to agree with them—they are actively discussed and debated. But many individuals and organizations agree with two, three, or all the principles, and support conservation efforts.

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1.6: Summary

1. Conservation biology has three goals: (a) to document Earth's biological diversity; (b) to investigate how humans influence species, evolution, and ecosystem processes; and (c) to investigate approaches to protect and restore biological communities, maintain genetic diversity, and prevent the extinction of species.
2. Because conservation is multidisciplinary and requires a deep understanding of natural processes and human society, conservation biologists must take on multiple roles. Specifically, conservation biologists, as a group, must be curious, good communicators, effective educators, law-abiding citizens, and effective managers and practitioners of conservation projects.
3. Conservation biology relies on scientific evidence and ethical principles that underpins the preservation of biodiversity. Conservation biologists generally agree that biodiversity should be preserved, untimely extinctions should be prevented, ecological complexity should be maintained, evolution should continue, and biodiversity has intrinsic value.
4. Science provides conservation biologists with useful tools that guide the setting of clear, achievable, and measurable goals, to monitor conservation actions to assess whether goals have been met, and to communicate in a clear and unbiased manner.
5. Environmental ethics appeals to people of different walks to life to preserve biodiversity. It holds that biodiversity must also be protected because human well-being and economic opportunities are linked to a healthy environment.

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1.7: Topics for Discussion

1. Is conservation biology substantially different in its approach from other fields of science, such as physics, chemistry, or medicine? If so, how? How is it linked to but different from environmentalism and social justice?
2. Looking at the titles of Chapters 9-11, what do you think are the biggest threats to biodiversity near where you live? Explain your answers.
3. There have been three broad conservation approaches throughout history: early models that secured natural resources for powerful people, fortress conservation, and integrated conservation. How do these approaches differ and how do they complement each other? How do you think each of these approaches can contribute to conservation today?
4. Which statements about the ethical principles of conserving biodiversity in this chapter do you agree with? Which do you disagree with? Explain your answers.

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CHAPTER OVERVIEW

2: The Process of Science

2.1: What is Science?
2.2: The Scientific Method
2.3: Scientific Papers
2.4: Basic and Applied Science
2.5: Data Dive- California Wildfires
2.6: Review

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2.1: What is Science?

Like other natural sciences, environmental science gathers knowledge about the natural world. Science is more than just a body of knowledge, science provides a means to evaluate and create new knowledge. The methods of science include careful observation, record keeping, logical and mathematical reasoning, experimentation, and submitting conclusions to the scrutiny of others. Science also requires considerable imagination and creativity; a well-designed experiment is commonly described as elegant or beautiful. Science has considerable practical implications and some science is dedicated to practical applications, such as the prevention of disease (figure 2.1.*a*). Other science proceeds largely motivated by curiosity. Whatever its goal, there is no doubt that science has transformed human existence and will continue to do so.

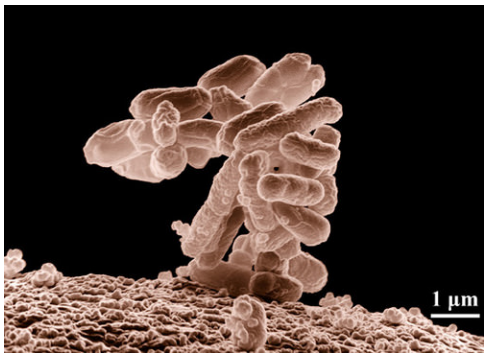


Figure 2.1.*a*: Biologists may choose to study *Escherichia coli* (*E. coli*), a bacterium that is a normal resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. In this micrograph, the bacterium is visualized using a scanning electron microscope and digital colorization. (credit: Eric Erbe; digital colorization by Christopher Pooley, USDA-ARS)

There are areas of knowledge, however, to which the methods of science cannot be applied. These include such things as morality, aesthetics, or spirituality. Science cannot investigate these areas because they are outside the realm of material phenomena, the phenomena of matter and energy, and cannot be observed and measured.

Evidence, Measurements, and Observations

Scientists use objective evidence over subjective evidence, to reach sound and logical conclusions. An **objective** observation is without personal bias and the same by all individuals. **Bias** refers to favoring one thing over another, and it can lead to inaccurate results. Humans are biased by nature, so they cannot be completely objective; the goal is to be as unbiased as possible. A **subjective** observation is based on a person's feelings and beliefs and is unique to that individual (figure 2.1.*b*).



Figure 2.1.*b*: This is Grand Canyon of the Yellowstone in Yellowstone National Park. An objective statement about this would be, "The picture is of a waterfall." A subjective statement would be, "The picture is beautiful."

Another way scientists avoid bias is by using quantitative over qualitative measurements whenever possible. A **quantitative measurement** is expressed with a specific numerical value. **Qualitative observations** are general or relative descriptions. For example, describing a rock as red or heavy is a qualitative observation. Determining a rock's color by measuring wavelengths of reflected light or its density by measuring the proportions of minerals it contains is quantitative. Numerical values are more precise than general descriptions, and they can be analyzed using statistical calculations. This is why quantitative measurements are much more useful to scientists than qualitative observations.

Inductive and Deductive Reasoning

One thing is common to all forms of science: an ultimate goal to know. Curiosity and inquiry are the driving forces for the development of science. Scientists seek to understand the world and the way it operates. Two methods of logical thinking are used: inductive reasoning and deductive reasoning.

Inductive reasoning is a form of logical thinking that uses related observations to arrive at a general conclusion. This type of reasoning is common in **descriptive science**. A life scientist such as a biologist makes observations and records them. The raw data can be supplemented with drawings, pictures, photos, or videos. From many observations, the scientist can infer conclusions (inductions) based on evidence. Inductive reasoning involves formulating generalizations inferred from careful observation and the analysis of a large amount of data. Surveying land use (which areas are forested, agricultural, urban, etc.) across the United States and then concluding that forested areas are concentrated in the West is an example of descriptive science.

In deductive reasoning, the pattern of thinking moves in the opposite direction as compared to inductive reasoning. **Deductive reasoning** is a form of logical thinking that uses a general principle or law to forecast specific results. From those general principles, a scientist can extrapolate and predict the specific results that would be valid as long as the general principles are valid. For example, a prediction would be that if the climate is becoming warmer in a region, the distribution of plants and animals should change. Comparisons have been made between distributions in the past and the present, and the many changes that have been found are consistent with a warming climate. Finding the change in distribution is evidence that the climate change conclusion is a valid one. Deductive reasoning, or deduction, is the type of logic used in hypothesis-based science (see below).

To summarize, inductive reasoning moves from the specific (an observation) to general (conclusion), and deductive reasoning moves from the general (a hypothesis or principle) to the specific (results).

Both types of logical thinking are related to the two main pathways of scientific study: descriptive science and hypothesis-based science. **Descriptive** (or discovery) **science** aims to observe, explore, and discover, while **hypothesis-based science** begins with a specific question or problem and a potential answer or solution that can be tested. The boundary between these two forms of study is often blurred, because most scientific endeavors combine both approaches. Observations lead to questions, questions lead to forming a hypothesis as a possible answer to those questions, and then the hypothesis is tested. Thus, descriptive science and hypothesis-based science are in continuous dialogue.

Science is also a Social Process

Scientists share their ideas with peers at conferences, seeking guidance and feedback (figure 2.1.*c*). Research papers and data submitted for publication are rigorously reviewed by qualified peers, scientists who are experts in the same field. The scientific review process aims to weed out misinformation, invalid research results, and wild speculation. Thus, it is slow, cautious, and conservative. Scientists tend to wait until a hypothesis is supported by an overwhelming amount of evidence from many independent researchers before accepting it as a **scientific theory**.



Figure 2.1.*c*: Scientists share information by publishing and attending conferences. The conference shown here focuses on peanut and mycotoxin (harmful chemicals produced by fungi) research. Image by Sharon Dowdy (CC-BY-NC).

Characteristics of Scientists

There is nothing mysterious or even particularly unusual about the things that scientists do. There are many ways to work on scientific problems. They all require common sense. Beyond that, they all display certain features that are especially - but not uniquely - characteristic of science.

- Skepticism — Good scientists use highly-critical standards in the judging of evidence. They approach data, claims, and theories (ideally, even their own!) with healthy doses of skepticism.
- Tolerance of uncertainty — Scientists often work for years - sometimes for an entire career - trying to understand one scientific problem. This often involves finding facts that, for a time, fail to fit into any coherent pattern and that even may support mutually contradictory explanations. Sometimes, as one listens to scientists vigorously defending their views, their confidence seems absolute. But deep in their hearts, they know that their views are based on probabilities and that a new piece of evidence may turn up at any time and force a major shift in their views.
- Although they certainly have no monopoly on hard work, their willingness to work long hours and years pursuing a problem is the mark of all good scientists. For science is hard work.

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2.2: The Scientific Method

The **scientific method** is a process of research with defined steps that include data collection and careful observation.

Observation

Scientific advances begin with **observations**. This involves noticing a pattern, either directly or indirectly from the literature. An example of a direct observation is noticing that there have been a lot of toads in your yard ever since you turned on the sprinklers, where as an indirect observation would be reading a scientific study reporting high densities of toads in urban areas with watered lawns.

During the Vietnam War (figure $2.2.a$), press reports from North Vietnam documented an increasing rate of birth defects. While this credibility of this information was initially questioned by the U.S., it evoked questions about what could be causing these birth defects. Furthermore, increased incidence of certain cancers and other diseases later emerged in Vietnam veterans who had returned to the U.S. This leads us to the next step of the scientific method, the question.

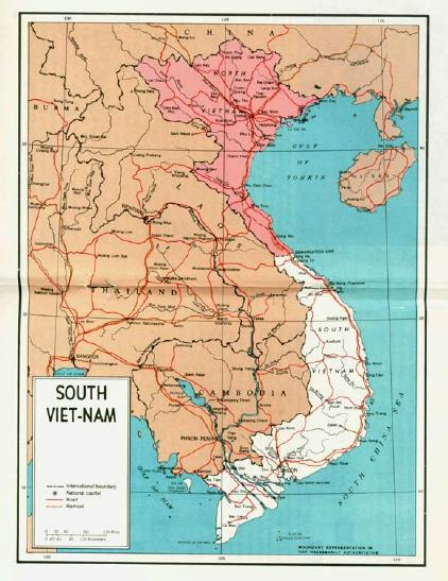


Figure $2.2.a$: A map of Vietnam 1954-1975. Image from Bureau of Public Affairs U.S. Government Printing Office (public domain).

Question

The **question** step of the scientific method is simply asking, what explains the observed pattern? Multiple questions can stem from a single observation. Scientists and the public began to ask, what is causing the birth defects in Vietnam and diseases in Vietnam veterans? Could it be associated with the widespread military use of the herbicide Agent Orange to clear the forests (figure $2.2.b-c$), which helped identify enemies more easily?



Figure $2.2.b$: Agent Orange drums in Vietnam. Image by U.S. Government (public domain).



Figure 2.2.*c*: A healthy mangrove forest (top), and another forest after application of Agent Orange. Image by unknown author (public domain).

Hypothesis and Prediction

The **hypothesis** is the expected answer to the question. The best hypotheses state the proposed direction of the effect (increases, decreases, etc.) and explain why the hypothesis could be true.

- OK hypothesis: Agent Orange influences rates of birth defects and disease.
- Better hypothesis: Agent Orange increases the incidence of birth defects and disease.
- Best hypothesis: Agent Orange increases the incidence of birth defects and disease because these health problems have been frequently reported by individuals exposed to this herbicide.

If two or more hypotheses meet this standard, the simpler one is preferred.

Predictions stem from the hypothesis. The prediction explains what results would support hypothesis. The prediction is more specific than the hypothesis because it references the details of the experiment. For example, "If Agent Orange causes health problems, then mice experimentally exposed to TCDD, a contaminant of Agent Orange, during development will have more frequent birth defects than control mice" (figure 2.2.*d*).

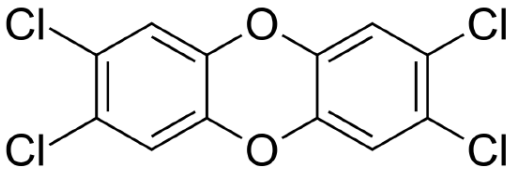


Figure 2.2.*d*: The chemical structure of TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin), which is produced when synthesizing the chemicals in Agent Orange. It contaminates Agent Orange at low but harmful concentrations. Image by Emeldir (public domain).

Hypotheses and predictions must be testable to ensure that it is valid. For example, a hypothesis that depends on what a bear thinks is not testable, because it can never be known what a bear thinks. It should also be **falsifiable**, meaning that they have the capacity to be tested and demonstrated to be untrue. An example of an unfalsifiable hypothesis is “Botticelli’s *Birth of Venus* is beautiful.” There is no experiment that might show this statement to be false. To test a hypothesis, a researcher will conduct one or more experiments designed to eliminate one or more of the hypotheses. This is important. A hypothesis can be disproven, or eliminated, but it can never be proven. Science does not deal in proofs like mathematics. If an experiment fails to disprove a hypothesis, then we find support for that explanation, but this is not to say that down the road a better explanation will not be found, or a more carefully designed experiment will be found to falsify the hypothesis.

Hypotheses are tentative explanations and are different from scientific theories. A **scientific theory** is a widely-accepted, thoroughly tested, and confirmed explanation for a set of observations or phenomena. Scientific theory is the foundation of scientific knowledge. In addition, in many scientific disciplines (less so in biology) there are **scientific laws**, often expressed in mathematical formulas, which describe how elements of nature will behave under certain specific conditions, but they do not offer explanations for why they occur.

Design an Experiment

Next, a scientific study (experiment) is planned to test the hypothesis and determine whether the results match the predictions. Each experiment will have one or more variables. The **independent variable** is what scientists hypothesize might be causing something else. In a manipulative experiment (see below), the independent variable is manipulated by the scientist. The **dependent variable** is the response, the variable ultimately measured in the study. **Controlled variables** (confounding factors) might affect the dependent variable, but they are not the focus of the study. Scientist attempt to standardize the controlled variables so that they do not influence the results. In our previous example, exposure to Agent Orange is the independent variable. It is hypothesized to cause a change in health (likelihood of having children with birth defects or developing a disease), the dependent variable. Many other things could affect health, including diet, exercise, and family history. These are the controlled variables.

There are two main types of scientific studies: experimental studies (manipulative experiments) and observational studies.

In a **manipulative experiment**, the independent variable is altered by the scientists, who then observe the response. In other words, the scientists apply a **treatment**. An example would be exposing developing mice to TCDD and comparing the rate of birth defects to a control group. The **control group** is group of test subjects that are as similar as possible to all other test subjects, with the exception that they don't receive the experimental treatment (those that do receive it are known as the experimental, treatment, or **test group**). The purpose of the control group is to establish what the dependent variable would be under normal conditions, in the absence of the experimental treatment. It serves as a baseline to which the test group can be compared. In this example, the control group would contain mice that were not exposed to TCDD but were otherwise handled the same way as the other mice (figure 2.2.*e*)



Figure 2.2.*e*: Laboratory mice. In a proper scientific study, the treatment would be applied to multiple mice. Another group of mice would not receive the treatment (the control group). Image by Aaron Logan (CC-BY).

In an **observational study**, scientists examine multiple samples with and without the presumed cause. An example would be monitoring the health of veterans who had varying levels of exposure to Agent Orange.

Scientific studies contain many **replicates.** Multiple samples ensure that any observed pattern is due to the treatment rather than naturally occurring differences between individuals. A scientific study should also be **repeatable**, meaning that if it is conducted again, following the same procedure, it should reproduce the same general results. Additionally, multiple studies will ultimately test the same hypothesis.

Results

Finally, the data are collected and the results are analyzed. As described in the Math Blast chapter, statistics can be used to describe the data and summarize data. They also provide a criterion for deciding whether the pattern in the data is strong enough to support

the hypothesis.

The manipulative experiment in our example found that mice exposed to high levels of 2,4,5-T (a component of Agent Orange) or TCDD (a contaminant found in Agent Orange) during development had a cleft palate birth defect more frequently than control mice (figure 2.2.f). Mice embryos were also more likely to die when exposed to TCDD compared to controls.



Figure 2.2.f: Cleft lip and palate, a birth defect in which these structures are split. Image by James Heilman, MD (CC-BY-SA).

An observational study found that self-reported exposure to Agent Orange was positively correlated with incidence of multiple diseases in Korean veterans of the Vietnam War, including various cancers, diseases of the cardiovascular and nervous systems, skin diseases, and psychological disorders. Note that a **positive correlation** simply means that the independent and dependent variables both increase or decrease together, but further data, such as the evidence provided by manipulative experiments is needed to document a **cause-and-effect relationship**. (A **negative correlation** occurs when one variable increases as the other decreases.)

Conclusion

Lastly, scientists make a conclusion regarding whether the data support the hypothesis. In the case of Agent Orange, the data, that mice exposed to TCDD and 2,4,5-T had higher frequencies of cleft palate, matches the prediction. Additionally, veterans exposed to Agent Orange had higher rates of certain diseases, further supporting the hypothesis. We can thus accept the hypothesis that Agent Orange increases the incidence of birth defects and disease.

In practice, the scientific method is not as rigid and structured as it might first appear. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds (figure 2.2.g). Even if the hypothesis was supported, scientists may still continue to test it in different ways. For example, scientists explore the impacts of Agent Orange, examining long-term health impacts as Vietnam veterans age.

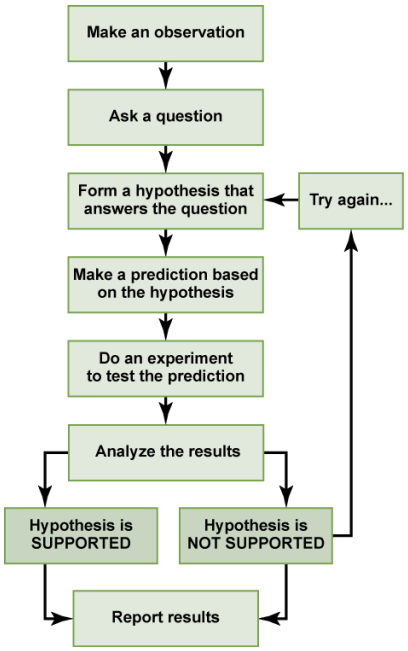


Figure 2.2.*g*: The scientific method is a series of defined steps that include experiments and careful observation. The steps are as follows: make an observation; ask a question; form a hypothesis that answers the question; make a prediction based on the hypothesis; do an experiment to test the prediction; analyze the results; and report the results. Whether the hypothesis is supported or not supported, the results are still reported. If a hypothesis is not supported by data, a new hypothesis can be proposed.

Scientific findings can influence decision making. In response to evidence regarding the effect of Agent Orange on human health, compensation is now available for Vietnam veterans who were exposed to Agent Orange and develop certain diseases. The use of Agent Orange is also banned in the U.S. Finally, the U.S. has began cleaning sites in Vietnam that are still contaminated with TCDD.

Building on the Work of Others

Only rarely does a scientific discovery spring full-blown on the scene. When it does, it is likely to create a revolution in the way scientists perceive the world around them and to open up new areas of scientific investigation. Darwin's theory of evolution and Mendel's rules of inheritance are examples of such revolutionary developments. Most science, however, consists of adding another brick to an edifice that has been slowly and painstakingly constructed by prior work.

The development of a new technique often lays the foundation for rapid advances along many different scientific avenues. Just consider the advances in biology that discovery of the light microscope and, later, the electron microscope have made possible. Throughout these pages, there are many examples of experimental procedures. Each was developed to solve a particular problem. However, each was then taken up by workers in other laboratories and applied to their problems.

In a similar way, the creation of a new explanation (hypothesis) in a scientific field often stimulates workers in related fields to reexamine their own field in the light of the new ideas. Darwin's theory of evolution, for example, has had an enormous impact on virtually every subspecialty in biology as well as environmental science. To this very day, scientists in specialties as different as biochemistry and conservation biology are guided in their work by evolutionary theory (figure 2.2.*g*).



Figure 2.2.*h*: Understanding the endangered mountain yellow-legged frog through the lens of evolution and genetics has aided its conservation. Image by Iasaac Chellman/NPS (CC-BY).

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2.3: Scientific Papers

This section discusses what peer review is and how scientific papers are structured.

Peer Review

Scientists must share their findings for other researchers to expand and build upon their discoveries. For this reason, an important aspect of a scientist's work is disseminating results and communicating with peers. Scientists can share results by presenting them at a scientific meeting or conference, but this approach can reach only the limited few who are present. Instead, most scientists present their results in peer-reviewed articles that are published in scientific journals (figure 2.3.a). **Peer-reviewed articles** are scientific papers that are evaluated, usually anonymously by a scientist's colleagues, or peers. These colleagues are qualified individuals, often experts in the same research area, who judge whether or not the scientist's work is suitable for publication. Peer reviewers assess experimental design, statistical analysis, presentation of data, and whether conclusions fit the results. The process of peer review helps to ensure that the research described in a scientific paper is original, significant, logical, ethical, and thorough. Scientists publish their work so other scientists can reproduce their experiments under similar or different conditions to expand on the findings. The experimental results must be consistent with the findings of other scientists.



Figure 2.3.a: The findings of scientific studies are published in peer-reviewed scientific journals. Image by free svg (public domain).

As you review scientific information, whether in an academic setting or as part of your day-to-day life, it is important to think about the credibility of that information. You might ask yourself: has this scientific information been through the rigorous process of peer review? Are the conclusions based on available data and accepted by the larger scientific community? Scientists are inherently skeptical, especially if conclusions are not supported by evidence (and you should be too).

Structure of Scientific Papers

Scientific papers are usually divided into several sections (not necessarily in this order).

Summary or Abstract

This section includes only the essence of the other sections. It should be as brief as possible, telling the reader what the goal of the experiment was, what was found, and the significance of the findings. The abstract is often placed at the beginning of the paper rather than at its end.

Introduction

This section of the paper describes the scientific question or problem that was the subject of the investigation. The introduction also includes references to earlier reports of these and other scientists that have served as the foundation for the present work. Finally, the introduction states the hypothesis.

Materials and Methods

Here are precisely described the materials used (e.g., strains of organism, source of the reagents) and all the methods followed. The goal of this section is to give all the details necessary for workers in other laboratories to be able to **repeat the experiments exactly**. When many complex procedures are involved, it is acceptable to refer to earlier papers describing these methods in greater detail.

Results

Here the authors report what happened in their experiments. This report is usually supplemented with graphs, tables, and photographs.

Discussion

Here the authors point out what they think is the significance of their findings. This is the place to show that the results are compatible with certain hypotheses and less compatible, or even incompatible, with others. If the results contradict the results of similar experiments in other laboratories, the discrepancies are noted here, and an attempt may be made to reconcile the differences.

Acknowledgments

In this brief but important section, the authors give credit to those who have assisted them in the work. These usually include technicians (who may have actually performed most of the experiments!) and other scientists who donated materials for the experiments and/or gave advice about them.

References

This section gives a careful listing of all earlier scientific work referred to in the main body of the paper. Most of the references are to other scientific papers. Each reference should provide enough information so that another person can locate the document. This means that each reference should include the name(s) of the author(s), the journal or book in which the report appears, and the year of publication. In the case of scientific journals, the volume number in which the paper appears and the page number on which the paper begins should be included. A digital object identifier (DOI) or url is often included. The full title of the article is often included as well, although some citation styles omit the title from the reference.

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2.4: Basic and Applied Science

Is it valuable to pursue science for the sake of simply gaining knowledge, or does scientific knowledge only have worth if we can apply it to solving a specific problem or bettering our lives? This question focuses on the differences between two types of science: basic science and applied science.

Basic science or “pure” science seeks to expand knowledge regardless of the short-term application of that knowledge. It is not focused on developing a product or a service of immediate public or commercial value. The immediate goal of basic science is knowledge for knowledge’s sake, though this does not mean that in the end it may not result in an application. Questions such as, "How have plants evolved to attract pollinators?" and "What factors determine which species will co-occur with each other?" fall under the scope of basic science (figure 2.4.*a*).



Figure 2.4.*a*: Many different plant species are co-occurring (growing together) at the Brisbane Botanic Gardens. Exploring which plants co-occur naturally falls under the scope of basic science. Image by Brisbane City Council (CC-BY).

In contrast, **applied science** aims to use science to solve real-world problems, such as improving crop yield, find a cure for a particular disease, or save animals threatened by a natural disaster. In applied science, the problem is usually defined for the researcher.

A layperson (nonscientist) may perceive applied science as “useful” and basic science as “useless”, posing the question, "What for?" to a scientist advocating knowledge acquisition. A careful look at the history of science, however, reveals that basic knowledge has resulted in many remarkable applications of great value. Many scientists think that a basic understanding of science is necessary before an application is developed; therefore, applied science relies on the results generated through basic science. Other scientists think that it is time to move on from basic science and instead to find solutions to actual problems. Both approaches are valid. It is true that there are problems that demand immediate attention; however, few solutions would be found without the help of the knowledge generated through basic science.

One example of how basic and applied science can work together to solve practical problems occurred after the discovery of DNA structure led to an understanding of the molecular mechanisms governing DNA replication. Strands of DNA, unique in every human, are found in our cells, where they provide the instructions necessary for life. During DNA replication, new copies of DNA are made, shortly before a cell divides to form new cells. Understanding the mechanisms of DNA replication (through basic science) enabled scientists to develop laboratory techniques that are now used to identify genetic diseases, pinpoint individuals who were at a crime scene, and determine paternity (all examples of applied science). Without basic science, it is unlikely that applied science would exist.

Another example of the link between basic and applied research is the Human Genome Project, a study in which each human chromosome was analyzed and mapped to determine the precise sequence of the DNA code and the exact location of each gene. (The gene is the basic unit of heredity; an individual’s complete collection of genes is his or her genome.) Other organisms have also been studied as part of this project to gain a better understanding of human chromosomes. The Human Genome Project (figure 2.4.*b*) relied on basic research carried out with non-human organisms and, later, with the human genome. An important end goal eventually became using the data for applied research seeking cures for genetic diseases.

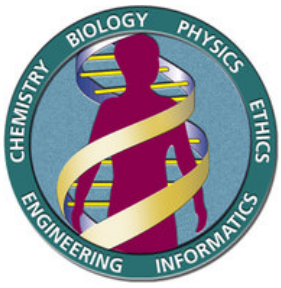


Figure 2.4.*b*: The Human Genome Project was a 13-year collaborative effort among researchers working in several different fields of science. The project was completed in 2003. (credit: the U.S. Department of Energy Genome Programs)

The discovery of penicillin, the first antibiotic, also originated in basic science. The mold *Penicillium* (figure 2.4.*c*) contaminated petri dishes of bacteria and unexpectedly inhibited their growth. Read more about The Real Story behind Penicillin.



Figure 2.4.*c*: The mold *Penicillium* growing on a petri dish. Image by Crulina 98 (CC-BY-SA).

Ecological modeling, which is closely intertwined with the field of environmental science, is another example in which applied science closely relies on basic science. **Ecological models** are complex equations through which computers can predict the outcome of different decisions or scenarios based on existing data. For example, a forest manager might use a model to determine which pattern of tree removal will promote forest health and produce a steady, sustainable supply of timber. The data used to create the ecological model are collected through a combination of basic and applied studies.

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2.5: Data Dive- California Wildfires

Overview

When the United States Forest Service was established in 1905 it was declared that, “Today we understand that forest fires are wholly within the control of men.” Humanity assumes time and time again that nature can be controlled, and the National Forest Service were shown how wrong their assumption was 5 years later… The Great Fire of 1910 burned about 3 million acres and killed 86 people. As a consequence of this fire, serious fire suppression policies were put in place and Smokey The Bear was slapped onto posters to represent the cause. At that point, Smokey the Bear told us, "only you can prevent forest fire," indicating that all fire is bad. It has only been in the last couple decades have these policies been questioned and the repercussions of fire suppression of them realized. Now Smokey has updated the saying to, "only you can prevent wildfire," indicating that only some types of fire are bad. The figure below illustrates the number of acres burned in California between 1987 and 2020:

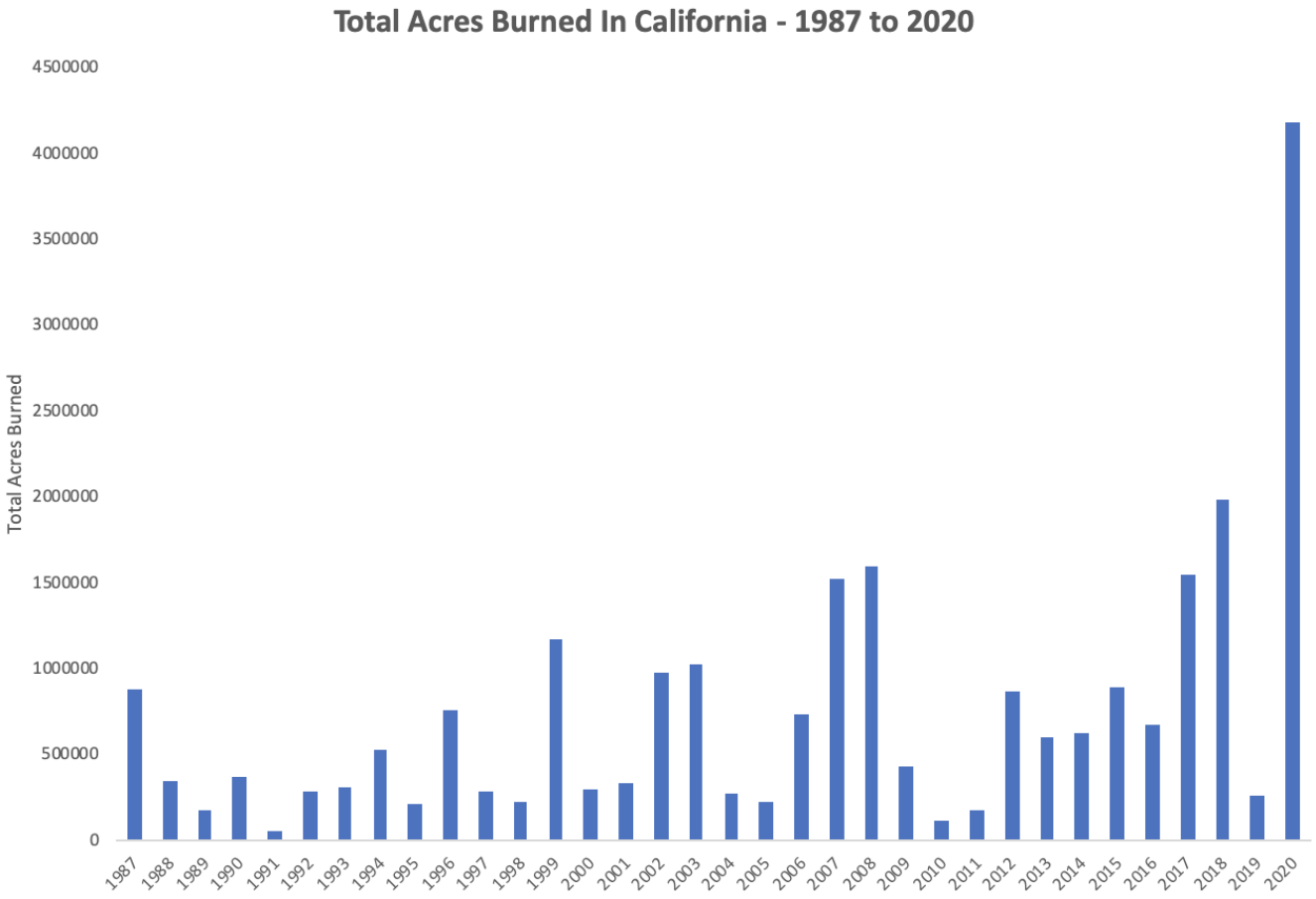


Figure 2.5.*a***:** Total acres burned through the years in California. Graph created by Rachel Schleiger (CC-BY-NC) modified from data collected by CalFire

Questions

1. What kind of graph is this?
2. What is the independent (explanatory) variable and the dependent (response) variable?
3. What question(s) are the authors trying to answer with this graph?
4. What trend(s) can be observed in this graph? Support your answer by referring to appropriate patterns in the graph.

5. How can we use the results of this graph to inform future fire policies/projects/etc?
6. What does the results of this graph make you curious about?

Raw Data For Above Graph(s)

Table 2.5.*a***:** Raw data table of total acres burned through the years in California. Table by Rachel Schleiger (CC-BY-NC) modified from data collected by CalFire

Year	Total Acres Burned
1987	873000
1988	345000
1989	173400
1990	365200
1991	44200
1992	282745
1993	309779
1994	526219
1995	209815
1996	752372
1997	283885
1998	215412
1999	1172850
2000	295026
2001	329126
2002	969890
2003	1020460
2004	264988
2005	222538
2006	736022
2007	1520362
2008	1593690
2009	422147
2010	109529
2011	168545
2012	869599
2013	601635
2014	625540
2015	893362
2016	669534
2017	1548429
2018	1975086
2019	259823

Year	Total Acres Burned
2020	4177856

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2.6: Review

Summary

After completing this chapter you should be able to...

- Describe the purpose of science.
- Distinguish between objective and subjective observations.
- Distinguish between quantitative measurements and qualitative observations.
- Distinguish between inductive and deductive reasoning and relate them to descriptive and hypothesis-based science.
- Outline the steps of the scientific method and explain its cyclical nature.
- Distinguish between manipulative experiments and observational studies.
- Identify the types of variables, control group, and replicates in a scientific study.
- Discuss the importance of peer review.
- Distinguish between basic and applied science and provide examples of the value of basic science.

Science is a means of systematically gathering information about the natural world. Science is based on **objective** observations, and following the scientific method helps scientists limit **bias**. Both **induction** and **deduction** are important to the scientific method. Observations lead to a question and hypothesis, an example of inductive reasoning. Making **falsifiable predictions** based on the hypothesis and testing them through **manipulative experiments** or **observational studies** requires deductive reasoning. Finally the results are collected and scientists conclude whether the data support the hypothesis. The scientific method is a cyclical process, in which the latter steps of the process can lead back to earlier steps.

Scientists publish their findings in **scientific journals**, which require **peer review**.

Applied science focuses on solving modern problems, but **basic science** simply focuses on expanding knowledge. However, the findings of basic science can later have useful applications.

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CHAPTER OVERVIEW

3: Population Ecology

- 3.1: Introduction to Population Ecology
- 3.2: Populations
  - 3.2.1: Population Dispersion
  - 3.2.2: Population Size
  - 3.2.3: Population Growth and Regulation
  - 3.2.4: Life History
  - 3.2.5: Data Dive- Wildlife Corridors
  - 3.2.6: Section Review
- 3.3: The Human Population
  - 3.3.1: The Human Population
  - 3.3.2: History of Human Population Growth
  - 3.3.3: The Rate of Human Population Growth
  - 3.3.4: Looking Ahead
  - 3.3.5: Human Impact on the Environment
  - 3.3.6: Data Dive- World Population Densities
  - 3.3.7: Section Review

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3.1: Introduction to Population Ecology

Ecology is the study of the interactions of living organisms with their environment. One core goal of ecology is to understand the distribution and abundance of living things in the physical environment. Attainment of this goal requires the integration of scientific disciplines inside and outside of biology, such as biochemistry, physiology, evolution, biodiversity, molecular biology, geology, and climatology. Some ecological research also applies aspects of chemistry and physics, and it frequently uses mathematical models.

Why study ecology? Perhaps you are interested in learning about the natural world and how living things have adapted to the physical conditions of their environment. Or, perhaps you're a future physician seeking to understand the connection between human health and ecology.

Humans are a part of the ecological landscape, and human health is one important part of human interaction with our physical and living environment. Lyme disease, for instance, serves as one modern-day example of the connection between our health and the natural world. More formally known as Lyme borreliosis, Lyme disease is a bacterial infection that can be transmitted to humans when they are bitten by the deer tick (*Ixodes scapularis*), which is the primary vector for this disease (figure 3.1.1). However, not all deer ticks carry the bacteria that will cause Lyme disease in humans, and *I. scapularis* can have other hosts besides deer. In fact, it turns out that the probability of infection depends on the type of host upon which the tick develops: a higher proportion of ticks that live on white-footed mice carry the bacterium than do ticks that live on deer. Knowledge about the environments and population densities in which the host species is abundant would help a physician or an epidemiologist better understand how Lyme disease is transmitted and how its incidence could be reduced.



(a) (b) (c)

Figure 3.1.1: The (a) deer tick carries the bacterium that produces Lyme disease in humans, often evident in (b) a symptomatic bull's eye rash. The (c) white-footed mouse is one well-known host to deer ticks carrying the Lyme disease bacterium. (credit a: modification of work by Scott Bauer, USDA ARS; credit b: modification of work by James Gathany, CDC; credit c: modification of work by Rob Ireton)

Ecologists ask questions across four levels of biological organization—organismal, population, community, and ecosystem. At the organismal level, ecologists study individual organisms and how they interact with their environments. At the population and community levels, ecologists explore, respectively, how a population of organisms changes over time and the ways in which that population interacts with other species in the community. Ecologists studying an ecosystem examine the living species (the biotic components) of the ecosystem as well as the nonliving portions (the abiotic components), such as air, water, and soil, of the environment. The objective of this unit will be to further explore these topics and how they connect to and overlap with environmental science.

Levels of Ecological Study

When a discipline such as biology is studied, it is often helpful to subdivide it into smaller, related areas. For instance, cell biologists interested in cell signaling need to understand the chemistry of the signal molecules (which are usually proteins) as well as the result of cell signaling. Ecologists interested in the factors that influence the survival of an endangered species might use mathematical models to predict how current conservation efforts affect endangered organisms. To produce a sound set of management options, a conservation biologist needs to collect accurate data, including current population size, factors affecting reproduction (like physiology and behavior), habitat requirements (such as plants and soils), and potential human influences on the endangered population and its habitat (which might be derived through studies in sociology and urban ecology). Within the discipline of ecology, researchers work at four specific levels, sometimes discretely and sometimes with overlap: organism, population, community, and ecosystem (figure 3.1.2).

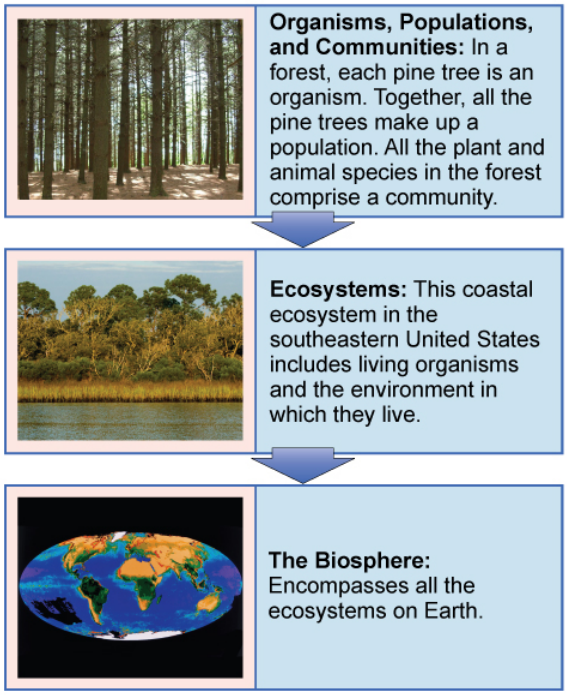


Figure 3.1.2: Ecologists study within several biological levels of organization. (credit “organisms”: modification of work by "Crystl"/Flickr; credit “ecosystems”: modification of work by Tom Carlisle, US Fish and Wildlife Service Headquarters; credit “biosphere”: NASA)

Organismal Ecology

Researchers studying ecology at the organismal level are interested in the adaptations that enable individuals to live in specific habitats. These adaptations can be morphological, physiological, and behavioral. For instance, the Karner blue butterfly (*Lycaeides melissa samuelis*) (figure 3.1.3) is considered a specialist because the females preferentially oviposit (that is, lay eggs) on wild lupine. This preferential adaptation means that the Karner blue butterfly is highly dependent on the presence of wild lupine plants for its continued survival.



Figure 3.1.3: The Karner blue butterfly (Lycaeides melissa samuelis) is a rare butterfly that lives only in open areas with few trees or shrubs, such as pine barrens and oak savannas. It can only lay its eggs on lupine plants. (credit: modification of work by J & K Hollingsworth, USFWS)

After hatching, the larval caterpillars emerge and spend four to six weeks feeding solely on wild lupine (figure 3.1.4). The caterpillars pupate (undergo metamorphosis) and emerge as butterflies after about four weeks. The adult butterflies feed on the nectar of flowers of wild lupine and other plant species. A researcher interested in studying Karner blue butterflies at the organismal level might, in addition to asking questions about egg laying, ask questions about the butterflies' preferred temperature (a physiological question) or the behavior of the caterpillars when they are at different larval stages (a behavioral question).



Figure 3.1.4: The wild lupine (Lupinus perennis) is the host plant for the Karner blue butterfly

Population Ecology

A population is a group of interbreeding organisms that are members of the same species living in the same area at the same time. (Organisms that are all members of the same species are called conspecifics.) A population is identified, in part, by where it lives, and its area of population may have natural or artificial boundaries: natural boundaries might be rivers, mountains, or deserts, while examples of artificial boundaries include mowed grass, manmade structures, or roads. The study of population ecology focuses on the number of individuals in an area and how and why population size changes over time. Population ecologists are particularly interested in counting the Karner blue butterfly, for example, because it is classified as federally endangered. However, the distribution and density of this species is highly influenced by the distribution and abundance of wild lupine. Researchers might ask questions about the factors leading to the decline of wild lupine and how these affect Karner blue butterflies. For example, ecologists know that wild lupine thrives in open areas where trees and shrubs are largely absent. In natural settings, intermittent wildfires regularly remove trees and shrubs, helping to maintain the open areas that wild lupine requires. Mathematical models can be used to understand how wildfire suppression by humans has led to the decline of this important plant for the Karner blue butterfly.

Community Ecology

A biological community consists of the different species within an area, typically a three-dimensional space, and the interactions within and among these species. Community ecologists are interested in the processes driving these interactions and their consequences. Questions about conspecific interactions often focus on competition among members of the same species for a limited resource. Ecologists also study interactions among various species; members of different species are called heterospecifics.

Examples of heterospecific interactions include predation, parasitism, herbivory, competition, and pollination. These interactions can have regulating effects on population sizes and can impact ecological and evolutionary processes affecting diversity.

For example, Karner blue butterfly larvae form mutualistic relationships with ants. Mutualism is a form of a long-term relationship that has coevolved between two species and from which each species benefits. For mutualism to exist between individual organisms, each species must receive some benefit from the other as a consequence of the relationship. Researchers have shown that there is an increase in the probability of survival when Karner blue butterfly larvae (caterpillars) are tended by ants. This might be because the larvae spend less time in each life stage when tended by ants, which provides an advantage for the larvae. Meanwhile, the Karner blue butterfly larvae secrete a carbohydrate-rich substance that is an important energy source for the ants. Both the Karner blue larvae and the ants benefit from their interaction.

Ecosystem Ecology

Ecosystem ecology is an extension of organismal, population, and community ecology. The ecosystem is composed of all the biotic components (living things) in an area along with the abiotic components (non-living things) of that area. Some of the abiotic components include air, water, and soil. Ecosystem biologists ask questions about how nutrients and energy are stored and how they move among organisms and the surrounding atmosphere, soil, and water.

The Karner blue butterflies and the wild lupine live in an oak-pine barren habitat. This habitat is characterized by natural disturbance and nutrient-poor soils that are low in nitrogen. The availability of nutrients is an important factor in the distribution of the plants that live in this habitat. Researchers interested in ecosystem ecology could ask questions about the importance of limited resources and the movement of resources, such as nutrients, though the biotic and abiotic portions of the ecosystem.

Career Connection: Ecologist

A career in ecology contributes to many facets of human society. Understanding ecological issues can help society meet the basic human needs of food, shelter, and health care. Ecologists can conduct their research in the laboratory and outside in natural environments (Figure 3.1.5). These natural environments can be as close to home as the stream running through your campus or as far away as the hydrothermal vents at the bottom of the Pacific Ocean. Ecologists manage natural resources such as white-tailed deer populations (*Odocoileus virginianus*) for hunting or aspen (*Populus* spp.) timber stands for paper production. Ecologists also work as educators who teach children and adults at various institutions including universities, high schools, museums, and nature centers. Ecologists may also work in advisory positions assisting local, state, and federal policymakers to develop laws that are ecologically sound, or they may develop those policies and legislation themselves. To become an ecologist requires an undergraduate degree, usually in a natural science. The undergraduate degree is often followed by specialized training or an advanced degree, depending on the area of ecology selected. Ecologists should also have a broad background in the physical sciences, as well as a sound foundation in mathematics and statistics.



Figure 3.1.5: This landscape ecologist is releasing a black-footed ferret into its native habitat as part of a study. (credit: USFWS Mountain Prairie Region, NPS)

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3.2: Populations

Section Hook

Roadkill, we've all seen it on the roadside. It is just one very unfortunate outcomes of our extensive road networks. Roads, especially freeways and busy highways, also break apart habitats. When habitats are broken up into smaller pieces it weakens wildlife populations which need to move freely across landscapes for resources, refuge, and mates. Over long time scales, these fragmented habitats decrease species diversity, weaken species population gene pools, and can lead to extirpation (elimination of local population(s)) and extinction. As a result of numerous studies, ecologists have found one solution, wildlife crossings (aka green corridors or wildlife corridors). Wildlife crossings look like an underpass or overpass. However, they are filled with dirt and plants to look more natural. These crossings enable wildlife populations to move more freely, and safely, across landscapes all over the globe.



Figure 3.2.a**:** A newly constructed wildlife overpass over a Singapore highway. Image by Benjamin P. Y-H. Lee (licensed under CC-BY-4.0)

Populations are interacting and interbreeding groups of individuals from the same species in a common area. The study of **population ecology** focuses on population size and the factors that regulate population growth.

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3.2.1: Population Dispersion

The **dispersion pattern** (distribution pattern) of a population describes the arrangement of individuals within a habitat at a particular point in time, and broad categories of patterns are used to describe them. The three dispersion patterns are clumped, random, and uniform (figure 3.2.1.a).



Figure 3.2.1.a: Species may have a random, clumped, or uniform distribution. Plants such as (a) dandelions with wind-dispersed seeds tend to be randomly distributed (represented by dots in no particular pattern). Animals such as (b) elephants that travel in groups exhibit a clumped distribution (represented by dots clustered together). Territorial birds such as (c) penguins tend to have a uniform distribution (represented by dots evenly spaced from each other). (credit a: modification of work by Rosendahl; credit b: modification of work by Rebecca Wood; credit c: modification of work by Ben Tubby)

Individuals that are grouped into patches have a **clumped distribution**, or aggregated distribution. This can occur if resources are distributed unequally; for example, pipevine swallowtail caterpillars would be clumped in areas with their host plant, California pipevine. Clumped distribution may also reflect the locations of suitable microhabitats, such as an herbaceous (non-woody) plant species that only grows in the shade clustering under trees. Plants that drop their seeds straight to the ground, such as oak trees, may also have this distribution. Finally, social behavior in animals results in a clumped distribution, such as wolves hunting in a pack, a herd of elephants, or a school of fish traveling together for safety.

Populations that have a **random distribution** are not arranged in any particular pattern. Some individuals may be close together while others may be far apart. An example of random distribution occurs with dandelion and other plants that have wind-dispersed seeds that germinate wherever they happen to fall in favorable environments.

Individuals that are equally spaced in the environment have a **uniform distribution**. Saguaro cacti are evenly spaced due to limited resources in the desert. (There is not sufficient water to support two large cacti side-by-side.) Uniform distributions can result from **interference competition**, when individuals take pre-emptive measures to avoid competition for resources. For example, some plants that secrete substances inhibiting the growth of nearby individuals (such as the release of toxic chemicals by sage plants), a phenomenon called **allelopathy**. Another example of interference competition occurs in territorial animal species, such as penguins that maintain a defined territory for nesting. The territorial defensive behaviors of each individual create a regular pattern of distribution of similar-sized territories and individuals within those territories. Thus, the distribution of the individuals within a population provides more information about how they interact with each other than does a simple density measurement (see Population Size and Density).

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3.2.2: Population Size

Populations are dynamic entities. Their size and composition fluctuate in response to numerous factors, including seasonal and yearly changes in the environment, natural disasters such as forest fires and volcanic eruptions, and competition for resources between and within species. The study of populations is called **demography.**

Population Size and Density

Populations are characterized by their **population size** (total number of individuals) and their **population density** (number of individuals per unit area; figure 3.2.2.a). A population may have a large number of individuals that are distributed densely, or sparsely. There are also populations with small numbers of individuals that may be dense or very sparsely distributed in a local area. Population size can affect potential for adaptation because it affects the amount of genetic variation present in the population. Density can have effects on interactions within a population such as competition for food, the ability of individuals to find a mate, and diseases spread. (Dispersion patterns can also affect these factors; for example, a solitary species with a random distribution might have difficulty finding a mate when compared to social species clumped together in groups.) Smaller organisms tend to be more densely distributed than larger organisms (figure 3.2.2.b).

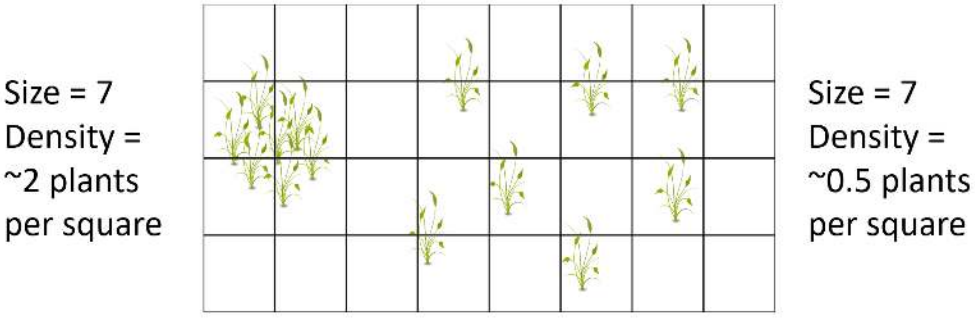


Figure 3.2.2.a: Both populations shown contain seven plants, so their populations size is the same. However, the population on the left has a higher population density (2 plants per square) than the population on the right (density = 0.5 plants per square). Image by Melissa Ha using Green Plant (public domain).

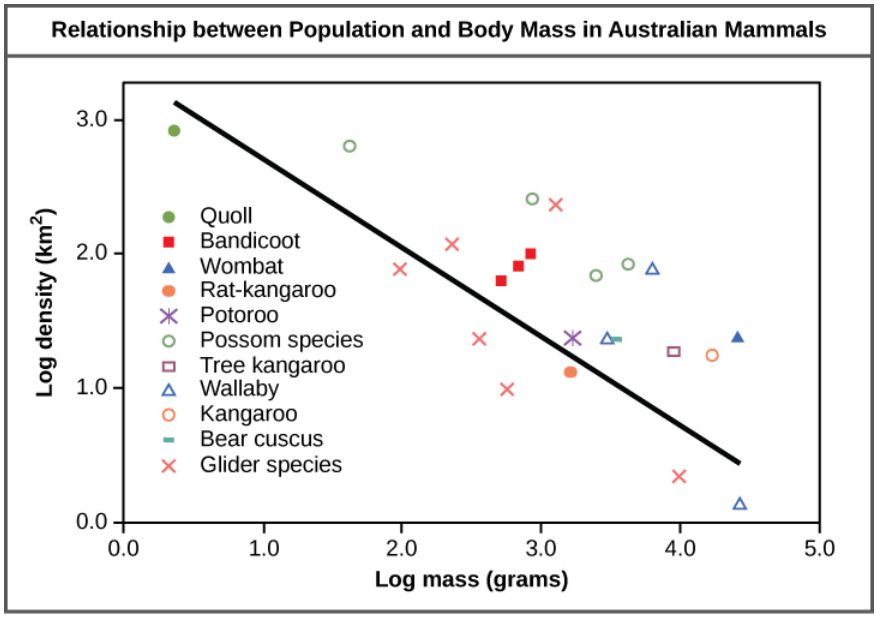


Figure 3.2.2.b: Australian mammals show a typical inverse relationship between population density and body size. Log mass in grams is on the x-axis, and log density in square kilometers (km^2) is on the y-axis. Each data point represents a different species, including the quoll, four bandicoot species, wombat, rat-kangaroo, potoroo, four possom species, tree kangaroo, three wallaby

species, kangaroo, bear cuscus, and six glider species. As this graph shows, population density typically decreases with increasing body size. For example, quolls have the lowest body mass and the highest density. The heaviest wallaby species has the lowest population density.

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3.2.3: Population Growth and Regulation

Population ecologists make use of a variety of methods to model population dynamics. An accurate model should be able to describe the changes occurring in a population and predict future changes. The two simplest models of population growth use deterministic equations (equations that do not account for random events) to describe the rate of change in the size of a population over time. The first of these models, **exponential growth**, describes populations that increase in numbers without any limits to their growth. The second model, **logistic growth**, introduces limits to reproductive growth that become more intense as the population size increases. Neither model adequately describes natural populations, but they provide points of comparison.

The Population Growth Rate (*r*)

The **population growth rate** (sometimes called the rate of increase or per capita growth rate, *r*) equals the **birth rate** (*b*) minus the **death rate** (*d*) divided by the **initial population size** (N_0).

$$r = (b - d) \div N_0$$

Another method of calculating the population growth rate involves final and initial population size (figure 3.2.3.*a*). In this case, **population growth rate** (*r*) equals the **final population size** (N) minus the **initial population size** (N_0) and divided by the **initial population size** (N_0).

$$r = (N - N_0) \div N_0$$



Figure 3.2.3.*a*: How could we calculate the growth rate of this caribou population per year if there were 200 individuals in 2016 and 300 individuals in 2018? Image by K. Joly/NPS (public domain).

Doubling Time

The **doubling time** is how long it will take for a population to become twice its initial size. The **doubling time** (*t*) is equal to 0.69 divided by the **population growth rate** (*r*), written as a proportion.

$$t = 0.69 \div r$$

Population ecologists sometimes round this equation and calculate doubling time using the **"Rule of 70"** (dividing 70 by the population growth rate, written as a percentage). To express population growth rate as a percentage, it is multiplied by 100%. Thus, the 0.69 in the original doubling time equation is also multiplied by 100. This value (69) is rounded to 70 for simplicity.

Exponential Growth

Charles Darwin, in developing his theory of natural selection, was influenced by the English clergyman Thomas Malthus. Malthus published his book in 1798 stating that populations with abundant natural resources grow very rapidly. However, they limit further growth by depleting their resources. The early pattern of accelerating population size is called exponential growth (figure 3.2.3.*b*).

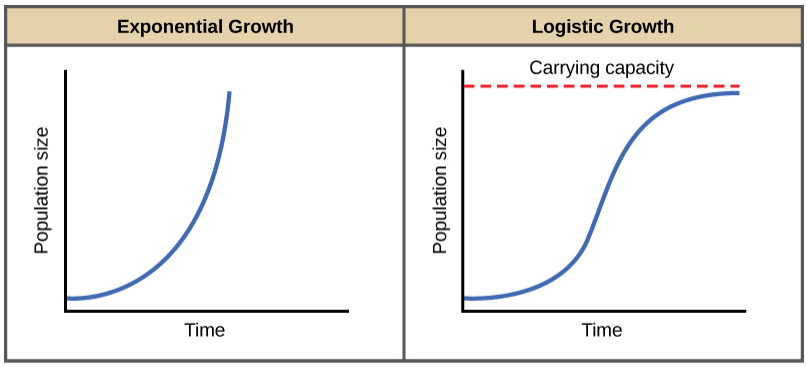


Figure 3.2.3.*b*: These graphs show exponential and logistic growth, with population size on the y-axis and time on the x-axis. When resources are unlimited, populations exhibit (a) exponential growth, shown in a J-shaped curve. When resources are limited, populations exhibit (b) logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity of the environment is reached. The logistic growth curve is S-shaped.

The best example of exponential growth in organisms is seen in bacteria. Bacteria are prokaryotes that reproduce quickly, about an hour for many species. If 1000 bacteria are placed in a large flask with an abundant supply of nutrients (so the nutrients will not become quickly depleted), the number of bacteria will have doubled from 1000 to 2000 after just an hour (figure 3.2.3.*c*). In another hour, each of the 2000 bacteria will divide, producing 4000 bacteria. After the third hour, there should be 8000 bacteria in the flask. The important concept of exponential growth is that the growth rate—the number of organisms added in each reproductive generation—is itself increasing; that is, the population size is increasing at a greater and greater rate. After 24 of these cycles, the population would have increased from 1000 to more than 16 billion bacteria. When the population size, *N*, is plotted over time, a J-shaped growth curve is produced (figure 3.2.3.*b*).



Figure 3.2.3.*c*: Bacteria growing with abundant nutrients in a flask will exhibit exponential growth. Image by Soledad Mirand-Rottman (CC-BY-SA).

The bacteria-in-a-flask example is not truly representative of the real world where resources are usually limited. However, when a species is introduced into a new habitat that it finds suitable, it may show exponential growth for a while. In the case of the bacteria in the flask, some bacteria will die during the experiment and thus not reproduce; therefore, the growth rate is lowered from a maximal rate in which there is no mortality.

Logistic Growth

Extended exponential growth is possible only when infinite natural resources are available; this is not the case in the real world. Charles Darwin recognized this fact in his description of the “struggle for existence,” which states that individuals will compete,

with members of their own or other species, for limited resources. The successful ones are more likely to survive and pass on the traits that made them successful to the next generation at a greater rate (natural selection). To model the reality of limited resources, population ecologists developed the logistic growth model.

In the real world, with its limited resources, exponential growth cannot continue indefinitely. Exponential growth may occur in environments where there are few individuals and plentiful resources, but when the number of individuals gets large enough, resources will be depleted and the growth rate will slow down. Eventually, the growth rate will plateau or level off (figure 3.2.3.*b*). This population size, which is determined by the maximum population size that a particular environment can sustain, is called the **carrying capacity**, symbolized as *K*. In real populations, a growing population often overshoots its carrying capacity and the death rate increases beyond the birth rate causing the population size to decline back to the carrying capacity or below it. Most populations usually fluctuate around the carrying capacity in an undulating fashion rather than existing right at it.

A graph of logistic growth yields the S-shaped curve (figure 3.2.3.*b*). It is a more realistic model of population growth than exponential growth. There are three different sections to an S-shaped curve. Initially, growth is exponential because there are few individuals and ample resources available. Then, as resources begin to become limited, the growth rate decreases. Finally, the growth rate levels off at the carrying capacity of the environment, with little change in population number over time.

While bacteria in a flask with abundant nutrients might initially exhibit exponential growth, bacteria grown with limited nutrients can exhibit logistic growth (figure 3.2.3.*d*).

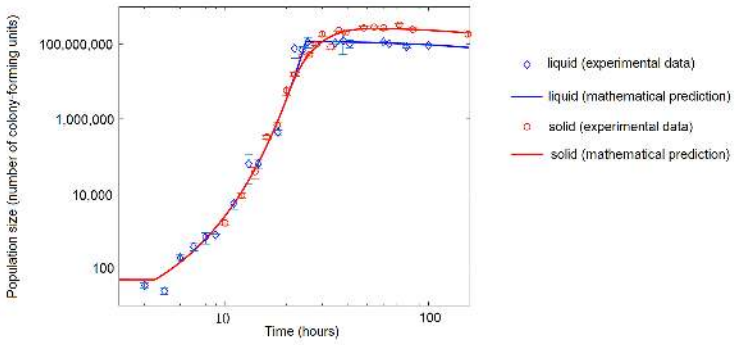


Figure 3.2.3.*d*: The growth of the bacterium *Escherichia coli* (*E. coli*) with limited nutrients over time in hours. Population size is in number of colony-forming units, which is a cell capable of dividing to produce a colony of cells. The bacteria were grown in liquid (blue diamonds) or on a semisolid medium (agar, red circles). The points represent actual measurements of populations size, and the lines represent a mathematical model, basically a prediction that is based on the data points. The data show logistic population growth, particularly in solid media. Initially, population size increases rapidly (concave part of curve), but the growth rate then stabilizes (straight line) before decreasing (convex part of curve) and leveling near the carrying capacity. Image modified from Shao X, Mugler A, Kim J, Jeong HJ, Levin BR, Nemenman I (2017) Growth of bacteria in 3-d colonies. PLoS Comput Biol 13(7): e1005679 (CC-BY).

In some populations, there are variations to the S-shaped curve. Examples in wild populations include sheep and harbor seals (figure 3.2.3.*e*). In both examples, the population size exceeds the carrying capacity for short periods of time and then falls below the carrying capacity afterwards. This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation the logistic model is confirmed.

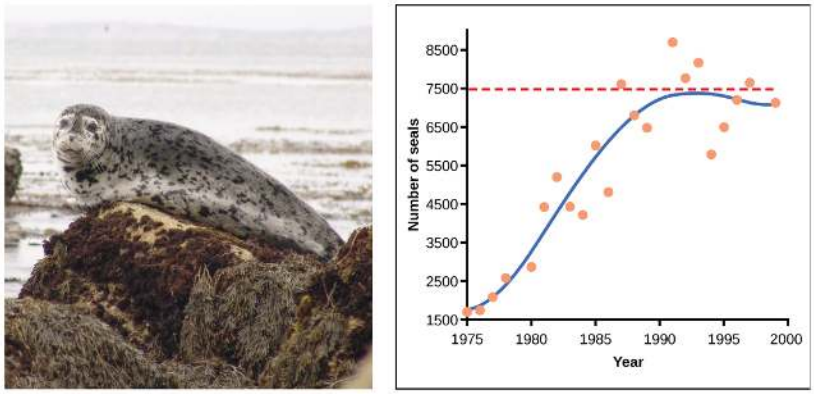


Figure 3.2.3.*e*: A natural population of seals shows logistic growth. The number of seals, ranging from 1500 to 8500, is on the y-axis, and the year, ranging from 1975-2000, is on the x-axis. Orange dots represent the observed population size each year, and the blue line represent the trend. From 1975 to 1983, the blue line curves upwards, representing an increase in both population size and population growth rate. From 1983 to 1992, the curve flattens, representing that population size is still increasing, but population growth rate is decreasing. After 1992, population fluctuates near the carrying capacity (dotted, horizontal line).

The logistic population growth model is not the only way that populations respond to limited resources. In some populations, growth is exponential until resources run low, wastes accumulate, or disease spreads (see limiting factors below), and the population then crashes. Thus, population growth rate (and size) may plummet rapidly instead of tapering as it approaches the carrying capacity.

Population Dynamics and Regulation

The logistic model of population growth, while valid in many natural populations and a useful model, is a simplification of real-world population dynamics. Implicit in the model is that the carrying capacity of the environment does not change, which is not the case. The carrying capacity varies annually. For example, some summers are hot and dry whereas others are cold and wet; in many areas, the carrying capacity during the winter is much lower than it is during the summer. Furthermore, some factors (**growth factors**) increase population growth rate while other factors (**limiting factors**) slow population growth. Examples of growth factors are resources like food, water, and space. Limiting factors can be classified as density-dependent or density-independent.

Density-dependent Regulation

Most **density-dependent factors** are biological in nature (biotic). Usually, the denser a population is, the greater its mortality rate. An example of density-dependent regulation is shown in figure 3.2.3.*f* with results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite of humans and other mammals. Denser populations of the parasite exhibited lower fecundity: they contained fewer eggs. One possible explanation for this is that females would be smaller in more dense populations (due to limited resources) and that smaller females would have fewer eggs. This hypothesis was tested and disproved in a 2009 study which showed that female weight had no influence. The actual cause of the density-dependence of fecundity in this organism is still unclear and awaiting further investigation.

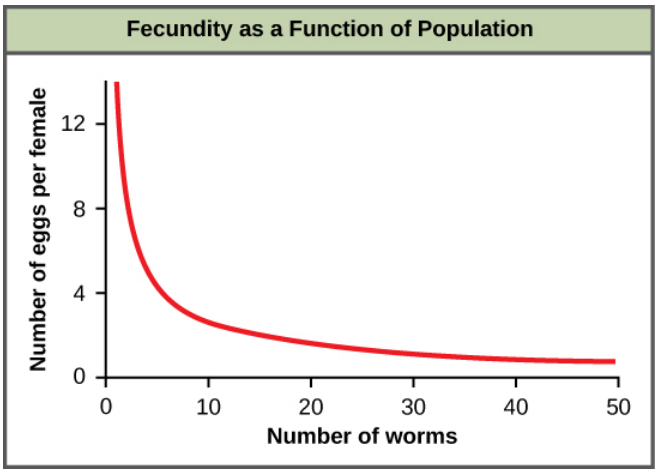


Figure 3.2.3.f: In this population of roundworms, fecundity (number of eggs per female) decreases with population size (number of worms). (Note that population size rather than population density is shown here, but population density does correlate with population size.) The number of eggs decreases rapidly at first, then levels off between 30 to 50 worms.

Density-dependent factors include predation, parasitism, herbivory, competition, and accumulation of waste. As a population increases, its predators are able to harvest it more easily. Prey density also affects population growth rate of predators: low prey density increases the mortality of its predator because it has more difficulty locating its food sources.

Parasites are able to pass from host to host more easily as the population density of the host increases. For this reason, epidemics among humans are particularly severe in cities. In fact, for most of the period since humans began living in cities, city populations have been maintained only through continual immigration from the countryside. Not until the development of community sanitation, immunization, and other public health measures did cities avoid periodic sharp drops in population as a result of epidemics. The recurrent epidemics of the "black death" in Europe that began in the fourteenth century caused a sharp decline in population. In just three years (1348–1350), at least one-quarter of the population of Europe died from the disease (probably plague).

Similarly, herbivores can more easily spread between individual plants in a dense population. This is why strip cropping (see Sustainable Agriculture) helps control pests. An herbivore or plant pathogen may infect one row of plants, but it is less likely to spread to more distant rows of that species.

While **interspecific competition** occurs between different species, **intraspecific competition** occurs when members of the same species harm each other by using the same resources. For example, in the summer of 1980, much of southern New England was struck by an infestation of the gypsy moth (figure 3.2.3.g). As the summer wore on, the larvae (caterpillars) pupated, the hatched adults mated, the females laid masses of eggs (each mass containing several hundred eggs) on virtually every tree in the region. In early May of 1981, the young caterpillars that hatched from these eggs began feeding and molting.



Figure 3.2.3.*g*: Gypsy moth caterpillars face intraspecific competition at high densities. Image by Editor at Large (CC-BY-SA).

The results were dramatic: In 72 hours, a 50-ft beech tree or a 25-ft white pine tree would be completely defoliated. Large patches of forest began to take on a winter appearance with their skeletons of bare branches. In fact, the infestation was so heavy that many trees were completely defoliated before the caterpillars could complete their larval development. The result: a massive die-off of the animals; very few succeeded in completing metamorphosis. Here, then, was a dramatic example of how competition among members of one species for a finite resource - in this case, food - caused a sharp drop in population. The effect was clearly density-dependent. The lower population densities of the previous summer had permitted most of the animals to complete their life cycle.

Density-independent Regulation

Density-independent factors, typically physical or chemical in nature (abiotic), influence the mortality of a population regardless of its density, including weather (figure 3.2.3.*h*), natural disasters (earthquakes, volcanoes, fires, etc.), and pollution. An individual deer may be killed in a forest fire regardless of how many deer happen to be in that area. Its chances of survival are the same whether the population density is high or low. The same holds true for cold winter weather.



Figure 3.2.3.*h*: Severe weather, like Hurricane Florence of 2018, can reduce population size regardless of density. Image by NASA Goddard Space Flight Center (CC-BY)

In real-life situations, population regulation is very complicated and density-dependent and independent factors can interact. A dense population that is reduced in a density-independent manner by some environmental factor(s) will be able to recover differently than a sparse population. For example, a population of deer affected by a harsh winter will recover faster if there are more deer remaining to reproduce.

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3.2.4: Life History

Life history characteristics, are those that relate to the survival, mortality, and reproduction of a species. Examples include birth rates, age at first reproduction, the number of offspring, and death rates. These characteristics evolve just like physical traits or behavior, leading to adaptations that affect population growth.

Reproductive Strategies

Population ecologists have hypothesized that suites of characteristics may evolve in species that lead to particular adaptations to their environments. These adaptations impact the kind of population growth their species experience. Population ecologists have described a continuum of life-history "strategies" with *K*-selected species on one end and *r*-selected species on the other (table 3.2.4.*a*). ***K*-selected species** are adapted to stable, predictable environments. Populations of *K*-selected species tend to exist close to their carrying capacity (which is represented by the letter "K" in the equation for logistic population growth). These species tend to have larger, but fewer, offspring, contribute large amounts of resources to each offspring, and have long generation times. Elephants would be an example of a *K*-selected species (figure 3.2.4.*a*). When a habitat becomes filled with a diverse collection of creatures competing with one another for the necessities of life, the advantage shifts to *K*-strategists. *K*-strategists have stable populations that are close to *K*. There is nothing to be gained from a high growth rate (*r*). The species will benefit most by a close adaptation to the conditions of its environment.

Table 3.2.4.*a***:** Comparison of *K*- and *r*-selected species

Characteristics of *K*-selected species	Characteristics of *r*-selected species
Mature late	Mature early
Greater longevity	Lower longevity
Increased parental care	Decreased parental care
Strong competitors	Weak competitors (strong colonizers)
Fewer offspring	More offspring
Larger offspring	Smaller offspring



(a) K-selected species



(b) r-selected species

Figure 3.2.4.a: (a) Elephants are considered K-selected species as they live long, mature late, and provide long-term parental care to few offspring. Oak trees produce many offspring that do not receive parental care, but are considered K-selected species based on longevity and late maturation. (b) Dandelions and jellyfish are both considered r-selected species as they mature early, have short lifespans, and produce many offspring that receive no parental care.

***r*-selected species** are adapted to unstable and unpredictable environments. They have large numbers of small offspring. Animals that are *r*-selected do not provide a lot of resources or parental care to offspring, and the offspring are relatively self-sufficient at birth. Examples of *r*-selected species are marine invertebrates such as jellyfish and plants such as the dandelion (figure 3.2.4.a). *r*-strategists have short life spans and reproduce quickly, resulting in short generation times. For example, the housefly can produce 7 generations each year (each of about 120 young). Ragweed is well-adapted to exploiting its environment in a hurry - before competitors can become established. It grows rapidly and produces a huge number of seeds (after releasing its pollen, the bane of many hay fever sufferers). Because ragweed's approach to continued survival is through rapid reproduction (a high value of *r)* it is called an *r*-strategist. Other weeds, many insects, and many rodents are also *r*-strategists. If fact, if we consider an organism a pest, it is probably an *r*-strategist.

The two extreme strategies are at two ends of a continuum on which real species life histories will exist. In addition, life history strategies do not need to evolve as suites but can evolve independently of each other; therefore, each species may have some characteristics that trend toward one extreme or the other. Nevertheless, the *r*- and *K*-selection theory provides a foundation for a more accurate life history framework. New demographic-based models of life history evolution have been developed, which incorporate many ecological concepts included in *r*- and *K*-selection theory as well as population age structure and mortality factors.

Life Tables

Life tables provide important information about the life history of an organism and the life expectancy of individuals at each age. They are modeled after actuarial tables used by the insurance industry for estimating human life expectancy. Life tables may include the probability of each age group dying before their next birthday, the percentage of surviving individuals dying at a particular age interval (their mortality rate, and their life expectancy at each interval). An example of a life table is shown in Table 3.2.4.*b* from a study of Dall mountain sheep, a species native to northwestern North America. Notice that the population is divided into age intervals (column A).

As can be seen from the mortality rate data (column D), a high death rate occurred when the sheep were between six months and a year old, and then increased even more from 8 to 12 years old, after which there were few survivors. The data indicate that if a sheep in this population were to survive to age one, it could be expected to live another 7.7 years on average, as shown by the life-expectancy numbers in column E. Life tables often include more information than shown in Table 3.2.4.*b*, such as fecundity (reproduction) rates for each age group.

Table 3.2.4.*b***:** Life Table of Dall Mountain Sheep

Age interval (years)	Number dying in age interval out of 1000 born	Number surviving at beginning of age interval out of 1000 born	Mortality rate per 1000 alive at beginning of age interval	Life expectancy or mean lifetime remaining to those attaining age interval
0–0.5	54	1000	54.0	7.06
0.5–1	145	946	153.3	—
1–2	12	801	15.0	7.7
2–3	13	789	16.5	6.8
3–4	12	776	15.5	5.9
4–5	30	764	39.3	5.0
5–6	46	734	62.7	4.2
6–7	48	688	69.8	3.4
7–8	69	640	107.8	2.6
8–9	132	571	231.2	1.9
9–10	187	439	426.0	1.3
10–11	156	252	619.0	0.9
11–12	90	96	937.5	0.6
12–13	3	6	500.0	1.2
13–14	3	3	1000	0.7

Survivorship Curves

Another tool used by population ecologists is a **survivorship curve**, which is a graph of the number of individuals surviving at each age interval versus time. These curves allow us to compare the life histories of different populations (figure 3.2.4.*c*). There are three types of survivorship curves. In a **type I survivorship curve**, mortality is low in the early and middle years and occurs mostly in older individuals. Organisms exhibiting a type I survivorship typically produce few offspring and provide good care to the offspring increasing the likelihood of their survival. Humans and most mammals exhibit a type I survivorship curve. In **type II survivorship curves**, mortality is relatively constant throughout the entire life span, and mortality is equally likely to occur at any point in the life span. Many bird populations provide examples of an intermediate or type II survivorship curve. In **type III**

survivorship curves, early ages experience the highest mortality with much lower mortality rates for organisms that make it to advanced years. Type III organisms typically produce large numbers of offspring, but provide very little or no care for them. Trees and marine invertebrates exhibit a type III survivorship curve because very few of these organisms survive their younger years, but those that do make it to an old age are more likely to survive for a relatively long period of time.

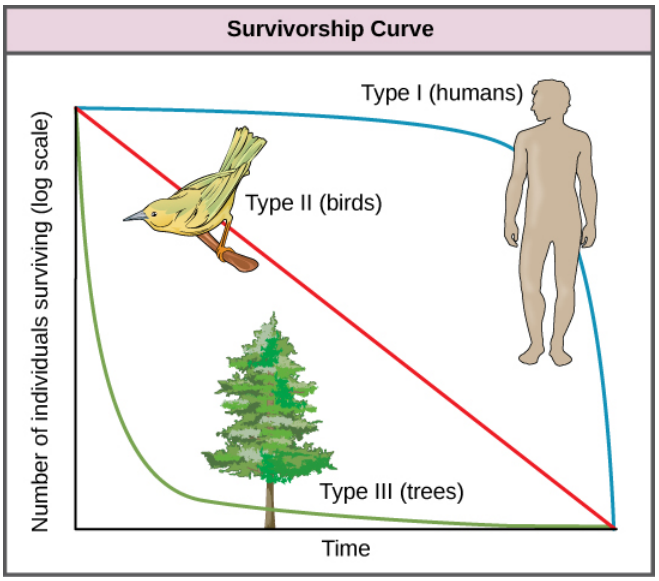


Figure 3.2.4.*c*: Survivorship curves show the chance of survival in a population according to age. The number of individuals surviving (on a log scale) is on the y-axis, and time (representing relative age) is on the x-axis. Humans and most mammals have a Type I survivorship curve, because death primarily occurs in the older years. The Type I survivorship curve is represented by a convex curve, which rapidly declines at the end. Birds have a Type II survivorship curve, as death at any age is equally probable. The Type II survivorship curve is represented by a straight line, going from the upper left to lower right of the graph. Trees have a Type III survivorship curve because very few survive the younger years, but after a certain age, individuals are much more likely to survive. The Type III survivorship curve is represented by a concave curve, which initially declines rapidly and then flattens.

While is no exact association between reproductive strategies (*K*- or *r*-selected) and survivorship curves (Type I, II, or III), *K*-selected species are more likely to have a Type III survivorship curve. *r*-selected species tend to have a Type I survivorship curve.

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3.2.5: Data Dive- Wildlife Corridors

Overview

In 1999 the Sonoran Desert Conservation Plan was created to help wildlife populations and habitats. As a result of this plan, biologists were able to identify landscapes with wildlife barriers and get funding to install wildlife corridors. On State Route (SR) 77 two wildlife corridors were installed, one overpass and one underpass. These corridors were the first of their kind to be built in the Sonoran Desert so it was difficult to estimate what level of success they would have. As such, a monitoring plan was put in place to document which species used the corridors and how often they used it as time passed since their installation. The figure below illustrates the usage of the wildlife corridors 2+ years after their installation:

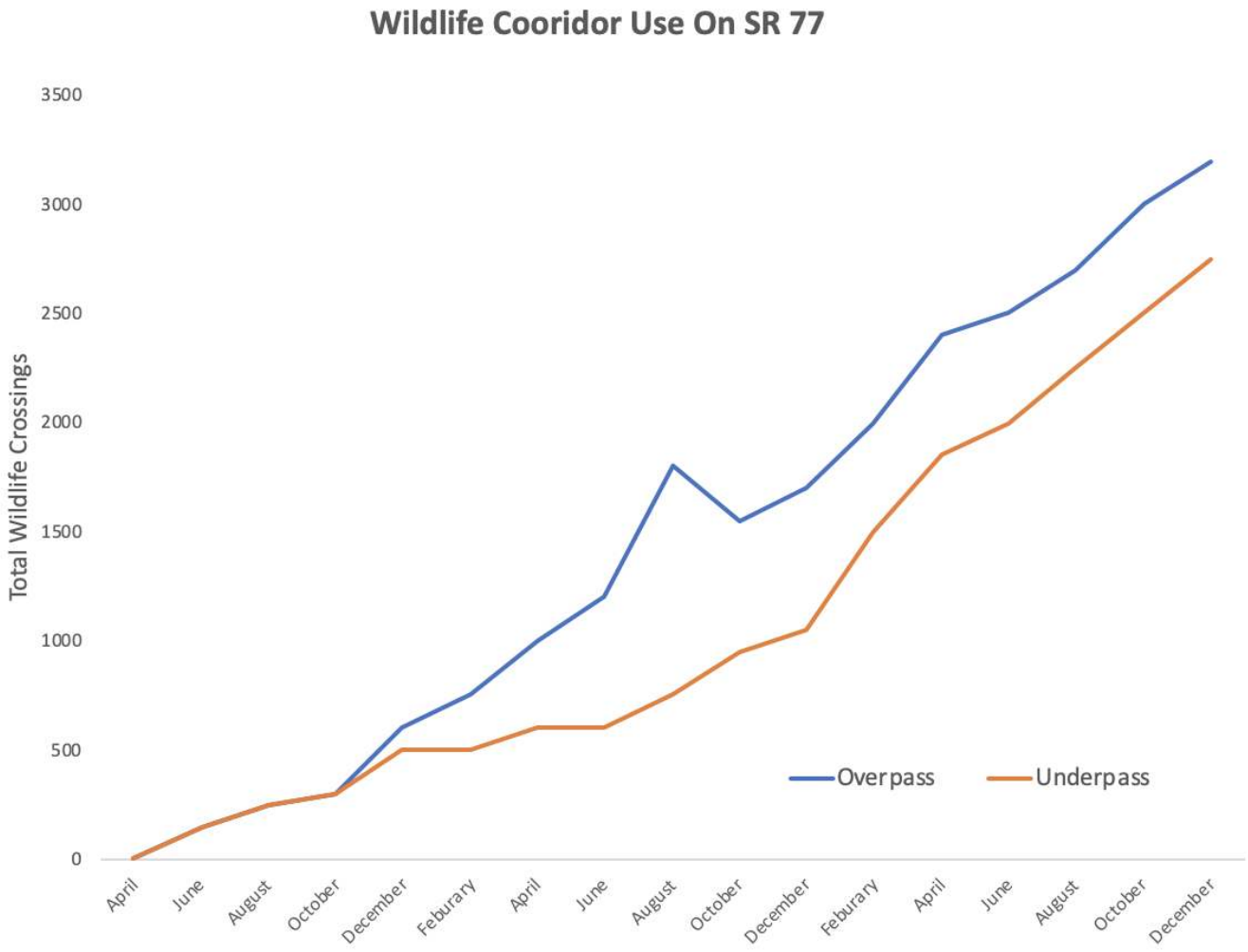


Figure 3.2.5.*a*: Total wildlife crossings after installation for overpass and underpass on SR 77. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Santa Catalina - Tortolita Mountain Corridor Progress Report

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. Does this graph show a positive or negative relationship between the variables? Support your answer by referring to trends observed in the graph.
4. Do you think like the authors are satisfied with the results in the graph? Why?

5. How can we use the results of this graph to inform future wildlife corridor installations?
6. What information/patterns is not clear from this graph?

Raw Data For Above Graph(s)

Table 3.2.5.a**:** Raw data for total wildlife crossings after installation for overpass and underpass on SR 77. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Santa Catalina - Tortolita Mountain Corridor Progress Report

Month	Overpass	Underpass
April	0	0
June	150	150
August	249	250
October	296	294
December	600	500
February	750	502
April	1000	600
June	1200	605
August	1800	750
October	1550	950
December	1700	1050
February	2000	1500
April	2400	1850
June	2500	2000
August	2700	2250
October	3000	2500
December	3200	2750

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3.2.6: Section Review

Summary

After completing this chapter you should be able to...

- Describe three different population dispersion patterns.
- Differentiate between population size and density.
- Explain how ecologists measure population size.
- Calculate population growth rate (*r*) and doubling time (*t*).
- Distinguish between exponential and logistic population growth models, explaining the role of the carrying capacity in logistic growth.
- Provide examples of density-dependent and density-independent factors that regulate populations.
- Compare *K*-selected and *r*-selected reproductive strategies.
- Interpret life tables.
- Compare type I, type II, and type III survivorship curves.

Populations are interacting, interbreeding groups of individuals from the same species. Ecologists measure characteristics of populations: **dispersion pattern**, **population size**, and **population density**. Populations with unlimited resources grow **exponentially**—with an accelerating growth rate. When resources become limiting, populations follow a **logistic growth curve** in which population size will level off at the **carrying capacity**. **Density-dependent factors** limit population growth as they reach their carrying capacity and include biotic factors such as predation, competition, and disease. Density-independent factors, such as storms and fires, are abiotic and decrease population size regardless of density.

Several frameworks explain how **life history** can influence population dynamics. ***K*-selected species** tend to have long life spans and produce few offspring with much parental care whereas ***r*-selected species** mature and reproduce rapidly, producing many offspring and offering little parental care. **Life tables** are useful to calculate life expectancies of individual population members. **Survivorship curves** show the number of individuals surviving at each age interval plotted versus time.

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SECTION OVERVIEW

3.3: The Human Population

3.3.1: The Human Population

3.3.2: History of Human Population Growth

3.3.3: The Rate of Human Population Growth

3.3.4: Looking Ahead

3.3.5: Human Impact on the Environment

3.3.6: Data Dive- World Population Densities

3.3.7: Section Review

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3.3.1: The Human Population

Section Hook

Why is the human species (*Homo sapiens*) so successful? We have the unique ability to not just occupy, but thrive, in diverse environments, even some of the most extreme. Through our social cooperation (despite large groups with no kin), language, art, and ingenuity (especially with tools and fire), our species became unstoppable. Modern humans have permanent settlements on all but one continent (Antarctica) and have exponentially increased our population. We have changed the world! However, this transformation has consequences for all species (including our own), necessitating updated survival strategies across the board.

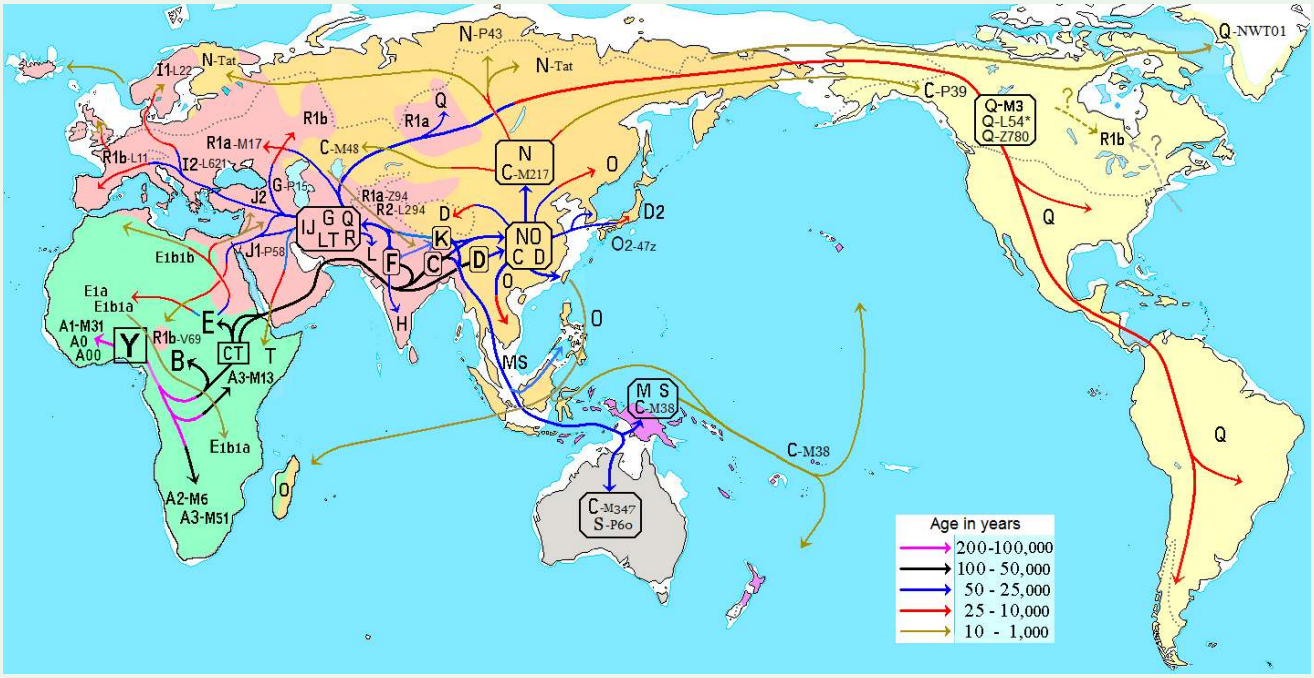


Figure 3.3.1.a Map demonstrating human spread across the globe. Image by Maulucioni (licensed under CC-BY 3.0)

Concepts of population ecology can be applied to human population growth. **Demography** is the study how human populations grow, shrink, and change in terms of age and gender compositions. Demographers also compare populations in different countries or regions. The human population has increased dramatically in the last few centuries and continues to grow (figure 3.3.1.a). Overpopulation risks human well-being and compromises ecosystem functioning.



Figure 3.3.1.*b*: The human population continues to grow. China is currently the most populous country with nearly 1.4 billion people in 2019. Image by Sino-German Urbanisation Partnership (public domain).

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3.3.2: History of Human Population Growth

The human population is growing rapidly. For most of human history, there were fewer than 1 billion people on the planet. During the time of the Agricultural Revolution, 10,000 B.C., there were only 5-10 million people on Earth - which is basically the population of New York City today. In 1800, during the Industrial Revolution, there were approximately 1 billion people on Earth. Continued agricultural expansion and extraction of fossil fuels and minerals led to rapid global economic growth and, in turn, population growth in the 19th century. We've added over 6 billion people to the human population in just a little over 200 years (figure 3.3.2.a). As of December 2024, the global human population is around 8.2 billion people.

Although global population size continues to increase, the rate of human population growth has decreased. This means that the population size is not increasing as quickly as it did in the past (figure 3.3.2.a).

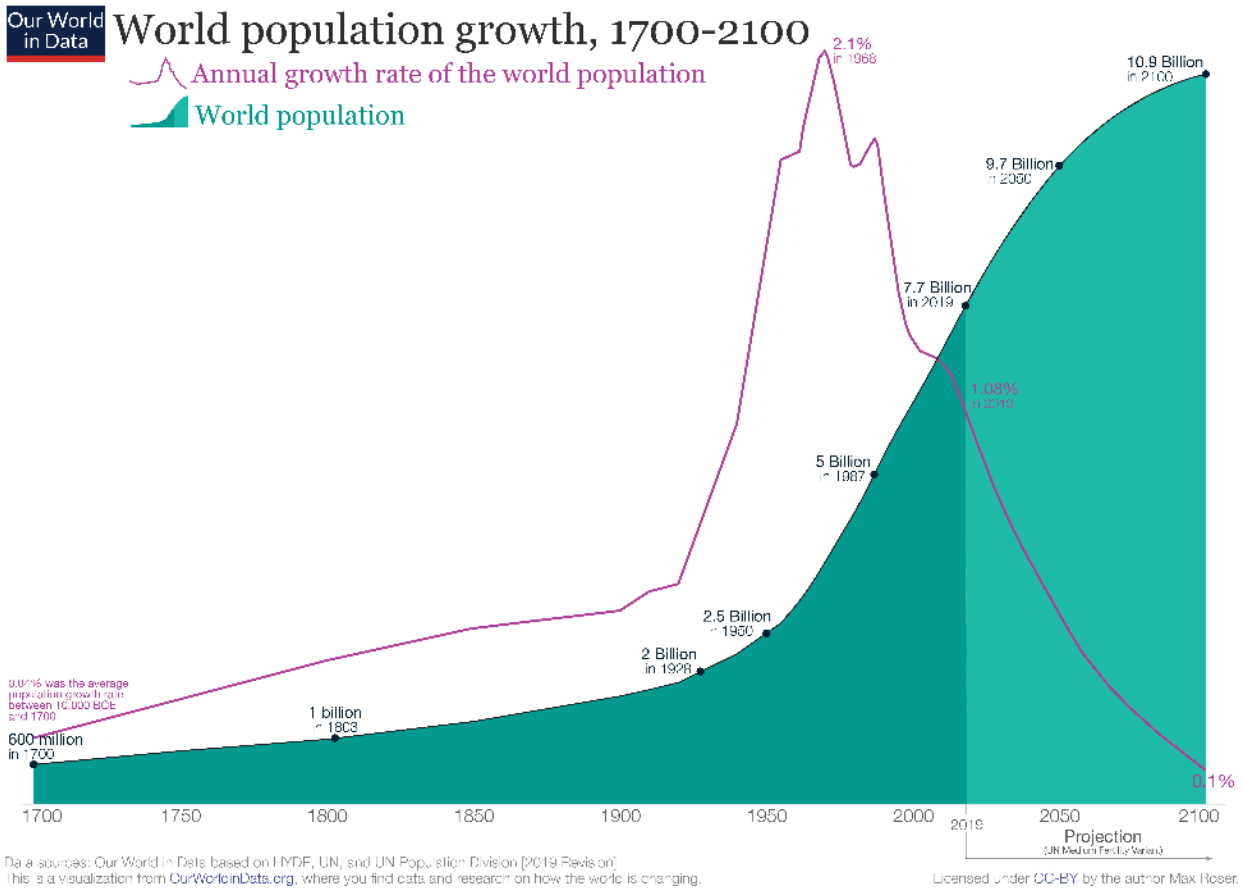


Figure 3.3.2.a: Human population growth. Since 1700, human population size (shaded in teal) has increased. It reached 1 billion in 1803, 2 billion in 1928, 2.5 billion in 1950, 5 billion in 1987, and 7.7 billion in 2019. It is projected to reach 10.9 billion in 2100. The population growth rate (pink line) was only 0.04% on average between 10,000 BCE and 1700. The population growth rate peaked in 1968 at 2.1%, and since then, it has slowed to 1.08% in 2019 and is projected to be at 0.1% in 2100. Image by Max Roser (2013) "Future Population Growth". Published online at OurWorldInData.org. (CC-BY)

The fundamental cause of the acceleration of growth rate for humans in the past 200 years has been the reduced death rate due to changes in public health and sanitation. Clean drinking water and proper disposal sewage has drastically improved health in developed nations. Also, medical innovations such as the use of antibiotics and vaccines have decreased the ability of infectious disease to limit human population growth. In the past, diseases such as the bubonic plaque of the fourteenth century killed between 30 and 60 percent of Europe's population and reduced the overall world population by as many as one hundred million people. Naturally, infectious disease continues to have an impact on human population growth, especially in poorer nations. For example, life expectancy in sub-Saharan Africa, which was increasing from 1950 to 1990, began to decline after 1985 largely as a result of HIV/AIDS mortality. According to a 2016 study by Marcus et al., The reduction in life expectancy caused by HIV/AIDS was estimated to be 8 years for 2016.

Human technology and particularly our harnessing of the energy contained in fossil fuels have caused unprecedented changes to Earth's environment, altering ecosystems to the point where some may be in danger of collapse. Changes on a global scale including depletion of the ozone layer, desertification and topsoil loss, and global climate change are caused by human activities.

Reference

Marcus, J. L., Chao, C. R., Leyden, W. A., Xu, L., Quesenberry, C. P., Jr, Klein, D. B., Towner, W. J., Horberg, M. A., & Silverberg, M. J. (2016). Narrowing the Gap in Life Expectancy Between HIV-Infected and HIV-Uninfected Individuals With Access to Care. *Journal of acquired immune deficiency syndromes (1999)*, *73*(1), 39–46.

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3.3.3: The Rate of Human Population Growth

Demographic Transition

Recall from the Populations chapter that the **population growth rate** (*r*) equals the birth rate minus the death rate. Slowly declining birth rates following an earlier sharp decline in death rates are today characteristic of most of the less-developed regions of the world. The shift from high birth and death rates to low birth as well as death rates is called the **demographic transition**.

Prior to World War II, advances in public health were largely limited to affluent, industrialized countries. But since then, many more countries have enjoyed improvements in public health - always with dramatic effect on death rates. For example, in 1945, the death rate in Sri Lanka (then called Ceylon) was 0.022 (2.2%). In 1946, a large-scale program to control mosquitos, which transmit malaria, was started. By eliminating the mosquito, the incidence of malaria dropped sharply. After 9 years, the death rate dropped to 0.010 (1%), and by 2012 was 0.006 (0.6%). However, a compensating decline in birth rates has come more slowly; the birth rate was 0.018 (1.8% in 2012). With birth rates higher than death rates, the population was increasing at an annual rate of 0.012 (1.2%) per year, with a doubling time of 57.5 years (t = 0.69/0.012).

Predicting Future Population Size

Doubling time is based on a constant population growth rate, but this rate can change depending on a number of factors, including total fertility rate (TFR) and the age structure of the population.

Total Fertility Rate

The **total fertility rate** (TFR) is the average number of children that each woman will have during her lifetime. The TFR is an average because, of course, some women will have more, some fewer, and some no children at all. Theoretically, when the TFR = 2, each pair of parents just replaces itself. Actually it takes a TFR of 2.1 or 2.2 to replace each generation - this number is called the **replacement fertility rate** - because some children will die before they grow up to have their own two children. In countries with low life expectancies, the replacement rate is even higher (2.2–3). Figure 3.3.3.*a* compares the total fertility rate in different countries.

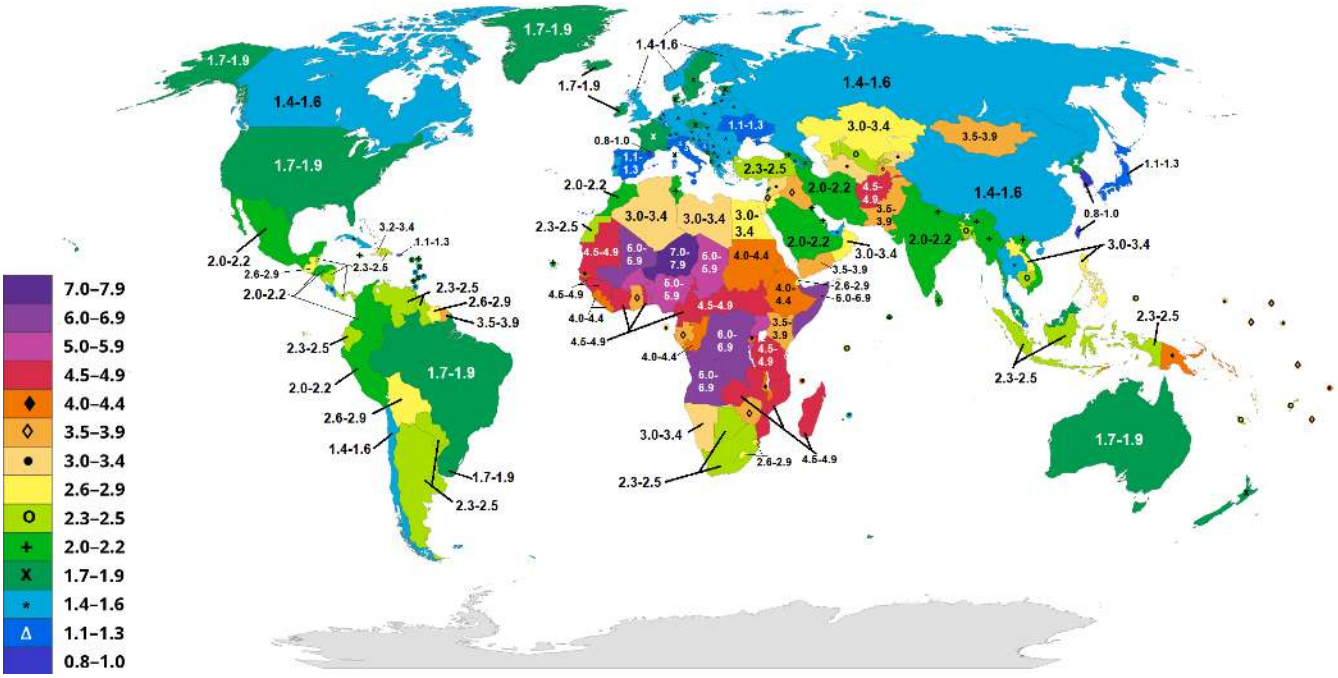


Figure 3.3.3.*a*: Total fertility rate by country in 2020. Most countries in North and South America have a total fertility rate of 1.7-2.5 children per woman, but fertility rates are lower (for example, Canada and Chile) or higher (for example, Guatamala and Bolivia) in a few countries. Most of Europe and northern and Eastern Asia have low fertility rates (generally 1.4-1.6 children per woman). Many Middle Eastern countries and those in southern and southeastern Asia have slightly higher fertility rates (generally 1.7-2.5 children per woman). The fertility rate in Australia is 1.7-1.9 children per woman. High fertility rates are common in African countries. For example, the fertility rate in Niger is 7.0-7.9. Image modified from Korakys (CC-BY-SA).

Age Structure

The **age structure** of a population, the proportion of a population in different age classes, is an important factor in population dynamics. The relationship between TFR and the population growth rate (*r*) depends on age structure. For example, if at one period a population has an unusually large number of children, they will — as they pass through their childbearing years — increase the *r* of the population even if their TFR goes no higher than 2. Most people have children between the ages of 15 and 49. So if a population has a large number of young people just entering their reproductive years, the rate of growth of that population is sure to rise.

Models that incorporate age structure allow better prediction of population growth, plus the ability to associate this growth with the level of economic development in a region. Countries with rapid growth associated with high birth rates have a pyramidal shape in their age structure diagrams, showing a preponderance of younger individuals, many of whom are of reproductive age (figure 3.3.3.*b*).

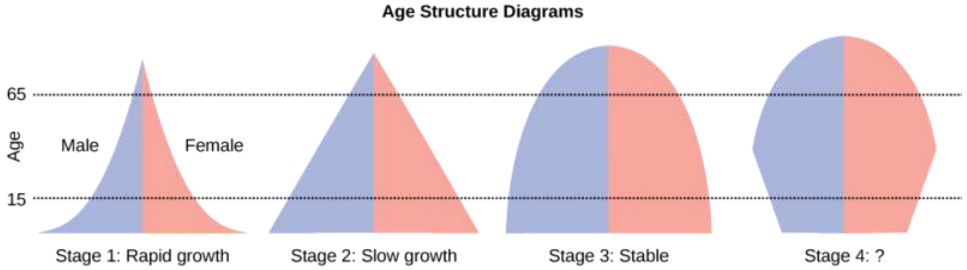


Figure 3.3.3.*b*: Typical age structure diagrams are shown. The rapid growth diagram narrows to a point, indicating that the number of individuals decreases rapidly with age. In the slow growth model, the number of individuals decreases steadily with age. Stable population diagrams are rounded on the top, showing that the number of individuals per age group decreases gradually, and then increases for the older part of the population.

The age structure of a population also reflects the recent pattern of mortality. In countries where injuries, starvation, and disease, etc. take a heavy toll throughout life, the age structure diagram has a broad base. In countries where almost everyone survives until

old age, the bases is narrower.

Rapid growth is most often observed in underdeveloped countries where individuals do not live to old age because of less-than-optimal living conditions, and there is a high birth rate. Age structures of areas with slow growth, including developed countries such as the United States, still have a pyramidal structure, but with many fewer young and reproductive-aged individuals and a greater proportion of older individuals compared to underdeveloped countries. Other developed countries, such as Italy, have zero population growth. The age structure of these populations is more conical, with an even greater percentage of middle-aged and older individuals.The actual growth rates in different countries are shown in figure 3.3.3.*c*, with the highest rates tending to be in the less economically developed countries of Africa and Asia.

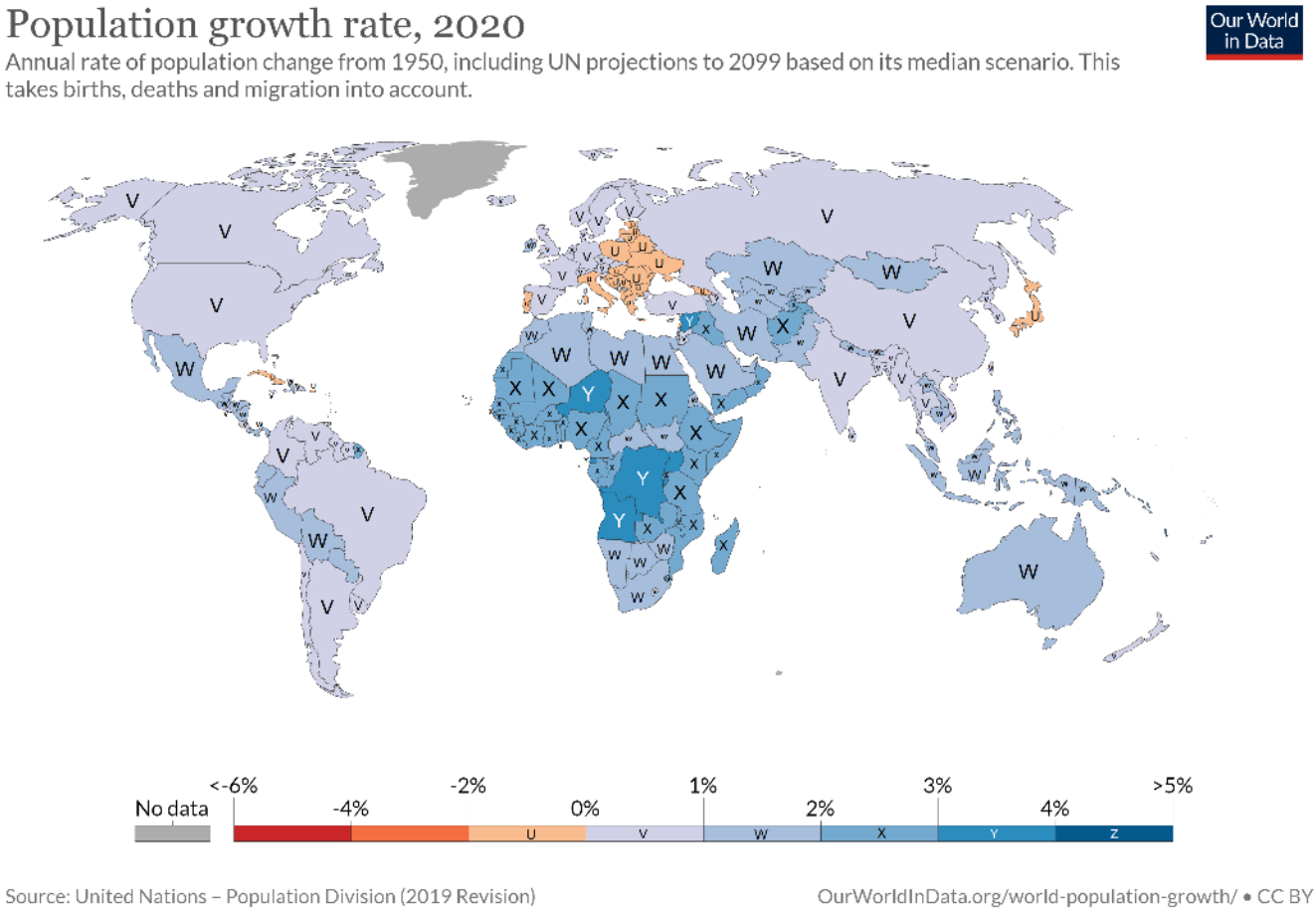


Figure 3.3.3.*c*: The percent growth rate of populations in 2020 in different countries is shown. The population growth rate is negative (meaning the population size is declining) in Cuba, Portugal, many countries in Eastern Europe, and Japan. Mexico, much of Central America, Ecuador, Peru, Bolivia, Paraguay, and Haiti have a population growth rate of 1-2%. Most other countries in North and South America have a population growth rate of 0-1%. Western and Northern Europe and most Asian countries have a population growth rate of 0-1%. In the Middle East, Southeast Asia, Australia, northern and southern Africa, Central African Republic, and South Sudan, the population growth rate is generally 1-2%. Examples of countries with a population growth rate above 2% include the remaining African countries, Syria, Yemen, Oman, Iraq, Afghanistan, and Tajikistan. Image modified from Max Roser, Hannah Ritchie and Esteban Ortiz-Ospina (2013) - "World Population Growth". Published online at OurWorldInData.org (CC-BY).

The U.S. Baby Boom

The TFR in the United States declined from more than 4 late in the nineteenth century to less than replacement in the early 1930s. However, when the small numbers of children born in the depression years reached adulthood, they went on a childbearing spree that produced the baby-boom generation (figure 3.3.3.*d*). In 1957, more children were born in the United States than ever before (or since).

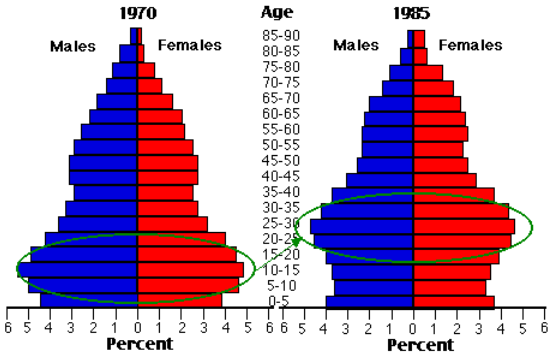


Figure 3.3.3.*d*: Age structure diagrams of the United States population in 1970 and 1985. The x-axis represents the percent of the population. The y-axis represents age groups in increments of five from 0-5 years all the way to 85-90 years. Blue bars to the left represent males, and red bars to the right represent females. Bars taper near the top of the diagram, showing that those in the oldest age categories represent a small percentage of the population. The 1970 age structure diagram bulges around the 10-15 age group, and this represents the baby boom (green oval). In 1985, this bulge has moved to the 25-30 age group.

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3.3.4: Looking Ahead

Population Projections

A consequence of exponential human population growth is that is takes less time to add a particular number of humans to our Earth. Figure 3.3.4.a shows that 123 years were necessary to add 1 billion humans in 1930, but it only took 24 years to add two billion people between 1975 and 1999. As already discussed, at some point it would appear that our ability to increase our carrying capacity indefinitely on a finite world is uncertain. Without new technological advances, the human growth rate has been predicted to continue to slow in the coming decades. However, the population will still be increasing and the threat of overpopulation remains.

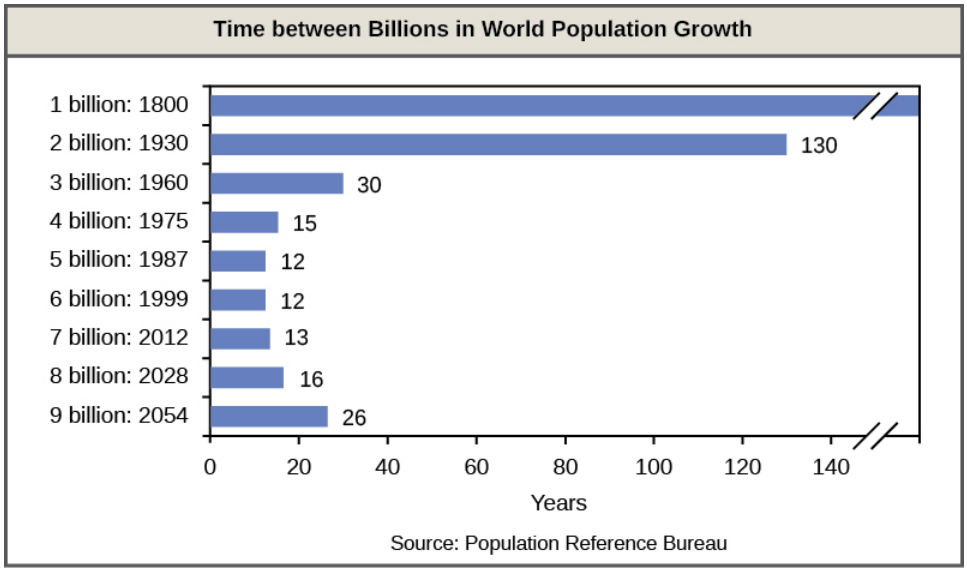


Figure 3.3.4.a: The time between the addition of each billion human beings to Earth decreases over time. By 1800, there were about a billion people on Earth. It took 130 years, until 1930, for the number to reach two million. Thirty years later, in 1960, the number reached three billion, and 15 years after that, in 1975, the number reached four billion. The population reached five billion in 1987, six billion in 1999, and 7 billion in 2011, each twelve years apart. The population reached 8 billion in 2022 and is projected to reach 9 billion in 2037. (credit: modification of work by Ryan T. Cragun)

Exponential growth cannot continue indefinitely. If the current world value for r (0.87% in 2024) remains unchanged, the global population would grow from its current 8.2 billion (December 2024) to over 10 billion by 2050. Experts predict that the global population will continue to grow until 2100, reaching a peak of almost 11 billion. So this begs the question(s)... What is the carrying capacity for humans on Earth? How long until we reach it, or have we already surpassed it? Then finally, what are the consequences of our current and projected populations?

Long-term Consequences

Humans are not unique in their ability to alter their environment. For example, beaver dams alter the stream environment where they are built. Humans, however, have the ability to alter their environment to increase its **carrying capacity**, sometimes to the detriment of other species. Earth's human population and their use of resources are growing rapidly, to the extent that some demographers say that humans have already exceeded our carrying capacity. This would mean that the Earth cannot indefinitely support our current population size. Long-term exponential growth carries with it the potential risks of famine, disease, and large-scale death, as well as social consequences of crowding such as increased crime.

The impact of humans on our environment depends not only on population size but also on resource use. The **ecological footprint** is a measure of the area of land needed to support an individual or country. This includes agricultural lands used to provide food, other lands used to provide goods (such as forests to provide timber) and fuels (such as oil fields to provide fossil fuels), and the land needed to dispose of wastes.

Countries differ in the average ecological footprint per person, and these differences are associated with region (figure 3.3.4.*b*). For example, in 2019, the ecological footprint per person in the United States was 7.8 global hectares compared to only 1.1 global hectares in India. (Visit footprintnetwork.org to see ecological footprints and related metrics for all countries Figure 3.3.4c). Many factors affect the size of an ecological footprint from economic development to resource conservation to individual product choice. Reducing our ecological footprints can increase our carrying capacity and decrease environmental impact. So maybe we should update the question of, "What the Earths carrying capacity for humans," to, "What is the carrying capacity of people on Earth at which we can provide a fair and decent life for all humans while causing the minimum impact on the environment?

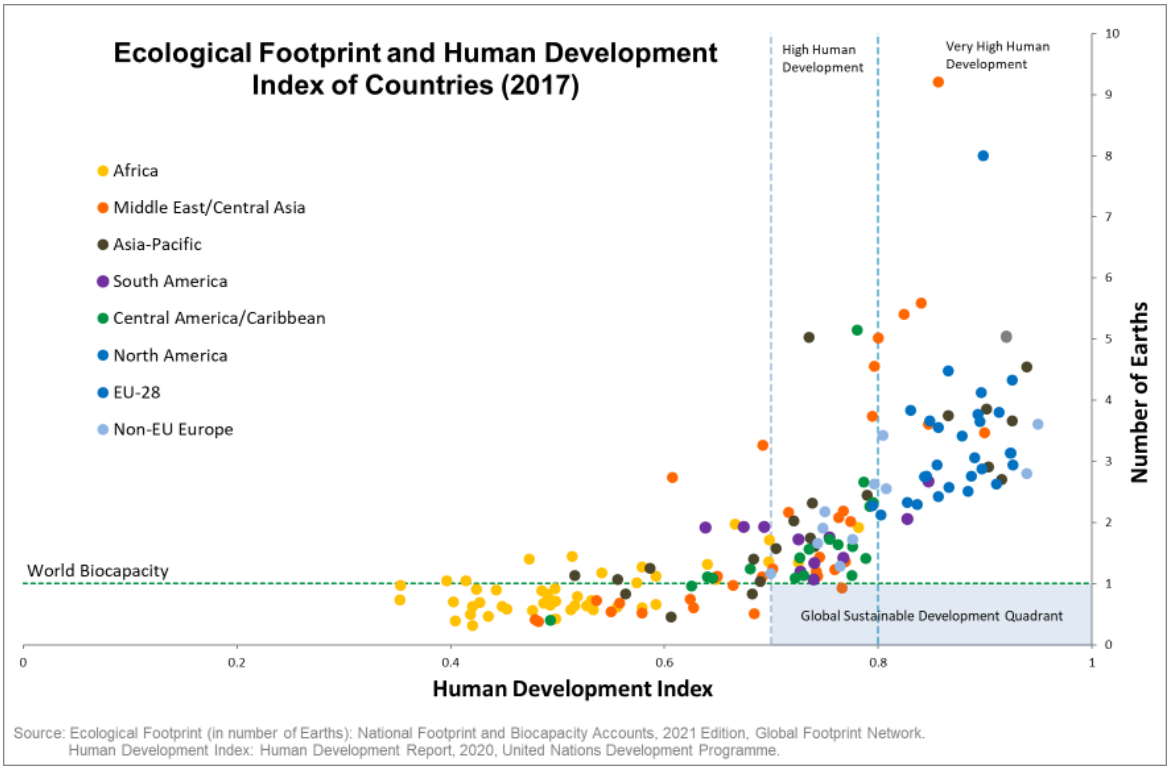


Figure 3.3.4.*b*: The ecological footprint per person in relation to the U.N. human development index for each country coded by region. Countries in some regions of the world have low ecological footprints per person, but this is because people are living in poverty (points in lower left of graph). This pattern is characteristic of many African countries. Other countries have large ecological footprints and live affluently (points in upper right of graph), including many European countries. To sustainably meet human needs, countries must achieve a high human development index and low ecological footprint (points in lower right of graph). (York University Ecological Footprint Initiative & Global Footprint Network. National Footprint and Biocapacity Accounts, 2021 edition. Produced for the Footprint Data Foundation and distributed by Global Footprint Network. Available online at: https://data.footprintnetwork.org. CC-BY-SA 4.0).

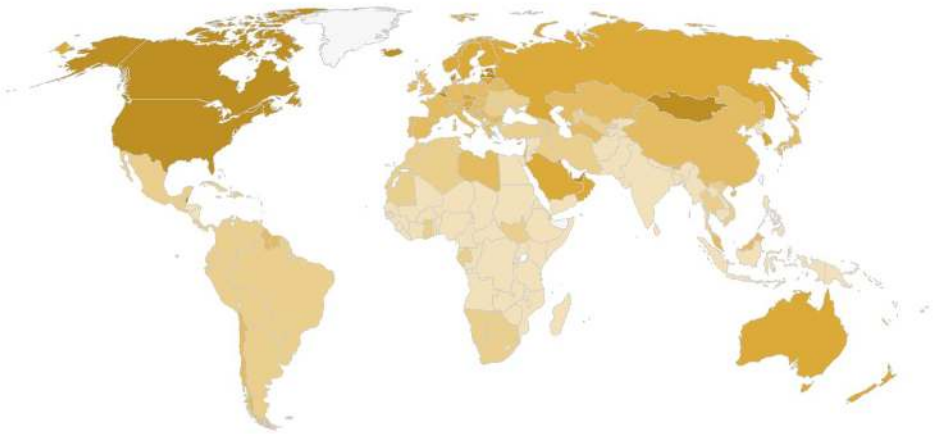


Figure 3.3.4c: *Per capita Ecological Footprint by country. The darkest color is > 6.7 ha and the lightest is < 1.7 ha. It is calculated by taking the ecological footprint of a country and dividing by the population. To live sustainably, everyone would need a footprint of 1.6 ha or less. CC-BY-SA 4.0 Footprint Data Foundation, York University Ecological Footprint Initiative, and Global Footprint Network: National Footprint and Biocapacity Accounts, 2023 edition. Downloaded 12/19/2024 from https://data.footprintnetwork.org.*

Are you wondering about the size of your ecological footprint? You can estimate it here.

Regulation

Reducing the population growth rate will limit the consequences of overpopulation; however, regulation of the human population is a complex issue that presents ethical considerations.

Efforts to moderate population control led to the 1979 One-Child Policy in China, which imposed fines on urban couples who had more than one child (figure 3.3.4.*c*). Additionally, only a couple's first child was granted educational and health care benefits. The effectiveness of the policy in limiting overall population growth is controversial, as was the policy itself. Tragically, this policy combined with the desire of many couples to have a male heir led to female infanticide. Furthermore, enforcement of the policy led to human rights abuses including forced sterilizations and forced abortions. Over the years, some restrictions associated with the One-Child Policy were lifted. For example, in 2013, an adult who was an only child was allowed to have two children. The policy ended in 2016, and as of May 2021, each couple is now permitted to have up to three children.



Figure 3.3.4.*c*: A poster explaining and promoting the One-Child Policy. Image by Arian Zwegers (CC-BY).

Zero population growth occurs when the birth rate equals the death rate such that the rate of population growth is zero. Logically, this would occur when total fertility rate equals replacement fertility rate, but as described in the previous section, this depends on the age structure of a population.

All else being equal, reductions in total fertility rate will slow human population growth. Total fertility rate is negatively correlated with improved standard of living, access to health care, and gender equality. As countries develop economically, individuals become increasingly dependent on urban jobs rather than the family farm for income and provisions. While a large family would be needed to tend the family farm, supporting many children in an urban area is expensive. As a result, economic development is associated with couples choosing to have fewer children.

Access to healthcare decreases childhood mortality and provides the option of birth control. While decreased infant and childhood mortality alone would increase the population growth rate, people tend to have fewer children when they can be confident that all of their children are likely to survive; thus, as childhood mortality declines, total fertility rate also declines, lowering the population growth rate.

The education of women and girls is also associated with a decreased total fertility rate. Furthermore, family planning education programs have had highly positive effects in some countries on limiting population growth rates and increasing standards of living. When women have knowledge of family planning, power to make decisions about their family size, and a variety of career options, fertility rate declines. In regions that have made recent strides in educating girls, families more often choose to have a small number of children so that they can afford to pay for their education regardless of gender.

References

Population Growth (Annual %). 2019 World Bank Group. Accessed 29 August 2020.

Growing at a slower pace, world population is expected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100. 2019. United Nations Department of Economic and Social Affairs. Accessed 29 August 2020.

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SECTION OVERVIEW

3.3.5: Human Impact on the Environment

The human presence and impact on this Earth has been changing with our population, technology, and affluence. In order to start understanding how these variables have an impact on Earth (in a general sense) the **IPAT** equation was created. As is the case for any equation, IPAT expresses a balance among interacting factors. It can be stated as:

$$I = P \times A \times T$$

where...

"I" represents the impacts of a given course of action on the environment

"P" is the relevant human population for the problem at hand

"A" is the level of consumption per person

"T" is impact per unit of consumption. Impact per unit of consumption is a general term for technology, interpreted in its broadest sense as any human-created invention, system, or organization that serves to either worsen or uncouple consumption from impact

The equation is not meant to be mathematically rigorous; rather it provides a way of organizing information for a “first-order” analysis. To achieve meaningful reductions of human impact, there are intense debates on where the focus should lie. Where one group sees expensive remedies with little demonstrable return, another sees opportunities for investment in new technologies, businesses, and employment sectors, with collateral improvements in global and national well-being.

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3.3.6: Data Dive- World Population Densities

Overview

The Socioeconomic Data and Applications Center (SEDAC), is one of the Distributed Active Archive Centers (DAACs) in the Earth Observing System Data and Information System (EOSDIS) of the U.S. National Aeronautics and Space Administration (NASA). Its main objective is to investigate human interactions in the environment and to develop and operate applications that support the integration of socioeconomic and earth science data and to serve as an "Information Gateway" between earth sciences and social sciences. One of the projects it continually updates is creating global population density maps. Their 2020 map can be observed below:

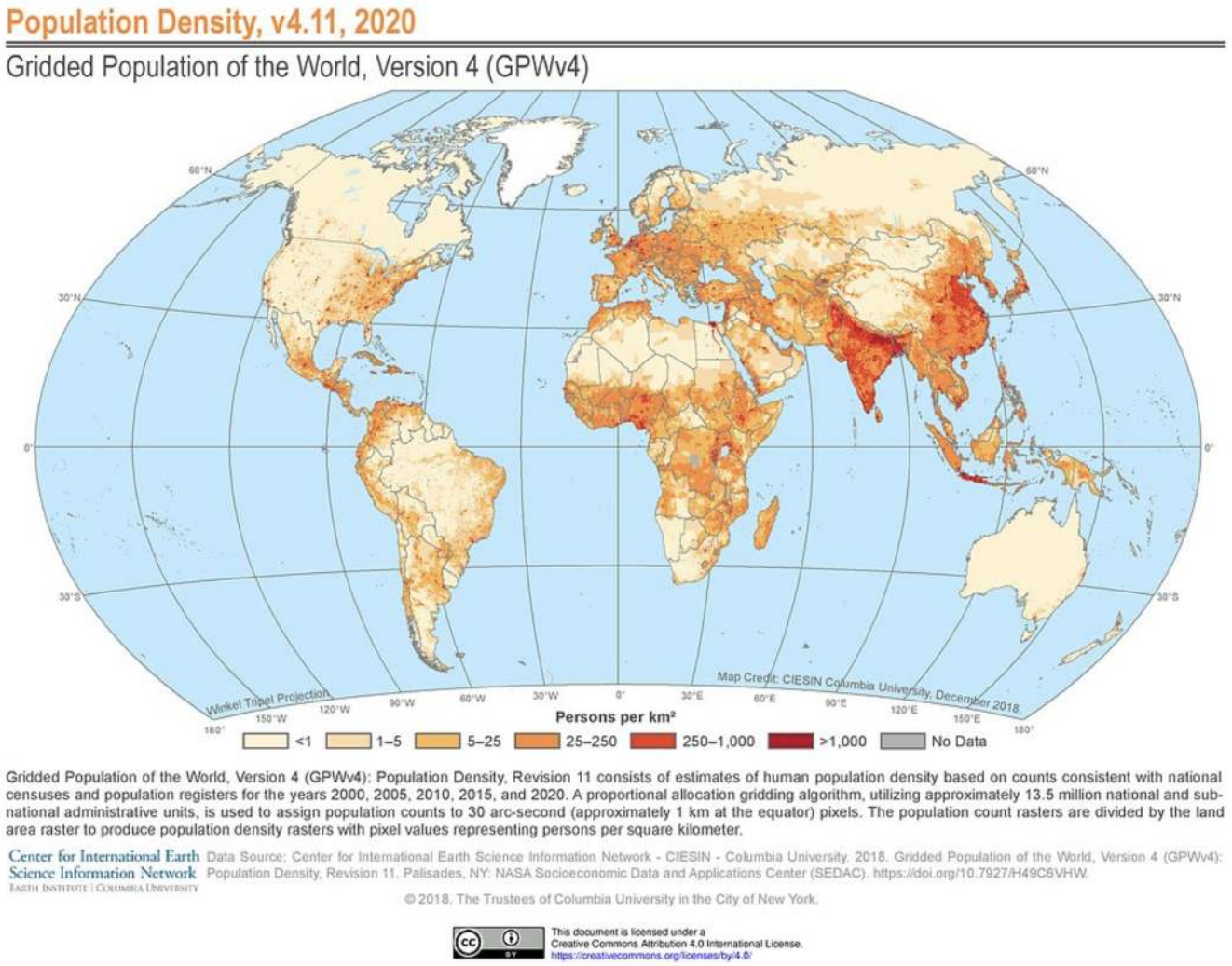


Figure 3.3.6.*a*: World density map. Graph by SEDAC (CC-BY-3.0) Gridded population of the world (version 4) illustrating population density for the year 2020. Density is indicated with darker or lighter shading using the following categories in persons per square kilometer (1, 1-5, 5-25, 25-250, 250-1000, 1000, and no data). North America has highest densities on the east coast of the United States, southern Mexico, Central American countries, and western and eastern coastlines of South America. All of Europe is high density. Africa has the highest densities in countries in the middle of the continent. In Asia, India, eastern China along with Asian islands have very high densities. (CC BY 4.0; The Trustees of Columbia University in the City of New York)

Questions

1. The data on the above graph is overlaid onto a world map. Why do you think this is a powerful way to display data?
2. What question(s) are the authors trying to answer with this graph and table?
3. Which areas of the globe have the highest density levels (darkest density shading)?

4. Are there any areas of the globe that surprise you (either high or low) with their density? Why?
5. How can policy makers/world leaders/health organizations use this information? Provide at least 3 ideas.
6. What is missing from this map? Hint: It's very large!

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3.3.7: Section Review

Summary

After completing this chapter you should be able to...

- Discuss the history of human population growth.
- Define demographic transition.
- Explain how total fertility rate and age structure affect current and future population growth rate.
- Interpret age structure diagrams.
- Discuss the long-term implications of unchecked human population growth with respect to carrying capacity and ecological footprints.
- Describe efforts to regulate human population size.

The world's human population is growing at an exponential rate. Humans have increased the world's carrying capacity through migration, agriculture, medical advances, and communication. The age structure of a population allows us to predict population growth. Unchecked human population growth could have dire long-term effects on our environment.

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CHAPTER OVERVIEW

4: Community Ecology

4.1: Biotic Interactions

4.1.1: Trophic Interactions

4.1.1.1: Predation

4.1.1.2: Herbivory

4.1.1.3: Parasitism

4.1.1.4: Food Chains and Food Webs

4.1.2: Competition

4.1.3: Facilitation

4.1.4: Symbiosis

4.2: Community Structure and Dynamics

4.3: Data Dive- Bison Impacts In Prairies

4.4: Section Review

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4.1: Biotic Interactions



Until the late 1800s, Bison (*Bison bison*) numbered tens of millions in the Great Plains of the United States. By 1890, roughly 1000 Bison were left because the United States government campaign to eradicate the native people, their culture, and habitats they relied on. Slowly, a movement started to try and save Bison from extinction. It took until the early 2000's for Bison numbers to reach a half a million. During this time, scientists were able to observe the Bison reintroduction back into the Great Plains. Bison were found to be the most critical species to restoring and maintaining the function and diversity in the Great Plains community. Both plants and animal populations in the community were strengthened from the return of the Bison. Understanding community dynamics is essential to conserving and restoring these systems and the species that define them. This is particularly critical for communities with one particular species that acts as a keystone to the health of the system.

Figure 4.1.1: American bison with starlings on its back. (Image by NPS photos/Kim Acker (Public Domain))

Populations typically do not live in isolation from other species. Populations that interact within a given area form a **community**. The organisms that form a community are found in **habitats**, physical environments where organisms live; however, **biotic** (living) components are considered part of a community. Scientists study ecology at the community level to understand how species interact with each other and compete for the same resources.

Biotic interactions refer to the relationships among organisms. They can be **intraspecific** (between members of the same species) or **interspecific** (between members of different species). When at least one of the interactants is harmed, the relationship is called an **antagonism. Trophic interactions**, in which one species consumes another, are antagonisms. **Competition** is another antagonism in which species at the same trophic level (that eat the same things) interact through using the same resources. Interactions in which at least one species benefits and neither is harmed are called **facilitation**, which can be categorized as **commensalism** or **mutualism.**





Figure 4.1.*a***:** A variety of biotic interactions occur among the species at The Seal Beach National Wildlife Refuge (top). For example, the Light-Footed Clapper Rail (bottom) benefits from the cordgrass in which it nests. However, predators such as red foxes harm this endangered bird. The refuge manages this harmful interaction by installing fencing to exclude the red fox, which historically did not occur in the area. Top image and bottom image by US Fish & Wildlife Service (public domain).

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4.1.1: Trophic Interactions

Trophic interactions occur when one organism feeds on another. The three main types of trophic interactions are **predation** (figure 4.1.1.*a*), **herbivory**, or **parasitism**. During these interactions, one species benefits by gaining food at the expense of the other, which either dies or loses nutrients, tissues, or organs (such as leaves). Trophic interactions involve the flow of energy, and the trophic interactions in a community can be represented by **food chains** and **food webs**.



Figure 4.1.1.*a***:** A hawk (*Buteo jamaicensis*) eats a vole (*Microtus californicus*), exemplifying predation, a common trophic interaction. Image by Jrockley (public domain).

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4.1.1.1: Predation

Perhaps the classical example of a biotic interaction is the predator-prey relationship. **Predation** occurs when one species (the **predator**) kills and eats multiple **prey** over its lifetime.

Predator-Prey Dynamics

Population sizes of predators and prey in a community are not constant over time, and they may vary in cycles that appear to be related. For example, 100 years of trapping data from North America shows how population dynamics of the lynx (predator) and the snowshoe hare (prey) cycle (figure 4.1.1.1.*a*-b).



Figure 4.1.1.1.*a*: The Canada lynx is an example of a predator. Image by Michael Zahra (CC-BY-SA).



Figure 4.1.1.1.*b*: The snowshoe hare is the prey of the Canada lynx. Image by the National Park Service (public domain).

This cycling of predator and prey population sizes has a period of approximately ten years, with the predator population lagging one to two years behind the prey population (figure 4.1.1.1.*a*-c). An apparent explanation for this pattern is that as the hare numbers increase, there is more food available for the lynx, allowing the lynx population to increase as well. When the lynx population grows to a threshold level, however, they kill so many hares that hare numbers begin to decline, followed by a decline in the lynx population because of scarcity of food. When the lynx population is low, the hare population size begins to increase due, in part, to low predation pressure, starting the cycle anew.

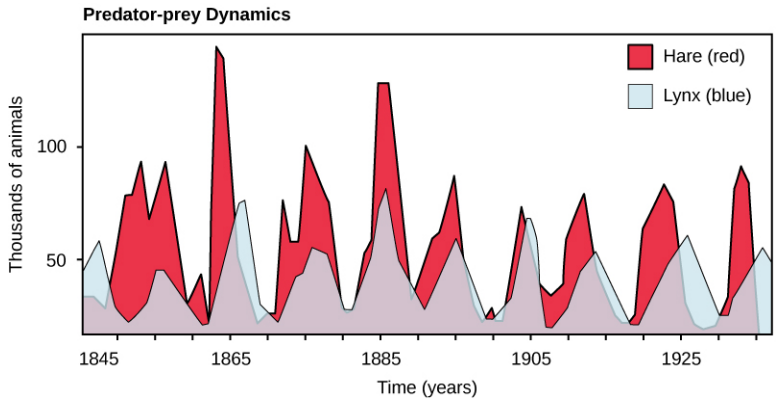


Figure 4.1.1.1.*c*: The cycling of Canada lynx and snowshoe hare populations in Northern Ontario is an example of predator-prey dynamics. The x-axis shows time in years, and the y-axis shows population size in thousands of animals. The lynx population is represented in blue (shorter peaks), and the hare population is represented in red (taller peaks). Both populations increase and decrease in 10-year cycles, with changes in the lynx population lagging a few years behind that of hare.

The dynamic of closely matched population cycling occurs because the snowshoe hare is the primary food source for the lynx. When predators have generalists, feeding on a variety of prey species, and prey are consumed by a variety of predators species, their population dynamics are less likely to cycle together.

Adaptations of Predators

Predators have a variety of adaptations to catch and consume prey, and the specific adaptations depend on the predator. For example, raptors, such as owls and hawks, have hooked beaks for tearing flesh and talons for grabbing prey. Mammal predators often have sharp teeth and claws. Some predators can run quickly to chase prey, and others "sit and wait", lunging forward when prey pass them. Some predators, like rattlesnakes and tarantulas, subdue their prey by injecting them with venom (figure 4.1.1.1.*d*). Predators often have large eyes located forward (like a wolf) rather than eyes spaced far apart on the sides of the head (like a sheep). Forward-facing eyes allow for depth perception, which is key to tracking prey. In contrast, peripheral vision is expanded when eyes are located to the sides, and this helps prey identify threats.



Figure 4.1.1.1.*d*: This Asian birdeater tarantula uses its fangs to inject its prey with poisonous venom. Image by Matt Reinbold (CC-BY-SA).

Defensive Traits in Prey

Prey evolve mechanical, chemical, physical, or behavioral defenses against predators. Some prey have armor (such as a turtle shell or the bony plates protecting armadillos), a **mechanical defense** that reduces predation by discouraging physical contact. Many animals produce or obtain **chemical defenses** from plants and store them to prevent predation. Other species use their body shape and coloration as **camouflage** to avoid being detected by predators, an example of a **physical defense**. The tropical walking stick is an insect with the coloration and body shape of a twig, which makes it very hard to see when it is stationary against a background

of real twigs (figure 4.1.1.1.*e*-a). In another example, the chameleon can change its color to match its surroundings (figure 4.1.1.1.*e*-b).



Figure 4.1.1.1.*e*: (a) The tropical walking stick and (b) the chameleon use their body shape and/or coloration to prevent detection by predators. (credit a: modification of work by Linda Tanner; credit b: modification of work by Frank Vassen)

Some species use coloration as a way of warning predators that they are distasteful or poisonous. For example, the monarch butterfly caterpillar sequesters poisons from its food (plants and milkweeds) to make itself poisonous or distasteful to potential predators. The caterpillar is bright yellow and black to advertise its toxicity. The caterpillar is also able to pass the sequestered toxins on to the adult monarch, which is also dramatically colored black and red as a warning to potential predators. Fire-bellied toads produce toxins that make them distasteful to their potential predators (figure 4.1.1.1.*f*). They have bright red or orange coloration on their bellies, which they display to a potential predator to advertise their poisonous nature and discourage an attack. Warning coloration only works if a predator uses eyesight to locate prey and can learn—a naïve predator must experience the negative consequences of eating one before it will avoid other similarly colored individuals.



Figure 4.1.1.1.*f*: The fire-bellied toad has bright coloration on its belly that serves to warn potential predators that it is toxic. (credit: modification of work by Roberto Verzo)

While some predators learn to avoid eating certain potential prey because of their coloration, other species have evolved mechanisms to mimic this coloration to avoid being eaten, even though they themselves may not be unpleasant to eat or contain toxic chemicals. In some cases of **mimicry**, a harmless species imitates the warning coloration of a harmful species. Assuming they share the same predators, this coloration then protects the harmless ones. Many insect species mimic the coloration of wasps, which are stinging, venomous insects, thereby discouraging predation (figure 4.1.1.1.*g*). In other cases of mimicry, multiple species share the same warning coloration, but all of them actually have defenses. The commonness of the signal improves the compliance of all the potential predators.



(a) (b)

Figure 4.1.1.1.*g*: One form of mimicry is when a harmless species mimics the coloration of a harmful species, as is seen with the (a) wasp (*Polistes* sp.) and the (b) hoverfly (*Syrphus* sp.). (credit: modification of work by Tom Ings)

Running from predators, hiding, and playing dead are examples of **behavioral defenses**. Some prey also exhibit behaviors that threaten predators. For example, snapping turtles stretch their legs to appear larger and snap aggressively at predators.

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4.1.1.2: Herbivory

When an animal feed on parts of another organism (usually a plant), **herbivory** occurs. For example, the koala eats the eucalyptus leaves (figure 4.1.1.2.a) or a cicada feeds a plant's sap (figure 4.1.1.2.b). Like predators, herbivores may feed on multiple individuals over their lives; however, herbivores do not necessarily kill the plants that they eat.



Figure 4.1.1.2.a: Koalas are herbivores that feed exclusively on eucalyptus leaves. They are thus considered specialists because the specialize on just one type of food. Image by Dr. Umesh Behari Mathur (CC-BY).



Figure 4.1.1.2.b: This floury baker cicada feeds on plant sap by piercing the tree with needle-like mouth parts. Image by Toby Hudson (CC-BY-SA).

Plant species have evolved numerous defenses that reduce herbivory. Thorns are an example of a mechanical defense that discourages large herbivores from feeding on a plant (Figure 4.1.1.2.c-a). Many plant species produce secondary plant compounds that serve no function for the plant except that they are toxic to animals and discourage consumption, acting as a chemical defense. For example, the foxglove produces several compounds, including digitalis, that are extremely toxic when eaten (Figure 4.1.1.2.c-b). (Biomedical scientists have repurposed the chemical produced by foxglove as a heart medication, which has saved lives for many decades.)



(a) (b)

Figure 4.1.1.2.*c*: The (a) honey locust tree uses thorns, a mechanical defense, against herbivores, while the (b) foxglove uses a chemical defense: toxins produces by the plant can cause nausea, vomiting, hallucinations, convulsions, or death when consumed. (credit a: modification of work by Huw Williams; credit b: modification of work by Philip Jägenstedt)

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4.1.1.3: Parasitism

Parasitism occurs when one organism (the **parasite**) takes nutrients from another (the **host**). The host is usually weakened by the parasite as it siphons resources the host would normally use to maintain itself. Parasites do not necessarily kill their hosts. When they do, it is often a slow process, allowing the parasite time to complete its reproductive cycle before it or its offspring are able to spread to another host. A parasite may remain attached to the same host for its full lifespan, but some parasites have complex life cycles involving multiple host species. For example, a tapeworm causes disease in humans when contaminated and under-cooked meat such as pork, fish, or beef is consumed. Figure 4.1.1.3.*a* illustrates the life cycle of the pork tapeworm. The tapeworm can live inside the intestine of the host for several years, benefiting from the host's food, and it may grow to be over 50 feet long by adding segments. The parasite moves from one host species to a second host species in order to complete its life cycle.

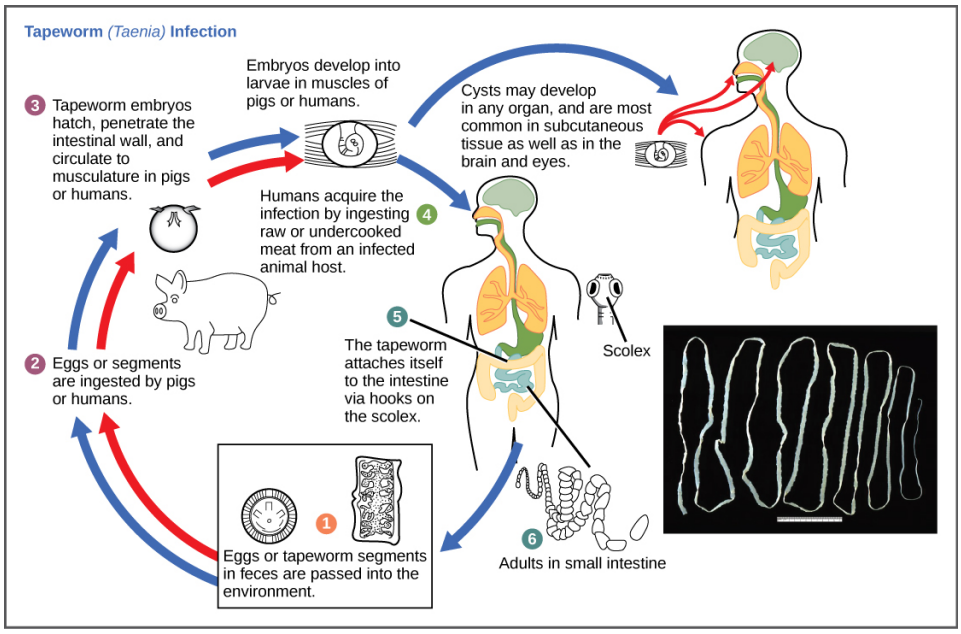


Figure 4.1.1.3.*a*: This diagram shows the life cycle of the tapeworm, a human worm parasite. In the first step, eggs or tapeworm segments from human feces contaminate the environment. Second, pigs ingest these eggs or segments. Third, the eggs mature into larvae, which encyst in the muscle tissue of the pig. It is also possible for humans to develop cysts if they ingest eggs. Fourth, humans become infected when they eat pork that is undercooked. Fifth, the larvae mature into adults, attaching themselves to the intestine wall. Sixth, adult tapeworms can grow many segments and become quite long. They produce the eggs or segments that continue the life cycle. (credit: modification of work by CDC)

Parasites infect many types of organisms, including other animals and plants. For example, fleas and roundworms are common dog parasites. Plants can be infected by fungi, bacteria, and viruses; there are also plants that parasitize other plants (figure 4.1.1.3.*b*). Even bacteria can be parasitized by viruses called bacteriophages.



Figure 4.1.1.3.*b*: Instead of conducting its own photosynthesis, the parasitic plant dodder siphons nutrients from its host plant. Image by Scot Nelson (public domain).

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4.1.1.4: Food Chains and Food Webs

Trophic interactions in a community can be represented by diagrams called **food chains** and **food webs**. Before discussing these representations in detail, we must first review the basics of energy. Energy flows through a community as a result of trophic interactions.

Energy

Virtually every task performed by living organisms requires energy. In general, **energy** is defined as the ability to do work, or to create some kind of change. Energy exists in different forms. Examples include light energy, kinetic energy, heat energy, potential energy, and chemical energy.

When an object is in motion, there is energy associated with that object. Think of a wrecking ball. Even a slow-moving wrecking ball can do a great deal of damage to other objects. Energy associated with objects in motion is called **kinetic energy**. **Heat energy** is the energy of motion in **matter** (anything that takes up space and has mass) and is considered a type of kinetic energy. The warmer the substance, the faster its molecules are moving. The rapid movement of molecules in the air, a speeding bullet, and a walking person all have kinetic energy. Now what if that same motionless wrecking ball is lifted two stories above ground with a crane? If the suspended wrecking ball is not moving, is there energy associated with it? The answer is yes. The energy that was required to lift the wrecking ball did not disappear, but is now stored in the wrecking ball by virtue of its position and the force of gravity acting on it. This type of energy is called **potential energy**. If the ball were to fall, the potential energy would be transformed into kinetic energy until all of the potential energy was exhausted when the ball rested on the ground. Wrecking balls also swing like a pendulum; through the swing, there is a constant change of potential energy (highest at the top of the swing) to kinetic energy (highest at the bottom of the swing). Other examples of potential energy include the energy of water held behind a dam or a person about to skydive out of an airplane (figure 4.1.1.4.*a*).



Figure 4.1.1.4.*a*: Still water has potential energy; moving water, such as in a waterfall or a rapidly flowing river, has kinetic energy. (credit “dam”: modification of work by “Pascal”/Flickr; credit “waterfall”: modification of work by Frank Gualtieri)

Potential energy is not only associated with the location of matter, but also with the structure of matter. **Chemical energy** is an example of potential energy that is stored in molecules. When molecules that are higher energy and less stable react to form products that are lower energy and more stable, this stored energy is released. Chemical energy is responsible for providing living cells with energy from food.

To appreciate the way energy flows into and out of biological systems, it is important to understand two of the physical laws that govern energy. The **first law of thermodynamics** states that the total amount of energy in the universe is constant and conserved. In other words, there has always been, and always will be, exactly the same amount of energy in the universe. Energy exists in many different forms. According to the first law of thermodynamics, energy may be transferred from place to place or transformed into different forms, but it cannot be created or destroyed. The transfers and transformations of energy take place around us all the time. Light bulbs transform electrical energy into light and heat energy. Gas stoves transform chemical energy from natural gas into heat energy. Plants perform one of the most biologically useful energy transformations on earth: that of converting the energy of sunlight to chemical energy stored within biological molecules, such as sugars (figure 4.1.1.4.*b*).

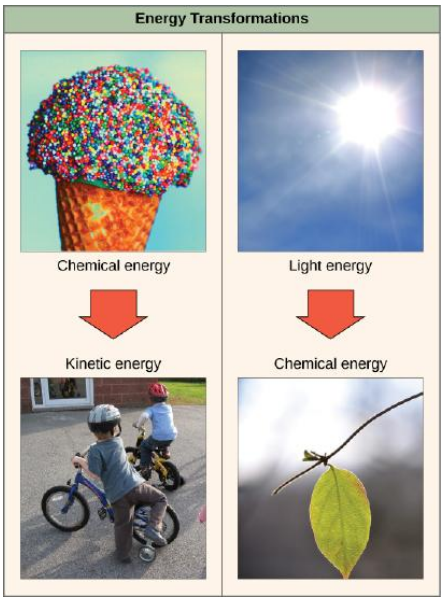


Figure 4.1.1.4.*b*: Shown are some examples of energy transferred and transformed from one system to another and from one form to another. The food we consume, represented by the ice cream cone, provides our cells with the chemical energy required to carry out bodily functions. This can be converted into kinetic energy (the energy of motion), which would be needed to ride a bike. Leaves conduct photosynthesis, converting light energy from the sun to chemical energy. (credit “ice cream”: modification of work by D. Sharon Pruitt; credit “kids”: modification of work by Max from Providence; credit “leaf”: modification of work by Cory Zanker)

The challenge for all living organisms is to obtain energy from their surroundings in forms that are usable to perform cellular work. A living cell’s primary tasks of obtaining, transforming, and using energy to do work may seem simple. However, the **second law of thermodynamics** explains why these tasks are harder than they appear. All energy transfers and transformations are never completely efficient. In every energy transfer, some amount of energy is lost in a form that is unusable. In most cases, this form is heat energy. For example, when a light bulb is turned on, some of the energy being converted from electrical energy into light energy is lost as heat energy. Likewise, some energy is lost as heat energy during the metabolic reactions that occur in organisms.

The concept of order and disorder relates to the second law of thermodynamics. The more energy that is lost by a system to its surroundings, the less ordered and more random the system is. Scientists refer to the measure of randomness or disorder within a system as **entropy**. High entropy means high disorder and low energy. Living things are highly ordered, requiring constant energy input to be maintained in a state of low entropy.

Energy Flow

Cells run on the chemical energy found mainly in carbohydrate molecules, and the majority of these molecules are produced by one process: **photosynthesis**. Through photosynthesis, certain organisms convert solar energy (sunlight) into chemical energy, which is then used to build carbohydrate molecules (figure 4.1.1.4.*c*). The energy that is harnessed from photosynthesis enters the communities continuously and is transferred from one organism to another. Therefore, directly or indirectly, the process of photosynthesis provides most of the energy required by living things on Earth. See the Carbon Cycle and Photosynthesis in OpenStax *Concepts of Biology* for more details about photosynthesis.

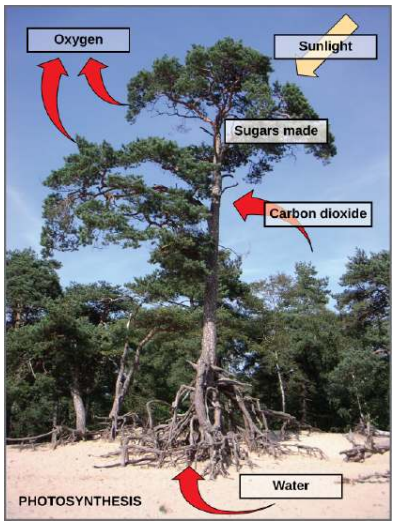


Figure 4.1.1.4.*c*: Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules. Image and caption by OpenStax (CC-BY). Access for free at openstax.org.

Organisms that conduct photosynthesis (such as plants, algae, and some bacteria), and organisms that synthesize sugars through other means are called **producers**. Without these organisms, energy would not be available to other living organisms, and life would not be possible. **Consumers**, like animals, fungi, and various microorganisms depend on producers, either directly or indirectly. For example, a deer obtains energy by eating plants. A wolf eating a deer obtains energy that originally came from the plants eaten by that deer (figure 4.1.1.4.*d*). Using this reasoning, all food eaten by humans can be traced back to producers that carry out photosynthesis (figure 4.1.1.4.*e*).



Figure 4.1.1.4.*d*: The energy stored in carbohydrate molecules from photosynthesis passes through the food chain. The predator that eats these deer is getting energy that originated in the photosynthetic vegetation that the deer consumed. (credit: Steve VanRiper, U.S. Fish and Wildlife Service)

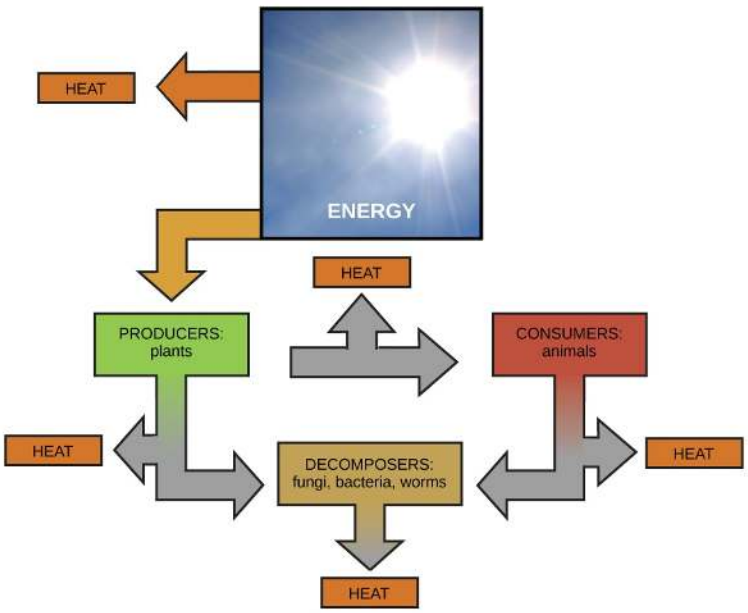


Figure 4.1.1.4.*e*: Ultimately, most life forms get their energy from the sun. This flow chart shows energy from the sun being captured by producers, such as plants, through photosynthesis. The energy is transferred to the consumers of the producers, such as animals. Energy can be obtained from producers directly (herbivores eat plants) or indirectly (carnivores eat herbivores). Decomposers eventually breakdown of dead organisms, including plant and animal material, and contribute to the nutrient pool. Fungi and bacteria are decomposers, and worms are detritivores (not shown). During each energy transfer, some of the energy in the system is lost as heat.

Consumers can be classified based on whether they eat animal or plant material (figure 4.1.1.4.*f*). Consumers that feed exclusively on animals are called **carnivores**. Lions, tigers, snakes, sharks, sea stars, spiders, and ladybugs are all carnivores. **Herbivores** are consumers that feed exclusively on plant material, and examples include deer, koalas, some bird species, crickets, and caterpillars. Herbivores can be further classified into **frugivores** (fruit-eaters), **granivores** (seed eaters), **nectivores** (nectar feeders), and **folivores** (leaf eaters). Consumers that eat both plant and animal material are considered **omnivores**. Humans, bears, chickens, cockroaches, and crayfish are examples of omnivores.



Figure 4.1.1.4.*f*: Carnivores like the lion (top left) eat primarily meat. The ladybug (lower left) is also a carnivore that consumes small insects called aphids. Herbivores, like the mule deer (middle) eat primarily plant material. Omnivores like the bear (top right) and crayfish (bottom right) eat both plant and animal based food. Lion by Kevin Pluck; ladybug by Jon Sullivan; mule deer by Bill Ebbesen; bear by Dave Menke; crayfish by Jon Sullivan. All from OpenStax (CC-BY). Access for free at openstax.org.

Dead producers and consumers are eaten by **detritivores** (which ingest dead tissues) and **decomposers** (which further break down these tissues into simple molecules by secreting digestive enzymes). Invertebrate animals, such as worms and millipedes, are examples of detritivores, whereas fungi and certain bacteria are examples decomposers.

Food Chains

A **food chain** is a linear sequence of organisms through which nutrients and energy pass as one organism eats another. Each organism in a food chain occupies a specific **trophic level** (energy level), its position in the food chain. The first trophic level in the food chain is the producers. The **primary consumers** (the herbivores that eat producers) are the second trophic level. Next are higher-level consumers. Higher-level consumers include **secondary consumers** (third trophic level), which are usually carnivores that eat the primary consumers, and **tertiary consumers** (fourth trophic level), which are carnivores that eat other carnivores. In the Lake Ontario food chain, shown in figure 4.1.1.4.*g*, the Chinook salmon is the apex consumer at the top of this food chain. Some communities have additional trophic levels (quaternary consumers, fifth order consumers, etc.). Finally, detritivores and decomposers break down dead and decaying organisms from any trophic level. There is a single path through a food chain.

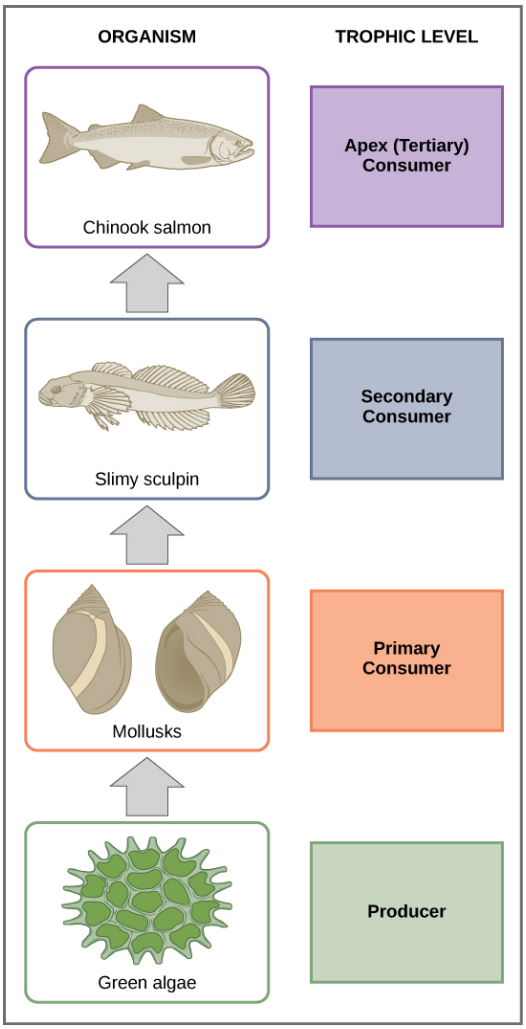


Figure 4.1.1.4.*g*: These are the trophic levels of a food chain in Lake Ontario at the United States–Canada border. Energy and nutrients flow from photosynthetic green algae (producers) at the base to the primary consumers, which are mollusks, or snails. The secondary consumers are small fish called slimy sculpin. The tertiary and apex consumer is Chinook salmon. Detritivores and decomposers are not shown. (credit: modification of work by National Oceanic and Atmospheric Administration/NOAA)

One major factor that limits the number of steps in a food chain is energy. Only about 10% of the energy in one trophic level is transferred to the next trophic level. This is because much energy is lost as heat during transfers between trophic levels or to decomposers due to the second law of thermodynamics. Thus, after four to six trophic energy transfers, the amount of energy remaining in the food chain may not be great enough to support viable populations at higher trophic levels (also see Community Productivity and Transfer Efficiency).

Certain environmental toxins can become more concentrated as they move up the food chain, with the highest concentrations occurring in the top consumers, a process called **biomagnification**. Essentially, a top consumer ingests all the toxins that had previously accumulated in the bodies of the organisms at the lower trophic levels. This explains why frequently eating certain fish, like tuna or swordfish, increases your exposure to mercury, a toxic heavy metal.

Food Webs

While food chains are simple and easy to analyze, there is a one problem when using food chains to describe most communities. Even when all organisms are grouped into appropriate trophic levels, some of these organisms can feed at more than one trophic level. In addition, species feed on and are eaten by more than one species. In other words, the linear model of trophic interactions, the food chain, is a hypothetical and overly simplistic representation of community structure. A holistic model—which includes all the interactions between different species and their complex interconnected relationships with each other and with the environment

—is a more accurate and descriptive model. A **food web** is a concept that accounts for the multiple trophic interactions between each species (figure 4.1.1.4.*h* and i).

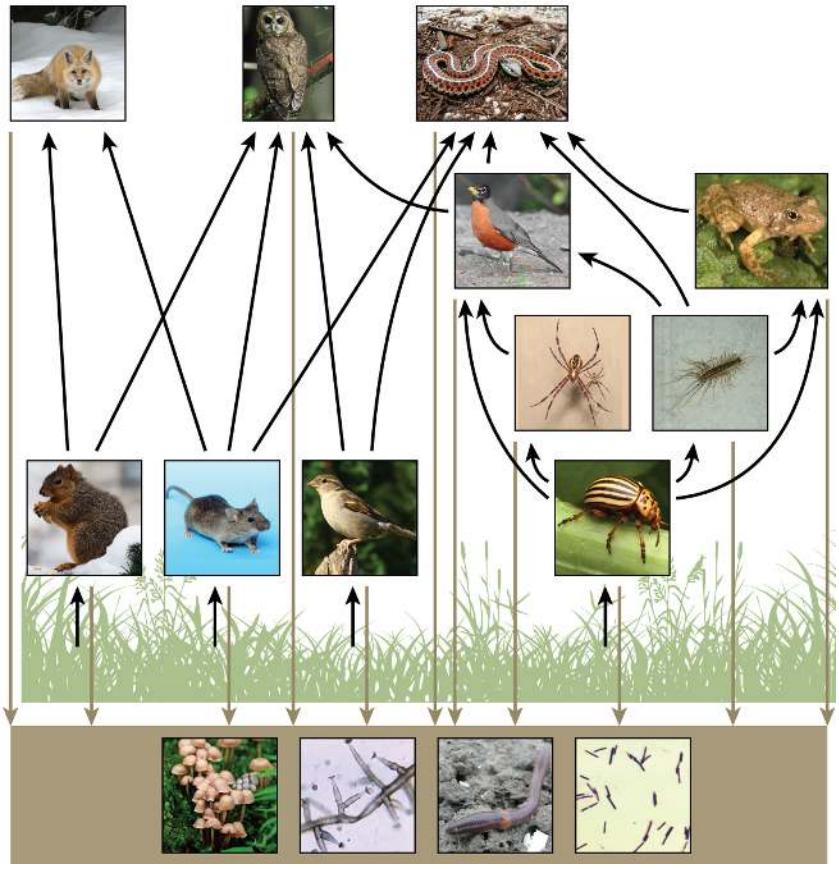


Figure 4.1.1.4.*h*: This food web shows the interactions among organisms across trophic levels. Arrows point from an organism that is consumed to the organism that consumes it and represent energy transfer. The producers (plants) capture energy from the sun. The level above the producers shows the primary consumers that eat the producers. Some examples are squirrels, mice, seed-eating birds, and beetles. Spiders and centipedes eat beetles. Robins eat beetles, spiders, and centipedes, and toads eat beetles and centipedes. Foxes eat squirrels and mice; owls eat squirrels, mice, seed-eating birds, and robins; and snakes eat mice, seed-eating birds, robins, centipedes, and toads. Some consumers are in between trophic levels because they eat a combination of primary, secondary, and/or tertiary consumers. All the producers and consumers eventually become nourishment for the decomposers (mushrooms, mold, and bacteria) and detritivores (earthworms) in the soil, which are depicted at the bottom of the illustration. (credit "fox": modification of work by Kevin Bacher, NPS; credit "owl": modification of work by John and Karen Hollingsworth, USFWS; credit "snake": modification of work by Steve Jurvetson; credit "robin": modification of work by Alan Vernon; credit "frog": modification of work by Alessandro Catenazzi; credit "spider": modification of work by "Sanba38″/Wikimedia Commons; credit "centipede": modification of work by "Bauerph"/Wikimedia Commons; credit "squirrel": modification of work by Dawn Huczek; credit "mouse": modification of work by NIGMS, NIH; credit "sparrow": modification of work by David Friel; credit "beetle": modification of work by Scott Bauer, USDA Agricultural Research Service; credit "mushrooms": modification of work by Chris Wee; credit "mold": modification of work by Dr. Lucille Georg, CDC; credit "earthworm": modification of work by Rob Hille; credit "bacteria": modification of work by Don Stalons, CDC)

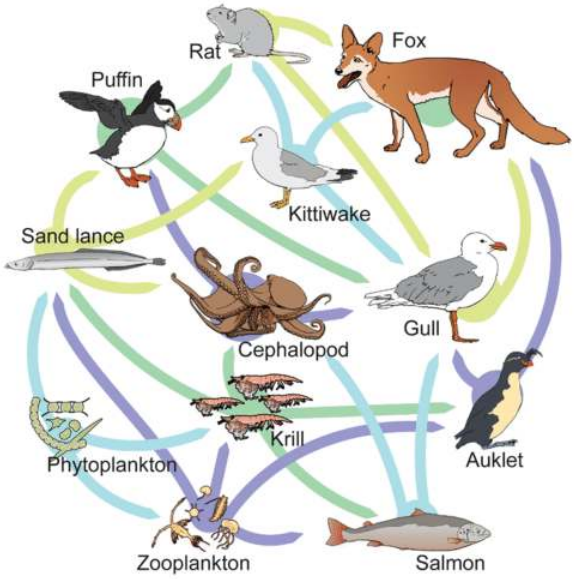


Figure 4.1.1.4.*i*: In this food web, each organism may have multiple food sources or be eaten by multiple species. Phytoplankton are the primary producers. They are consumed by sand lances, krill, and zooplankton. Sand lances are consumed by puffins, kittiwake, and cephalopods. Krill are consumed by the sand lance, cephalopods, auklets, and salmon. Zooplankton are consumed by the sand lance, krill, auklets, and salmon. Puffins are eaten by rats and gulls. Kittiwakes are eaten by rats, foxes, and gulls. Cephalopods are consumed by puffins and gulls. Auklets are consumed by gulls and foxes. Salmon are consumed by cephalopods and gulls. Rats are consumed by foxes and gulls. Gulls are consumed by foxes. Detritivores and decomposers are not shown. Image by Mariana Ruiz Villarreal (LadyofHats) for CK-12 Foundation (CC-BY-NC).

The trophic level of each species in a food web is not necessarily a whole number. In figure 4.1.1.4.*i*, phytoplankton are the primary producers (trophic level 1). Zooplankton only feed on phytoplankton, making them primary consumers (trophic level 2). Determining the trophic level of the other species is more complex. For example, krill eat both phytoplankton and zooplankton. If krill only ate phytoplankton they would primary consumers (trophic level 2). If they ate only zooplankton, they would be secondary consumers (trophic level 3). Since, krill consume both, their trophic level is 2.5.

Community Productivity and Transfer Efficiency

The rate at which photosynthetic producers incorporate energy from the sun is called **gross primary productivity**. In a cattail marsh, plants only trap 2.2% of the energy from the sun that reaches them. Three percent of the energy is reflected, and another 94.8% is used to heat and evaporate water within and surrounding the plant. However, not all of the energy incorporated by producers is available to the other organisms in the food web because producers must also grow and reproduce, which consumes energy. At least half of the 2.2% trapped by cattail marsh plants is used to meet the plants own energy needs.

Net primary productivity is the energy that remains in the producers after accounting for the metabolic needs of the producers and heat loss. The net productivity is then available to the primary consumers at the next trophic level. One way to measure net primary productivity is to collect and weigh the plant material produced on a m^2 (about 10.7 ft^2) of land over a given interval. One gram of plant material (e.g., stems and leaves), which is largely the carbohydrate cellulose, yields about 4.25 kcal of energy when burned. Net primary productivity can range from 500 kcal/m^2/yr in the desert to 15,000 kcal/m^2/yr in a tropical rain forest.

In an aquatic community in Silver Springs, Florida, the gross primary productivity (total energy accumulated by the primary producers) was 20,810 kcal/m^2/yr (figure 4.1.1.4.*j*). The net primary productivity (energy available to consumers) was only 7,632 kcal/m^2/yr after accounting for energy lost as heat and energy require to meet the producer's metabolic needs.

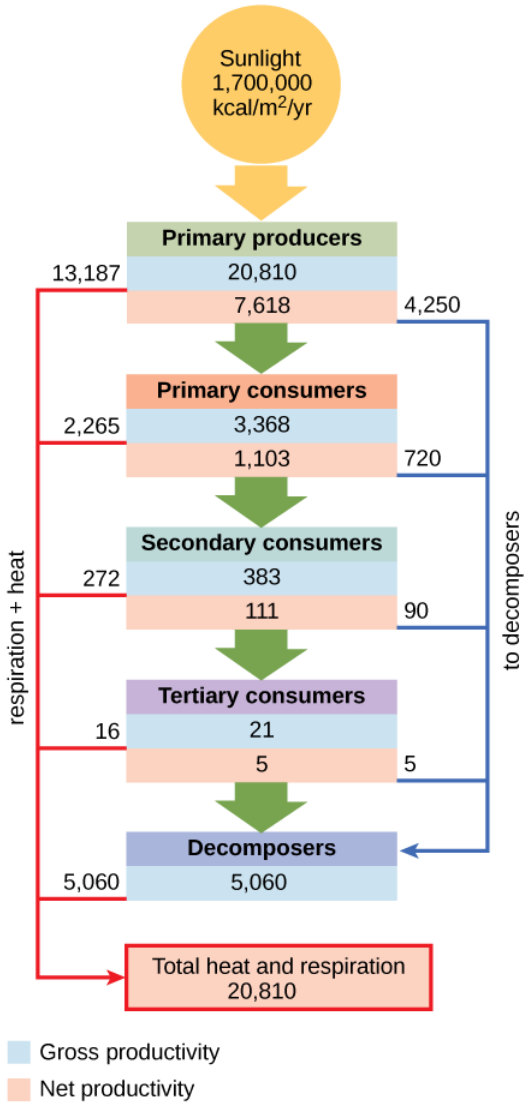


Figure 4.1.1.4.*j*: The flow of energy through a spring ecosystem in Silver Springs, Florida. The gross productivity (blue) for each trophic level is listed just above the net productivity (red). Notice that the energy decreases with each increase in trophic level. The energy content of primary producers (gross productivity) is 20,810 kcal/m^2/yr. The gross productivity of primary consumers is much smaller, about 3,368 kcal/m^2/yr. The gross productivity of secondary consumers is 383 kcal/m^2/yr, and the gross productivity of tertiary consumers is only 21 kcal/m^2/yr. The net productivity of each trophic level is less than the gross productivity because some energy is used to meet metabolic needs (respiration), and some energy is lost as heat. For example, the net productivity of primary consumers was 1,103 kcal/m^2/yr, only about a third of the gross productivity. Some of the energy in each trophic level (a total of 5,060 kcal/m^2/yr) is transferred to decomposers. All of the energy initially captured by primary producers (20,810 kcal/m^2/yr) is eventually released from the system.

Only a fraction of the energy captured by one trophic level is assimilated into biomass, which makes it available to the next trophic level. Assimilation is the biomass of the present trophic level after accounting for the energy lost due to incomplete ingestion of food, energy used to conduct work by that trophic level, and energy lost as waste. Incomplete ingestion refers to the fact that some consumers eat only a part of their food. For example, when a lion kills an antelope, it will eat everything except the hide and bones. The lion is missing the energy-rich bone marrow inside the bone, so the lion does not make use of all the calories its prey could provide. In Silver Springs, only 1103 kcal/m^2/yr from the 7618 kcal/m^2/yr of energy available to primary consumers was assimilated into their biomass. (The **trophic level transfer efficiency** between the first two trophic levels was approximately 14.8 percent.)

An animal's source of heat influences its energy needs. **Ectotherms**, such as invertebrates, fish, amphibians, and reptiles, rely on external sources for body heat, and **endotherms**, such as birds and mammals, rely on internally generated heat. Generally,

ectotherms require less of the energy to meet their metabolic needs and than endotherms do, and therefore, many endotherms have to eat more often than ectotherms.

The inefficiency of energy use by endotherms has broad implications for the world's food supply. It is widely accepted that the meat industry uses large amounts of crops to feed livestock, and because a low percentage of this is assimilated into biomass, much of the energy from animal feed is lost. For example, it costs about 1¢ to produce 1000 dietary calories (kcal) of corn or soybeans, but approximately $0.19 to produce a similar number of calories growing cattle for beef consumption. The same energy content of milk from cattle is also costly, at approximately $0.16 per 1000 kcal. Thus, there has been a growing movement worldwide to promote the consumption of non-meat and non-dairy foods so that less energy is wasted feeding animals for the meat industry.

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4.1.2: Competition

Resources are often limited within a habitat and multiple species may compete to obtain them. **Competition** occurs when organisms use the same resources, and one or both organisms is harmed. Competing species are often occupy the same trophic level and compete for food, but species on different trophic levels could still compete for space, water, etc. **Intraspecific competition** occurs within a species. For example, most penguins defend territories from other individuals of the same species because they compete for suitable habitat and other resources (figure 4.1.2.*a*). **Interspecific competition** occurs between different species. For example, the **invasive** vine, kudzu, competes with trees in the southeastern United States for light (figure 4.1.2.*b*). Kudzu is considered invasive in this region because it occurs outside of its historical range (Asia and Australia) and causes ecological harm.



Figure 4.1.2.*a*: Adélie penguins at Cape Adare in Ross Sea, Antarctica. These penguins defend small territories in which they nest. Image by Brocken Inaglory (CC-BY-SA).



Figure 4.1.2.*b*: Kudzu is a vine that covers trees, shrubs, and other structures. It can fully block its competitors' access to light, eventually killing them. Image by Katie Ashdown (CC-BY).

Ecologists have come to understand that all species have an **ecological niche**: the unique set of resources used by a species, which includes its interactions with other species. The **competitive exclusion principle** states that two species cannot occupy the exact same niche in a habitat. In other words, different species cannot coexist in a community if they are competing for all the same resources. Competition harms one or both competitors because it wastes energy. In an experimental test of competitive exclusion, two species of the freshwater microbe *Paramecium* were cultured separately and together. When cultured separately, both species

reproduced, and the number of cells (individuals) increased. However, when the two species were grown together, one species (*P. aurelia*) grew, and the the other species (*P. caudatum*) was eliminated. Because both species occupied the same ecological niche, they could not coexist. *Paramecium aurelia* was the superior competitor in this case (figure 4.1.2.*c*). Competitive exclusion may be avoided if a population evolves to make use of a different resource, a different area of the habitat, or feeds during a different time of day. This is called **resource partitioning**. The two species are then said to occupy different microniches. These species coexist by minimizing direct competition.

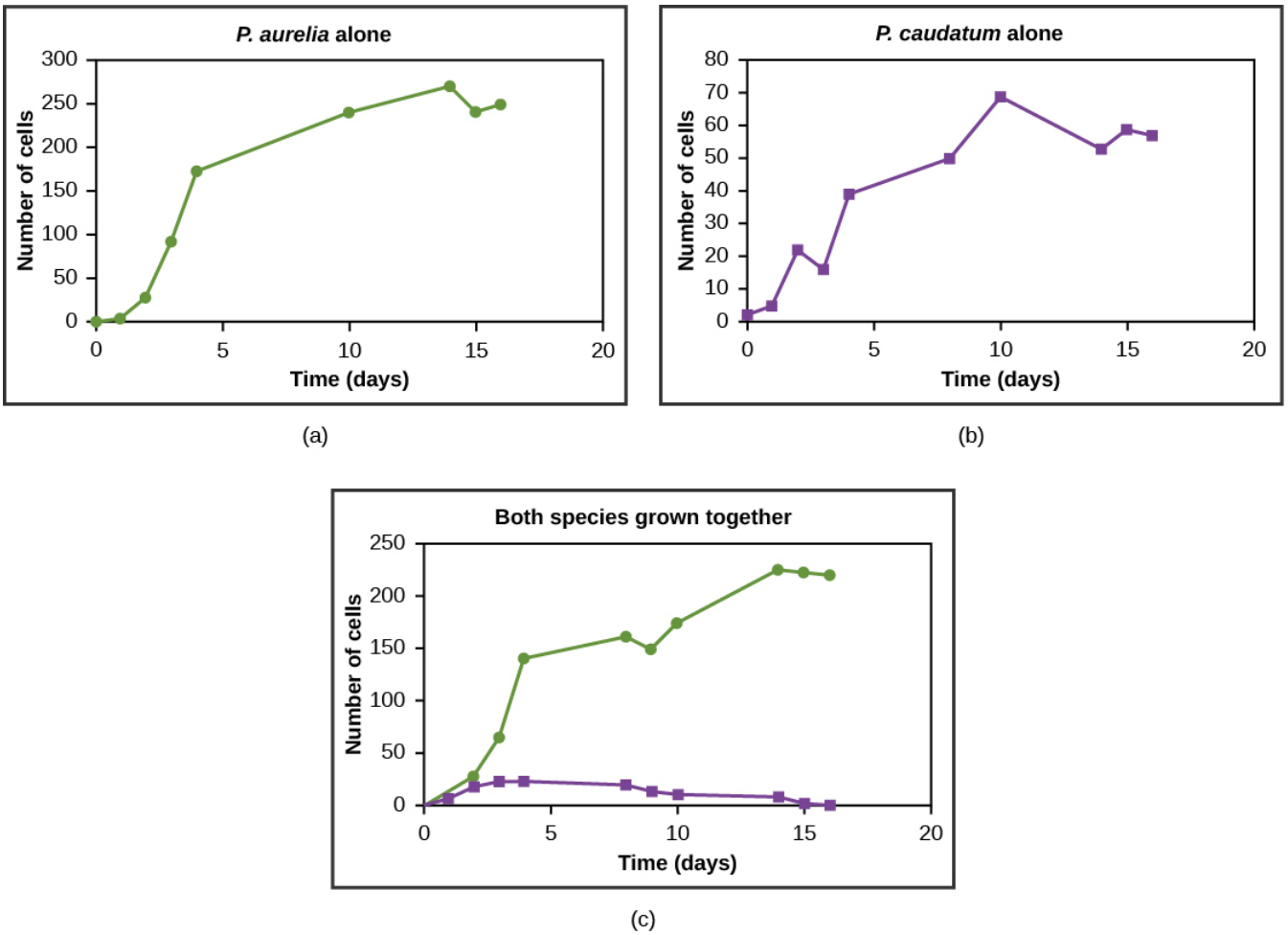


Figure 4.1.2.*c*: Graphs a, b, and c all plot number of cells versus time in days. When *Paramecium aurelia* and *P. caudatum* were grown individually in the laboratory (a and b), the two species both reproduced and reached a relatively high cell density. When the two species were placed together in the same test tube (habitat, c), *P. aurelia* (top, green) reached nearly the same cell density as it exhibited when grown alone, but *P. caudatum* (bottom, purple) hardly grew at all, and eventually its population drops to zero. *Paramecium aurelia* outcompeted *P. caudatum* for food, leading to the latter's eventual extinction.

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4.1.3: Facilitation

Interactions in which one or both species benefit and neither is harmed are called facilitation. There are two types of facilitation: commensalism and mutualism.

Commensalism

Commensalism is a type of facilitation that occurs when one species benefits from an interaction, while the other neither benefits or is harmed. Many potential commensal relationships are difficult to identify because it is difficult to demonstrate that one partner is unaffected by the presence of the other. Birds nesting in trees provide an example of a commensal relationship (figure 4.1.3.*a*). The tree is not harmed by the presence of the nest among its branches. The nests are light and produce little strain on the structural integrity of the branch, and most of the leaves, which the tree uses to get energy by photosynthesis, are above the nest so they are unaffected. The bird, on the other hand, benefits greatly. If the bird had to nest in the open, its eggs and young would be vulnerable to predators.



Figure 4.1.3.*a*: The Southern Masked-Weaver is starting to make a nest in a tree in Zambezi Valley, Zambia. This is an example of a commensal relationship, in which one species (the bird) benefits, while the other (the tree) neither benefits nor is harmed. (credit: "Hanay"/Wikimedia Commons)

Another example or a commensal relationship involves the Little Blue Heron and the White Ibis, which are both wading birds. The Little Blue Heron catches more fish in the presence of the White Ibis, but the White Ibis is unaffected. Interestingly, Little Blue Herons attempt to catch fish more often in the presence of the species, but the success rate of their attempts does not change. Nevertheless, more frequent attempts still increases the total number of fish caught. The White Ibis may make fish more visible to Little Blue Herons, causing changes in their behavior (figure 4.1.3.*b*).



Figure 4.1.3.*b*: The Little Blue Heron (left) and the White Ibis (right) have a commensal relationship. Image by Russ (CC-BY).

Mutualism

In a **mutualism**, both species benefit from their interaction. For example, pollinators, such as bees, butterflies, and hummingbirds, benefit because they eat the collect pollen and/or nectar that they collect from flowers. The plants also benefit because their pollen is dispersed to other plants, allowing them to reproduce. Both the pollinators and the plants benefit, demonstrating a mutualism (figure 4.1.3.*c*). Clownfish and anemones are another example of mutualisms. Clownfish gain protection from living among anemones. In return, clownfish clean the anemones and scare away predators. In addition, their waste provides nutrients (figure 4.1.3.*d*).



Figure 4.1.3.*c*: A male Broad-Tailed Hummingbird visits a scarlet gilia flower at the Rocky Mountain Biological Laboratory. The hummingbird gains food (nectar) while aiding the gilia flower with reproduction. Image by David W. Inouye (CC-BY).



Figure 4.1.3.*d*: These clownfish have a mutual relationship with the sea anemones in which they live. Image by Samuel Chow (CC-BY).

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4.1.4: Symbiosis

Some biological interactions are brief, such as predation. In others, species are closely associated for long periods. Such associations are called **symbiotic** ("living together"). One species always benefits in a symbiosis, but the other may be harmed (parasitism), unaffected (commensalism), or benefited (mutualism). Some experts considered all parasitisms, commmensalisms, and mutualisms to be symbiotic, but others only consider interactions in which species are living together in a close association (such as when one species lives on or in the other) as symbiotic.

Termites have a symbiotic relationship with microorganisms called protozoa that live in the insect's gut (figure 4.1.4.a-a). The termite benefits from the ability of the protozoa to digest cellulose, a carbohydrate important in plant structure. However, the protozoa are able to digest cellulose only because of the presence of symbiotic bacteria within their cells that produce the cellulase enzyme. The termite itself cannot do this; without the protozoa, it would not be able to obtain energy from its food (cellulose from the wood it chews and eats). The protozoa benefit by having a protective environment and a constant supply of food from the wood chewing actions of the termite. In turn, the protists benefit from the enzymes provided by their bacterial endosymbionts, while the bacteria benefit from a doubly protective environment and a constant source of nutrients from two hosts.

Lichen are a symbiotic relationship between a fungus and algae (or a photosynthetic bacteria; Figure 4.1.4.a-b). In lichen, the algal cells are fully surrounded by the fungus. The sugars produced by the algae through photosynthesis provide nourishment for both organisms. The physical structure of the fungus protects the algae from the elements and makes certain nutrients in the atmosphere more available to the algae. The algae of lichens can sometimes live independently given the right environment, but many of the fungal partners are unable to live on their own. Note that while both lichen and the example involving termites mutually benefit the species involved, symbioses are not always mutualisms.



Figure 4.1.4.a: (a) Termites form a symbiotic relationship with protozoa living in their guts. Their association which allows both organisms to obtain energy from the cellulose the termite consumes. (b) Lichen is a fungus that has symbiotic photosynthetic algae living in close association. (credit a: modification of work by Scott Bauer, USDA; credit b: modification of work by Cory Zanker)

The remora and the shark is a commensal symbiosis. The top fin of the remora is modified into a sucker with which it forms an attachment to the shark. When the shark feeds, the remora picks up scraps. Additionally, the remora gains transportation and protection. The shark makes no attempt to prey on the remora and is unaffected by it (figure 4.1.4.b).



Figure 4.1.4.b: A remora attached to the top of a shark in an aquarium. This is an example of a symbiosis because the remora lives in close association with the shark. Image by Brian Snelson (CC-BY)

There are many additional examples of symbiosis. Coral are small animals that harbor photosynthetic microorganisms called dinoflagellates. (The corals group together and deposit hardened calcium carbonate skeletons.) **Mycorrhizae** are fungi that surround or live within plant root cells and help plants absorb nutrients from the soil in exchange for sugars. In fact truffles are often found in oak forests because the fungus that produce this spore-forming body establishes mycorrhizae on oak roots. **Root nodules** are structures on the roots of legume plants that house nitrogen-fixing bacteria (see The Nitrogen Cycle). **Epiphytes** are plants adapted to live on top of other plants and are common in the tropical rainforest (see Biomes). Humans have a diversity of microorganisms, called the **normal flora**, that live in and on our bodies. While we often think of bacteria as causing infection (a parasitism), the species of our normal floral exemplify commensalism and mutualism. For example, our gut microbiota aids with digestion and helps us synthesize certain vitamins.

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4.2: Community Structure and Dynamics

Communities are complex systems that can be characterized by **community structure** (the number and size of populations and their interactions) and **community dynamics** (how the members and their interactions change over time). Understanding community structure and dynamics allows us to minimize impacts on ecosystems and manage ecological communities we benefit from.

Keystone Species

A **keystone species** is one whose presence has inordinate influence in maintaining the prevalence of various species, the ecological community's structure, and sometimes its biodiversity. *Pisaster ochraceus*, the intertidal sea star, is a keystone species in the northwestern portion of the United States (figure 4.2.*a*). Studies have shown that when this organism is removed from communities, mussel populations (their natural prey) increase, which completely alters the species composition and reduces biodiversity. Another keystone species is the banded tetra, a fish in tropical streams, which supplies nearly all of the phosphorus, a necessary inorganic nutrient, to the rest of the community. The banded tetra feeds largely on insects from the terrestrial ecosystem and then excretes phosphorus into the aquatic ecosystem. The relationships between populations in the community, and possibly the biodiversity, would change dramatically if these fish were to become extinct.



Figure 4.2.*a*: Sea stars are keystone species of the intertidal zone.

Community Dynamics

Community dynamics are the changes in community structure and composition over time, often following environmental disturbances such as volcanoes, earthquakes, storms, fires, and climate change. Communities with a relatively constant number of species are said to be at equilibrium. The equilibrium is dynamic with species identities and relationships changing over time, but maintaining relatively constant numbers. Following a disturbance, the community may or may not return to the equilibrium state.

Succession describes the sequential appearance and disappearance of species in a community over time after a severe disturbance. In **primary succession**, newly exposed or newly formed rock is colonized by living organisms. In **secondary succession**, a part of an ecosystem is disturbed and remnants of the previous community remain. In both cases, there is a sequential change in species until a more-or-less permanent community develops.

Primary Succession and Pioneer Species

Primary succession occurs when new land is formed, or when the soil and all life is removed from pre-existing land. An example of the former is the eruption of volcanoes on the Big Island of Hawaii, which results in lava that flows into the ocean and continually forms new land. From this process, approximately 32 acres of land are added to the Big Island each year. An example of pre-existing soil being removed is through the activity of glaciers. The massive weight of the glacier scours the landscape down to the bedrock as the glacier moves. This removes any original soil and leaves exposed rock once the glacier melts and retreats.

In both cases, the ecosystem starts with bare rock that is devoid of life. New soil is slowly formed as weathering and other natural forces break down the rock and lead to the establishment of hearty organisms, such as lichens and some plants, which are collectively known as **pioneer species** (figure 4.2.*b*) because they are the first to appear. These species help to further break down the mineral-rich rock into soil where other, less hardy but more competitive species, such as grasses, shrubs, and trees, will grow and eventually replace the pioneer species. Over time the area will reach an equilibrium state, with a set of organisms quite different from the pioneer species.



Figure 4.2.*b*: During primary succession in lava on Maui, Hawaii, succulent plants are the pioneer species. (credit: Forest and Kim Starr)

The relationship between pioneer species and the more competitive (late-successional) species illustrates the complexity of biotic interactions. Pioneer species facilitate the growth of the late-successional species, and this initially appears to be a commensalism. However, the late-successional species later outcompete the pioneer species, shifting the interaction to competition.

Secondary Succession

A classic example of secondary succession occurs in forests cleared by wildfire, or by clearcut logging (figure 4.2.*c*). Wildfires will burn most vegetation, and unless the animals can flee the area, they are killed. Their nutrients, however, are returned to the ground in the form of ash. Thus, although the community has been dramatically altered, there is a soil ecosystem present that provides a foundation for rapid recolonization.

Before the fire, the vegetation was dominated by tall trees with access to the major plant energy resource: sunlight. Their height gave them access to sunlight while also shading the ground and other low-lying species. After the fire, though, these trees are no longer dominant. Thus, the first plants to grow back are usually annual plants followed within a few years by quickly growing and spreading grasses and other pioneer species. Due, at least in part, to changes in the environment brought on by the growth of grasses and forbs, over many years, shrubs emerge along with small trees. These organisms are called intermediate species. Eventually, over 150 years or more, the forest will reach its equilibrium point and resemble the community before the fire. This equilibrium state is referred to as the **climax community**, which will remain until the next disturbance. The climax community is typically characteristic of a given climate and geology. Although the community in equilibrium looks the same once it is attained, the equilibrium is a dynamic one with constant changes in abundance and sometimes species identities.

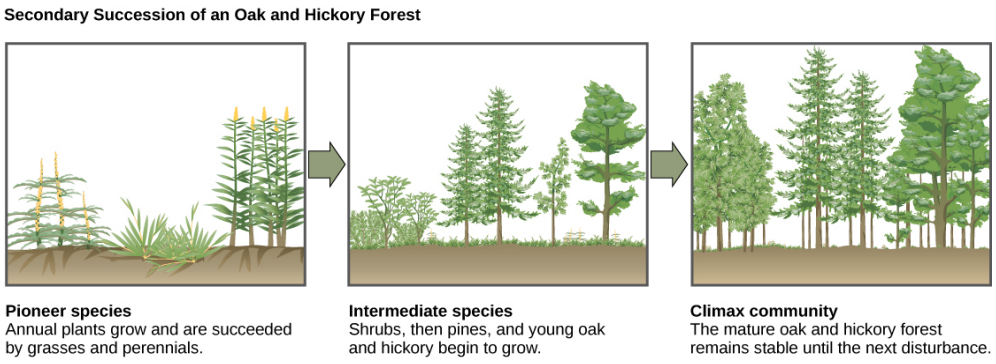


Figure 4.2.*c*: Succession in an oak and hickory forest. Secondary succession occurs when a disturbance (reduction in biomass) occurs, but the entire community does not die as a result of the disturbance. First, pioneer species grow. These include annual plants, which are succeeding by perennial grasses and other perennials. Next, intermediate species, grow. These include shrubs followed by pines and young oak and hickory. Finally, the climax community is established, which consists of mature oak and hickory trees. These remain intact until the next disturbance.

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4.3: Data Dive- Bison Impacts In Prairies

Overview

In many grassland ecosystems the activities of large grazers, like bison, play a key role in shaping grassland habitat structure and diversity. A 2017 study sought to investigate how bison in tall-grass prairies affect local plant competition. Specifically, they wanted to know if bison have a positive impact on herbaceous forbs (non-woody flower species). To investigate this, they observed plant communities in tall-grass prairies in the presence and absence of bison. The two graphs below display some of the results in this study:

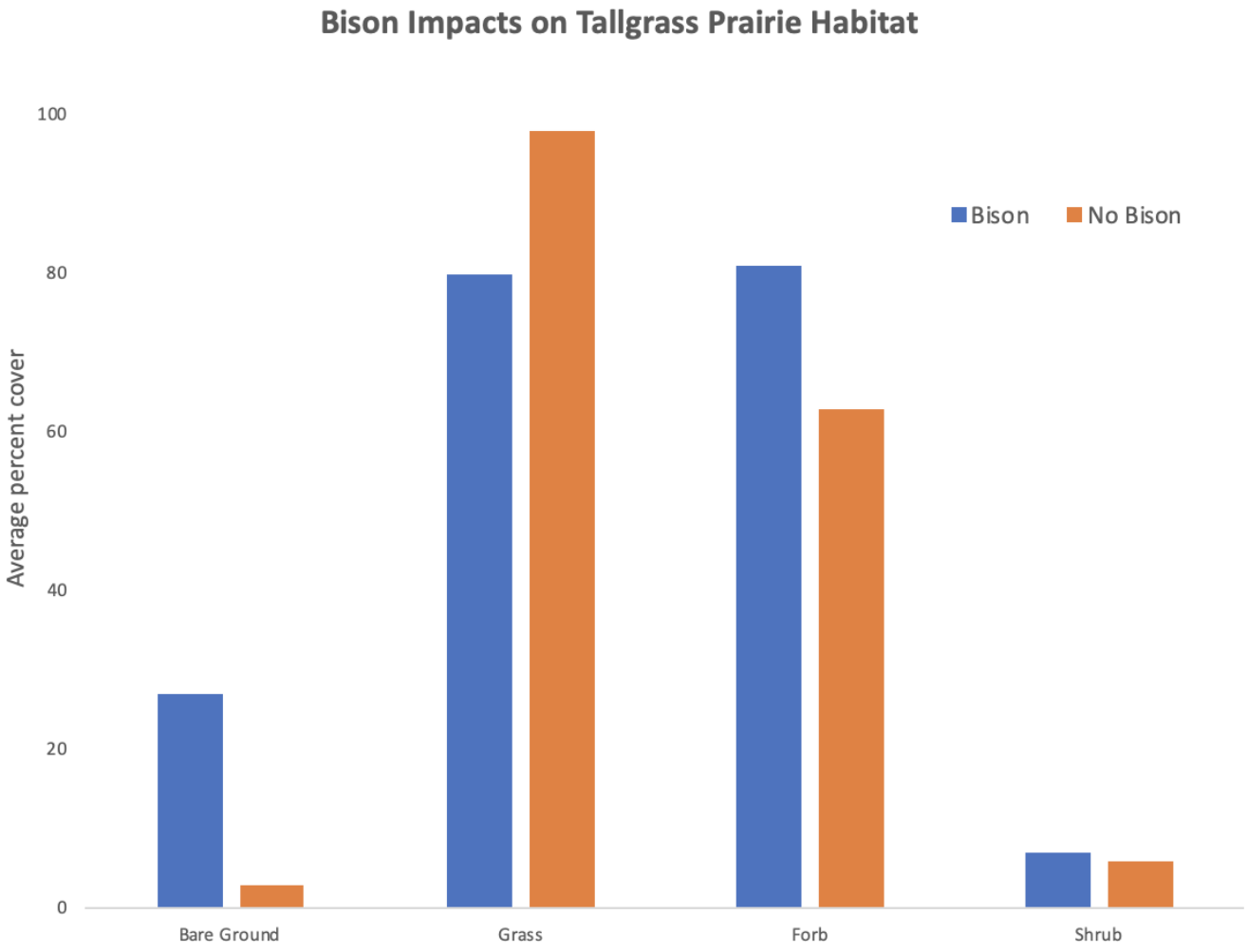


Figure 4.3.2*a*: Average percent cover (aka what percent of an area a species took up) for grasses, forbs, shrubs, and bare ground in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

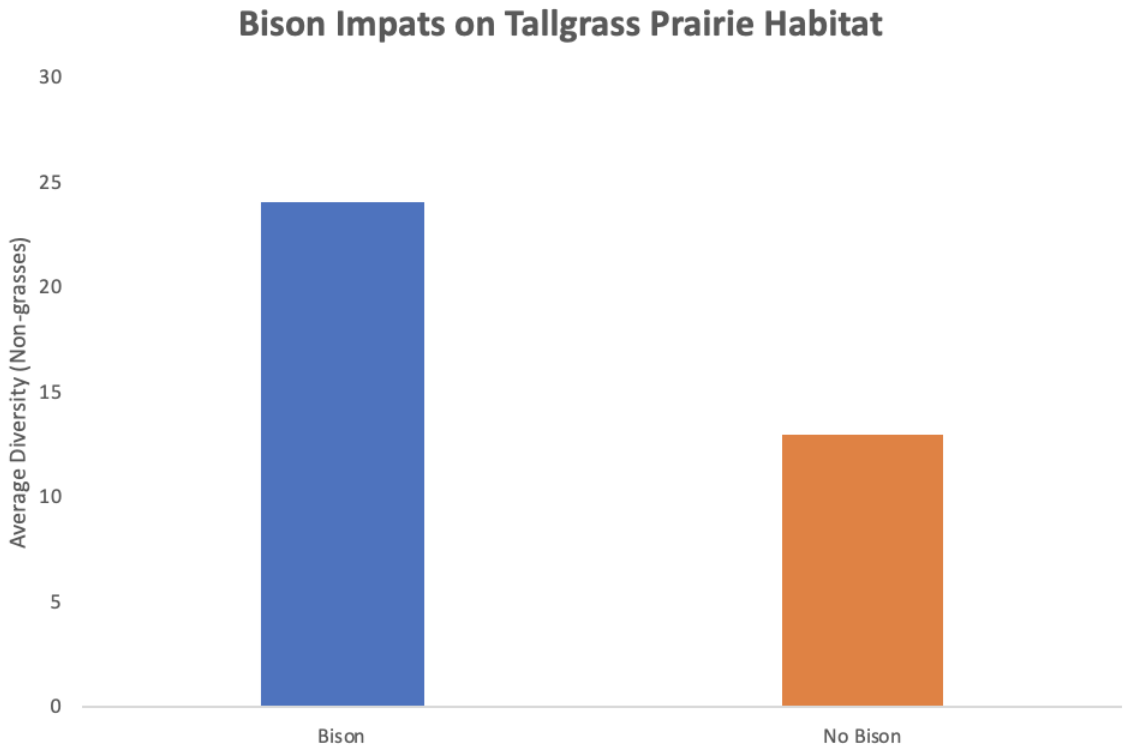


Figure 4.3.*b*: Average diversity of non-grasses in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

Questions

1. What kind of graphs are these?
2. Does the presence of bison increase diversity? How do you know this? Which graph(s) support this?
3. How does the presence of bison affect the percent cover of bare ground, grasses, forbs, and shrubs?
4. Based on the authors objectives/predictions described above, do the results of these graphs support them? Why/why not?
5. How can we use the results of this graph to inform conservation projects for tallgrass prairies in the future?
6. What does the results of this graph make you curious about?

Raw Data From Above Graph(s)

Table 4.3.2*a***:** Raw data for average percent covers (aka what percent of an area a species took up) for grasses, forbs, shrubs, and bare ground in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

Status	Average Percent Cover With Bison	Average Percent Cover With No Bison
Bare Ground	27	3
Grass	80	98
Forb	81	63
Shrub	7	6

Table 4.3.*b***:** Raw data for average diversity of non-grasses in tall-grass prairies with and without bison. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Elson A and Hartnett D, 2017.

Average Diversity (Non-Grasses) With Bison	Average Diversity (Non-Grasses) With No Bison
24	13

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4.4: Section Review

Summary

After completing this chapter you should be able to...

- Name and distinguish among the major types of biotic interactions, providing examples of each.
- Describe how prey have adapted to reduce predation and how plants have adapted to reduce herbivory.
- Define energy and distinguish among the different types of energy.
- Explain the first and second laws of thermodynamics as they relate to trophic interactions in a community.
- Distinguish between and interpret food webs and food chains, explaining the advantages of each representation and identifying the trophic levels in each.
- Explain what limits the number of trophic levels in a community.
- Define symbiosis and provide examples.
- Explain the role of keystone species in maintaining community structure.
- Summarize the process of succession.

Communities consists of populations of different species interacting in a common area. **Biotic interactions** describe the relationships among organisms, and **trophic interactions**, including **predation**, **herbivory**, and **parasitism**, are the biotic interactions that involve one organism eating another. Trophic interactions are diagrammed through **food chains** and **food webs**.

Some biotic interactions are not trophic. For example, **competition** is a biotic interaction in which one or both organisms that use the same resources are harmed, and it can occur between individuals of the same species (**intraspecific**) or between members of different species (**interspecific**). **Facilitation** refers to interactions in which one or both species benefit and neither is harmed. Examples include **commensalism** and **mutualism**. A **symbiosis** is a close association in which species are living together.

Communities are characterized by their **structure** (number and size of populations and their interactions) and **dynamics** (how the community structure changes). **Keystone species** have a great influence on community structure, which is disproportionately large relative to their abundance. **Succession** describes how community composition changes over time following a disturbance.

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CHAPTER OVERVIEW

5: Ecosystems

5.1: Ecosystem Types and Dynamics
5.2: Matter
5.3: Biogeochemical Cycles
5.4: Fresh Water Supply and the Water Cycle
5.4.1: Water Usage
5.4.2: Water Scarcity and Solutions
5.5: Soils
5.6: Soil Degradation
5.7: Data Dive- Beaver Impacts on Wetlands
5.8: Review

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Thumbnail image - This sage thrasher's diet, like that of almost all organisms, depends on photosynthesis.

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5.1: Ecosystem Types and Dynamics



Figure 5.1.1: In semi-urban areas beavers (*Castor canadensis*) are considered a nuisance as their dams block drainage pipes and cause flooding. However, in wild areas beavers are one of the most important species. Beaver dams are known for altering the flow of water. However, these dams not only slow down the movement of water, but they spread and store water in a way that is much more efficient than human-made dams. In addition, they slow and spread sediment and nutrients as they move through watersheds. What this does is create a mosaic of habitats across a landscape, both aquatic and terrestrial. More habitats lead to more species, both for plants and animals. In this way, beavers create ecosystems, one stick at a time. (Image by NeexPix (Public domain))

An **ecosystem** is a community of organisms (**biotic components**) and their **abiotic** (non-living) environment. Ecosystems can be small, such as the tide pools found near the rocky shores of many oceans, or large, such as those found in the tropical rainforest of the Amazon in Brazil (figure 5.1.a).



(a) (b)

Figure 5.1.a**:** A (a) tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while the (b) Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

Ecosystem Categories

There are three broad categories of ecosystems based on their general environment: freshwater, marine, and terrestrial. Within these three categories are individual ecosystem types based on the environmental habitat and organisms present.

Freshwater ecosystems are the least common, occurring on only 1.8 percent of Earth's surface. These systems comprise lakes, rivers, streams, and springs; they are quite diverse and support a variety of animals, plants, fungi, protists and prokaryotes.

Marine ecosystems are the most common, comprising 75 percent of Earth's surface and consisting of three basic types: shallow ocean, deep ocean water, and deep ocean bottom. Shallow ocean ecosystems include extremely biodiverse coral reef ecosystems. Small photosynthetic organisms suspended in ocean waters, collectively known as **phytoplankton,** perform 40 percent of all photosynthesis on Earth. Deep ocean bottom ecosystems contain a wide variety of marine organisms. These ecosystems are so deep that light is unable to reach them. Freshwater and marine ecosystems are found in **aquatic biomes**, which are discussed in the Biomes chapter.

Terrestrial ecosystems, also known for their diversity, are grouped into large categories called biomes. A **biome** is a large-scale community of organisms, primarily defined on land by the dominant plant types that exist in geographic regions of the planet with similar climatic conditions. Examples of biomes include tropical rainforests, savannas, deserts, grasslands, temperate forests, and tundras. Grouping these ecosystems into just a few biome categories obscures the great diversity of the individual ecosystems within them. For example, the saguaro cacti (*Carnegiea gigantean*) and other plant life in the Sonoran Desert, in the United States, are relatively diverse compared with the desolate rocky desert of Boa Vista, an island off the coast of Western Africa (figure 5.1.*b*).



(a) (b)

Figure 5.1.*b***:** Desert ecosystems, like all ecosystems, can vary greatly. The desert in (a) Saguaro National Park, Arizona, has abundant plant life, while the rocky desert of (b) Boa Vista island, Cape Verde, Africa, is devoid of plant life. (credit a: modification of work by Jay Galvin; credit b: modification of work by Ingo Wölbern)

Ecosystem Dynamics

Ecosystems are complex with many interacting parts. They are routinely exposed to various **disturbances**, or changes in the environment that affect their compositions: yearly variations in rainfall and temperature and the slower processes of plant growth, which may take several years. Many of these disturbances are a result of natural processes. For example, when lightning causes a forest fire and destroys part of a forest ecosystem, the ground is eventually populated by grasses, then by bushes and shrubs, and later by mature trees, restoring the forest to its former state. The impact of environmental disturbances caused by human activities is as important as the changes caused by natural processes. Human agricultural practices, air pollution, acid rain, global deforestation, overfishing, eutrophication, oil spills, and illegal dumping on land and into the ocean are all issues of concern to conservationists.

Equilibrium is the steady state of an ecosystem where all organisms are in balance with their environment and with each other. In ecology, two parameters are used to measure changes in ecosystems: resistance and resilience. The ability of an ecosystem to

remain at equilibrium in spite of disturbances is called **resistance**. The speed at which an ecosystem recovers equilibrium after being disturbed, called its **resilience**. Ecosystem resistance and resilience are especially important when considering human impact. The nature of an ecosystem may change to such a degree that it can lose its resilience entirely. This process can lead to the complete destruction or irreversible altering of the ecosystem.

Foundation Species

Foundation species are considered the "base" or "bedrock" of an ecosystem, having the greatest influence on its overall structure. They are often primary producers, and they are typically an abundant organism. For example, kelp, a species of brown algae, is a foundation species that forms the basis of the kelp forests off the coast of California.

Foundation species may physically modify the environment to produce and maintain habitats that benefit the other organisms that use them. Examples include the kelp described above or tree species found in a forest. The photosynthetic corals of the coral reef also provide structure by physically modifying the environment (figure $5.1.c$). The calcium carbonate deposits of living and dead coral make up most of the reef structure, which protects many other species from waves and ocean currents.

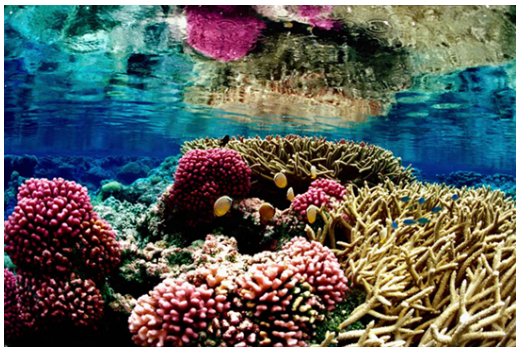


Figure $5.1.c$**:** Coral is the foundation species of coral reef ecosystems. (credit: Jim E. Maragos, USFWS)

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5.2: Matter

Matter is the "stuff" found in ecosystems. Technically, **matter** is defined as anything that occupies space or has mass. **Mass** is resistance to acceleration. Put more simply, mass is similar to weight, but weight accounts for acceleration due to gravity. Matter moves between biotic and abiotic ecosystem components through **biogeochemical cycles**. Fully understanding these cycles, requires a background in the particles that comprise matter, atoms.

Atoms and Molecules

Elements are substances that cannot be broken down or transformed chemically into other substances (figure 5.2.*a*). A total of 118 elements have been defined; however, only 92 occur naturally and fewer than 30 are found in organisms. The remaining 26 elements are unstable and therefore do not exist for very long or are theoretical and have yet to be detected. Each element is designated by its chemical symbol (such as H, N, O, C, and Na), and possesses unique properties. These unique properties allow elements to combine and to bond with each other in specific ways.

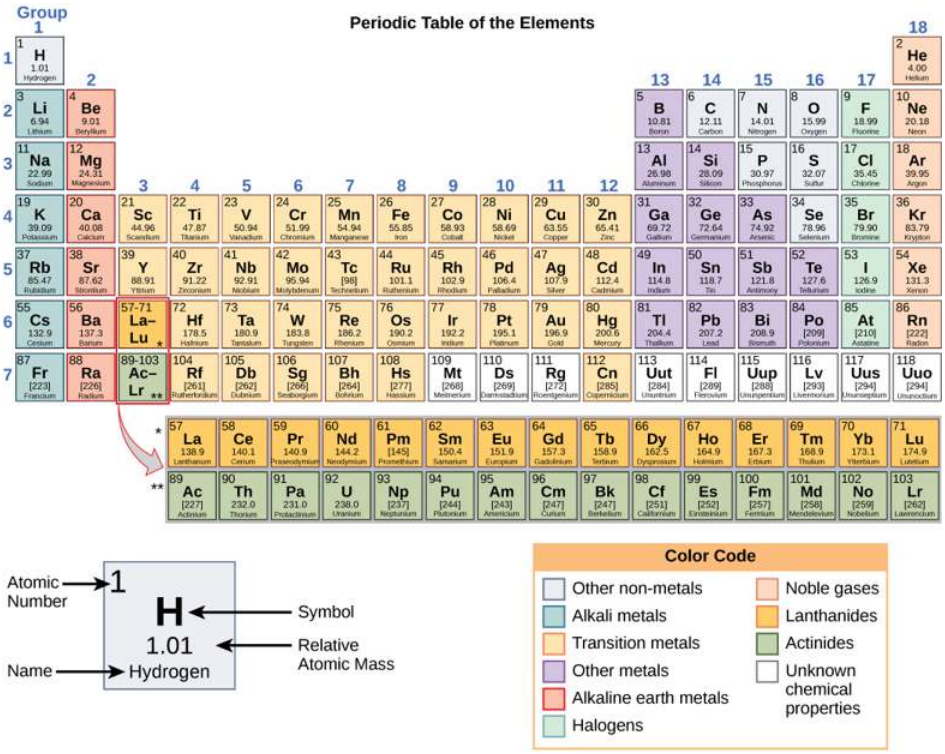


Figure 5.2.*a*: The periodic table of elements organizes chemical elements based on their properties. Each element is represented by a one- or two-letter symbol. Additionally, the atomic number, name, and atomic mass are listed for each element. Click here for an accessible periodic table of elements. Image by OpenStax (CC-BY)

An **atom** is the smallest component of an element that retains all of the chemical properties of that element. For example, one hydrogen atom has all of the properties of the element hydrogen, such as it exists as a gas at room temperature and it bonds with oxygen to create a water molecule. Hydrogen atoms cannot be broken down into anything smaller while still retaining the properties of hydrogen. If a hydrogen atom were broken down into smaller particles, it would no longer have the properties of hydrogen.

All atoms contain protons, electrons, and neutrons (figure 5.2.*b*). The only exception is hydrogen (H), which is typically only made of one proton and one electron. A **proton** is a positively charged particle that resides in the nucleus (the core of the atom) of an atom and has a mass of 1 and a charge of +1. An **electron** is a negatively charged particle that travels in the space around the nucleus. In other words, it resides outside of the nucleus. It has a negligible mass and has a charge of –1. **Neutrons**, like protons, reside in the nucleus of an atom. They have a mass of 1 and no charge. The positive (protons) and negative (electrons) charges balance each other in a neutral atom, which has a net zero charge.

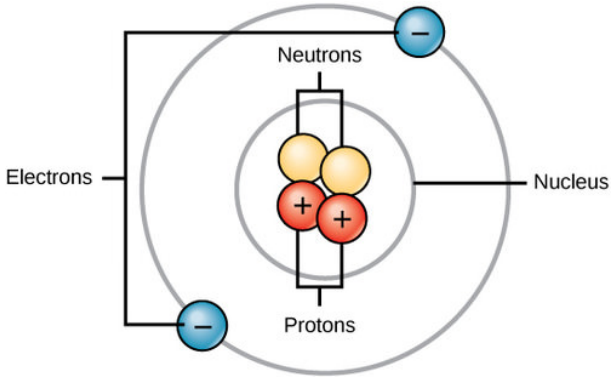


Figure 5.2.*b*: Atoms are comprised of protons (red with a plus sign, +) and neutrons (yellow) located within the nucleus, and electrons (blue with a minus sign, −)surrounding the nucleus. The nucleus of an atom should not be confused with the nucleus of a cell.

Each element contains a different number of protons and neutrons, giving it its own atomic number and mass number. The **atomic number** of an element is equal to the number of protons that element contains. The **mass number** is the number of protons plus the number of neutrons of that element. Therefore, it is possible to determine the number of neutrons by subtracting the atomic number from the mass number.

At the most basic level, all organisms are made of a combination of elements. They contain atoms that combine together to form **molecules**. Molecules are chemicals made from two or more atoms bonded together. Some molecules are very simple, like O_2, which is comprised of just two oxygen atoms. Some molecules used by organisms, such as DNA, are made of many millions of atoms.Molecules can interact to form **cells**, the structural and functional units of life. In multicellular organisms, such as animals, these cells combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are formed.

Chemical Bonds

How elements interact with one another depends on the number of electrons and how they are arranged. When an atom does not contain equal numbers of protons and electrons it is called an **ion**. Because the number of electrons does not equal the number of protons, each ion has a net **charge**. For example, if sodium loses an electron, it now has 11 protons and only 10 electrons, leaving it with an overall charge of +1. Positive ions are formed by losing electrons and are called **cations**. Negative ions are formed by gaining electrons and are called **anions**. Elemental anionic names are changed to end in -ide. As an example, when chlorine becomes an ion it is referred to as chloride.

Ionic and covalent bonds are strong bonds formed between two atoms. These bonds hold atoms together in a relatively stable state. **Ionic bonds** are formed between two oppositely charged ions (an anion and a cation). Because positive and negative charges attract, these ions are held together much like two oppositely charged magnets would stick together. **Covalent bonds** form when electrons are shared between two atoms. Each atom shares one of their electrons, which then orbits the nuclei of both atoms, holding the two atoms together. Covalent bonds are the strongest and most common form of chemical bond in organisms. Unlike most ionic bonds, covalent bonds do not dissociate in water. **Hydrogen bonds** form when molecules have an uneven distribution of electrons and thus have partially positive and partially negative ends. They are thus attracted to each other (figure 5.2.*c*). Technically, hydrogen bonds only occur between hydrogen and either oxygen (O), nitrogen (N), or fluorine (F). Sometimes hydrogen bonds connect different parts or large molecules, as is the case in DNA and proteins. Hydrogen bonds are weaker than ionic and covalent bonds and can break easily. (Note that hydrogen bonds are among the strongest of intermolecular forces, those that occur **between** molecules, however.)

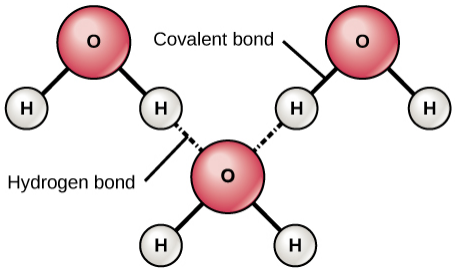


Figure 5.2.*c*: Hydrogen bonds form between slightly positive and slightly negative charges of certain molecules, such as water. Each water molecule consists of an oxygen atom (O) connected to two hydrogen atoms (H) by covalent bonds (solid lines). Dashed lines represent hydrogen bonds between water molecules.

Biological Macromolecules

Organisms contain large, organic molecules called **biological macromolecules**. **Organic molecules** are those that contain carbon covalently bonded to hydrogen. (In contrast, **inorganic molecules** lack carbon bonded to hydrogen and are often simpler than organic molecules.) In addition, they may contain oxygen, nitrogen, phosphorus, sulfur, and additional elements.There are four major classes of biological macromolecules: **carbohydrates**, **lipids**, **proteins**, and **nucleic acids.** Each is an important component of the cell and performs a wide array of functions.

It is often said that life is “carbon-based”. This means that carbon atoms, bonded to other carbon atoms or other elements, form the fundamental components of many of the molecules found uniquely in living things. Other elements play important roles in biological molecules, but carbon certainly qualifies as the “foundation” element for molecules in living things. It is the bonding properties of carbon atoms that are responsible for its important role. Carbon can form four covalent bonds with other atoms or molecules. The simplest organic carbon molecule is methane (CH_4), in which four hydrogen atoms bind to a carbon atom (figure 5.2.*d*).

Carbohydrates include what are commonly referred to as simple sugars, like glucose, and complex carbohydrates such as starch. While many types of carbohydrates are used for energy, some are used for structure by most organisms, including plants and animals. For example, cellulose is a complex carbohydrate that adds rigidity and strength to the outer layer of plant cells (the cell walls).

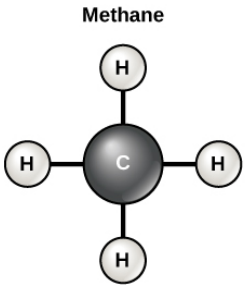


Figure 5.2.*d*: Carbon can form four covalent bonds to create an organic molecule. The simplest carbon molecule is methane (CH_4), depicted here.

Lipids include a diverse group of compounds that are united by a common feature: lipids are insoluble in water. Lipids perform many different functions in a cell. Cells store energy for long-term use in the form of lipids called fats. Lipids also provide insulation from the environment for plants and animals. For example, they help keep aquatic birds and mammals dry because of their water-repelling nature. Lipids are also the building blocks of many hormones and are an important constituent of the membranes that surround cells and form many of their internal structures.

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. They are all polymers of amino acids. The functions of proteins are very diverse because there are 20 different chemically distinct amino acids that form long chains, and the amino acids can be in any order. Proteins can function in facilitated chemical reactions in organisms, such as photosynthesis, transmitting messages as hormones, causing muscles to contract, and much more.

Nucleic acids are very large molecules that are important to the continuity of life. They carry the genetic blueprint of a cell and thus the instructions for its functionality. The two main types of nucleic acids are deoxyribonucleic acid (**DNA**) and ribonucleic acid (RNA). DNA is the genetic material found in all organisms, ranging from single-celled bacteria to multicellular mammals. The other type of nucleic acid, **RNA**, is mostly involved in protein synthesis. DNA and RNA are made up of small building blocks known as **nucleotides**. DNA has a beautiful double-helical structure (Figure 5.2.e).

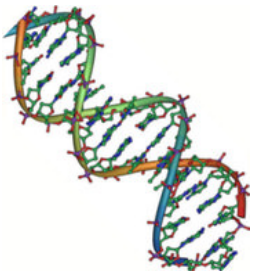


Figure 5.2.e: The double-helix model shows DNA as two parallel strands of intertwining molecules.

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5.3: Biogeochemical Cycles

Biogeochemical cycles, also known as nutrient cycles, describe the movement of chemical elements through different media, such as the atmosphere, soil, rocks, bodies of water, and organisms. Biogeochemical cycles keep essential elements available to plants and other organisms.

Energy flows directionally through ecosystems, entering as sunlight (or inorganic molecules for chemoautotrophs) and leaving as heat during energy transformation between trophic levels. Rather than flowing through an ecosystem, the matter that makes up organisms is conserved and recycled. The **law of conservation of mass** states that matter is neither created nor destroyed. For example, after a chemical reaction, the mass of the products (ending molecules) will be the same as the mass of the reactants (starting molecules). The same is true in an ecosystem. Matter moves through different media, and atoms may react to form new molecules, but the amount of matter remains constant.

The biogeochemical cycles of four elements—carbon, nitrogen, phosphorus, and sulfur—are discussed below. The cycling of these elements is interconnected with the water cycle. For example, the movement of water is critical for the leaching of sulfur and phosphorus into rivers, lakes, and oceans. Today, **anthropogenic** (human) activities are altering all major ecosystems and the biogeochemical cycles they drive.

The Carbon Cycle

Carbon is the basic building block of all organic materials, and therefore, of living organisms. The carbon cycle is actually comprised of several interconnected cycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes (figure $5.3.a$). The overall effect is that carbon is constantly recycled in the dynamic processes taking place in the atmosphere, at the surface and in the crust of the earth. The vast majority of carbon resides as inorganic minerals in crustal rocks. Other **reservoirs** of carbon, places where carbon accumulates, include the oceans and atmosphere. Some of the carbon atoms in your body today may long ago have resided in a dinosaur's body, or perhaps were once buried deep in the Earth's crust as carbonate rock minerals.

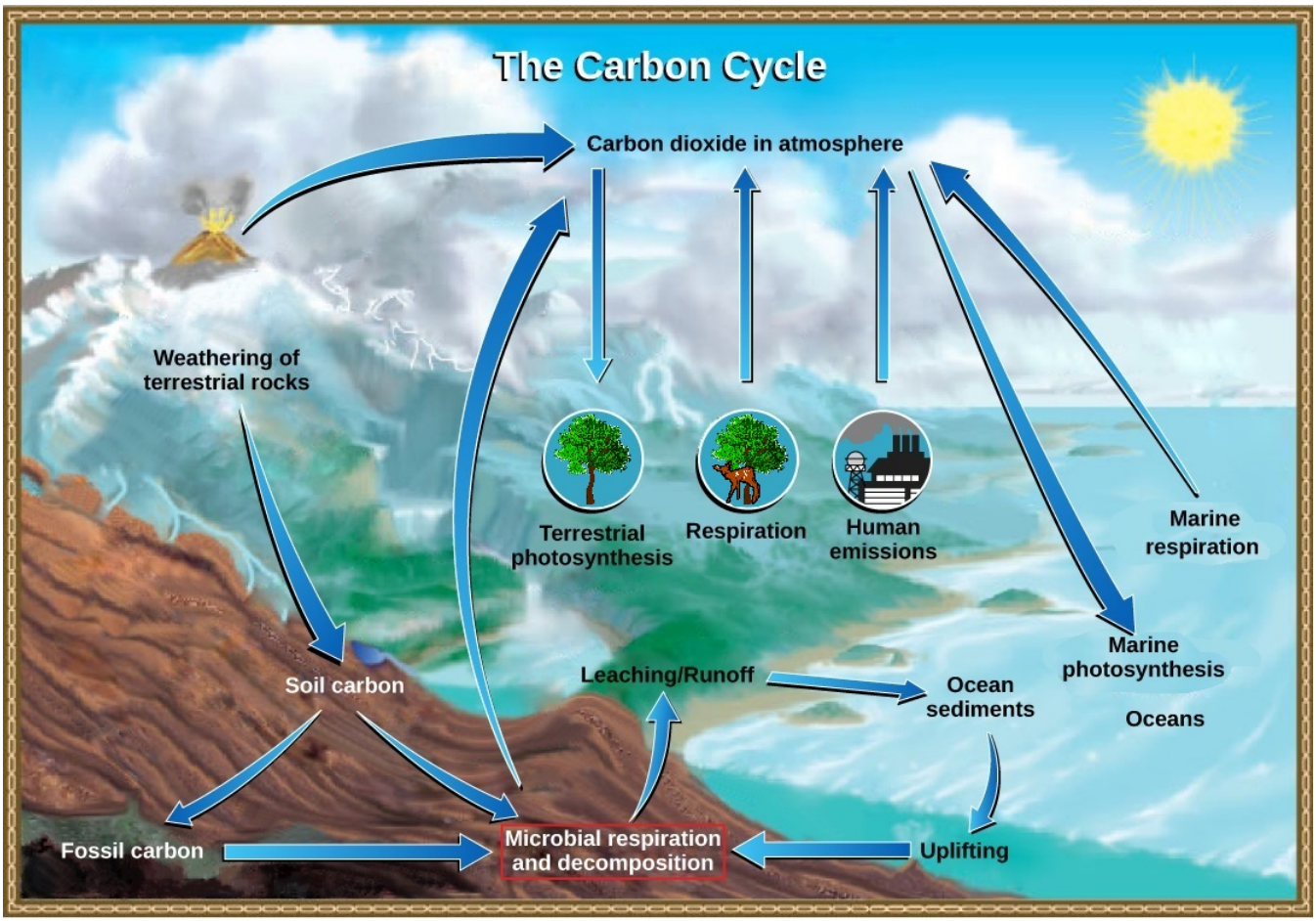


Figure 5.3.*a*: Carbon dioxide in the atmosphere is converted to organic carbon through photosynthesis by terrestrial organisms (like trees) and marine organisms (like algae). Respiration by terrestrial organisms (like trees and deer) and marine organisms (like algae and fish) release carbon dioxide back into the atmosphere. Additionally, microbes that decompose dead organisms release carbon dioxide through respiration. Weathering of terrestrial rocks also brings carbon into the soil. Carbon in the soil enters the water through leaching and runoff. It can accumulate into ocean sediments and reenter land through uplifting. Long-term storage of organic carbon occurs when matter from living organisms is buried deep underground and becomes fossilized. Volcanic activity and, more recently, human emissions stored carbon back into the carbon cycle. Modified from John M. Evans and Howard Perlman, USGS using tree and deer (both public domain).

Carbon Cycles Slowly between Land and the Ocean

On land, carbon is stored in soil as organic carbon in the form of decomposing organisms or terrestrial rocks. Decomposed plants and algae are sometimes buried and compressed between layers of sediments. After millions of years fossil fuels such as coal, oil, and natural gas are formed. The **weathering** of terrestrial rock and minerals release carbon into the soil.

Carbon-containing compounds in the soil can be washed into bodies of water through **leaching.** This water eventually enters the ocean. Atmospheric carbon dioxide also dissolves in the ocean, reacting with water molecules to form carbonate ions (CO_3^{2-}). Some of these ions combine with calcium ions in the seawater to form calcium carbonate ($CaCO_3$), a major component of the shells of marine organisms. These organisms eventually die and their shells form sediments on the ocean floor. Over geologic time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

Carbonate also precipitates in sediments, forming carbonate rocks, such as limestone. Carbon sediments from the ocean floor are taken deep within Earth by the process of **subduction**: the movement of one tectonic plate beneath another. The ocean sediments are subducted by the actions of **plate tectonics**, melted and then returned to the surface during volcanic activity. Plate tectonics can also cause **uplifting**, returning ocean sediments to land.

Carbon Cycles Quickly between Organisms and the Atmosphere

Carbon dioxide is converted into glucose, an energy-rich organic molecule through **photosynthesis** by plants, algae, and some bacteria (figure 5.3.*b*). They can then produce other organic molecules like complex carbohydrates (such as starch), proteins and lipids, which animals can eat. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (bicarbonate, HCO_3^-).



Figure 5.3.*b*: (a) Plants, (b) algae, and (c) certain bacteria, called cyanobacteria, are can carry out photosynthesis. Algae can grow over enormous areas in water, at times completely covering the surface. (credit a: Steve Hillebrand, U.S. Fish and Wildlife Service; credit b: "eutrophication&hypoxia"/Flickr; credit c: NASA; scale-bar data from Matt Russell)

Plants, animals, and other organisms break down these organic molecules during the process of **aerobic cellular respiration**, which consumes oxygen and releases energy, water and carbon dioxide. Carbon dioxide is returned to the atmosphere during gaseous exchange. Another process by which organic material is recycled is the decomposition of dead organisms. During this process, bacteria and fungi break down the complex organic compounds. Decomposers may do respiration, releasing carbon dioxide, or other processes that release methane (CH_4).

Photosynthesis and respiration are actually reciprocal to one another with regard to the cycling of carbon: photosynthesis removes carbon dioxide from the atmosphere and respiration returns it (figure 5.3.*c*). A significant disruption of one process can therefore affect the amount of carbon dioxide in the atmosphere.

Photosynthesis Equation							
Carbon dioxide	+	Water	SUNLIGHT →	Sugar	+	Oxygen	
$6CO_2$		$6H_2O$		$C_6H_{12}O_6$		$6O_2$	

Figure 5.3.*c*: This equation means that six molecules of carbon dioxide (CO_2) combine with six molecules of water (H_2O) in the presence of sunlight. This produces one molecule of glucose ($C_6H_{12}O_6$) and six molecules of oxygen (O_2).

Cellular respiration is only one process that releases carbon dioxide. Physical processes, such as the eruption of volcanoes and release from **hydrothermal vents** (openings in the ocean floor) add carbon dioxide to the atmosphere. Additionally, the **combustion** of wood and fossil fuels releases carbon dioxide. The level of carbon dioxide in the atmosphere is greatly influenced by the reservoir of carbon in the oceans. The exchange of carbon between the atmosphere and water reservoirs influences how much carbon is found in each.

Importance of the Carbon Cycle

The carbon cycle is crucially important to the biosphere. If not for the recycling processes, carbon might long ago have become completely sequestered in crustal rocks and sediments, and life would no longer exist (figure 5.3.*e*). Photosynthesis not only makes energy and carbon available to higher trophic levels, but it also releases gaseous oxygen (O_2). Gaseous oxygen is necessary for cellular respiration to occur. Photosynthetic bacteria were likely the first organisms to perform photosynthesis, dating back 2-3 billion years ago. Thanks to their activity, and a diversity of present-day photosynthesizing organisms, Earth's atmosphere is currently about 21% O_2. Also, this O_2 is vital for the creation of the ozone layer, which protects life from harmful ultraviolet radiation emitted by the sun. Ozone (O_3) is created from the breakdown and reassembly of O_2.



Figure 5.3.*e*: Decomposers will break down the organic compounds in this fallen tree at Cliffs of the Neuse State Park in Wayne County, North Carolina, releasing carbon dioxide into the atmosphere. Decomposition ensures that carbon dioxide will be available in the atmosphere for photosynthetic organisms, which then provide carbon for consumers. Image by Gerry Dincher (CC-BY-SA).

The global carbon cycle contributes substantially to the provisioning ecosystem services upon which humans depend. We harvest approximately 25% of the total plant biomass that is produced each year on the land surface to supply food, fuel wood and fiber from croplands, pastures and forests. In addition, the global carbon cycle plays a key role in regulating ecosystem services because it significantly influences climate via its effects on atmospheric CO_2 concentrations.

Human Alteration of the Carbon Cycle

Atmospheric CO_2 concentration increased from 280 parts per million (ppm) to 413 ppm between the start of industrial revolution in the late eighteenth century and 2020. This reflected a new flux in the global carbon cycle—anthropogenic CO_2 emissions—where humans release CO_2 into the atmosphere by burning fossil fuels and changing land use. Fossil fuel burning takes carbon from coal, gas, and oil reserves, where it would be otherwise stored on very long time scales, and introduces it into the active carbon cycle. Land use change releases carbon from soil and plant biomass pools into the atmosphere, particularly through the process of deforestation for wood extraction or conversion of land to agriculture. In 2018, the additional flux of carbon into the atmosphere from anthropogenic sources was estimated to be 36.6 gigatons of carbon (GtC = 1 billion tons of carbon)—a significant disturbance to the natural carbon cycle that had been in balance for several thousand years previously. High levels of carbon dioxide in the atmosphere cause warming that results in climate change. (See Threats to Biodiversity and Climate Change for more details.)

The Nitrogen Cycle

All organisms require nitrogen because it is an important component of nucleic acids, proteins, and other organic molecules. Getting nitrogen into living organisms is difficult. Plants and algae are not equipped to incorporate nitrogen from the atmosphere (where it exists as tightly bonded, triple covalent N_2) although this molecule comprises approximately 78 percent of the atmosphere. Because most of the nitrogen is stored in the atmosphere, the atmosphere is considered a reservoir of nitrogen.

The nitrogen molecule (N_2) is quite inert. To break it apart so that its atoms can combine with other atoms requires the input of substantial amounts of energy. **Nitrogen fixation** is the process of converting nitrogen gas into ammonia (NH_3), which spontaneously becomes ammonium (NH_4^+). Ammonium is found in bodies of water and in the soil (figure 5.3.*f*).

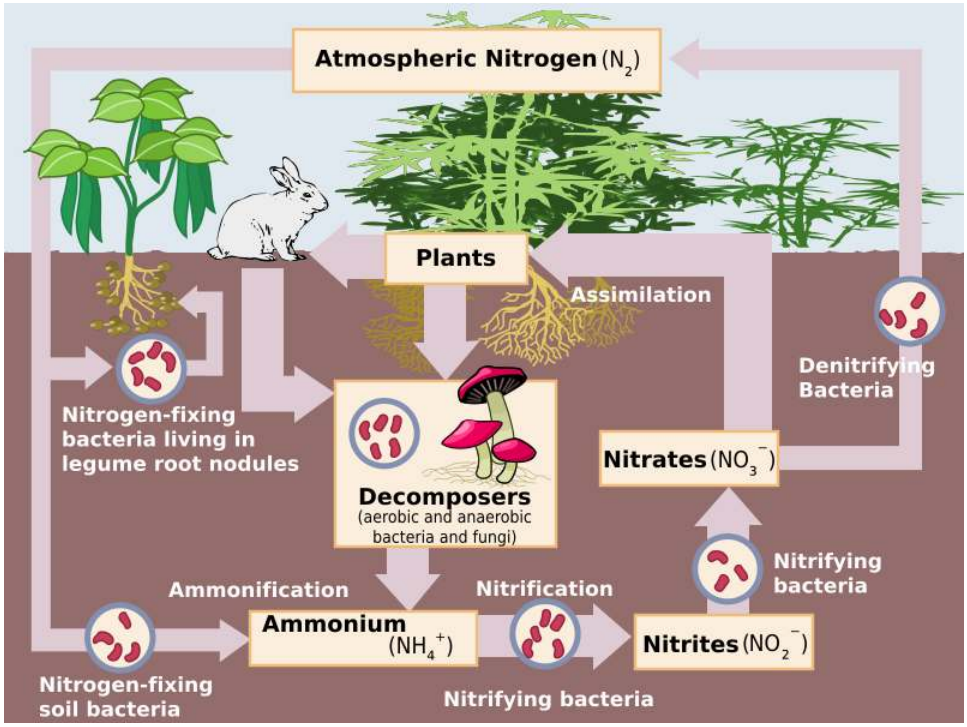


Figure 5.3.*f*: In the nitrogen cycle, nitrogen-fixing bacteria in the soil or legume root nodules convert nitrogen gas (N_2) from the atmosphere to ammonium (NH_4^+). Nitrification occurs when bacteria convert ammonium to nitrites (NO_2^-) and then to nitrates (NO_3^-). Nitrates re-enter the atmosphere as nitrogen gas through denitrification by bacteria. Plants assimilate ammonium and nitrates, producing organic nitrogen, which is available to consumers. Decomposers, including aerobic and anaerobic bacteria and fungi, break down organic nitrogen and release ammonium through ammonification. (credit: "Nitrogen cycle" by Johann Dréo & Raeky is licensed under CC BY-SA 3.0)

Three processes are responsible for most of the nitrogen fixation in the biosphere. The first is **atmospheric fixation** by lightning. The enormous energy of lightning breaks nitrogen molecules and enables their atoms to combine with oxygen in the air forming nitrogen oxides. These dissolve in rain, forming nitrates, that are carried to the earth. Atmospheric nitrogen fixation probably contributes some 5-8% of the total nitrogen fixed. The second process is **industrial fixation.** Under great pressure, at a temperature of 600°C (1112°F), and with the use of a **catalyst** (which facilitates chemical reactions), atmospheric nitrogen and hydrogen can be combined to form ammonia (NH_3). Ammonia can be used directly as fertilizer, but most of it is further processed to urea and ammonium nitrate (NH_4NO_3).

The third process is **biological fixation** by certain free-living or symbiotic bacteria. Some form a symbiotic relationship with plants in the legume family, which includes beans, peas, soybeans, alfalfa, and clovers (figure 5.3.*g*). Some nitrogen-fixing bacteria even establish symbiotic relationships with animals, e.g., termites and "shipworms" (wood-eating bivalves). Nitrogen-fixing cyanobacteria are essential to maintaining the fertility of semi-aquatic environments like rice paddies. Although the first stable product of the process is ammonia, this is quickly incorporated into protein and other organic nitrogen compounds.



Figure 5.3.*g*: Nitrogen-fixing bacteria live in the spherical nodules of this soybean root. Image by United Soybean Board (CC-BY).

Ammonium is converted by bacteria and archaea into nitrites (NO_2^-) and then nitrates (NO_3^-) through the process of **nitrification**. Like ammonium, nitrites and nitrates are found in water and the soil. Some nitrates are converted back into nitrogen gas, which is released into the atmosphere. The process, called **denitrification**, is conducted by bacteria.

Plants and other producers directly use ammonium and nitrates to make organic molecules through the process of **assimilation**. This nitrogen is now available to consumers. Organic nitrogen is especially important to the study of ecosystem dynamics because many processes, such as primary production, are limited by the available supply of nitrogen.

Consumers excrete organic nitrogen compounds that return to the environment. Additionally dead organisms at each trophic level contain organic nitrogen. Microorganisms, such as bacteria and fungi, decompose these wastes and dead tissues, ultimately producing ammonium through the process of **ammonification.**

In marine ecosystems, nitrogen compounds created by bacteria, or through decomposition, collects in ocean floor sediments. It can then be moved to land in geologic time by uplift of Earth's crust and thereby incorporated into terrestrial rock. Although the movement of nitrogen from rock directly into living systems has been traditionally seen as insignificant compared with nitrogen fixed from the atmosphere, a recent study showed that this process may indeed be significant and should be included in any study of the global nitrogen cycle.

Human activity can alter the nitrogen cycle by two primary means: the combustion of fossil fuels, which releases different **nitrogen oxides** into the atmosphere, and by the use of artificial fertilizers in agriculture. Atmospheric nitrogen (other than N_2) is associated with several effects on Earth's ecosystems. Nitrogen oxides (HNO_3) can react in the atmosphere to form nitric acid, a form of **acid deposition**, also known as acid rain. Acid deposition damages healthy trees, destroys aquatic systems and erodes building materials such as marble and limestone. Like carbon dioxide, nitrous oxide (N_2O) causes warming resulting in climate change.

Humans are primarily dependent on the nitrogen cycle as a supporting ecosystem service for crop and forest productivity. Nitrogen fertilizers are added to enhance the growth of many crops and plantations (figure 5.3.*h*). The enhanced use of fertilizers in agriculture was a key feature of the green revolution that boosted global crop yields in the 1970s. The industrial production of nitrogen-rich fertilizers has increased substantially over time and now matches more than half of the input to the land from biological nitrogen fixation (90 megatons = 1 million tons of nitrogen each year). If the nitrogen fixation from legume crops is included, then the anthropogenic flux of nitrogen from the atmosphere to the land exceeds natural fluxes to the land. Fertilizers are washed into lakes, streams, and rivers by surface runoff, resulting in saltwater and freshwater **eutrophication**, a process whereby nutrient runoff causes the overgrowth of algae, the depletion of oxygen, and death of aquatic fauna.



Figure 5.3.*h*: Fertilizer containing nitrogen is conventionally applied at large scales in agriculture. Image by Bob Nichols, USDA Natural Resources Conservation Service (public domain).

The Phosphorus Cycle

Several forms of nitrogen (nitrogen gas, ammnoium, nitrates, etc.) were involved in the nitrogen cycle, but phosphorus remains primarily in the form of the phosphate ion (PO_4^{3-}). Also in contrast to the nitrogen cycle, there is no form of phosphorus in the atmosphere. Phosphorus is used to make nucleic acids and the phospholipids that comprise biological membranes.

Rocks are a reservoir for phosphorus, and these rocks have their origins in the ocean. Phosphate-containing ocean sediments form primarily from the bodies of ocean organisms and from their excretions. However, volcanic ash, aerosols, and mineral dust may also be significant phosphate sources. This sediment then is moved to land over geologic time by the uplifting of Earth's surface (figure 5.3.*i*). The movement of phosphate from the ocean to the land and through the soil is extremely slow, with the average phosphate ion having an oceanic residence time between 20,000 and 100,000 years.

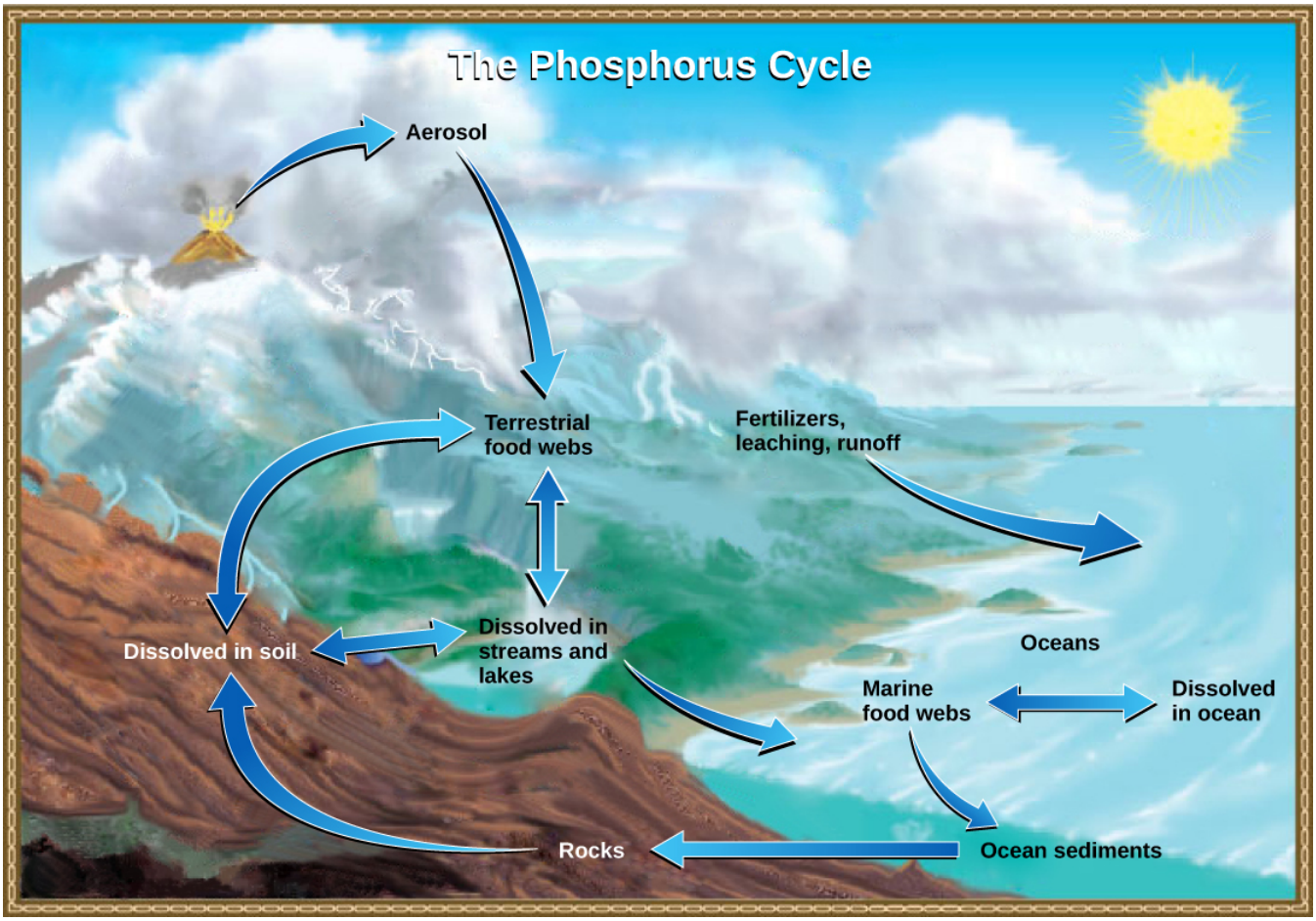


Figure 5.3.i: In nature, phosphorus exists as the phosphate ion (PO_4^{3-}). Phosphate enters the atmosphere from volcanic aerosols, which precipitate to Earth. Weathering of rocks also releases phosphate into the soil and water, where it becomes available to terrestrial food webs. Some of the phosphate from terrestrial food webs dissolves in streams and lakes, and the remainder enters the soil. Phosphate enters the ocean via surface runoff, groundwater flow, and river flow, where it becomes dissolved in ocean water or enters marine food webs. Some phosphate falls to the ocean floor where it becomes sediment. If uplifting occurs, this sediment can return to land. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

Marine birds play a unique role in the phosphorous cycle. These birds take up phosphorous from ocean fish. Their droppings on land (**guano**) contain high levels of phosphorous and are sometimes mined for commercial use. A 2020 study estimated that the **ecosystem services** (natural processes and products that benefit humans) provided by guano are worth $470 million per year.

Weathering of rocks releases phosphates into the soil and bodies of water. Plants can assimilate phosphates in the soil and incorporate it into organic molecules, making phosphorus available to consumers in terrestrial food webs. Waste and dead organisms are decomposed by fungi and bacteria, releasing phosphates back into the soil. Some phosphate is leached from the soil, entering into rivers, lakes, and the ocean. Primary producers in aquatic food webs, such as algae and photosynthetic bacteria, assimilate phosphate, and organic phosphate is thus available to consumers in aquatic food webs. Similar to terrestrial food webs, phosphorus is reciprocally exchanged between phosphate dissolved in the ocean and organic phosphorus in marine organisms.

The movement of phosphorus from rock to living organisms is normally a very slow process, but some human activities speed up the process. Phosphate-bearing rock is often mined for use in the manufacture of fertilizers and detergents. This commercial production greatly accelerates the phosphorous cycle. In addition, runoff from agricultural land and the release of sewage into water systems can cause a local overload of phosphate. The increased availability of phosphate can cause overgrowth of algae. This reduces the oxygen level, causing eutrophication and the destruction of other aquatic species.

Eutrophication and Dead Zones

Eutrophication occurs when excess phosphorus and nitrogen from fertilizer runoff or sewage causes excessive growth of algae. Algal blooms that block light and therefore kill aquatic plants in rivers, lakes, and seas. The subsequent death and decay of these

organisms depletes dissolved oxygen, which leads to the death of aquatic organisms such as shellfish and fish. This process is responsible for **dead zones**, large areas in lakes and oceans near the mouths of rivers that are periodically depleted of their normal flora and fauna, and for massive fish kills, which often occur during the summer months (figure 5.3.*j*). There are more than 500 dead zones worldwide. One of the worst dead zones is off the coast of the United States in the Gulf of Mexico. Fertilizer runoff from the Mississippi River basin created a dead zone, which reached its peak size of 8,776 square miles in 2017. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems including the Chesapeake Bay in the eastern United States.

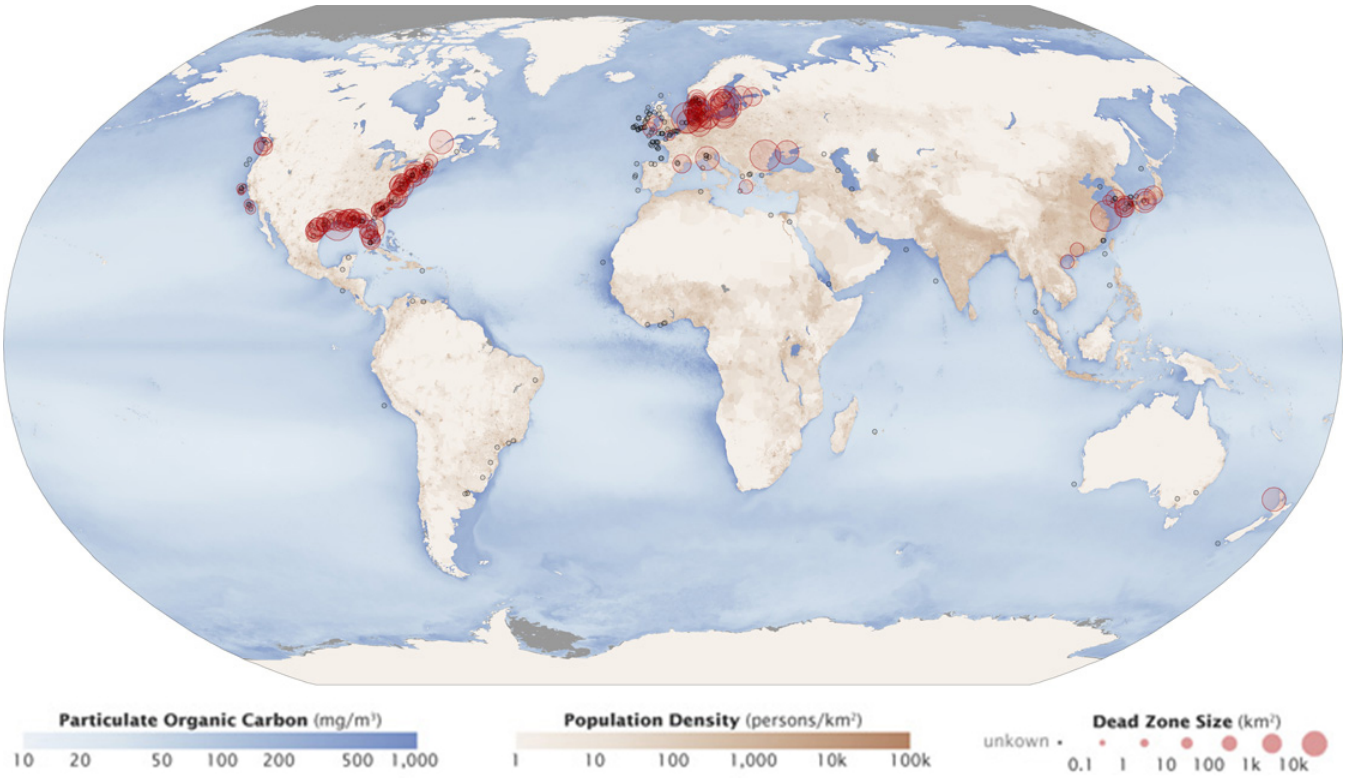


Figure 5.3.*j*: Dead zones occur when phosphorus and nitrogen from fertilizers cause excessive growth of microorganisms, which depletes oxygen and kills fauna. This map shows dead zones around the world in 2008. Worldwide, large dead zones are found in coastal areas of high population density. (credit: NASA Earth Observatory)

Everyday Connection: Chesapeake Bay

The Chesapeake Bay has long been valued as one of the most scenic areas on Earth; it is now in distress and is recognized as a declining ecosystem. In the 1970s, the Chesapeake Bay was one of the first ecosystems to have identified dead zones, which continue to kill many fish and bottom-dwelling species, such as clams, oysters, and worms (figure 5.3.*k*). Several species have declined in the Chesapeake Bay due to surface water runoff containing excess nutrients from artificial fertilizer used on land. The source of the fertilizers (with high nitrogen and phosphate content) is not limited to agricultural practices. There are many nearby urban areas and more than 150 rivers and streams empty into the bay that are carrying fertilizer runoff from lawns and gardens. Thus, the decline of the Chesapeake Bay is a complex issue and requires the cooperation of industry, agriculture, and everyday homeowners.



(a) (b)

Figure 5.3.*k*: This (a) satellite image shows the Chesapeake Bay, an ecosystem affected by phosphate and nitrate runoff. A (b) member of the Army Corps of Engineers holds a clump of oysters being used as a part of the oyster restoration effort in the bay. (credit a: modification of work by NASA/MODIS; credit b: modification of work by U.S. Army)

Of particular interest to conservationists is the oyster population; it is estimated that more than 200,000 acres of oyster reefs existed in the bay in the 1700s, but that number has now declined to only 36,000 acres. Oyster harvesting was once a major industry for Chesapeake Bay, but it declined 88 percent between 1982 and 2007. This decline was due not only to fertilizer runoff and dead zones but also to overexploitation. Oysters require a certain minimum population density because they must be in close proximity to reproduce. Human activity has altered the oyster population and locations, greatly disrupting the ecosystem.

The restoration of the oyster population in the Chesapeake Bay has been ongoing for several years with mixed success. Not only do many people find oysters good to eat, but they also clean up the bay. Oysters are filter feeders, and as they eat, they clean the water around them. In the 1700s, it was estimated that it took only a few days for the oyster population to filter the entire volume of the bay. Today, with changed water conditions, it is estimated that the present population would take nearly a year to do the same job.

Restoration efforts have been ongoing for several years by non-profit organizations, such as the Chesapeake Bay Foundation. The restoration goal is to find a way to increase population density so the oysters can reproduce more efficiently. Many disease-resistant varieties (developed at the Virginia Institute of Marine Science for the College of William and Mary) are now available and have been used in the construction of experimental oyster reefs. Efforts to clean and restore the bay by Virginia and Delaware have been hampered because much of the pollution entering the bay comes from other states, which stresses the need for inter-state cooperation to gain successful restoration.

The new, hearty oyster strains have also spawned a new and economically viable industry—oyster aquaculture—which not only supplies oysters for food and profit, but also has the added benefit of cleaning the bay.

The Sulfur Cycle

Sulfur is an essential element for the molecules of living things. As part of the amino acid cysteine, it is critical to the three-dimensional shape of proteins. As shown in Figure 5.3.*l*, sulfur cycles among the oceans, land, and atmosphere. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), which enters the atmosphere in three ways: first, from the decomposition of organic molecules; second, from volcanic activity and geothermal vents; and, third, from the burning of fossil fuels by humans.

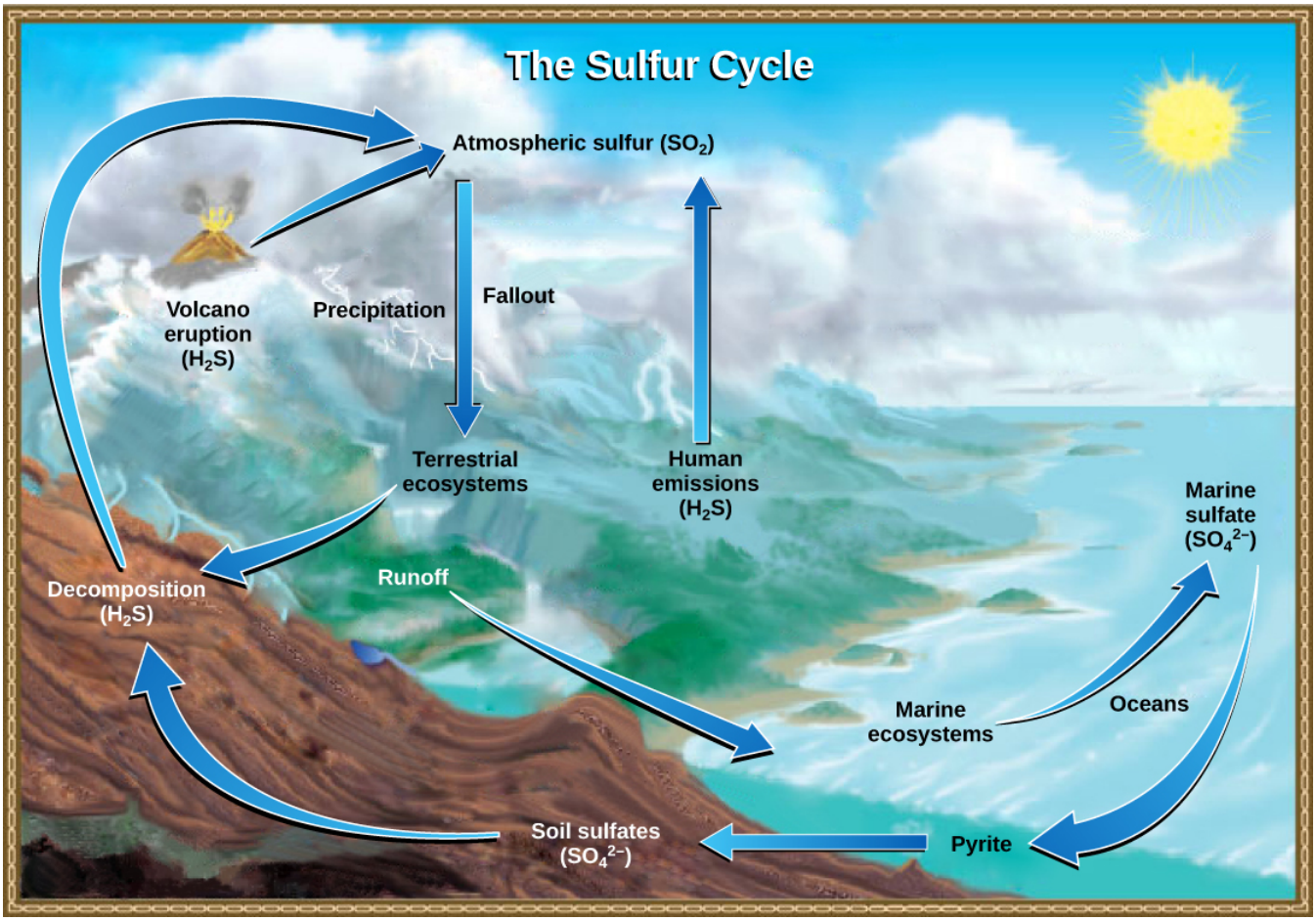


Figure 5.3.1: The sulfur cycle. Sulfur dioxide (SO_2) from the atmosphere is dissolved in precipitation as weak sulfuric acid or falls directly to Earth as fallout. This releases sulfates (SO_4^{2-}) into the soil and water. Soil sulfates can be carried as runoff into the water. Marine sulfate can form pyrite, and this can break down to release soil sulfates. Organisms in terrestrial and marine ecosystems assimilate sulfate, adding sulfur to organic molecules, such as proteins (not shown). Decomposition of these organisms returns sulfates to the soil. Microorganisms can convert sulfates to hydrogen sulfide (H_2S) and vice versa. Decomposition, volcanic eruptions, and human activities (including burning fossil fuels) can release hydrogen sulfide (H_2S) or sulfur dioxide into the atmosphere. (credit: modification of work by John M. Evans and Howard Perlman, USGS)

On land, sulfur is deposited in four major ways: precipitation, direct fallout from the atmosphere, rock weathering, and geothermal vents. Atmospheric sulfur is found in the form of sulfur dioxide (SO_2), and as rain falls through the atmosphere, sulfur is dissolved in the form of weak sulfuric acid (H_2SO_4). Sulfur can also fall directly from the atmosphere in a process called **fallout**. Also, as sulfur-containing rocks weather, sulfur is released into the soil. These rocks originate from ocean sediments that are moved to land by the geologic uplifting of ocean sediments. Terrestrial ecosystems can then make use of these soil sulfates (SO_4^{2-}), which enter the food web by being taken up by plant roots. When these plants decompose and die, sulfur is released back into the atmosphere as hydrogen sulfide (H_2S) gas.

Sulfur enters the ocean in runoff from land, from atmospheric fallout, and from hydrothermal vents. Some ecosystems rely on microorganisms using sulfur as a biological energy source (in contrast to ecosystems with photosynthetic producers). This sulfur then supports marine ecosystems in the form of sulfates.

Human activities have played a major role in altering the balance of the global sulfur cycle. The burning of large quantities of fossil fuels, especially from coal, releases sulfur dioxide, which reacts with the atmosphere to form sulfuric acid. Like nitric acid, sulfuric acid contributes to acid deposition.

Suggested Supplementary Reading

Bruckner, M. 2018. The Gulf of Mexico Dead Zone. [Website]

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5.4: Fresh Water Supply and the Water Cycle

Water, air, and food are the most important natural resources to people. Humans can live only a few minutes without oxygen, less than a week without water, and about a month without food. Water also is essential for our oxygen and food supply. Plants breakdown water and use it to create oxygen during the process of photosynthesis.

Human babies are approximately 75% water, and adults are 60% water. Our brain is about 85% water, blood and kidneys are 83% water, muscles are 76% water, and even bones are 22% water. We constantly lose water by perspiration. In temperate climates we should drink about two quarts of water per day, and people in hot desert climates should drink up to 10 quarts of water per day. Loss of 15% of body-water usually causes death.

Water Reservoirs

Water is the only common substance that occurs naturally on Earth in three forms: solid, liquid and gas. The **hydrosphere** is the area of Earth where water movement and water storage occurs. **Water reservoirs** are the locations where water is stored. (Note that this term can also refer to artificial lakes created by dams.) Water is found as a liquid on the surface (rivers, lakes, oceans) and beneath the surface (groundwater), as ice (polar ice caps and glaciers), and as water vapor in the atmosphere. Figure 5.4.*a* illustrates the average time that an individual water molecule may spend in the Earth's major water reservoirs. **Residence time** is a measure of the average time an individual water molecule stays in a particular reservoir.

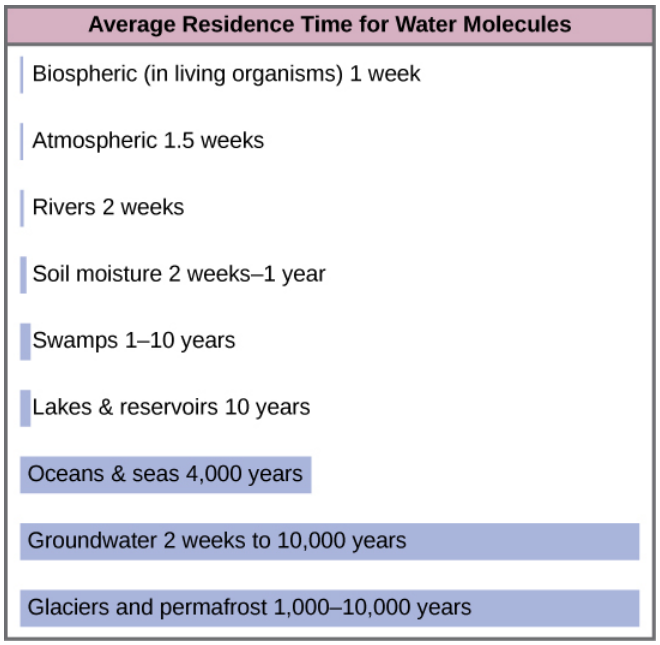
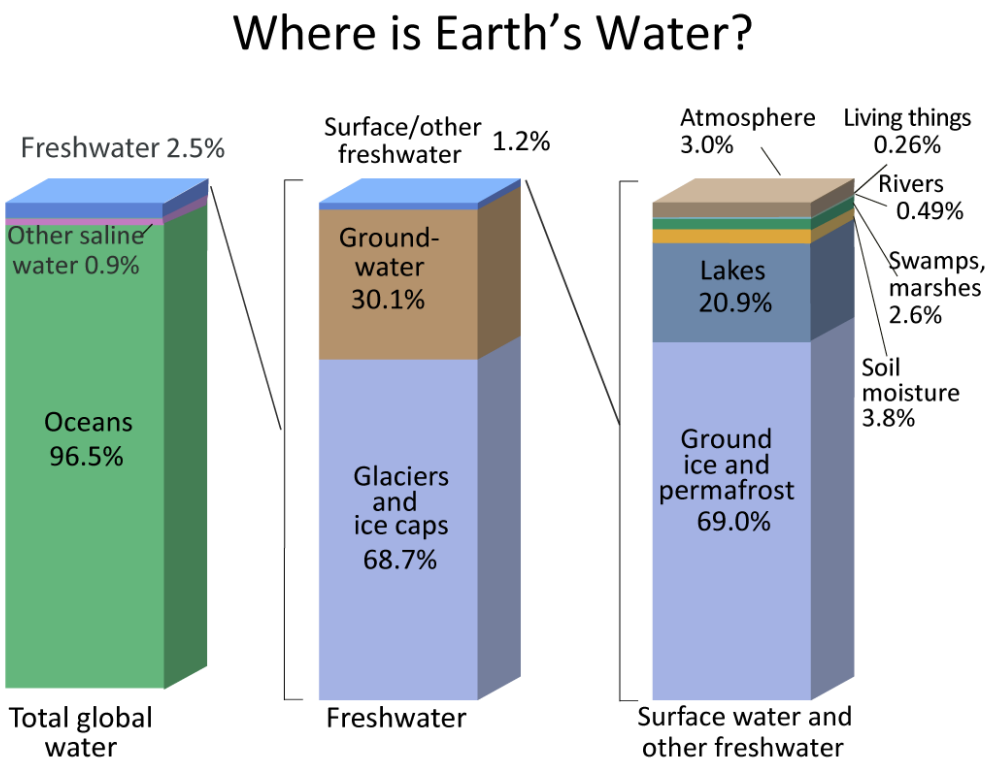


Figure 5.4.*a*: Average residence time that water remains in each reservoir. Water remains in organisms for about one week, in the atmosphere for 1.5 weeks, in rivers for two weeks, as soil moisture from two weeks to a year, in swamps for 1-10 years, in lakes for 10 years, in oceans and seas for 4,000 years, as groundwater for 2 weeks to 10,000 years, and in glaciers or as permafrost for 1,000-10,000 years. Image from OpenStax (CC-BY).

Earth is truly the Water Planet. The abundance of liquid water on Earth's surface distinguishes us from other bodies in the solar system. About 71% of Earth's surface is covered by water, and approximately half of Earth's surface is obscured by clouds (also made of water) at any time. There is a very large volume of water on our planet, about 1.4 billion cubic kilometers (km^3) = 330 million cubic miles, or about 53 billion gallons per person on Earth. All of Earth's water could cover the United States to a depth of 145 km (90 mi).

Despite the vast volumes of water on Earth, only 2.5% is fresh water (figure 5.4.*b*), and only 0.01% is available for humans to use. If all of world's water was shrunk to the size of 1 gallon, then the total amount of fresh water would be about 1/3 cup, and the amount of readily usable fresh water would be 2-3 tablespoons. Much of Earth's fresh water is trapped in glaciers and polar ice caps (figure 5.4.*c*), and this water is inconveniently located, mostly in Antarctica and Greenland. Shallow **groundwater** (water located below the Earth's surface) is the largest reservoir of usable fresh water. Many organisms are dependent on surface waters, such as

lakes and rivers, which comprise a small fraction of fresh water on Earth. A lack of these surface waters can have negative effects on ecosystems.



Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

Figure 5.4.*b*: Bar chart of the distribution of Earth's water, including total global water, fresh water, and surface water. Oceans are the largest of Earth's water reservoirs, and only 2.5% of Earth's water is fresh water. Most of this fresh water (68.7%) is in glaciers and ice caps, 30.1% is groundwater, and 1.2% is surface and other fresh water. Of this 1.2%, 3.0% is found in the atmosphere, 0.26% in living things, 0.49% in rivers, 2.6% in swamps and marshes, 3.8% as soil moisture, 20.9% in lakes, and 69.0% as ground ice and permafrost. Image from USGS/Igor Shiklomanov (public domain).



Figure 5.4.*c*: Mountain Glacier in Argentina. Glaciers are the largest reservoir of fresh water, but they are not used much as a water resource directly by society because of their distance from most people. Source: Luca Galuzzi – www.galuzzi.it

The Water Cycle

The **water cycle** (hydrologic cycle) shows the movement of water through different reservoirs, which include oceans, atmosphere, glaciers, groundwater, lakes, rivers, and organisms (figure 5.4.*d*). Solar energy, which warms the oceans and other surface waters, and gravity drive the motion of water in the water cycle. This leads to **evaporation** (liquid water to water vapor) of liquid surface water, **sublimation** (ice to water vapor) of frozen water, and **transpiration** (the loss of water from plants to the atmosphere). When water in the soil is taken up by plant roots, it moves through tubes in the plant (the vascular system), evaporates within the space of the leaf, and transpires through the stomata (small microscope openings) of the leaves. Ecologists combine transpiration and evaporation into a single term that describes water returned to the atmosphere: **evapotranspiration**. Thus, large amounts of water move into the atmosphere as water vapor.

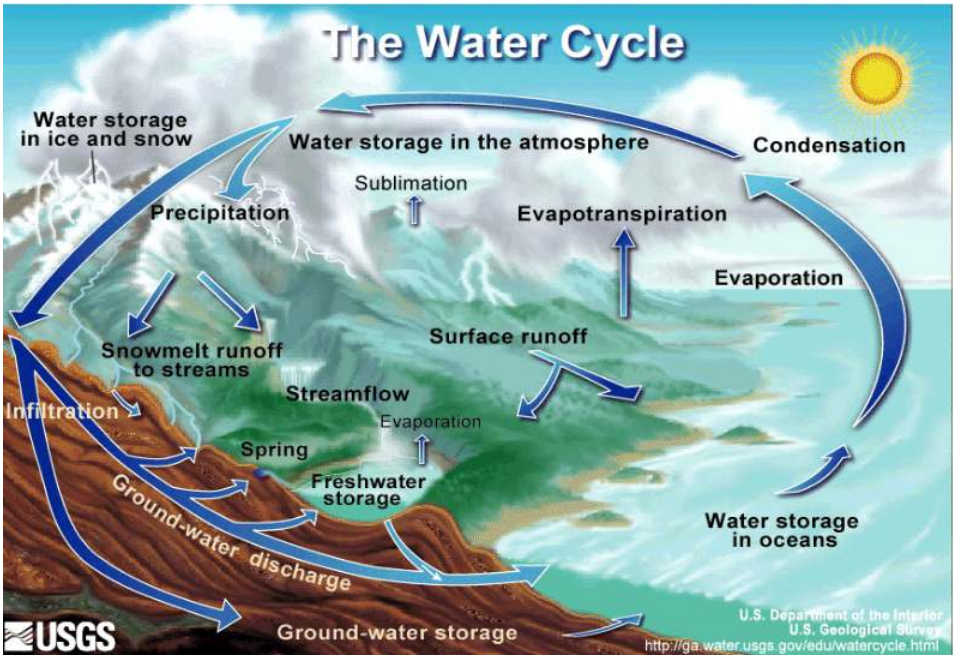


Figure 5.4.*d*: The water cycle. Arrows depict movement of water to different reservoirs located above, at, and below Earth's surface. Evapotranspiration and sublimination add water to the atmosphere, where it condenses to form clouds. Water is thus stored in the atmosphere. Through precipitation, water returns to the Earth's surface. When precipitation occurs at high elevation, water is stored as snow or ice. When the snow melts, the resultant runoff can add to streams. Water from precipitation can also infiltrate to replenish groundwater storage or form surface runoff. Groundwater discharge, water from streams, and surface runoff flows into bodies of fresh water and ocean. Source: United States Geological Survey

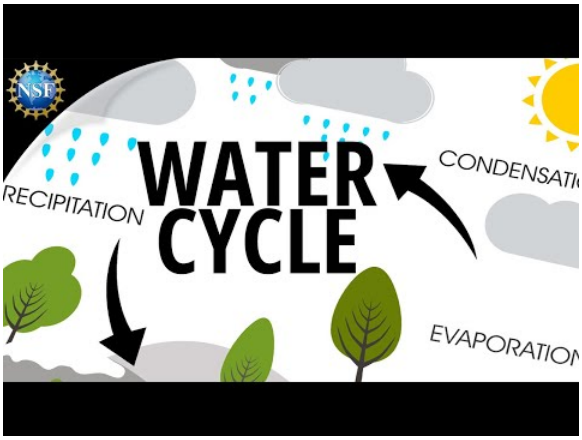
Water vapor in the atmosphere can migrate long-distances from ocean to over land by way of prevailing winds. Over the ocean or land, the air can cool and cause the water to **condense** back into liquid water. This usually happens in the form of very small water droplets that form around a microscopic piece of dust or salt called condensation nuclei. These small water droplets are visible as a cloud. Clouds build and once the water droplets are big enough, they fall to earth as **precipitation** (rain, snow, hail, or sleet), which returns water to Earth's surface.

Precipitation that reaches land can immediately return to the atmosphere, add to groundwater, or form surface runoff. In most natural terrestrial environments, rain encounters vegetation before it reaches the soil surface. A significant percentage of water evaporates immediately from the surfaces of plants or directly from the soil surface. Groundwater is replenished when water **infiltrates** into the soil and finally fills the pore spaces between particles in dirt, sand, and gravel or in the fissures in rocks. Groundwater slowly moves through rock and unconsolidated materials and some of it eventually reaches the surface again, where it discharges as springs and into streams, lakes, and the ocean. Many streams flow not because they are replenished from rainwater directly but because they receive a constant inflow from the groundwater below. Also, surface water in streams and lakes can infiltrate again to recharge groundwater. Therefore, the surface water and groundwater systems are connected. Groundwater can also ultimately flow into the ocean through subsurface groundwater flow, but some groundwater is found very deep in the bedrock and can persist there for millennia. **Surface runoff** is the flow of fresh water over land either from rain or melting ice. Runoff can

make its way through streams and lakes to the oceans. Surface runoff will occur only if the soil becomes saturated with water in a heavy rainfall.

The steps of the water cycle are explained in the video below.





Salinity and the Water Cycle

An important part of the water cycle is how water varies in salinity, which is the abundance of dissolved ions in water. The salt water in the oceans is highly saline, with about 35,000 mg of dissolved ions per liter of seawater. Evaporation is a distillation process that produces nearly pure water with almost no dissolved ions. As water vaporizes, it leaves the dissolved ions in the original liquid phase. Eventually, condensation forms clouds and sometimes precipitation. After rainwater falls onto land, it dissolves minerals in rock and soil, which increases its salinity. Rain and surface runoff are major ways in which minerals, including phosphorus and sulfur, are cycled from land to water. The environmental effects of runoff were discussed in Biogeochemical Cycles. Fresh water (such as lakes, rivers, and near-surface groundwater) has a relatively low salinity.

Human Interactions with The Water Cycle

Humans alter the water cycle by extracting large amounts of fresh water from surface waters as well as groundwater (see Water Usage). Additionally, changes in land use, such as deforestation, agriculture, and urbanization, reduce vegetation cover, which reduces infiltration and increases surface runoff. (Vegetation naturally traps precipitation as it falls, slows the flow surface runoff, and increases the infiltration rate.) This intensifies flooding and exacerbates erosion, lowering soil quality and causing sediment pollution in water. Additionally, humans redirect the flow of water by building dams and aqueducts (figure $5.4.e$). So much water is

removed or redirected from the Colorado River in the western United States that, despite its considerable size, in some years it is dry before reaching the sea in Mexico. In an extreme example, the Aral Sea in Central Asia has decreased to only 10% of its initial size after water was diverted for agriculture (see this case study for more details).



Figure 5.4.e: The California Aqueduct carries water needed for agriculture from Northern California to Southern California. Image by USGS (public domain).

Water Resources

Freshwater resources are ultimately replenished by precipitation. This water can then be obtained from surface water, such as rivers and lakes, and from aquifers, which store groundwater.

Primary Fresh Water Resources: Precipitation

Precipitation levels are unevenly distributed around the globe, affecting fresh water availability (figure 5.4.f). In general, due the uneven heating of the Earth and global air circulation cells resulting from the Earth's rotation, air rises near the equator and near 60° north and south latitude and sinks at the poles and 30° north and south latitude. As discussed in Climate Effects on Biomes, the intense sunlight at the equator heats air, causing it to rise and cool, which decreases the ability of the air mass to hold water vapor and results in frequent rainstorms. Around 30 degrees north and south latitude, descending air conditions produce warmer air, which increases its ability to hold water vapor and results in dry conditions. Both the dry air conditions and the warm temperatures of these latitude belts favor evaporation.

The size of continents, mountains, prevailing winds, ocean circulation patterns, and even the proximity of bodies of water can affect local climate patterns. For example, when cold winds blow across the relatively warm Great Salt Lake, the air warms, which causes it to pick up moisture. This local increase in the moisture content of the air may eventually fall as snow or rain on nearby mountains, a phenomenon known as “lake-effect precipitation”.

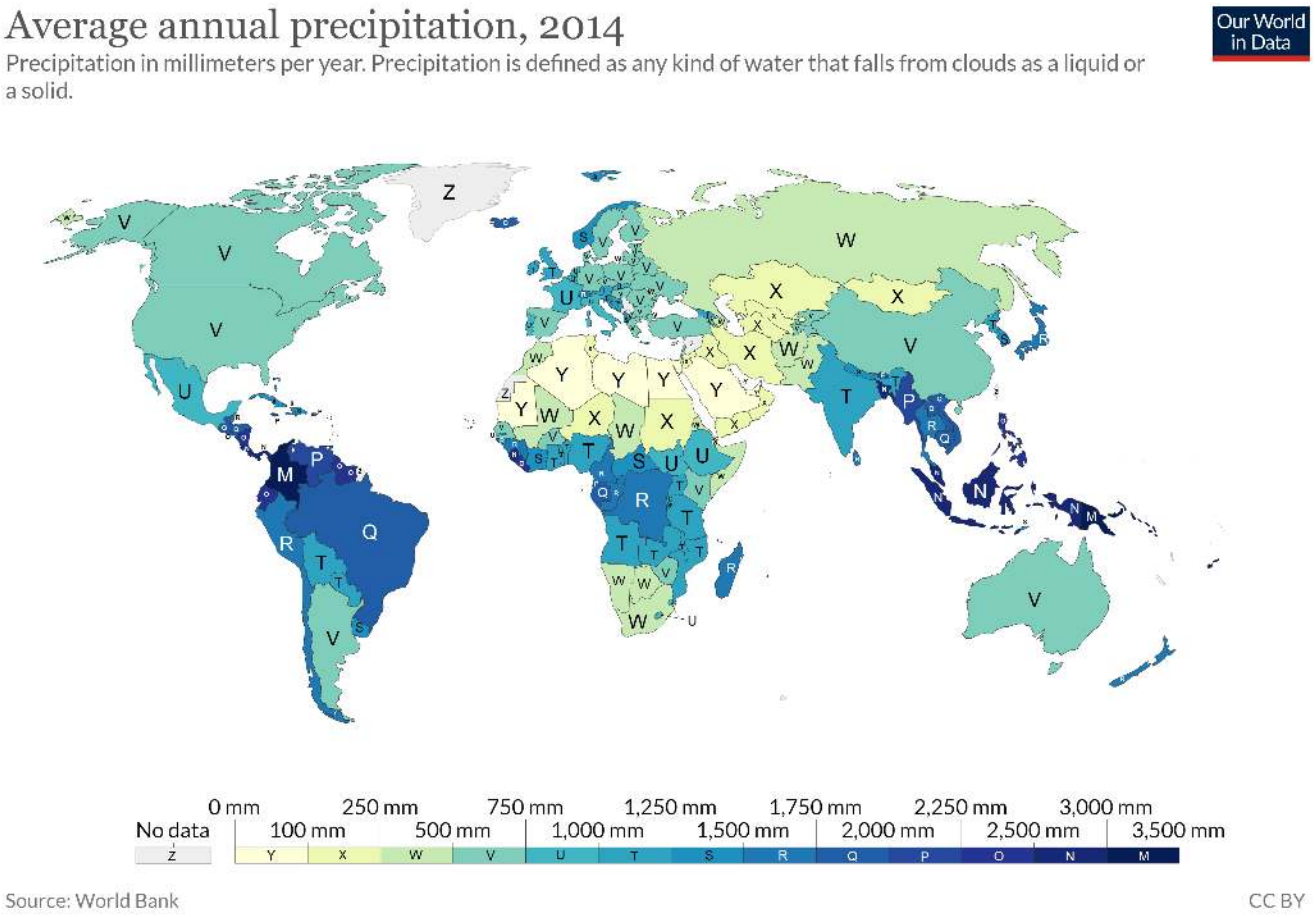


Figure 5.4.*f*: Annual average precipitation by country in 2014. Countries with the highest rainfall (3000-3500 mm) are Nicaragua, Costa Rica, Panama, Columbia, Sierra Leone (in West Africa), Bangladesh, and many of the islands is Southeast Asia. Countries with the least rainfall (0-100 mm) are Saudi Arabia and several North African countries. The United States has intermediate rainfall (500-750 mm). The world's rainforests grow in areas with high rainfall while areas with very little rainfall are deserts. Image modified from Our World in Data/World Bank (CC-BY).

In the United States, the 100th Meridian roughly marks the boundary between the humid and arid parts of the country (figure 5.4.*g*). Irrigation is required to grow crops west of the 100th Meridian. In the West, surface water is stored in reservoirs (artificial lakes) and mountain snowpacks and strategically released through a system of canals during times of high use.

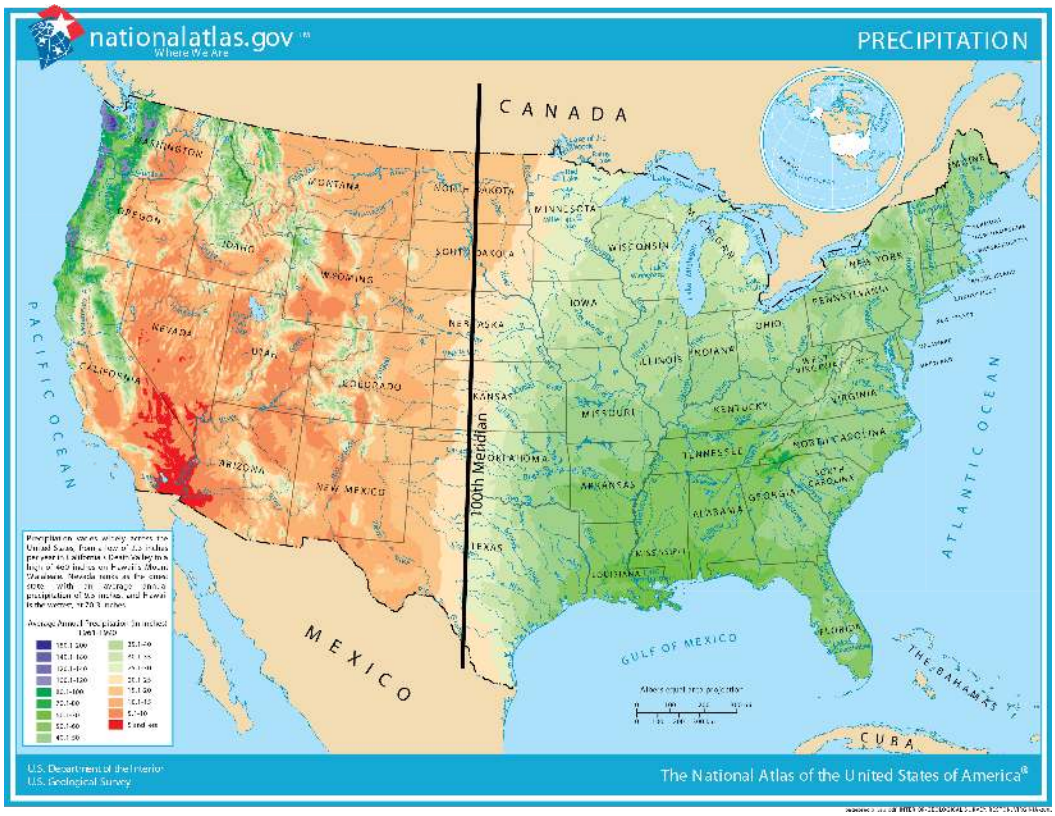


Figure 5.4.*g*: Distribution of precipitation in the United States. The 100th Meridian is approximately where the average precipitation transitions from relatively wet to dry. Eastern states are mostly green, indicating greater precipitation than most western states, which are mainly orange or red (indicating low precipitation). (Source: U.S. Geological Survey)

Surface Water: Rivers and Lakes

Rivers are an important water resource for irrigation of cropland and drinking water for many cities around the world. Flowing water from rain and melted snow on land enters river channels by surface runoff (figure 5.4.*h*) and seepage from surrounding land. The geographic area drained by a river and its tributaries is called a **watershed**. The Mississippi River watershed includes approximately 40% of the U.S., a measure that includes the smaller watersheds, such as the Ohio River and Missouri River that help to comprise it. Rivers that have had international disputes over water supply include the Colorado (Mexico, southwest U.S.), Nile (Egypt, Ethiopia, Sudan), Euphrates (Iraq, Syria, Turkey), Ganges (Bangladesh, India), and Jordan (Israel, Jordan, Syria).

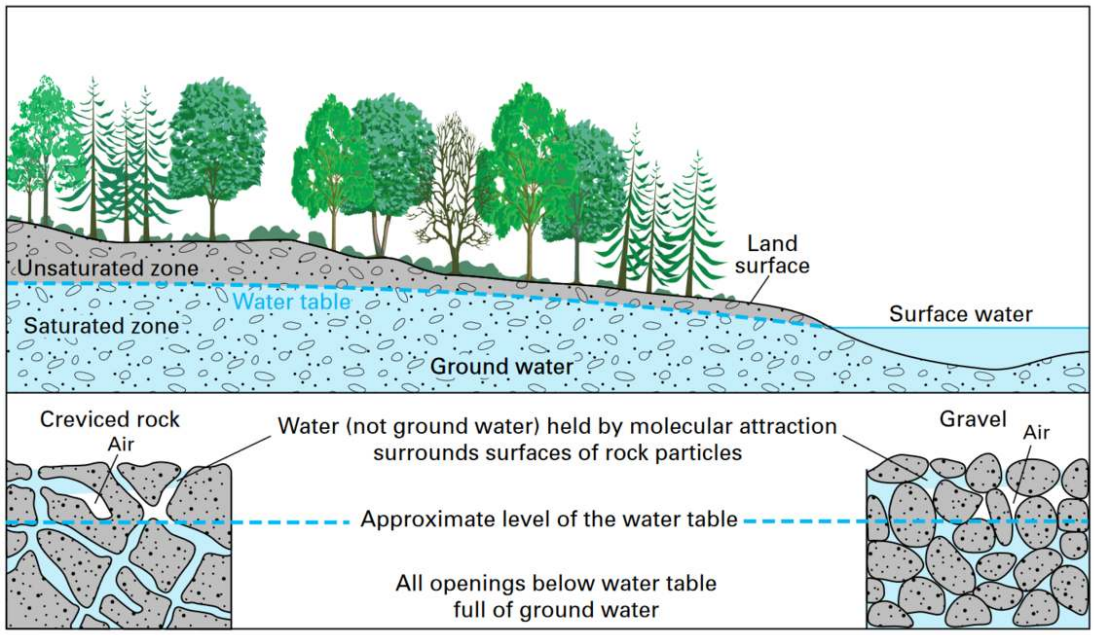


Figure 5.4.*h*: Surface runoff, part of overland flow in the water cycle Source: James M. Pease at Wikimedia Commons

In addition to rivers, lakes can also be an excellent source of fresh water for human use. They usually receive water from surface runoff and groundwater. By building dams, people create artificial lakes (**reservoirs**).

Groundwater Resources

Although most people in the world use surface water, groundwater is a much larger reservoir of usable fresh water, containing more than 30 times more water than rivers and lakes combined. A large area of subsurface, porous rock unit or sediment that holds extractable groundwater is an **aquifer**. The **saturated zone** of an aquifer is where groundwater completely fills pore spaces in earth materials. The **water table** is the uppermost level at which the pores are fully saturated with water (figure 5.4.*i*).



How ground water occurs in rocks.

Figure 5.4.*i*: The unsaturated and saturated zones of an aquifer, which stores groundwater. The water table is the upper level of the saturated zone. The land surface is covered in vegetation, and the top of the surface water is continuous with the water table. The bottom of the image shows creviced rock (left) and gravel (right), both of which contain spaces that store air and water. Above the water table, water (not groundwater) is held by molecular attraction and surrounds the surfaces of rock particles. All openings below the water table are full of water table. Image by USGS (public domain)

A combination of a place to put water (porosity) and the ability to move water (permeability) makes a good aquifer. **Porosity** is a measure of the open space in rocks –expressed as the percentage of open space that makes up the total volume of the rock or sediment material. **Permeability** is a measure of the interconnectedness of pores in a rock or sediment. The connections between pores allows for that material to transmit water. Porosity and permeability are functions of soil particle composition. For example, clays generally have very high porosity, but the pores are poorly connected, thereby causing low permeability.

Aquifers are commonly drilled, and wells installed, to provide water for agriculture and personal use. In many cases aquifers are being depleted faster than they are being replenished by water infiltrating down from above. Groundwater is a particularly important resource in arid climates, where surface water may be scarce. In addition, groundwater is the primary water source for rural homeowners, providing 98% of that water demand in the U.S.

As groundwater is pumped from water wells, there usually is a localized drop in the water table around the well called a **cone of depression** (figure 5.4.*j*). When there are a large number of wells that have been pumping water for a long time, the regional water table can drop significantly. This is called **groundwater mining**, which can force the drilling of deeper, more expensive wells that commonly encounter more saline groundwater. Rivers, lakes, and artificial lakes (reservoirs) can also be depleted due to overuse. Some large rivers, such as the Colorado in the U.S. and Yellow in China, run dry in some years.

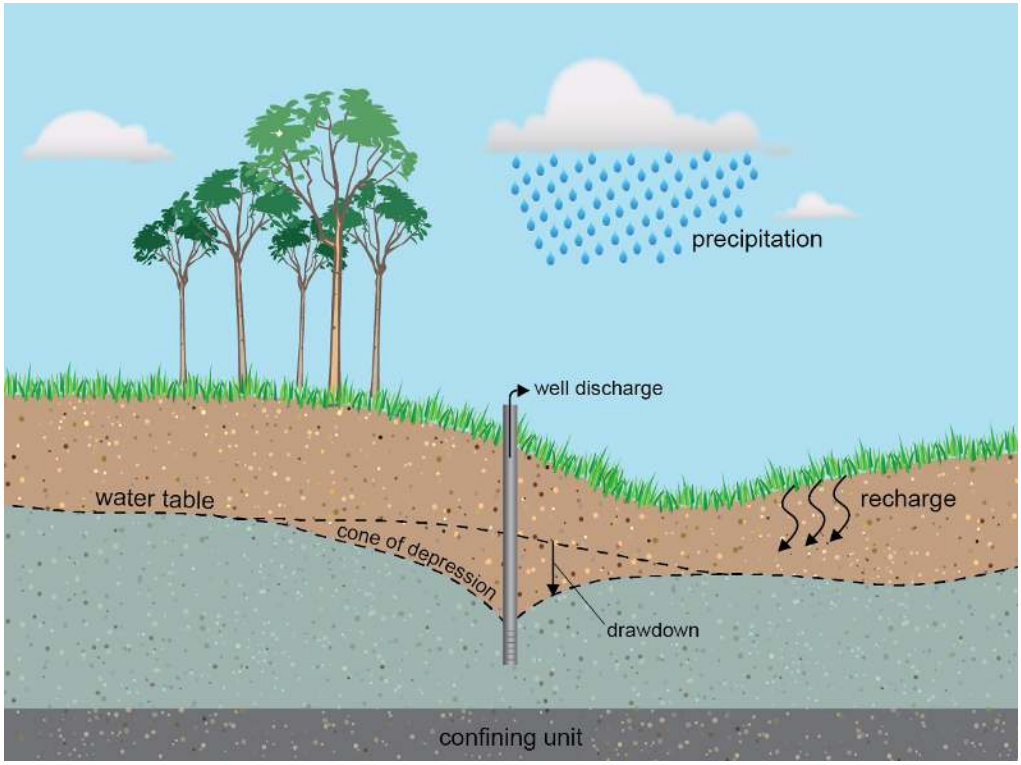


Figure 5.4.*j*: As groundwater is extracted from the well, the water table of the aquifer dips, forming a cone of depression. Drawdown is between the water table and the cone of depression. Precipitation is represented by water droplets falling from a cloud. It soaks into the ground, recharging the aquifer. At the bottom of the aquifer is the confining unit, which is impermeable to water. Image by Tara Gross/USGS (public domain).

Another water resource problem associated with groundwater mining is **saltwater intrusion**, where overpumping of freshwater aquifers near ocean coastlines causes salt water to enter freshwater zones. The drop of the water table around a cone of depression in an aquifer can change the direction of regional groundwater flow, which could send nearby pollution toward the pumping well instead of away from it. Finally, problems of **subsidence** (gradual sinking of the land surface over a large area) and **sinkholes** (rapid sinking of the land surface over a small area) can develop due to a drop in the water table. Because the pores in the aquifer collapse as subsidence occurs, this permanently reduces the capacity of the aquifer to hold water in the future.

Groundwater is replenished through infiltration, seepage from surface water (lakes, rivers, reservoirs, and swamps), surface water deliberately pumped into the ground, irrigation, and underground wastewater treatment systems (septic tanks). **Recharge areas** are locations where surface water infiltrates into the ground rather than running into rivers or evaporating (figure 5.4.*k*). Recharge areas are generally the topographically highest location of an aquifer. They are characterized by streams that lie below the water table and sediment or rock that allows infiltration into the subsurface. Wetlands, for example, are excellent recharge areas. Recharge areas mark the beginning of groundwater flow paths.

Recharge can be induced through the aquifer management practice of aquifer storage and recovery. Injection wells allow for humans to increase the rate of recharge into an aquifer system by pumping water into an aquifer (figure 5.4.*k*). Injection wells are regulated by state and federal governments to ensure that the injected water is not negatively impacting the quality or supply of the existing groundwater in the aquifer. Some aquifers are capable of storing significant quantities of water, allowing water managers to use the aquifer system like a surface reservoir. Water is stored in the aquifer during periods of low water demand and high water supply and later extracted during times of high water demand and low water supply.

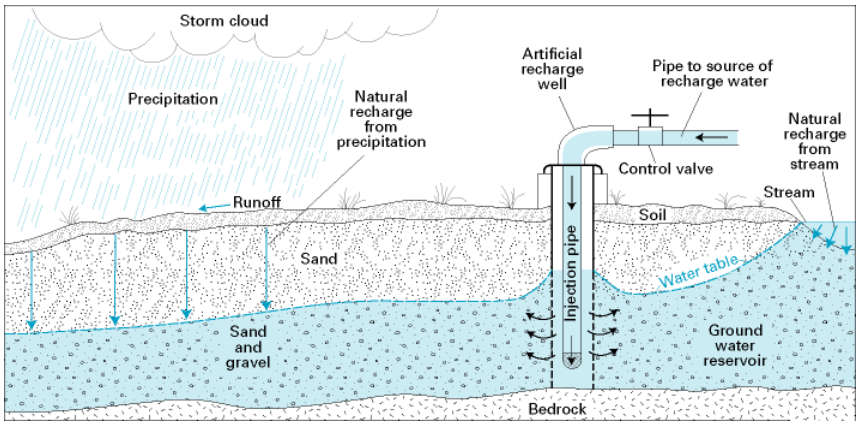


Figure 5.4.*k*: Groundwater can be replenished through natural recharge areas as well as artificial injection wells. In this diagram, precipitation emerges from a storm cloud. Some of the water washes away as runoff, and some water infiltrates through the sand (natural recharge from precipitation). The water fills the sand and gravel in the aquifer (labeled ground water reservoir). Below the aquifer is bedrock, which is impermeable to water. Another natural source of recharge is from streams. Through an artificial recharge well, water flows from a pipe through a control valve into an injection pipe. This also adds to the groundwater. Image by USGS (public domain).

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5.4.1: Water Usage

Freshwater supply is one of the most important ecosystem services. In 2014, global water consumption was 3999 km^3 per year (over 1,000 trillion gallons!). The greatest use of this water is for irrigation in agriculture, but significant quantities of water are also extracted for public and municipal use, as well as industrial applications and power generation (figure 5.4.1.a).

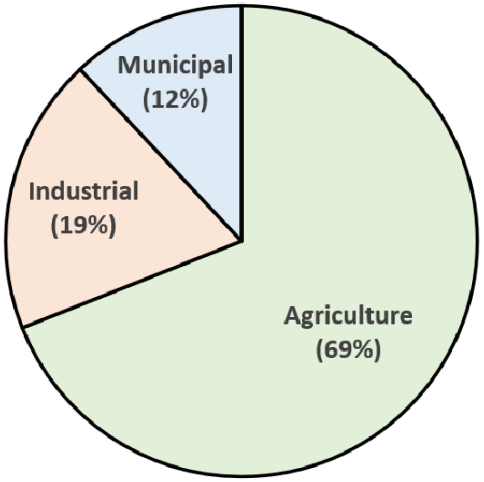


Figure 5.4.1.a: Global water usage by sector. Municipal refers to domestic use, such as by local businesses and households. Data from FAO. Image by Melissa Ha (CC-BY-NC).

Humans require only about 1 gallon per day to survive, but a typical person in a U.S. household uses approximately 80-100 gallons per day, which includes cooking, washing dishes and clothes, flushing the toilet, and bathing. Additionally, we rely on the food, energy, and mineral resources, which all require water to produce. For example, approximately three gallons are needed to produce a tomato, 150 gallons for a loaf of bread, and 1,600 for a pound of beef. (You can learn more about the water footprint of different foods using this interactive website.) Figure 5.4.1.d compares water requirements for different crops. Twenty-one gallons are needed to produce one kilowatt-hour (kWh) of electricity from a traditional power plant (about 1 kWh is needed to heat an oven for 30 minutes), and one ton of steel consumes about 63,000 gallons of water. The **water demand** of an area is a function of the population and other uses of water.

In the United States, 281 billion gallons of water were withdrawn per day in 2015, of which 82 billion gallons are fresh groundwater (figure 5.4.1.b). The state of California accounts for 9% of national water withdrawal (figure 5.4.1.c).

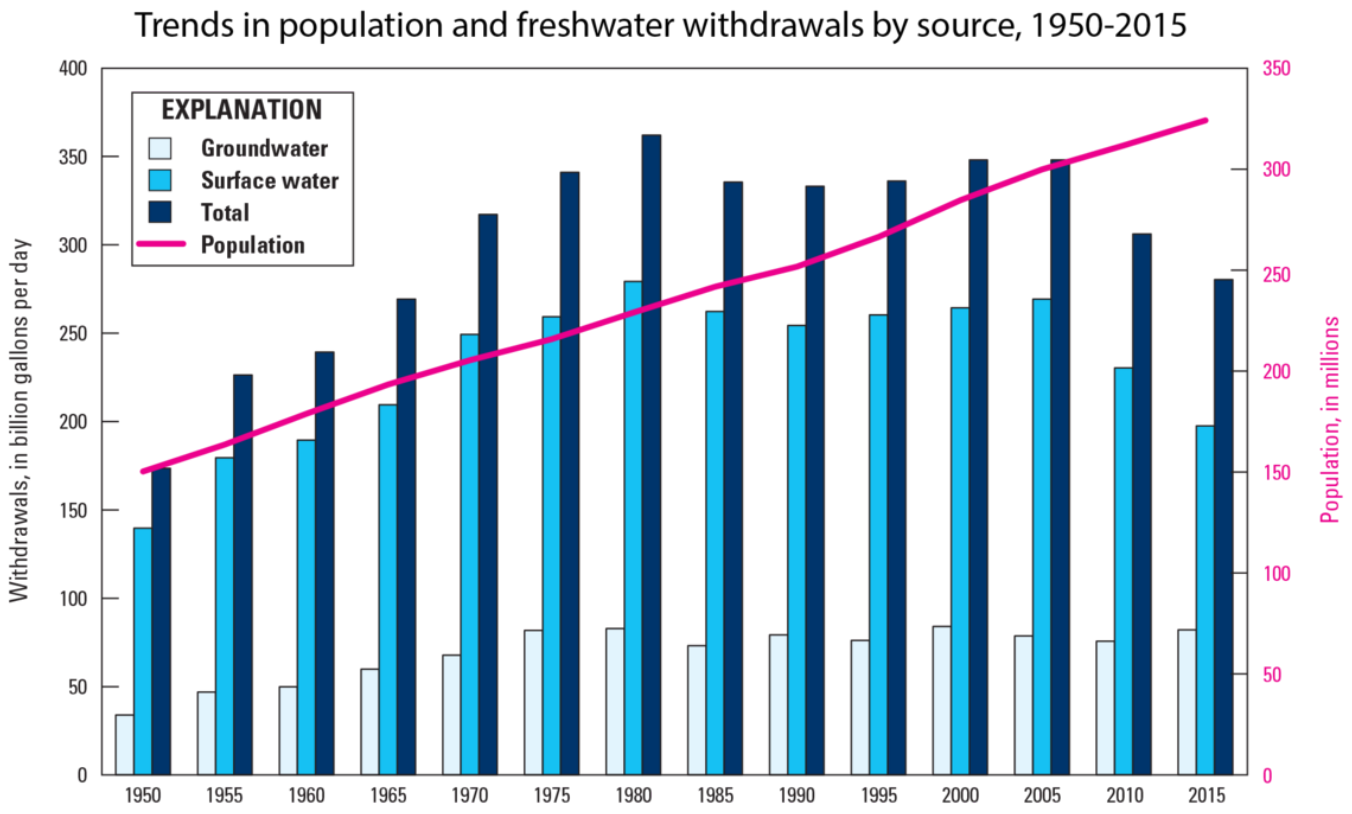


Figure 5.4.1.*b*: Average daily freshwater withdrawals (in billion gallons per day, left y-axis) over time (x-axis) in the United States. Light blue bars (left) represent groundwater withdrawals, medium blue (middle) represents withdrawals from surface water, and dark blue bars (right) represent total withdrawals in billions of gallons per day. In 1950, total withdrawals were around 170 billion gallons per day. This gradually increased until 1980 at just over 350 billion gallons per day. In 1985, total withdrawals dropped to around 325 billion gallons and stayed relatively constant until decreasing in 2010. In 2015, total withdrawals were around 260 billion gallons. Most of the changes in withdrawals overtime were due to changes in surface water withdrawals rather than groundwater withdrawals. Surface water withdrawals have generally been 2-3 times greater than groundwater withdrawals. The pink line represents the United States population size in millions (right y-axis), which has increased from roughly 170 million in 1950 to about 325 million in 2015. Image by USGS (public domain).

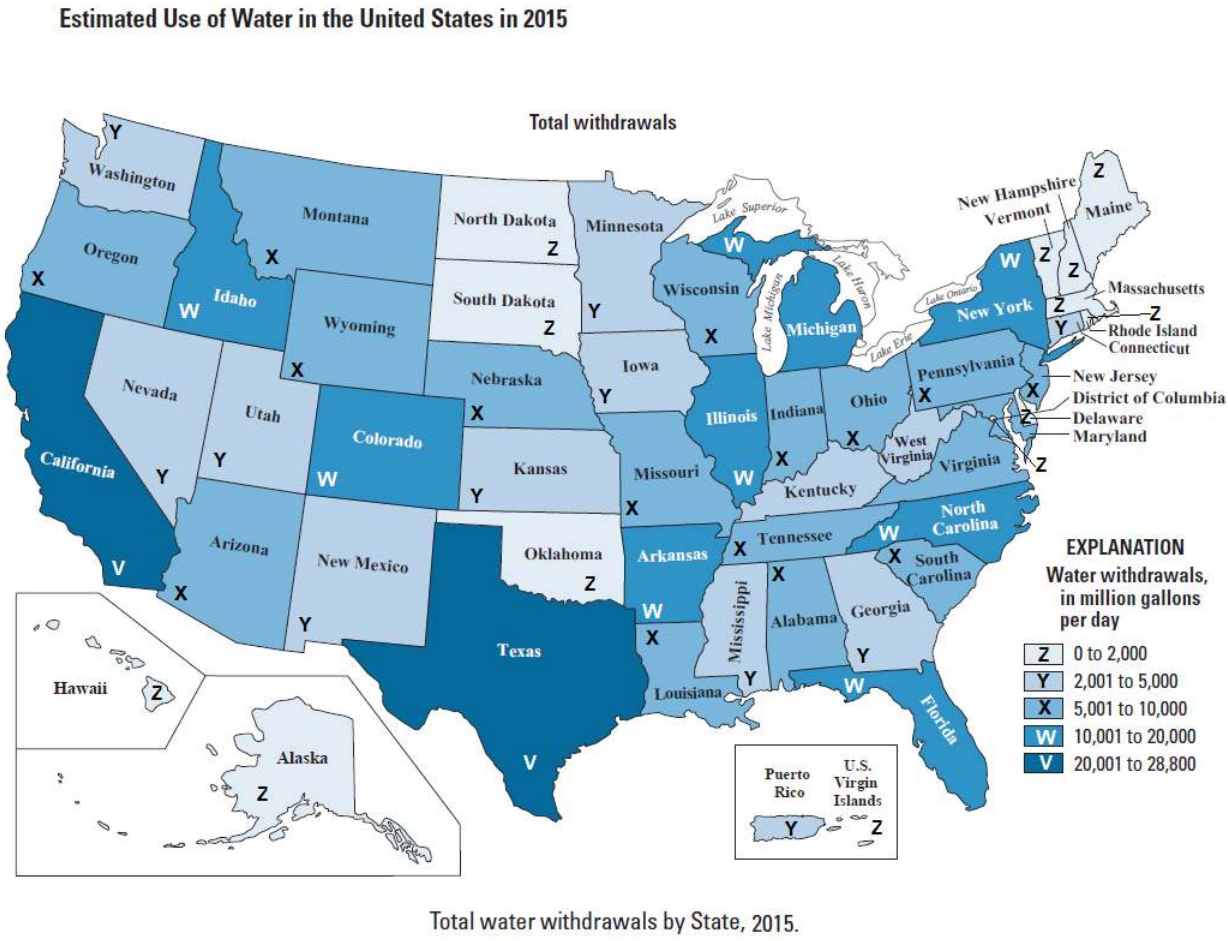


Figure 5.4.1.*c*: Total water withdrawals by state in 2015. The lightest blue (Z) indicates 0-2,000 million gallons per day, and the darkest blue (V) indicates 20,001-28,800 million gallons per day. California and Texas consume the most water, and Alaska, Hawaii, the Dakotas, Oklahoma, and some New England states consume the least. Image modified from USGS (public domain).

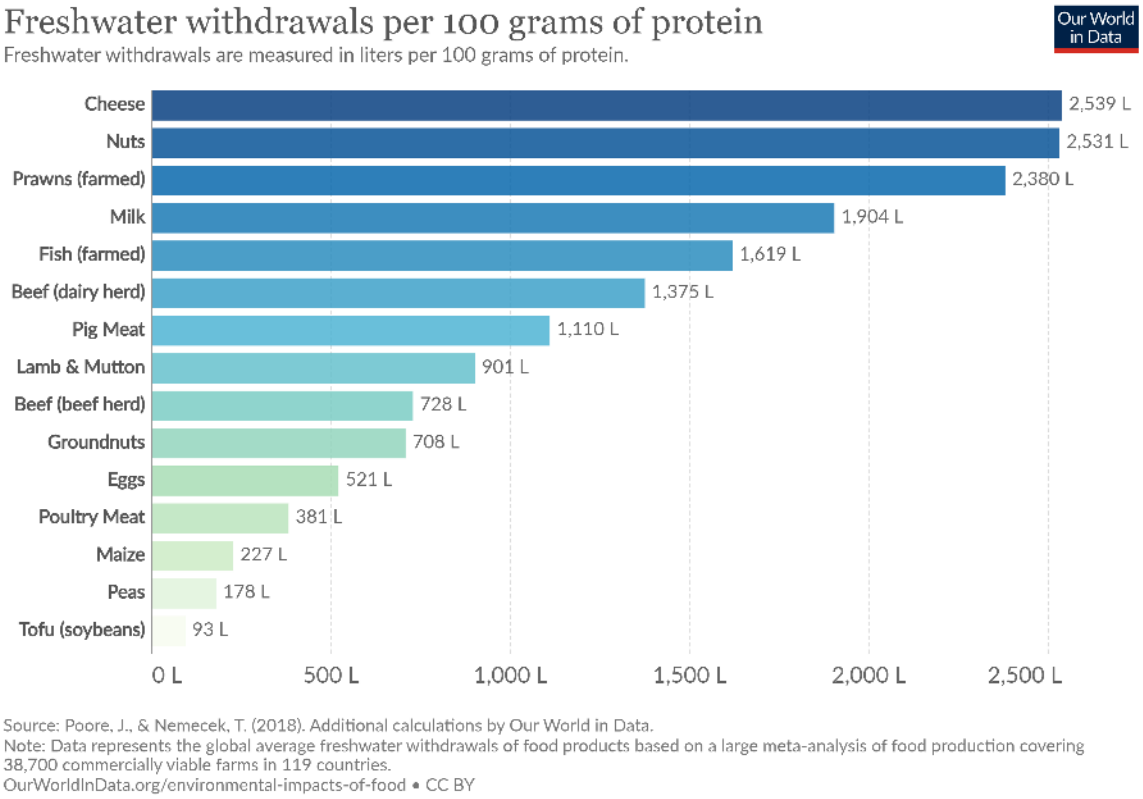


Figure 5.4.1.d: Water use by various crops measured per 100 grams of protein. (Our World in Data from Poore and Nemecek, CC-BY)

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5.4.2: Water Scarcity and Solutions

One of the most important environmental goals is to provide clean water to all people. Fortunately, water is a renewable resource and is difficult to destroy. Evaporation and precipitation combine to replenish our fresh water supply constantly; however, water availability is complicated by its uneven distribution over the Earth. In addition, solutions to water scarcity create their own set of environmental problems including habitat fragmentation and freshwater ecosystem loss. Climate change will also challenge our current water management infrastructure as water distribution changes and short term weather events intensify. The IUCN estimates a 50% increase in water demand by the human population by 2030. Freshwater biodivesity has declined 80% since 1970 (IUCN 2021).

Water Scarcity

The **water crisis** refers to a global situation where people in many areas lack access to sufficient water, clean water, or both. Arid climate and densely populated areas have combined in many parts of the world to create water shortages, which are projected to worsen in the coming years due to population growth, water overuse, water pollution, and climate change. Specifically, climate change shifts precipitation patterns and causes the snow pack that recharges rivers to melt earlier in the year. Furthermore, rising sea levels associated with climate change worsen saltwater intrusion.

Water scarcity refers to water shortages, which can be physical or economic (figure 5.4.2.*a*). **Physical water scarcity** is the lack of sufficient water resources in an area; that is, water is depleted more quickly than it is replenished. Unpredictable precipitation patterns associated with climate change, which increase the risk of flooding and drought, exacerbates physical water scarcity. **Economic water scarcity** occurs when people cannot afford access to water. The United Nations estimates that over half of the global population faces water scarcity for one or more months of the year (see The Sustainable Development Goals Report 2019). According to the World Health Organization and UNICEF, 785 million people lack access to even a basic drinking water service (see Drinking Water) and two billion people lack access to improved sanitation as simple as a pit latrine (see Sanitation), and three billion people lack a facility to wash their hands (see Hand Hygiene for All). As a result, nearly 829,000 people die every year from diarrheal diseases, and 297,000 of those deaths occur among children under the age of five (see Drinking Water).

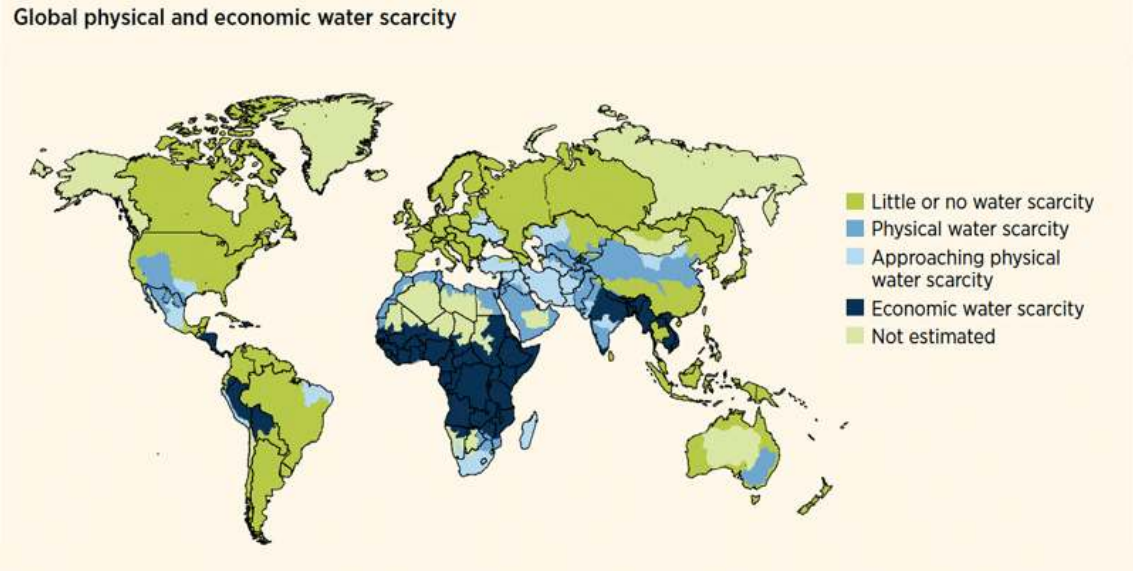


Figure 5.4.2.*a*: Regions facing or approaching water scarcity in 2012. Physical water stress occurs in the southwestern United States, the Middle East, North Africa, southern India, and southeast Australia. Economic water stress occurs in Central and East Africa, western India, and Southeast Asia. Image by World Water Assessment Programme (WWAP; public domain).

Solutions for Addressing Water Shortages

While some human activities have exacerbated the water crisis, humans have also developed technologies to better acquire or conserve freshwater. Solutions to addressing water shortages include dams and reservoirs, rainwater harvesting, aqueducts,

desalination, water reuse, and water conservation.

Dams and Reservoirs

Reservoirs (artificial lakes) that form behind dams in rivers can collect water during wet times and store it for use during dry spells (figure 5.4.2.*b*). They also can be used for urban water supplies. Other benefits of dams and reservoirs are hydroelectricity, flood control, and recreation. Some of the drawbacks are evaporative loss of water in arid climates and downstream river channel erosion. Additionally, dams reduce water flow downstream, which could lead to political conflicts when rivers span states or countries.

The negative ecosystem impacts of dams are another major drawback. For example, dams change a river to a lake habitat and interfere with migration and spawning of fish. Furthermore, warming of the surface water in the reservior influences the temperature of the water downstream, impacting the fish and aquatic invertebrates that are adapted to colder water. Dams also trap sediments that would otherwise continue to flow down the river, creating habitat and supplying nutrietns downstream.



Figure 5.4.2.*b*: The Hoover Dam on the Colorado River in Nevada. Behind the dam is Lake Mead, the largest reservoir in the United States. Image by Dsimic (CC-BY-SA).

Rainwater Harvesting

Rainwater harvesting involves catching and storing rainwater before it reaches the ground. Figure 5.4.2.*c* shows a complex rainwater harvesting system (rain water capture system) proposed for federal buildings, but smaller, simpler systems (sometimes called rain barrels) can be used by individual homeowners (figure 5.4.2.*d*).

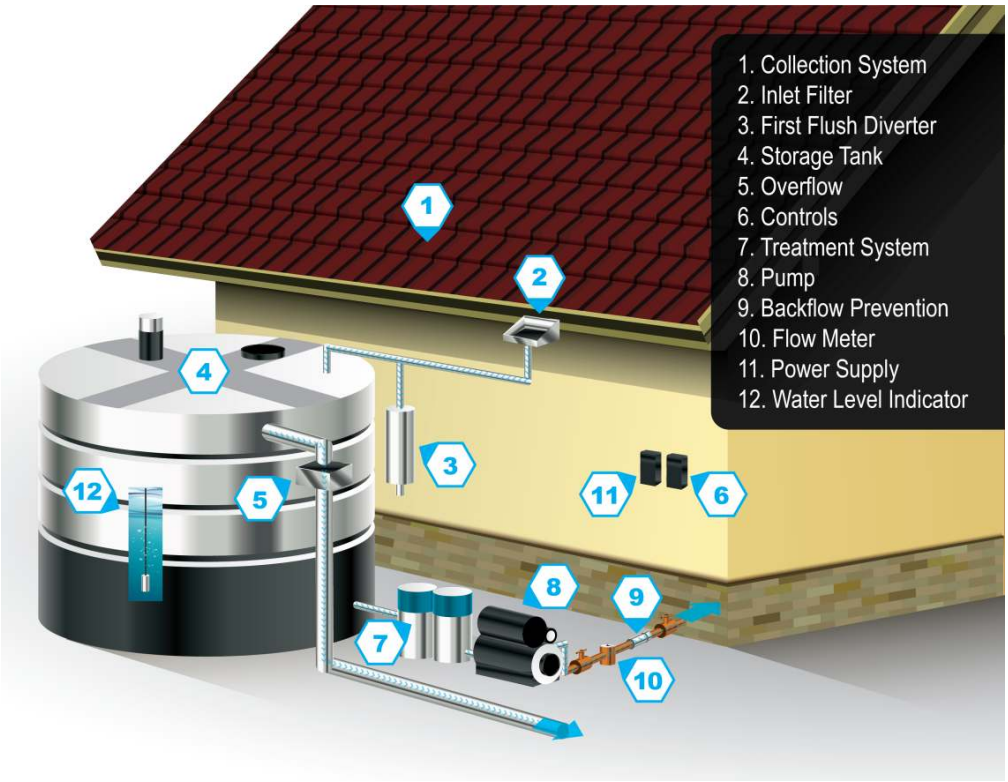


Figure 5.4.2.*c*: The components of a rainwater harvesting system include (1) the collection system consisting of the roof surface and gutters that capture rain water and send it to (2) the inlet filter, a screen that catches large debris. (3) The first flush diverter removes debris not captured by the inlet filter from the initial stream of rainwater. (4) The storage tank is composed of food-grade polyester resin material approved by the U.S. Food and Drug Administration (FDA), which is green in color and helps to reduce bacterial growth. (5) The overflow is a drainage spout that releases excess water if the storage tank is full. The (6) control system monitors the water level and filtration system, and the (7) treatment system is responsible for filtration and disinfection, treating water until it is potable (safe to drink). The (8) pump moves water through the system to where it will be used, and the (9) backflow preventer ensures that water cannot flow backwards through the system in cases of low water pressure (when the storage tank is low). (10) The flow meter (with data logger) measure water production. The (11) power supply may rely on conventional energy sources or solar energy, and the (12) water level indicator monitors the water level in the storage tank. Caption modified from and image from Office of Energy Efficiency and Renewable Energy, Department of Energy (public domain).



Figure 5.4.2.*d*: A rain barrel is a simple rainwater harvesting system. Homeowners commonly use the stored water to irrigate their gardens. Image by Walton LaVonda, USFWS (public domain).

Aqueducts

Aqueducts can move water from where it is plentiful to where it is needed. Aqueducts can be controversial and politically difficult especially if the water transfer distances are large. One drawback is the water diversion can cause drought in the area from where the water is drawn. For example, Owens Lake and Mono Lake in central California began to disappear after their river flow was diverted to the Los Angeles aqueduct (figure 5.4.2.*e*). Without water supply, Owens Lake dried and became a major source of particulate matter, polluting the air during dust storms (see Air Pollution). Owens Lake remains almost completely dry, but Mono Lake has recovered more significantly due to legal intervention. Learn more about the Los Angeles Aqueduct here.



Figure 5.4.2.*e*: The Los Angeles Aqueduct diverts the flow of several eastern California rivers to the city of Los Angeles. Image by Los Angeles (CC-BY-SA).

Desalination

One method that can actually increase the amount of freshwater on Earth is **desalination**, which involves removing dissolved salt and minerals from seawater or saline groundwater (figure 5.4.2.f). An advantage of this approach is that there is a virtually unlimited supply of saltwater. There are several ways to desalinate seawater including boiling, filtration, electrodialysis (applying an electric current to removed the ions which comprise salts), and reverse osmosis (figure 5.4.2.g). All of these procedures are moderately to very expensive and require considerable energy input, making the water produced much more expensive than freshwater from conventional sources. In addition, the process creates highly saline wastewater, which must be disposed of and creates significant environmental impact. Desalination is most common in the Middle East, where energy from oil is abundant but water is scarce.



Figure 5.4.2.f: Port Stanvac Desalination Plant under construction in South Australia. Image by Vmenkov (CC-BY-SA).

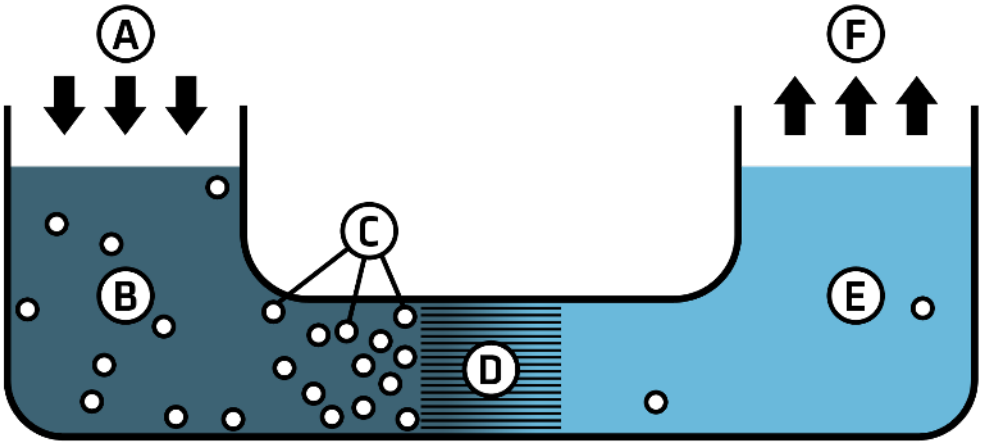


Figure 5.4.2.g: Reverse osmosis is one method of desalination. In this process, pressure (A) is applied to salt water, which contains ions (charged atoms or molecules) and other contaminants (C). The water is forced through a semipermeable membrane (D), through which the contaminants cannot pass. Clean freshwater that is safe to drink (E) is then distributed (F). Image by Colby Fisher (CC-BY-SA).

Water Reuse (Water Recycling)

Water recycling refers to reusing water for appropriate purposes such as agriculture, municipal water supply, industrial processes, and environmental restoration (figure 5.4.2.h). This could occur at the scale of a single household, for example, installing plumbing

that reroutes water drained from the sink to flush the toilet. Water recycling can also occur at large scales. For example, wastewater from the sewage system is regularly treated to an extent, but it can be treated further to produce **potable water** (which is safe to drink) and then pumped into depleted aquifers. This approach limits saltwater intrusion of aquifers near the coast and reduces dependence on precipitation and subsequent infiltration to recharge aquifers. Orange County Water District in California employed this system following an information campaign to explain the purification process and ensure public confidence in the safety of the treated wastewater.

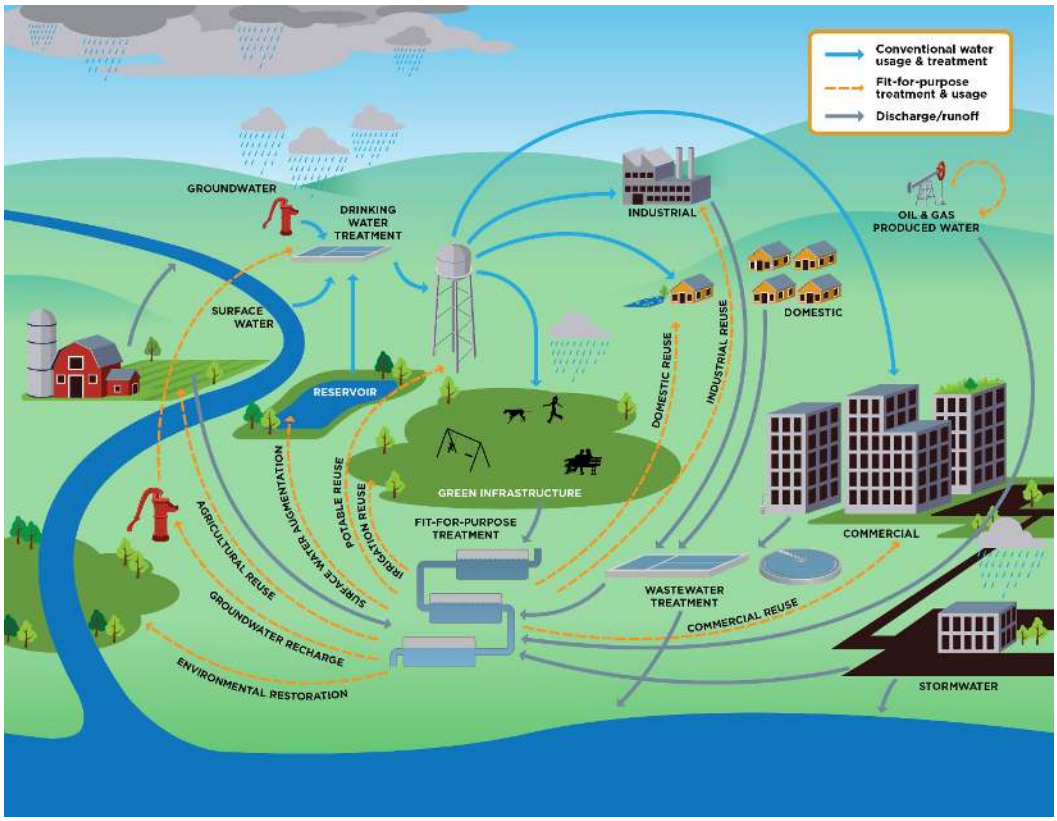


Figure 5.4.2.*h*: Flowchart of water reuse. Surface water, groundwater, and water from reservoirs undergoes drinking water treatment. From there, it serves commercial, industrial, and domestic purposes and supports green infrastructure. Used water is treated to the extent needed for its purpose (fit-for-purpose treatment). Fit-for-purpose treatment and usage include environmental restoration, ground water recharge, agricultural reuse, surface water augmentation, portable reuse, irrigation reuse, domestic reuse, industrial reuse, and commercial reuse. Discharge from industrial, domestic, and commercial buildings is processed through wastewater treatment. Image by EPA (public domain).

Water Conservation

Water conservation refers to using less water and using it more efficiently. Around the home, conservation can involve both water-saving technologies and behavioral decisions. Examples of water-saving technologies include high-efficiency clothes washers and low-flow showers and toilets. Water-conserving behaviors include turning off the water while you brush your teeth, taking shorter showers and showers instead of baths, and fixing leaky faucets. A dishwasher uses less water than washing dishes by hand, particularly the dishwasher is only run when it is full. Similarly, running fewer, larger loads of laundry conserves water relative to more frequent, smaller loads. Choosing foods with a low water footprint (like eggs) over those with a high water footprint (like beef) can also conserve water.

Gardening offers several water-saving opportunities. If you live in a dry climate, consider growing only native, drought-tolerant vegetation, which requires little irrigation (figure 5.4.2.*h*). When you do irrigate your garden, do so only as needed and early in the morning, when less water will be lost to evaporation. Drip systems assist in delivering only the needed amount of water in a way that minimizes evaporation. These strategies can also be applied at large scales in agriculture, which is extremely important considering the high agricultural demands on our water supply relative to municipal use. Water conservation strategies in

agriculture include growing crops in areas where the natural rainfall can support them, more efficient irrigation systems such as drip systems, and no-till farming, which reduces evaporative losses by covering the soil.



Figure 5.4.2.*i*: Using water-efficient plants and irrigation not only looks beautiful, but saves resources and supports biodiversity and natural pollinators. Image and caption from CA Department of Water Resources (public domain).

Bottled water is not a sustainable solution to the water crisis. Bottled water is not necessarily any safer than the U.S. public water supply, it costs on average about 700 times more than U.S. tap water, and every year it uses approximately 200 billion plastic and glass bottles that have a relatively low rate of recycling. Compared to tap water, it uses much more energy, mainly in bottle manufacturing and long-distance transportation. (Purchasing a water filter is a more sustainable solution than bottled water if you do not like the taste of tap water.)

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5.5: Soils

Soil is the outer loose layer that covers the surface of Earth. Soil quality is a major determinant, along with climate, of plant distribution and growth. Soil quality depends not only on the chemical composition of the soil, but also climate, topography, and organisms living in the soil. In agriculture, the history of the soil, such as the cultivating practices and previous crops, modify the characteristics and fertility of that soil.

Importance of Soil

Soil is important to our society primarily because it provides the foundation of agriculture and forestry. Soil plays a key role in plant growth. Beneficial aspects to plants include providing physical support, water, heat, nutrients, and oxygen. Mineral nutrients from the soil can dissolve in water and then become available to plants. Through their roots, plants absorb water and minerals (e.g., nitrates, phosphates, potassium, copper, zinc). With these and carbon dioxide acquired during photosynthesis, plants produce carbohydrates, proteins, lipids, nucleic acids, and the vitamins, on which consumers depend.

Soil plays a role in nearly all biogeochemical cycles on the Earth's surface. Global cycling of key elements such as carbon (C), nitrogen (N), phosphorous (P), and sulfur (S) all pass through soil. In the hydrologic (water) cycle, soil helps to mediate **infiltration** (percolating) from the surface into the groundwater. Microorganisms living in soil can also be important components of biogeochemical cycles through the action of decomposition and other processes such as nitrogen fixation.

Several elements are considered essential for plant growth. Carbon (C), hydrogen (H), and oxygen (O) are required in large quantities, but they are not absorbed as mineral nutrients from the soil. Plants obtain carbon from carbon dioxide in the atmosphere and hydrogen from the water absorbed by the roots. Oxygen atoms come from carbon dioxide acquired during and gaseous oxygen in the atmosphere (acquire through aerobic cellular respiration) as well as water. Of the mineral nutrients absorbed from the soil, **macronutrients**, including nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), sulfur (S), and silicon (Si) are needed by plants in significant quantities. **Micronutrients** are essential elements that are needed only in small quantities, but can still be limiting to plant growth since these nutrients are not so abundant in nature. Micronutrients include chlorine (Cl), iron (Fe), boron (B), manganese (Mn), sodium (Na), zinc (Zn), copper (Cu), nickel (Ni), and molybdenum (Mo). There are some other elements that tend to aid plant growth but are not absolutely essential.

Although many aspects of soil are beneficial to plants, excessively high levels of trace metals (either naturally occurring or added by humans) or applied herbicides can be toxic to some plants (figure $5.5.a$).



Figure $5.5.a$: These native plants are affected by herbicides that were used to kill nearby weeds. Image by Matt Lavin (CC-BY-SA).

Micronutrients and macronutrients are desirable in particular concentrations and can be detrimental to plant growth when concentrations in soil solution are either too low (limiting) or too high (toxicity). Mineral nutrients are useful to plants only if they are in an extractable form in soil solutions, such as a dissolved ion rather than in solid mineral. Many nutrients move through the soil and into the root system as a result of concentration gradients, moving by diffusion from high to low concentrations. However, some nutrients are selectively absorbed by the root membranes, enabling concentrations to become higher inside the plant than in the soil.

An important factor affecting soil fertility is soil **pH** (the negative log of the hydrogen ion concentration). Soil pH is a measure of the acidity or alkalinity of the soil solution. On the pH scale (0 to 14) a value of seven represents a neutral solution; a value less than seven represents an **acidic** solution and a value greater than seven represents an **alkaline** solution (figure 5.5.*b*). Soil pH affects the health of microorganisms in the soil and controls the availability of nutrients in the soil solution. Strongly acidic soils (less than 5.5) hinder the growth of bacteria that decompose organic matter in the soil. This results in a buildup of organic matter that has yet to be decomposed, which leaves important nutrients such as nitrogen in forms that are unusable by plants. Soil pH also affects the solubility of nutrient-bearing minerals. This is important because the nutrients must be dissolved in solution for plants to assimilate them through their roots. Most minerals are more soluble in slightly acidic soils than in neutral or slightly alkaline soils. Strongly acid soils (pH four to five), though, can result in high concentrations of aluminum, iron and manganese in the soil solution, which may inhibit the growth of some plants.

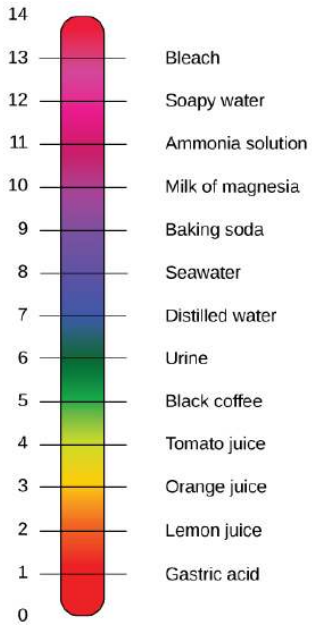


Figure 5.5.*b*: The pH scale measures the amount of hydrogen ions (H^+) in a substance. This shows the pH of common household solutions. Those with a pH greater than 7 are basic (alkaline), and those with a pH less than 7 are acidic. The solutions from high to low pH are bleach (13), soapy water (12), ammonia solution (11), milk of magnesia (10), baking soda (9), seawater (8), distilled water (7), urine (6), black coffee (5), tomato juice (4), orange juice (3), lemon juice (2), and gastric acid (1). Note that pH values are approximate. Image and caption (modified) from OpenStax/Edward Stevens (CC-BY). Access for free at openstax.org.

Several factors determine soil pH. Organic material in soil decreases pH to an extent, but it also acts as a **buffer**, limiting changes in pH. Climate is also important, with high amounts of rainfall increasing leaching and lowering pH. Some types of parent material, such as those high in silicon, decrease pH, while others, such as limestone increase pH.

Soil Composition

Soil consists of organic matter (about 5%), inorganic mineral matter (40-45% of soil volume), water (about 25%) and air (about 25%). The amount of each of the four major components of soil depends on the amount of vegetation, soil compaction, and water present in the soil.

The organic material consists of dead organisms in various stages of decomposition. It is dark-colored because it contains **humus**, partially decayed matter containing organic acids. Humus enriches the soil with nutrients, gives the soil a loose texture that holds

water, and allows air to diffuse through it. Oxygen is important for plant roots and many inhabitants of the soil. The organic component of soil serves as a cementing agent, returns nutrients to the plant, allows soil to store moisture, makes soil tillable for farming, and provides energy for soil microorganisms. Most soil microorganisms—bacteria, algae, or fungi—are dormant in dry soil, but become active once moisture is available.

The inorganic material of soil consists of rock, slowly broken down into smaller particles that vary in size. Soil particles that are 100 µm to 2 mm in diameter are **sand**. (A **micrometer**, µm, 10^{-6} m, or a millionth of a meter.) Soil particles between 2 and 100 µm are called **silt**, and even smaller particles, less than 2 µm in diameter, are called **clay**.

Soil should ideally contain 50 percent solid material and 50 percent pore space (figure 5.5.*c*). **Pore space** refers to the gaps in between soil particles. The larger the soil particles, the larger the pore spaces. Water can quickly pass through large pore spaces, so soils high in sand drain easily. Smaller soil particles have more surface area relative to volume and produce narrow pore spaces. Water clings to these surfaces, and soils high in clay thus retain water. (Clay is also negatively charged, which attracts water.) About one-half of the pore space should contain water, and the other half should contain air.

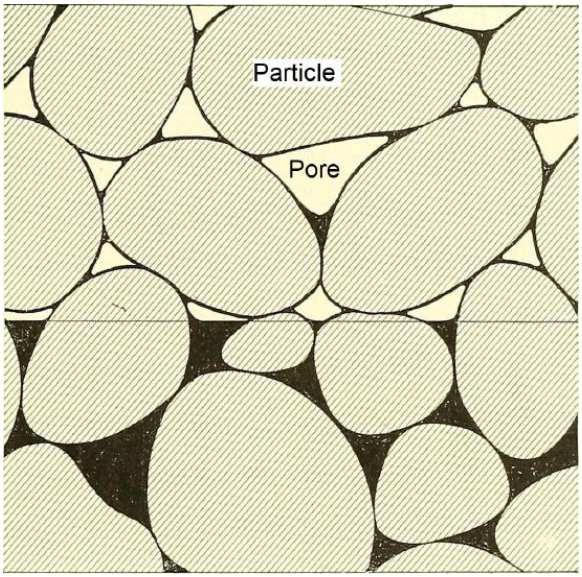


Figure 5.5.*c*: Soil particles and the pore spaces in between them. The black shading represents water, which fills the pore spaces in the lower portion of the soil and clings to narrow portions of pore space in the top portion of the soil. Image from "Forest physiography; physiography of the United States and principles of soils in relation to forestry" (public domain).

Soil texture is based on percentages of sand, silt, and clay (figure 5.5.*d*). Soils that have a high percentage of one particle size are named after that particle (a clay soil has a high percentage of clay). Other soils have a mixture of two particle sizes and very little of the third size. For example, silty clay has roughly 50% clay and 50% silt while sandy clay has 50-60% sand and 35-50% clay. Some soils have no dominant particle size and contain a mixture of sand, silt, and humus. These soils are called **loams**, and they are optimal for agriculture. A medium loam has roughly 40% sand, 40% silt, and 20% clay. Larger particles (sand) facilitate drainage, and small particles (clay) facilitate water retention, so loam soils both have good drainage and can remain moist. Soils that deviate slightly from a medium loam include loamy sand, sandy loam, sandy clay loam, clay loam, silty clay loam, and silty loam.

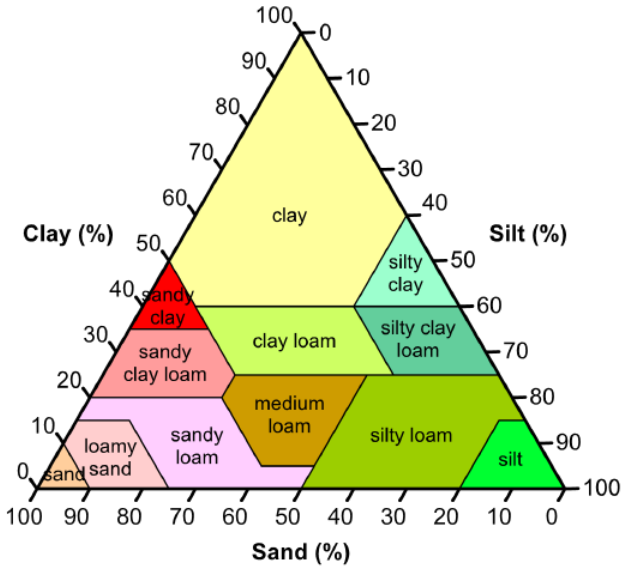


Figure 5.5.*d*: A soil texture triangle is used to determine the soil texture based on the percentages of sand, silt, and clay. The left axis represents the percentage of clay. The right axis represents the percentage of silt. The bottom axis represents the percentage of sand. Most soils that contain more than 40% are classified as clays. Exceptions are silty clays, which contain 40-60% clay and 40-60% silt. Another exception are sandy clays, which contain 35-50% clay and 50-70% sand. Clay loams and silty clay loams contain 25-40% clay. Clay loams contain 20-60% silt, and silty clay loams contain 60-75% silt. Sandy clay loams contain 20-35% clay and 50-80% sand. Medium loams contain 5-25% clay, 20-50% silt, and 30-55% sand. Soils with more than 50% silt and no more than 25% clay are either silty loams or silts. Silts have 80-100% silt and no more than 15% clay. Sand have 90-100% sand. Loamy sands have 75-90% sand and no more than 15% clay. A soil with a composition that does not fit into the already described categories would be a sandy loam. To determine the soil texture, first find the percentage of clay and trace a line horizontally to the right. At the same time, find the percentage of silt and trace a line diagonally (down and to the left, parallel to the clay axis). The two lines will meet at the correct soil type. For example, traced lines from 20% clay and 40% silt intersect at the medium loam category. To confirm, trace a diagonal line (down and to the right, parallel to the sit axis) from this point to the sand axis. This line cross the axis at 40%. In summary, a line can be traced from each axis that is parallel to axis that is counterclockwise of it. Image by Richard Wheeler/Zephyris at English Wikipedia (CC-BY-SA).

Organic Versus Mineral Soils

Soils can be divided into two groups based on how they form. **Organic soils** are those that are formed from sedimentation and often contain more than 30% organic matter. They form when organic matter, such as leaf litter, is deposited more quickly than it can be decomposed (figure 5.5.*e*). **Mineral soils** are formed from the weathering of rocks, typically contain no more than 30% organic matter, and are primarily composed of inorganic material. **Weathering** occurs when biological, physical, and chemical processes, such as erosion, leaching, or high temperatures, break down rocks.



Figure 5.5.*e*): Decomposition of organic material occurs very slowly in this acidic bog. The organic material accumulates, which is characteristic of organic soils. Image by William L. Farr (CC-BY-SA).

Soil Horizons

Soil distribution is not uniform because its formation results in the production of layers; together, the vertical section of a soil is called the **soil profile**. Within the soil profile, soil scientists define zones called horizons. A **horizon** is a soil layer with distinct physical and chemical properties that differ from those of other layers.

The soil profile has four distinct layers: 1) O horizon; 2) A horizon; 3) B horizon and 4) C horizon (figure 5.5.*f*-g). Upper horizons (labeled as the A and O horizons) are richer in organic material and so are important in plant growth, while deeper layers (such as the B and C horizons) retain more of the original features of the bedrock below. Some soils may have additional layers (like the E horizon, figure 5.5.*f*), or lack one of these layers. The thickness of the layers is also variable, and depends on the factors that influence soil formation. In general, immature soils may have O, A, and C horizons, whereas mature soils may display all of these, plus additional layers.

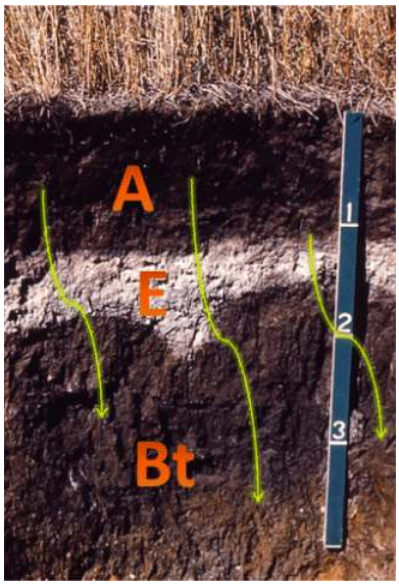


Figure 5.5.*f*): Soil Profile. Photograph shows a soil profile from South Dakota revealing three horizons. The A horizon (topsoil) is dark brown and extend about 1 foot. Below it is the white E (eluviated) horizon, which is about 6 inches thick. The B horizon (subsoil, labeled Bt) is the medium brown and the lowest visible layer The yellow arrows symbolize translocation of fine clays to the B horizon. The scale is in feet. Source: University of Idaho and modified by D. Grimley.

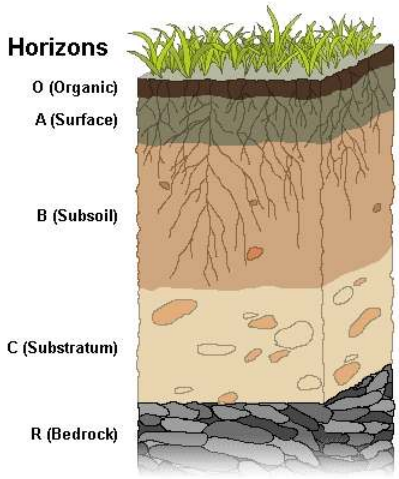


Figure 5.5.g): This image shows the different horizons, or layers, in soil. Vegetation grows at the surface. The top, deep brown layer is the O (organic) horizon. Below this is the gray A horizon (topsoil, or surface). Next is the light brown B horizon (subsoil). The C horizon (substratum, or soil base) is tan and includes larger pieces of rocks. The gray bedrock is the deepest layer. The E (eluviated) horizon that is sometimes found between the A and B horizons is absent here. This work by Wilsonbiggs is licensed under CC BY-SA 4.0

O horizon

The very top of the **O horizon** consists of partially decayed organic debris like leaves. This horizon is usually dark in color because of humus.

A horizon

The **A horizon** (topsoil) consists of a mixture of organic material with inorganic products of weathering, and it is therefore the beginning of true mineral soil. In this area, rainwater percolates through the soil and carries materials from the surface. The A horizon may be only 5 cm (2 in.), or it may over a meter. For instance, river deltas like the Mississippi River delta have deep layers of topsoil. Microbial processes occur in the top soil, and this horizon supports plant growth. Many organisms, such as earthworms and insects live among the plant roots in this horizon.

B horizon

The **B horizon** (subsoil) consists of small particles that have moved downward, resulting in a dense layer in the soil. In some soils, the B horizon contains nodules or a layer of calcium carbonate. The subsoil is usually lighter in color than topsoil and often contains an accumulation of minerals.

C horizon

The **C horizon** (soil base), includes the **parent material**, the organic and inorganic substances from which soils form. Weathering parent material represents the first steps in the chemical breakdown of rock into soil. Often the weathered parent material is underlain by the parent material itself, although in some places it has been carried from another location by wind, water, or glaciers. Beneath the C horizon lies bedrock. The chemical nature of the parent material, whether granite, limestone, or sandstone, for example, has a great influence on the fertility of the soil derived from it.

Factors Affecting Soil Formation and Composition

The fundamental factors that affect soil genesis can be categorized into five elements: climate, organisms, topography, parent material, and time. One could say that the relief, climate, and organisms dictate the local soil environment and act together to cause weathering and mixing of the soil parent material over time.

Climate

The role of climate in soil development includes aspects of temperature and precipitation. Soils in very cold areas with permafrost conditions (such as the arctic tundra) tend to be shallow and weakly developed due to the short growing season. In warm, tropical climates, soils tend to be thicker (but lacking in organic matter), with extensive leaching and mineral alteration. In such climates,

organic matter decomposition and chemical weathering occur at an accelerated rate. The presence of moisture and nutrients from weathering will also promote biological activity: a key component of a quality soil. See the Biomes chapter for more details about the effect of climate on soils.

Ancient soils, sometimes buried and preserved in the subsurface, are referred to as **paleosols** (figure 5.5.h) and reflect past climatic and environmental conditions.

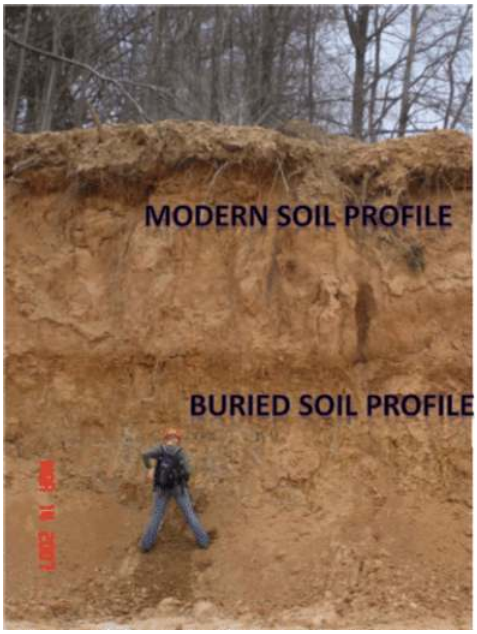


Figure 5.5.h: Modern versus Buried Soil Profiles. A buried soil profile, or paleosol (above geologist ‘s head), represents soil development during the last interglacial period. A modern soil profile (Alfisol) occurs near the land surface. Source: D. Grimley.

Organisms

The presence of living organisms in the soil (**soil biota**) greatly affects soil formation and structure. A diversity of animals are found in the soil such as nematodes, spiders, insects, centipedes, millipedes, pillbugs, slugs, and earthworms (figure 5.5.i). The soil also contains microorganisms like bacteria, archaea, fungi, and "protists". Animals and microorganisms can produce pores and crevices, and plant roots can penetrate into crevices to produce more fragmentation. Additionally, leaves and other material that fall from plants decompose and contribute to soil composition. Microorganisms not only decompose organic matter, but contribute to other processes in nutrient cycles, such as nitrogen fixation.

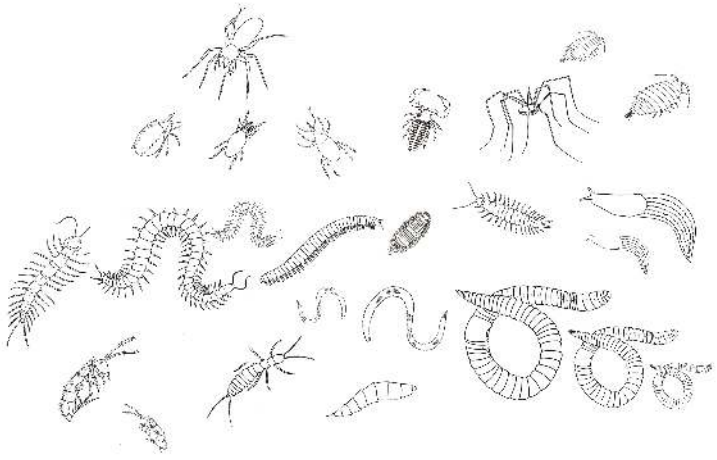


Figure 5.5.i: Illustration of animals commonly found in the soil. Image by Arne Hendriks (CC-BY)

Parent Material

Mineral soils form directly from the weathering of bedrock, the solid rock that lies beneath the soil, and therefore, they have a similar composition to the original rock. Other soils form in materials that came from elsewhere, such as sand and glacial drift. Materials located in the depth of the soil are relatively unchanged compared with the deposited material. Sediments in rivers may have different characteristics, depending on whether the stream moves quickly or slowly. A fast-moving river could have sediments of rocks and sand, whereas a slow-moving river could have fine-textured material, such as clay.

The type of parent material may also affect the rapidity of soil development. Parent materials that are highly weatherable (such as volcanic ash) will transform more quickly into highly developed soils, whereas parent materials that are quartz-rich, for example, will take longer to develop. Parent materials also provide nutrients to plants and can affect soil internal drainage.

Topography

Regional surface features (familiarly called “the lay of the land”) can have a major influence on the characteristics and fertility of a soil. Topography affects water runoff, which strips away parent material and affects plant growth. Soils on steep slopes are more prone to erosion and may be thinner than soils that are on relatively level ground. **Infiltration**, the percolating of water through the soil, is limited in steep soils.

The local topography can have important microclimatic effects. In the northern hemisphere, south-facing slopes are exposed to more direct sunlight angles and are thus warmer and drier than north-facing slopes. The cooler, moister north-facing slopes have a more dynamic plant community and thicker soils because extensive root systems stabilize the soil and reduce erosion (figure 5.5.j).



Figure 5.5.j: A north-facing slope (left) and south-facing slope (right) in the Mediterranean climate (chaparral) of the Santa Monica Mountains, California. Vegetation on the north-facing slope is denser due to cool, moist conditions relative to the south-facing slope. Image by Noah Elhardt (CC-BY).

Time

Time is an important factor in soil formation because soils develop over long periods. Soil formation is a dynamic process. Materials are deposited over time, decompose, and transform into other materials that can be used by living organisms or deposited onto the surface of the soil.

In general, soil profiles tend to become thicker (deeper), more developed, and more altered over time. However, the rate of change is greater for soils in youthful stages of development. The degree of soil alteration and deepening slows with time and at some point, after tens or hundreds of thousands of years, may approach an equilibrium condition where erosion and deepening (removals and additions) become balanced. **Young soils** (< 10,000 years old) are strongly influenced by parent material and typically develop horizons and character rapidly. Over time, as weathering processes deepen, mix, and alter the soil, the parent material becomes less recognizable as chemical, physical, and biological processes take effect. **Moderate age soils** (roughly 10,000 to 500,000 years old) are slowing in profile development and deepening, and may begin to approach equilibrium conditions. **Old soils** (>500,000 years old) have generally reached their limit as far as soil horizonation and physical structure, but may continue to alter chemically or mineralogically.

Soil development is not always continual. Geologic events such as landslides, glacier advance, or the rising of shorelines can rapidly bury soils. Erosion in rivers and shorelines can cause removal or truncation of soils, and wind or flooding slowly deposit sediment that adds to the soil. Animals can mix the soil and sometimes cause **soil regression**, a reversal or "bump in the road" for the normal path of development, and this increases development over time.

Soil Taxonomy

Soils are classified into one of 12 soil orders based on soil horizons, how they form, and their chemical compositions. For example, Mollisols (figure 5.5.*f*), which are found in temperate grasslands, have a thick topsoil rich in organic content. Aridisols, on the other hand, are dry soils that contain calcium carbonate and are found in deserts. Each soil order is further divided into suborders. See USDA's The Twelve Orders of Soil Taxonomy and The Twelve Soil Orders from the University of Idaho for more details.

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5.6: Soil Degradation

Once fertile topsoil is lost, it is not easily replaced. **Soil degradation** refers to deterioration in the quality of the soil and the resultant reduction in its capacity to produce. Soils are degraded primarily by erosion, compaction, and salinization. Such processes often arise from poor soil management during agricultural activities. In extreme cases, soil degradation can lead to **desertification** (conversion of land to desert-like conditions) of croplands and rangelands in semi-arid regions. See the Sustainable Agriculture section for strategies to preserve soil quality (**soil conservation**).

Erosion

Erosion is the biggest cause of soil degradation. Soil productivity is reduced as a result of losses of nutrients, water holding capacity, and organic matter. **Water holding capacity** is a measure of of the soils ability to retain water. The two agents of erosion are wind and water, which act to remove the finer particles from the soil. **Wind erosion** occurs mostly in flat, dry areas and moist, sandy areas along bodies of water. Wind not only removes soil, but also dries and degrades the soil structure. **Water erosion** is the most prevalent type of erosion. It occurs when raindrops splash on the ground and when water moves down slope as a thin film, small streams, or a large stream.

Some amount of soil erosion is a natural process along sloping areas and/or in areas with soft or materials that do not stick together and are susceptible to movement by water, wind, or gravity. For instance, soil material can be mobilized in strong windstorms, along the banks of rivers, in landslides, or by wave action along coastlines. However, human activities such as construction, logging, and off-road vehicle use promote erosion by removing the natural vegetation cover protecting the soil. Agricultural practices such as overgrazing and leaving plowed fields bare for extended periods contribute to farmland erosion. Each year, an estimated two billion metric tons of soil are eroded from farmlands in the United States alone. The soil transported by the erosion processes can also create problems elsewhere (for example, by clogging waterways and filling ditches and low-lying land areas). The areas most vulnerable to soil erosion include locations with thin organic (A and O) horizons and hilly terrains (figure $5.6.a$).

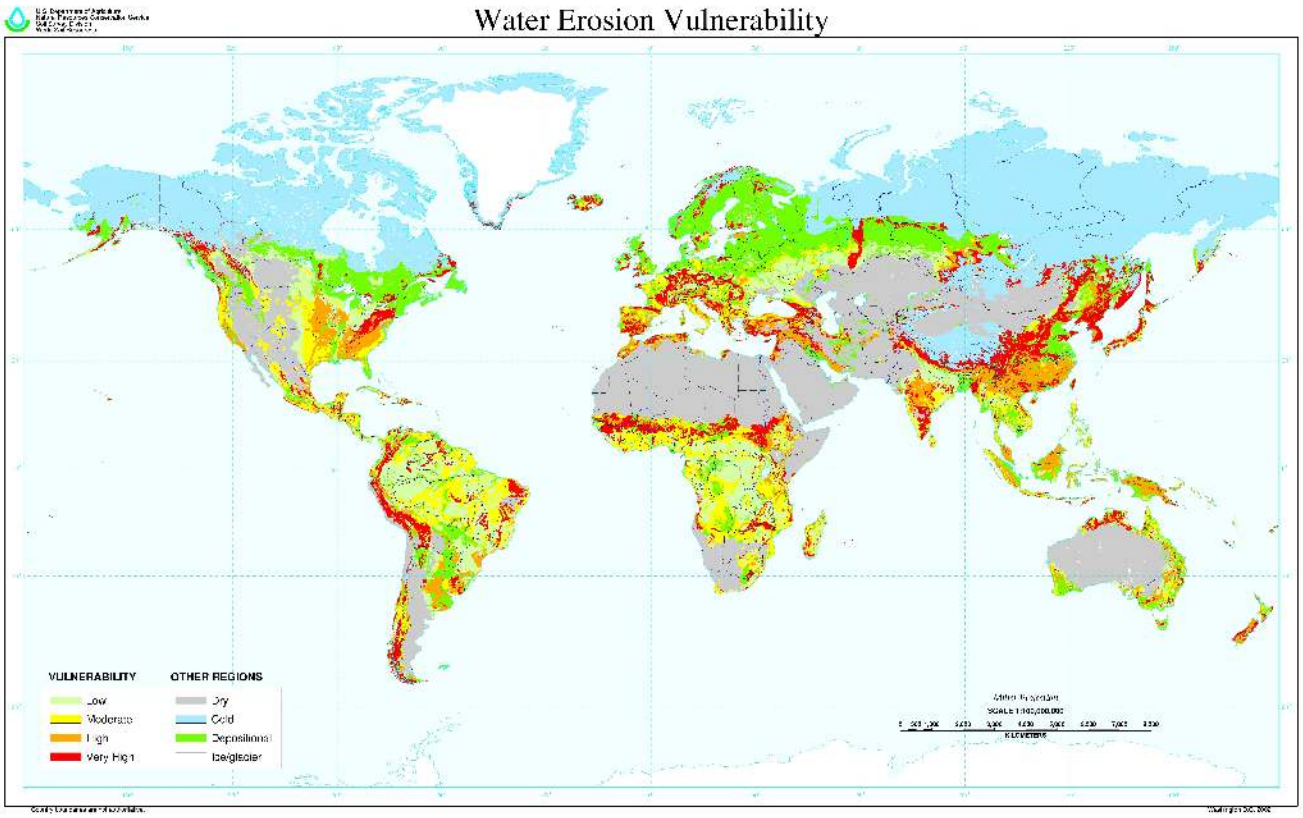


Figure 5.6.*a*: Global map of water erosion vulnerability. There are four levels of vulnerability: very high (red), high (orange), moderate (yellow), and low (light green). Examples of regions with very high vulnerability to erosion by water include the west coast of South America, parts of the eastern United States, regions around the Mediterranean Sea, a strip across western and central Africa, Korean and Japan, Northern Australia, and New Zealand. Examples of regions with low vulnerability include northern South America, the Democratic Republic of Congo, northern India and Nepal, and western Russia. Other regions are labeled as dry (gray), cold (light blue), depositional (bright green), or ice/glacier (white). For example, northern regions are cold and ice/glacier. Much of the western United States, Chile and Argentina, northern Africa, the Middle East, Kazakhstan, Mongolia, and much of Australia are considered dry. The largest depositional area (region where sediments accumulate) is northeastern Europe. Image by USDA-NRCS, Soil Science Division, World Soil Resources (public domain).

Compaction

In modern agricultural practices, heavy machinery is used to prepare the seedbed, for planting, to control weeds, and to harvest the crop. The use of heavy equipment has many advantages in saving time and labor, but can cause compaction of soil and disruption of the natural soil biota. Much compaction is reversible and some is unavoidable with modern practices; however, serious compaction issues can occur when the equipment is used excessively during times when the soil has a high water content. The problem with soil compaction is that increased soil density limits root penetration depth and may inhibit proper plant growth.

Salinization

When considerable quantities of salt accumulate in the soil in a process known as **salinization**, many plants are unable to grow properly or even survive. This is especially a problem in irrigated farmland. Groundwater used for irrigation contains small amounts of dissolved salts. Irrigation water that is not absorbed into the soil evaporates, leaving the salts behind. This process repeats itself and eventually severe salinization of the soil occurs. A related problem is water logging of the soil. When cropland is irrigated with excessive amounts of water in order to leach salts that have accumulated in the soil, the excess water is sometimes unable to drain away properly. In this case it accumulates underground and causes a rise in the subsurface water table. If the saline water rises to the level of the plant roots, plant growth is inhibited.

Desertification

Land that was previously suited for growing crops may be turned into desert by climate change and the activities of humans, such as poor farming practices, livestock overgrazing, and overuse of available water. This process, called **desertification**, is a serious problem worldwide. Plants and soil types that are non-arid (not dry) specifically help water soak into the ground (infiltration) and water retention. When desertification begins, it leads to a reduction in vegetation and degraded soil quality, and this further increases the aridity and spreads the desert via a **positive feedback loop** (meaning that the processes feed on themselves promoting an increasing spiral).

Figure 5.6.*b* shows areas of the world and their vulnerability to desertification. Note the red and orange areas in the western and midwestern United States. The Dust Bowl of the 1930s is a classic example of human-caused desertification (figure 5.6.*c*). Poor cultivation and grazing practices -- coupled with severe drought conditions -- led to severe wind erosion of soil in a region of the Great Plains that became known as the "Dust Bowl". Wind stripped large areas of farmlands of topsoil, and formed clouds of dust that traveled as far as the eastern United States.

Sometimes there is a conflict between what is known to prevent desertification and what an individual farmer feels is needed to do to make a living. Mitigating the desertification process includes both societal steps and individual education on alternatives.

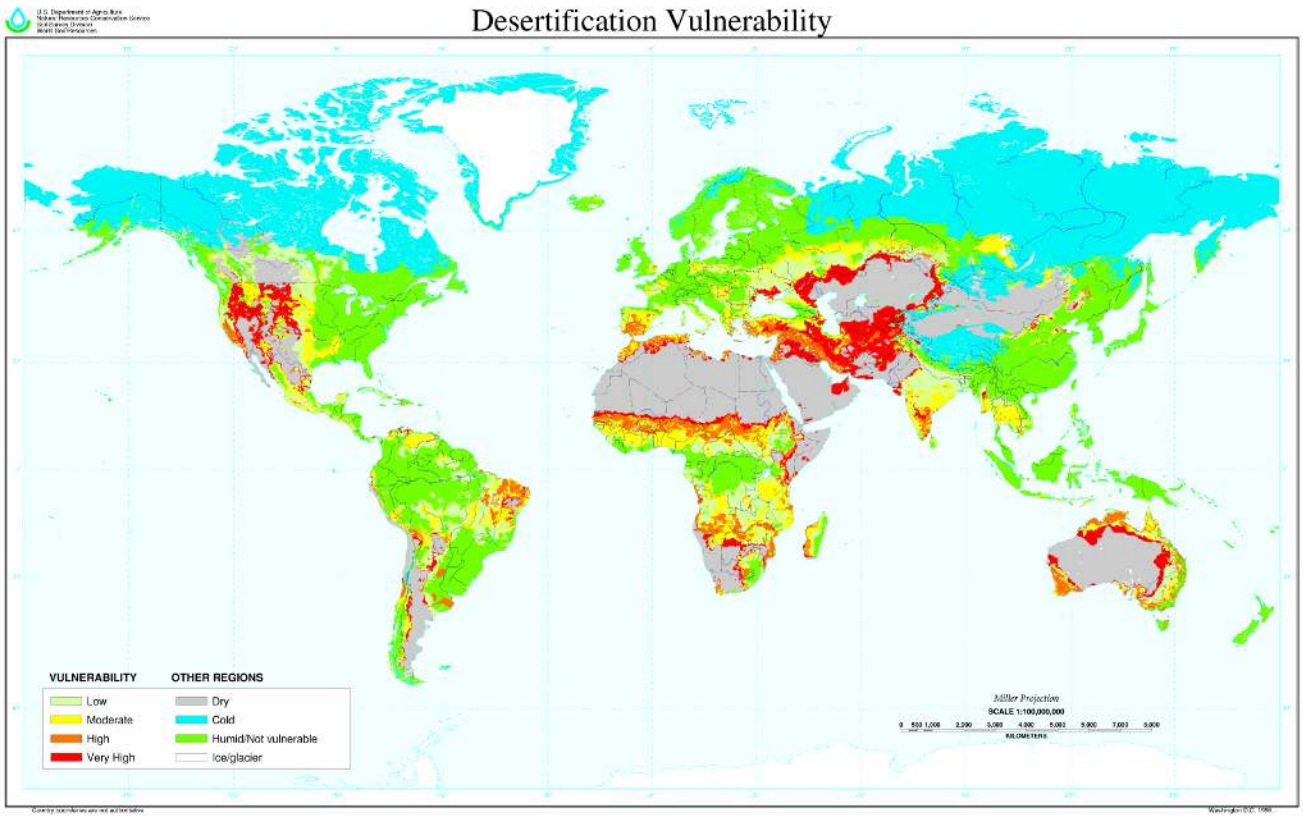


Figure 5.6.*b*: World map showing desertification vulnerability. There are four levels of vulnerability: very high (red), high (orange), moderate (yellow), and low (light green). Examples of regions with a very high vulnerability to desertification include the northwestern United States, a strip through western and central Africa, parts of the middle East, and parts of Australia. Examples of regions with low vulnerability include parts of Canada, parts of western Europe, and parts of Angola and the Democratic Republic of Congo. Other regions are labeled as dry (gray), cold (light blue), humid/not vulnerable (bright green), or ice/glacier (white). For example, northern regions are cold and ice/glacier. Some of southwestern United States, Chile and Argentina, northern Africa, the Middle East, Kazakhstan, Mongolia, and much of Australia are considered dry. Examples of humid/not vulnerable areas include the eastern United States, northern and eastern South America, western Europe, Central Africa, and East Asia. Image by USDA (public domain).



Figure 5.6.*c*: A cloud of dust in Kansas in 1935, part of the Dust Bowl. Image by NOAA Photo Library (public domain).

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5.7: Data Dive- Beaver Impacts on Wetlands

Overview

An ecosystem engineer is any animal that creates, significantly modifies, maintains or destroys a habitat. These organisms impact both the abiotic and biotic components of a habitat and can thus completely change landscapes. One 2017 study sought to understand if beavers (classic ecosystem engineer) could even be used as a tool for habitat restoration of wetlands. Specifically, this study focused on quantifying if wetland biodiversity improved as a result of reintroducing beavers on a landscape degraded by agriculture. Figure 2.4.6a below displays some of the results in this study:

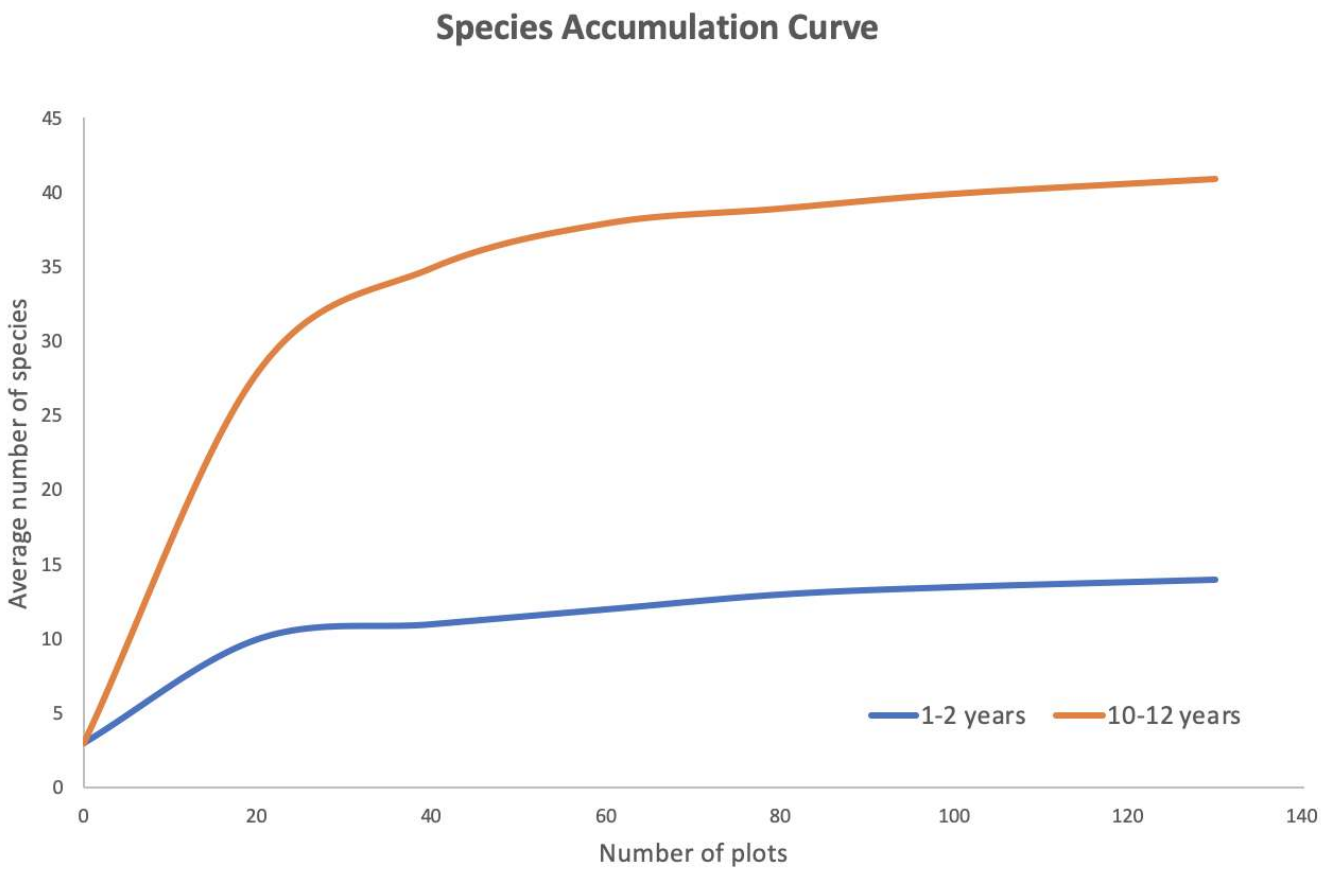


Figure 5.7.a: Average number of species observed in sample plots 1-2 years and 10-12 years after beavers were introduced. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Law A, Graywood MJ, Jones KC, Ramsay P, and Willby NJ 2017.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. What trend(s) can be observed in this graph between the 1-2 and 10-12 timetables? Support your answer by referring to appropriate patterns in the graph.
4. Do you think like the authors are satisfied with the results in the graph? Why?
5. How can the results of this graph to inform future reintroduction of beavers where wetland restoration is needed?
6. What information/patterns is not clear from this graph?

Raw Data From Above Graph(s)

Table 5.7.*a*: Raw data for average number of species observed in sample plots 1-2 years and 10-12 years after beavers were introduced. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Law A, Graywood MJ, Jones KC, Ramsay P, and Willby NJ 2017.

Number Of Plots	Average Number Of Species After 1-2 Years	Average Number Of Species After 10-12 Years
0	3	3
20	10	28
40	11	35
60	12	38
80	13	39
100	13.5	40
130	14	41

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5.8: Review

Summary

After completing this chapter you should be able to...

- Differentiate between abiotic and biotic ecosystem components.
- Describe the three main categories of ecosystems.
- Explain the law of conservation of mass.
- Discuss the biogeochemical cycles of carbon, nitrogen, phosphorus, and sulfur.
- Explain how human activities have impacted these cycles and the potential consequences for Earth.
- Explain how soil characteristics influence plant growth.
- Identify and describe each component of soil.
- Distinguish among sand, silt, and clay and explain how particle size influences soil texture.
- Describe each horizon in a typical soil profile.
- Explain how soils are formed, describing each of the five major factors that affect soil formation and composition.
- Describe the major types and causes of soil degredation.

Ecosystems consist of living (**biotic**) and nonliving (**abiotic**) components. They can be classified as freshwater, marine, or terrestrial. **Resistance** and **resilience** are measures of ecosystem health.

Matter is anything that occupies space and has mass. Pure forms of matter are called **elements** and the smallest units of an element are **atoms**. Atoms form molecules through **ionic, covalent,** or **hydrogen bonding**. Molecules that contain carbon and hydrogen covalent bonds are called **organic**. There are four main type of large organic molecules (**biological macromolecules**) in organisms: carbohydrates, lipids, proteins, and nucleic acids.

The chemical elements that organisms need continuously cycle through ecosystems. Cycles of matter are called **biogeochemical cycles,** or **nutrient cycles**, because they include both biotic and abiotic components and processes. Examples of biogeochemical cycles include the carbon, nitrogen, phosphorus, and sulfur cycles, and each of these can be altered through human activities.

Soil consists of organic and inorganic material as well as water and air. The organic material of soil is made of **humus**, which improves soil structure and provides nutrients. Soil inorganic material consists of rock slowly broken down into smaller particles that vary in size, such as sand, silt, and loam. Soils form slowly as a result of biological, physical, and chemical processes. Soil is not homogenous because its formation results in the production of layers called a **soil profile**. Most soils have four distinct **horizons,** or layers: O, A, B, and C. Their composition is influenced by the climate, presence of living organisms, topography, parent material, and time. The processes of erosion, compaction, and desertification degrade soils. While these processes occur naturally to an extent, they are exacerbated by certain agricultural practices, deforestation, and other human activities.

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CHAPTER OVERVIEW

6: Biomes

6.1: Climate and Biomes

6.2: Terrestrial Biomes

6.3: Aquatic Biomes

6.4: Data Dive- Biome Carbon Storage

6.5: Review

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6.1: Climate and Biomes

Biomes are large-scale environments that are distinguished by characteristic climate and vegetation (figure 6.1.*a*). Biomes are also characterized by the animals and other organisms there, which are influenced by vegetation and climate patterns. The Earth's biomes are categorized into two major groups: terrestrial and aquatic. **Terrestrial biomes** are based on land, while **aquatic biomes** include both ocean and freshwater biomes. Altitude and latitude, which affect temperature and precipitation determine the distribution of biomes.

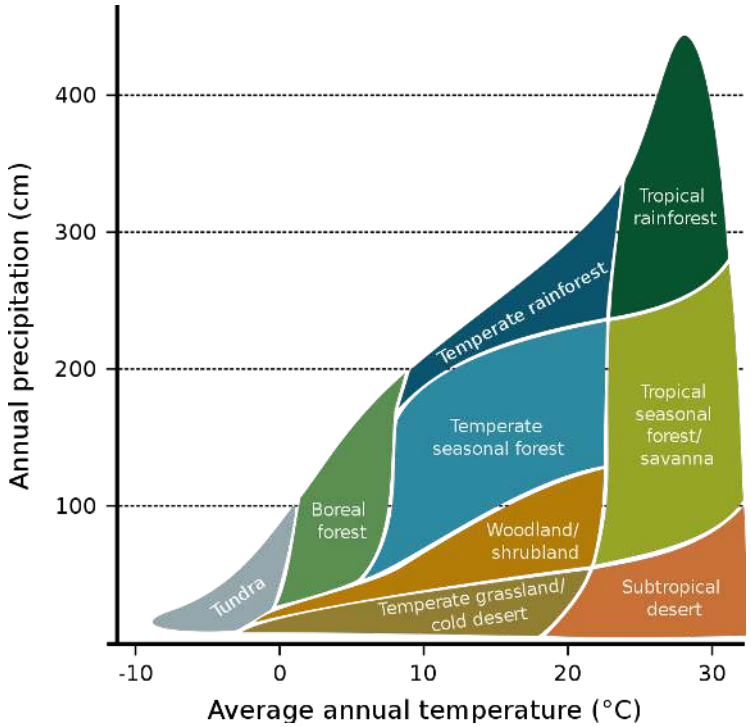


Figure 6.1.*a*: Average annual temperature and annual precipitation are two climatic factors that determine the distribution of biomes. This graph shows annual precipitation in centimeters on the y-axis and average annual temperature in degrees Celsius on the x-axis. Tropical rainforests have the highest temperatures and most precipitation. Tropical seasonal forests and savannas have high temperatures (20-30°C) with precipitation from approximately 50 to 270 centimeters. Subtropical deserts have similarly high temperatures but dry conditions. Temperate grasslands and cold deserts range in average annual temperature from below 0 to 22°C and have less than 50 centimeters of precipitation per year. Woodlands/shrublands (such as the chaparral) have the same temperature range as cold deserts but can receive a little over 100 cm of precipitation per year. Temperate forests have intermediate temperatures (approximately 16-22°C), but temperate rainforests receive more precipitation than temperate seasonal forests. Boreal forests receive a little less precipitation than temperate forests, but are colder (approximately 1-10°C). The tundra has the coldest temperatures and little precipitation. Deserts have a range of temperatures but low precipitation. Image by Navarras (public domain).

Low latitudes (near the equator) have high temperatures, while high latitudes (near the poles) have low temperatures. This is because the sun hits the equator more directly. Sunlight hits the poles at an angle, reducing the intensity of light (and heat energy) per unit of area. Temperature also decreases with altitude. At high altitudes, the atmosphere is thinner and traps less heat energy from the sun. Because temperatures decline with altitude as well as latitude, similar biomes exist on mountains even when they are at low latitudes. As a rule of thumb, a climb of 1000 feet (about 300 m) is equivalent in changed flora and fauna to a trip northward of some 600 miles (966 km).

Where precipitation is moderately abundant — 40 inches (about 1 m) or more per year — and distributed fairly evenly throughout the year, the major determinant is temperature. It is not simply a matter of average temperature, but includes such limiting factors as whether it ever freezes or length of the growing season. Biomes are thus characterized not only by average temperature and precipitation but also their seasonality.

Not only does latitude influence temperature, but it also affects precipitation. For example, deserts tend to occur at latitudes of around 30° and at the poles, both north and south, driven by circulation and prevailing wind patterns in the atmosphere. The engine

that drives circulation in the atmosphere and oceans is solar energy, which is determined by the average position of the sun over the Earth's surface. Direct light provides uneven heating depending on latitude and angle of incidence, with high solar energy in the tropics, and little or no energy at the poles. Atmospheric circulation and geographic location are the primary causal agents of deserts. At approximately 30° north and south of the equator, sinking air produces **trade wind deserts** like the Sahara and the Outback of Australia (figure 6.1.*b*).

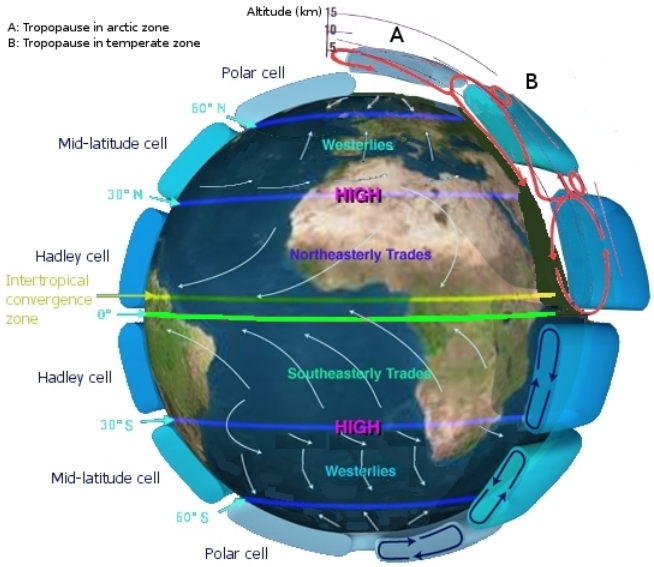


Figure 6.1.*b*: The generalized circulation of the atmosphere. Solar energy falling on the equatorial belt heats the air and causes it to rise. The rising air cools and its contained moisture falls back on the tropics as rain. The drier air then continues to spread toward the north and south where it sinks back at about 30 degrees north and south latitudes. This sinking drier air creates belts of predominant high pressure along which desert conditions prevail. These belts of predominantly high pressure have air that descends along these belts and flows either north to become the westerlies or south to become the trade winds. Note the arrows indicating general directions of winds in the latitude zones. The trade winds are predominant in the tropics and the westerlies in the mid-latitudes.

The MinuteEarth video below discusses the global climate patterns which lead to deserts.



Rainshadow deserts are produced where prevailing winds with moist air dries as it is forced to rise over mountains. The prevailing winds in the western half of North America blow in from the Pacific laden with moisture. Each time this air rises up from the western slopes of, successively, the Coast Ranges, the Sierras and Cascades, and finally the Rockies, it cools and its capacity to hold moisture decreases. The excess moisture condenses to rain or snow, which drenches the mountain slopes beneath. When the air reaches the eastern slopes, it is relatively dry, and much less precipitation falls. This phenomenon is called the **rainshadow effect** (figure 6.1.*c*). How much rain falls and when influences the type of biome. For example, the **Great Basin Desert** (figure 6.1.*d*) is a rain shadow desert produced as moist air from the Pacific rises by lifting over the Sierra Nevada Mountain (and other) and loses moisture from previous condensation and precipitation on the rainy side of the range(s).

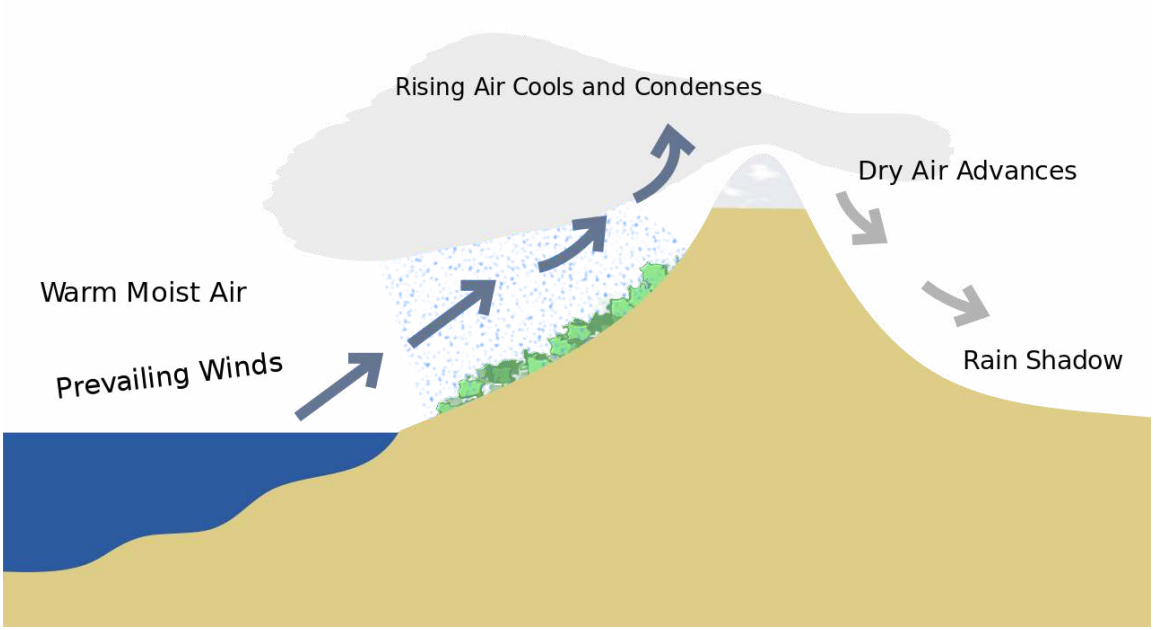


Figure 6.1.*c*: The rain shadow effect. Warm, moist air is carried up a mountain by prevailing winds. The rising air cools and condenses, resulting in precipitation as it moves up the mountain. The dry air advances down the other side of the mountain, resulting in a rain shadow (a dry region). Image by domdomegg (CC-BY).



Figure 6.1.*d*: Map of the Great Basin Desert. Image by USGS (public domain).

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6.2: Terrestrial Biomes

Because each biome is defined by climate, the same biome can occur in geographically distinct areas with similar climates (figure 6.2.a). You can further explore the distribution of biomes using the HHMI Biome Viewer.

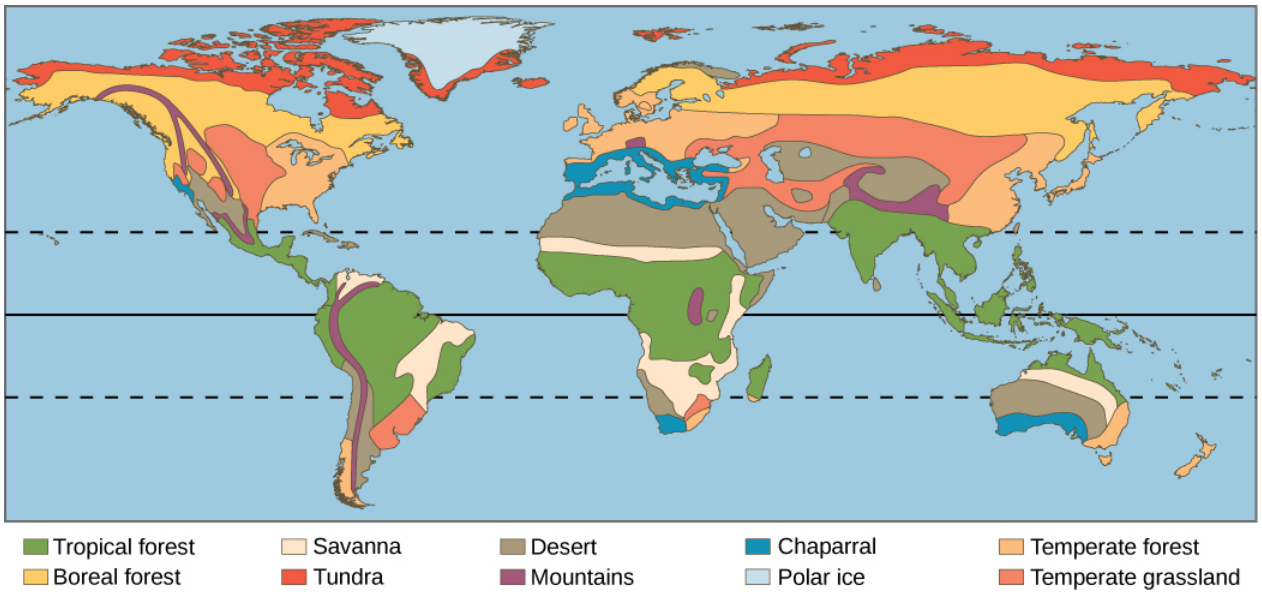


Figure 6.2.a: Each of the world's eight major biomes is distinguished by characteristic temperatures and amount of precipitation. Tropical forests are found closest to the equator (solid black line). Savannas are just north or south of tropical forests. Deserts occur at 30 degrees north and south (dashed black line). Chaparral is in southern California, around the Mediterranean sea, at the southern tip of Africa, and along the southwestern Australian coast. Temperate forests are found the eastern United States, tip of South America, western Europe, northeastern Asia, eastern Australia, and New Zealand. Boreal forests are found in Canada, Scandinavian countries, and Russia. Temperate grasslands are found in western South America, the central United States, western Europe, and central Asia. Tundra is at the north of the map. Much of Greenland is polar ice. Key mountains include the Sierra Nevada, Rocky Mountains, Andes, and Mitumba Mountains.

There are eight major terrestrial biomes: tropical rainforests, savannas, deserts, chaparral, temperate grasslands, temperate forests, taiga (boreal forests), and Arctic tundra.

Tropical Rainforests

Tropical rainforests, found in equatorial regions (figure 6.2.a), are the most biodiverse terrestrial biome (figure 6.2.b). In the Western Hemisphere, the tropical rain forest reaches its fullest development in the jungles of Central and South America. The trees are very tall and of a great variety of species. One rarely finds two trees of the same species growing close to one another. Most of the animals — mammals and reptiles, as well as birds and insects — live in the trees.



Figure 6.2.*b*: Species diversity is very high in tropical wet forests, such as these forests of Madre de Dios, Peru, near the Amazon River. (credit: Roosevelt Garcia)

This biodiversity is under extraordinary threat primarily through logging and deforestation for agriculture. Tropical rainforests have also been described as nature's pharmacy because of the potential for new drugs that is largely hidden in the chemicals produced by the huge diversity of plants, animals, and other organisms. The vegetation is characterized by plants with spreading roots and broad leaves. The broad-leafed trees are mostly **evergreen**, with leaves that persist throughout the year, but in tropical seasonal forests (see below), some are **deciduous,** with leaves falling off in the dry season.

The temperature and sunlight profiles of tropical rainforests are stable in comparison to other terrestrial biomes, with average temperatures ranging from 20°C to 34°C (68°F to 93°F). Month-to-month temperatures are relatively constant in tropical rainforests, in contrast to forests farther from the equator. This lack of temperature seasonality leads to year-round plant growth rather than just seasonal growth. In contrast to other ecosystems, a consistent daily amount of sunlight (11–12 hours per day year-round) provides more solar radiation and therefore more opportunity for **net primary productivity** (a measure of how carbon is stored by the photosynthesis that occurs in a community).

The annual rainfall in tropical rainforests ranges from 125 to 660 cm (50–200 in). Some tropical rainforests have relatively consistent rainfall whereas others (the **tropical seasonal forests**) have distinct wet months, in which there can be more than 30 cm (11–12 in) of precipitation, as well as dry months in which there are fewer than 10 cm (3.5 in) of rainfall. Nevertheless, the driest month of a tropical rainforest can still exceed the annual rainfall of some other biomes, such as deserts.

Tropical rainforests are characterized by vertical layering of vegetation and the formation of distinct habitats for animals within each layer. The vegetation is so dense that little light reaches the forest floor. On the forest floor is a sparse layer of plants and decaying plant matter. Above that is an **understory** of short, shrubby foliage. A layer of trees rises above this understory and is topped by a closed upper canopy—the uppermost overhead layer of branches and leaves. Some additional trees emerge through this closed upper canopy. These layers provide diverse and complex habitats for the variety of plants, animals, and other organisms. Many species of animals use the variety of plants and the complex structure of the tropical wet forests for food and shelter. Some organisms live several meters above ground, rarely descending to the forest floor.

Epiphytes

Epiphytes are plants that live perched on sturdier plants. They do not take nourishment from their host as parasitic plants do. Because their roots do not reach the ground, they depend on the air to bring them moisture and inorganic nutrients. Examples of epiphytes include many orchids, ferns (figure 6.2.*c*), and bromeliads (members of the pineapple family like "Spanish moss").



Figure 6.2.c: Epiphytes, graceful fern (*Niphidium crassifolium*), grow at the Soberania National Park in Panama. Image by Katja Schulz (CC-BY)

Tropical Soils

While productivity is high in tropical rainforests, the soils themselves tend to be of very poor quality. Because of the high rainfall, nutrients are quickly washed out of the topsoil unless they are incorporated in the forest plants. As plant and animal debris falls to the ground, it is quickly decomposed because of the warmth and moisture there. Thus minerals are found mainly in the forest plants, not in the soil. When the plants are removed and cultivation attempted, the soils quickly lose fertility. The situation is made worse by the lack of humus. Additionally, the topsoil may be no thicker than 5 cm (~2 inches), and most of these soils have high iron and aluminum content. Once exposed to the sun, these soils quickly bake into a bricklike material that cannot be cultivated.

Savannas

Savannas have mostly **perennial, herbaceous** plants (non-woody plants that persist for more than one year) with scattered trees, and they are located in Africa, South America, and northern Australia. Savannas are usually hot, tropical areas with temperatures averaging from 24 °C to 29 °C (75 °F to 84 °F) and an annual rainfall of 10–40 cm (3.9–15.7 in). Savannas have an extensive dry season; for this reason, forest trees do not grow as well as they do in the tropical rainforest. As a result, grasses and **forbs** (herbaceous plants other than grasses) are dominant (figure $6.2.d-e$). Since fire is an important source of disturbance in this biome, plants have evolved well-developed root systems that allow them to quickly resprout after a fire. Depending on the region, large grazing animals like giraffes, zebras, and gazelles and their predators (cheetahs, lions, etc.) are found in savannas.



Figure 6.2.*d*: Savannas, like this one in Taita Hills Wildlife Sanctuary in Kenya, are dominated by grasses. (credit: Christopher T. Cooper)



Figure 6.2.*e*: Although savannas are dominated by grasses, small woodlands, such as this one in Mount Archer National Park in Queensland, Australia, may dot the landscape. (credit: "Ethel Aardvark"/Wikimedia Commons)

Deserts

Deserts exist between 15° and 30° north and south latitude. As discussed in the previous section (Climate and Biomes), deserts are frequently located on the downwind, or lee side, of mountain ranges due to the rain shadow effect. This is typical of the North American deserts, such as the Mohave and Sonoran deserts and the previously mentioned Great Basin Desert. Deserts in other regions (tradewind deserts), such as the Sahara and the Outback of Australia (both previously mentioned) as well as the Namib Desert in southwestern Africa and are dry because of the high-pressure, dry air descending at those latitudes.

Deserts are very dry; evaporation typically exceeds precipitation. Deserts are characterized by low annual precipitation of fewer than 30 cm (12 in) with little monthly variation and lack of predictability in rainfall. Some years may receive tiny amounts of rainfall, while others receive more. In some cases, the annual rainfall can be as low as 2 cm (0.8 in) in deserts located in central Australia ("the Outback") and northern Africa.

Hot deserts (subtropical deserts) can have daytime soil surface temperatures above 60°C (140°F) and nighttime temperatures approaching 0°C (32°F). **Cold deserts** that experience freezing temperatures during the winter and any precipitation is in the form of snowfall. The largest of these deserts are the Gobi Desert in northern China and southern Mongolia, the Taklimakan Desert in western China, the Turkestan Desert, and the Great Basin Desert of the United States.

The low species diversity of this biome is closely related to its low and unpredictable precipitation. Despite the relatively low diversity, desert species exhibit fascinating adaptations to the harshness of their environment. Very dry deserts lack perennial vegetation that lives from one year to the next; instead, many plants are annuals that grow quickly and reproduce when rainfall does occur, then they die. Perennial plants in deserts are characterized by adaptations that conserve water: deep roots, reduced foliage, and water-storing stems (figure 6.2.*f*). Seed plants in the desert produce seeds that can lie dormant for extended periods between rains. Most animal life in deserts has adapted to a nocturnal life, spending the hot daytime hours beneath the ground. The Namib Desert is the oldest on the planet, and has probably been dry for more than 55 million years. It supports a number of endemic species (species found only there) because of this great age. For example, the unusual gymnosperm *Welwitschia mirabilis*is the only extant species of an entire order of plants. There are also five species of reptiles considered endemic to the Namib.



Figure 6.2.*f*: Many desert plants have tiny leaves or no leaves at all to reduce water loss. The leaves of ocotillo, shown here in the Chihuahuan Desert in Big Bend National Park, Texas, appear only after rainfall and then are shed. (credit "bare ocotillo": "Leaflet"/Wikimedia Commons)

Many of the animals in the desert (mammals, lizards and snakes, insects, and even some birds) are adapted for burrowing to escape the scorching heat of the desert sun. Many of them limit their forays for food to the night.

The net primary productivity of the desert is low. High productivity can sometimes be achieved with **irrigation**, but these gains are often only temporary because it leads to the buildup of **salts** and **minerals**. Large areas of formerly unproductive desert in the United States, Israel, and Egypt have been converted into fertile fields through irrigation. However, even the best irrigation water contains dissolved salts. Because the rainfall in deserts is so low, any water that does not immediately run off remains near the surface and is largely lost by evaporation. The salts it carries are left near the top of the soil. Their accumulation may make the soil so alkaline (basic) and so salty that it is prohibitive to agriculture (figure 6.2.*g*). In the U. S., the situation is especially severe in the Great Basin because water flowing down from the mountains—bearing its load of dissolved salts—cannot flow on to the ocean but simply flows out onto the valley floors and evaporates.



Figure 6.2.*g*: Salt formations at the Badwater Basin in Death Valley, California. Minerals accumulate when water pools in this low-lying area, making conditions impossible for agriculture. Some plants, like pickleweed and saltgrass, are adapted to grow around the edges of the salt flats. Image by "Mike" Michael L. Baird (CC-BY).

Mediterranean Scrub (Chaparral)

The **Mediterranean scrub**, is also called chaparral or scrub forest and is found in California, along the Mediterranean Sea, and along the southern coast of Australia (figure 6.2.*h*). The annual rainfall in this biome ranges from 65 cm to 75 cm (25.6–29.5 in) and the majority of the rain falls in the winter. Summers are very dry and many chaparral plants are dormant during the summertime.



Figure 6.2.*h*: The chaparral is dominated by shrubs. (credit: Miguel Vieira)

The Mediterranean scrub vegetation is dominated by shrubs and is adapted to periodic fires, with some plants producing seeds that germinate only after a hot fire. The ashes left behind after a fire are rich in nutrients like nitrogen and fertilize the soil, promoting plant regrowth. Fire is a natural part of the maintenance of this biome. The trees in the chaparral are mostly oaks, both deciduous and evergreen. Scrub oaks and shrubs like manzanita and the California lilac (not a relative of the eastern lilac) form dense, evergreen thickets. All of these plants are adapted to drought by such mechanisms as waxy, waterproof coatings on their leaves. Many plants that thrive in one chaparral region are successfully cultivated in other chaparral regions. For example, vineyards, olives, and figs from their native Mediterranean and eucalyptus trees from Australia thrive in California. However, blue gum eucalyptus from Australia disrupts California ecosystems by changing the hydrology and outcompeting native plants.

Temperate Grasslands

Temperate grasslands are found throughout central North America, where they are also known as prairies (figure 6.2.*i*), and in Eurasia, where they are known as steppes. Temperate grasslands have pronounced annual fluctuations in temperature with hot summers and cold winters. The annual temperature variation produces specific growing seasons for plants. Plant growth is possible when temperatures are warm enough to sustain plant growth, which occurs in the spring, summer, and fall.



Figure 6.2.*h*: The American bison (Bison bison), more commonly called the buffalo, is a grazing mammal that once populated American prairies in huge numbers. (credit: Jack Dykinga, USDA ARS)

Temperate grasslands have few trees except for those found growing along rivers or streams. The dominant vegetation tends to consist of grasses. The treeless condition is maintained by low precipitation, frequent fires, and grazing. Fires, which are a natural disturbance in temperate grasslands, can be ignited by lightning strikes. It also appears that the lightning-caused fire regime in North American grasslands was enhanced by intentional burning by humans. When fire is suppressed in temperate grasslands, the vegetation eventually converts to scrub and dense forests. Often, the restoration or management of temperate grasslands requires the use of controlled burns to suppress the growth of trees and maintain the grasses.

Annual precipitation ranges from 25.4 cm to 88.9 cm (10–35 in) and is concentrated in the summer and spring. In the plains of North America, the annual rainfall is sufficiently low (~50 cm, 20") that little or no rainfall percolates down to the water table. Calcium and other minerals are not carried below the reach of plant roots and so remain available for use. This keeps the pH and general fertility high. The grasses in undisturbed prairie are perennial. Their extensive root systems help prevent soil erosion, and the return of the season's above-ground growth to the topsoil returns minerals and provides humus to it. These advantages are diminished when annual grasses such as wheat and corn are grown instead and removed in the harvest.The self-restoring fertility of the soils of the plains states accounts for this region being the "breadbasket" of the nation (and other countries as well).

Temperate Forests

Temperate forests are the most common biome in eastern North America, Western Europe, Eastern Asia, Chile, and New Zealand (figure 6.2.*i*). This biome is found throughout mid-latitude regions. Temperatures range between –30°C and 30°C (–22°F to 86°F) and drop to below freezing on an annual basis. These temperatures mean that temperate forests have defined growing seasons during the spring, summer, and early fall.



Figure 6.2.*i*: Deciduous trees are the dominant plant in the temperate forest. (credit: Oliver Herold)

Temperate forests may be deciduous, mixed (with deciduous and evergreen trees), or coniferous (with evergreen conifers). Examples of temperate deciduous trees are beech, maple, oak, and hickory. The deciduous trees of temperate forests drop their leaves in the winter; thus, little photosynthesis occurs during the dormant winter period. (In other biomes, such as chaparral and tropical seasonal forests, trees or shrubs may drop their leaves during the summer or dry season.) Each spring, new leaves appear as temperature increases. Because of the dormant period, the net primary productivity of temperate forests is less than that of tropical rainforests. In addition, temperate forests show far less diversity of tree species than tropical rainforest biomes. Large stands dominated by a single species are common.

The deciduous trees of the temperate forests leaf out and shade much of the ground. However, more sunlight reaches the ground in this biome than in tropical rainforests because trees in temperate forests do not grow as tall as the trees in tropical rainforests. The soils of the temperate forests are rich in inorganic and organic nutrients compared to tropical rainforests. This is because of the thick layer of leaf litter on forest floors and reduced leaching of nutrients by rainfall. As this leaf litter decays, nutrients are returned to the soil. The leaf litter also protects soil from erosion, insulates the ground, and provides habitats for invertebrates and their predators. Deer, raccoons, and salamanders are characteristic inhabitants of temperate forests.

Precipitation is relatively constant throughout the year and ranges between 75 cm and 150 cm (29.5–59 in). Enough water falls on the soil so that much of it soaks deep into the ground and carries minerals with it. Such soils tend to be acidic and of low and (if unattended) diminishing fertility. Only by regular fertilization and liming (to restore calcium and raise pH) can productive agriculture be carried out in them. In the U.S., the soils east of the Appalachian Mountains tend to be of this sort.

Taiga

The **taiga**, also known as **boreal forest** in North America, is found roughly between 50° and 60° north latitude across most of Canada, Alaska, Russia, and northern Europe ((figure 6.2.*i*). Boreal forests are also found above a certain elevation (and below high elevations where trees cannot grow) in mountain ranges throughout the Northern Hemisphere. This biome has cold, dry winters and short, cool, wet summers. The annual precipitation is from 40 cm to 100 cm (15.7–39 in) and usually takes the form of snow. Although precipitation is relatively low, the taiga is dotted with lakes, bogs, and marshes because the cold temperatures limit evaporation.



Figure 6.2.*j*: The boreal forest (taiga) has low lying plants and conifer trees. (credit: L.B. Brubaker, NOAA)

The long and cold winters in the boreal forest have led to the predominance of cold-tolerant cone-bearing plants. These are evergreen coniferous trees like pines, spruce, and fir, which retain their needle-shaped leaves year-round. Evergreen trees can photosynthesize earlier in the spring than deciduous trees because less energy from the sun is required to warm a needle-like leaf than a broad leaf. In the taiga, evergreen trees grow faster than deciduous trees. In addition, soils in boreal forest regions tend to be acidic with little available nitrogen. Leaves are a nitrogen-rich structure, and deciduous trees must produce a new set of these nitrogen-rich structures each year. Therefore, coniferous trees that retain nitrogen-rich needles in a nitrogen-limiting environment may have had a competitive advantage over the broad-leafed deciduous trees.

In North America, the moose is such a typical member that it has led to the name: "spruce-moose" biome. Deer, bears, and wolves are also found in the taiga. Before the long, snowy winter sets in, many of the mammals hibernate, and many of the birds migrate south.

The net primary productivity of taiga is lower than that of temperate forests and tropical rainforests. The aboveground **biomass** (mass of living organisms) of taiga is high because these slow-growing tree species are long-lived and accumulate standing biomass over time. Species diversity is less than that seen in temperate forests and tropical rainforests. Taiga lacks the layered forest structure seen in tropical rainforests or, to a lesser degree, temperate forests. The structure of the taiga is often only a layer of trees and the understory of low-lying plants and lichen. When conifer needles are dropped, they decompose more slowly than broad leaves; therefore, fewer nutrients are returned to the soil to fuel plant growth.

At the coldest parts of the taiga, the soil remains frozen year after year, forming a layer called **permafrost**. When the permafrost melts in unusually warm years, the trees are no longer supported by this hard surface and lean in different directions, forming a "drunken forest". At extreme latitudes, the trees of the taiga become stunted by the harshness of the subarctic climate. Where they finally disappear (above the "tree line"), the Arctic tundra begins.

Arctic Tundra

The **Arctic tundra** lies north of the subarctic boreal forests and is located throughout the Arctic regions of the Northern Hemisphere. Tundra also exists at elevations above the tree line on mountains. The average winter temperature is –34°C (–29.2°F), and the average summer temperature is 3°C–12°C (37°F –52°F). Plants in the Arctic tundra have a short growing season of approximately 50–60 days. However, during this time, there are almost 24 hours of daylight and plant growth is rapid. The annual precipitation of the Arctic tundra is low (15–25 cm or 6–10 in) with little annual variation in precipitation. And, as in the taiga, there is little evaporation because of the cold temperatures.

There is little species diversity, low net primary productivity, and low above-ground biomass. Like some of the taiga, the soils of the Arctic tundra may remain in a perennially frozen state, forming permafrost. The permafrost makes it impossible for roots to penetrate far into the soil and slows the decay of organic matter, which inhibits the release of nutrients from organic matter. The surface layer of soil above the permafrost melts in the brief summer, water is released and provides for a burst of productivity while temperatures and long days permit it. Because of these harsh growing conditions, the Arctic tundra is particularly sensitive to disturbances (disruptions that decrease biomass, such as heavy machinery passing through and squishing some of the plants).

Plants in the Arctic tundra are generally low to the ground and include low shrubs, sphagnum moss, grasses, lichens, and small flowering plants (figure 6.2.k). Caribou feed on this growth as do vast numbers of insects. Swarms of migrating birds, especially waterfowl, invade the tundra in the summer to raise their young, feeding them on a large variety of aquatic invertebrates and vertebrates. As the brief arctic summer draws to a close, the birds fly south, and all but a few of the permanent residents, in one way or another, prepare themselves to spend the winter in a dormant state.



Figure 6.2.k: Low-growing plants such lichen and grasses are common in tundra. Credit: Nunavut tundra by Flickr: My Nunavut is licensed under CC-BY.

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6.3: Aquatic Biomes

Abiotic Factors Influencing Aquatic Biomes

Like terrestrial biomes, **aquatic biomes** are influenced by a series of abiotic factors. The aquatic medium—water— has different physical and chemical properties than air. Even if the water in a pond or other body of water is perfectly clear (there are no suspended particles), water still absorbs light. As one descends into a deep body of water, there will eventually be a depth which the sunlight cannot reach. While there are some abiotic and biotic factors in a terrestrial ecosystem that might obscure light (like fog, dust, or insect swarms), usually these are not permanent features of the environment. The importance of light in aquatic biomes is central to the communities of organisms found in both freshwater and marine ecosystems. In freshwater systems, temperature stratification due to differences in density is perhaps the most critical abiotic factor and is related to the energy aspects of light. The thermal properties of water (rates of heating and cooling) are significant to the function of marine systems and have major impacts on global climate and weather patterns. Marine systems are also influenced by large-scale physical water movements, such as currents; these are less important in most freshwater lakes.

Marine Biomes

The ocean is the largest **marine biome**. It is a continuous body of salt water that is relatively uniform in chemical composition; it is a weak solution of mineral salts and decayed biological matter. Within the ocean, coral reefs are a second kind of marine biome. Estuaries, coastal areas where salt water and fresh water mix, form a third unique marine biome.

Ocean

The physical diversity of the ocean is a significant influence on plants, animals, and other organisms. The ocean is categorized by several areas (Figure 6.3.*a*). Each area has a distinct group of species adapted to the biotic and abiotic conditions particular to it. The **intertidal zone**, which is the zone between high and low tide, is the oceanic region that is closest to land. Generally, most people think of this portion of the ocean as a sandy beach. In some cases, the intertidal zone is indeed a sandy beach, but it can also be rocky or muddy. Organisms are exposed to air and sunlight at low tide and are underwater most of the time, especially during high tide. Therefore, living things that thrive in the intertidal zone are adapted to being dry for long periods of time. The shore of the intertidal zone is also repeatedly struck by waves, and the organisms found there are adapted to withstand damage from the pounding action of the waves (figure 6.3.*b*). The exoskeletons of shoreline crustaceans (such as the shore crab, *Carcinus maenas*) are tough and protect them from desiccation (drying out) and wave damage. Another consequence of the pounding waves is that few algae and plants establish themselves in the constantly moving rocks, sand, or mud.

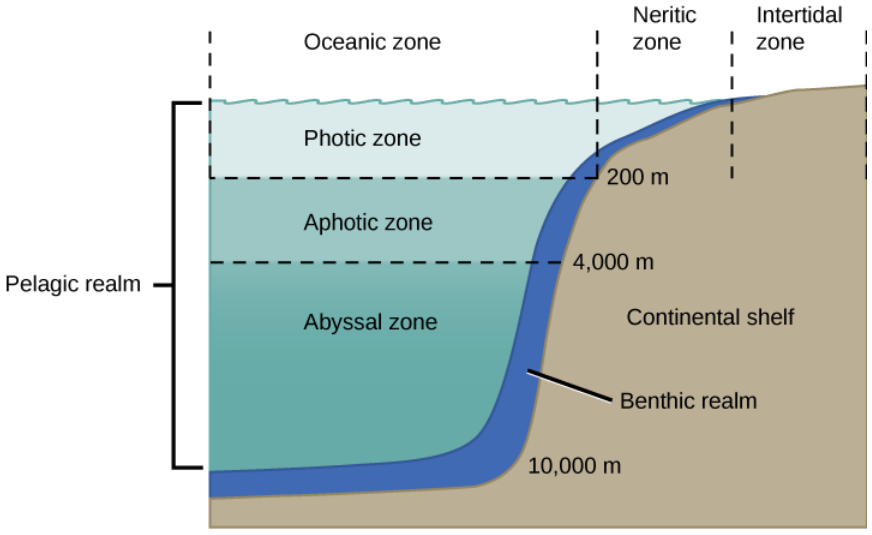


Figure 6.3.*a*: The ocean is divided into different zones based on distance from the shoreline and water depth. The intertidal zone is the closest to shore followed by the neretic and oceanic zone. The photic zone is 0-200 meters deep. The aphotic zone is 200-4,000 meters deep. The abyssal zone is 4,000-10,000 meters deep. These three zones form the pelagic realm, and the benthic realm is below the pelagic realm, along the continental shelf.



Figure 6.3.*b*: Sea urchins, mussel shells, and starfish are often found in the intertidal zone, shown here in Kachemak Bay, Alaska. (credit: NOAA)

The **neritic zone** extends from the intertidal zone to depths of about 200 m (or 650 ft) at the edge of the continental shelf. Because light can penetrate this depth, photosynthesis can occur. The water here contains silt and is well-oxygenated, low in pressure, and stable in temperature. Phytoplankton and floating *Sargassum* (a type of free-floating marine seaweed) provide a habitat for some sea life found in the neritic zone. Zooplankton, protists, small fishes, and shrimp are found in the neritic zone and are the base of the food chain for most of the world's fisheries.

Beyond the neritic zone is the open ocean area known as the **oceanic zone**. Within the oceanic zone there is thermal stratification where warm and cold waters mix because of ocean currents. Abundant plankton serve as the base of the food chain for larger animals such as whales and dolphins. Nutrients are scarce and this is a relatively less productive part of the marine biome. When photosynthetic organisms and the protists and animals that feed on them die, their bodies fall to the bottom of the ocean where they remain.

All of the ocean's open water is referred to as the **pelagic realm**. The pelagic realm is divided into the photic, aphotic, and abyssal zones from top to bottom based on how far light reaches into the water. The **photic zone**, which is the portion of the ocean that light can penetrate (approximately 200 m or 650 ft). At depths greater than 200 m, light cannot penetrate; thus, this is referred to as the **aphotic zone**. The majority of organisms in the aphotic zone include sea cucumbers (phylum Echinodermata) and other organisms that survive on the nutrients contained in the dead bodies of organisms in the photic zone.

The deepest part of the ocean is the **abyssal zone**, which is at depths of 4000 m or greater. Both the aphotic and abyssal zones lack sufficient light for photosynthesis, and together, they constitute most of the ocean. The deepest part of the ocean, the Challenger Deep (in the Mariana Trench, located in the western Pacific Ocean), is about 11,000 m (about 6.8 mi) deep. To give some perspective on the depth of this trench, the ocean is, on average, 4267 m deep. These zones are relevant to freshwater lakes as well. The abyssal zone is very cold and has very high pressure, high oxygen content, and low nutrient content. There are a variety of invertebrates and fishes found in this zone, but the abyssal zone does not have plants because of the lack of light. Cracks in the Earth's crust called **hydrothermal vents** are found primarily in the abyssal zone (figure 6.3.*c*). Around these vents, bacteria that utilize the hydrogen sulfide and other minerals emitted as an energy source serve as the base of the food chain found in the abyssal zone.

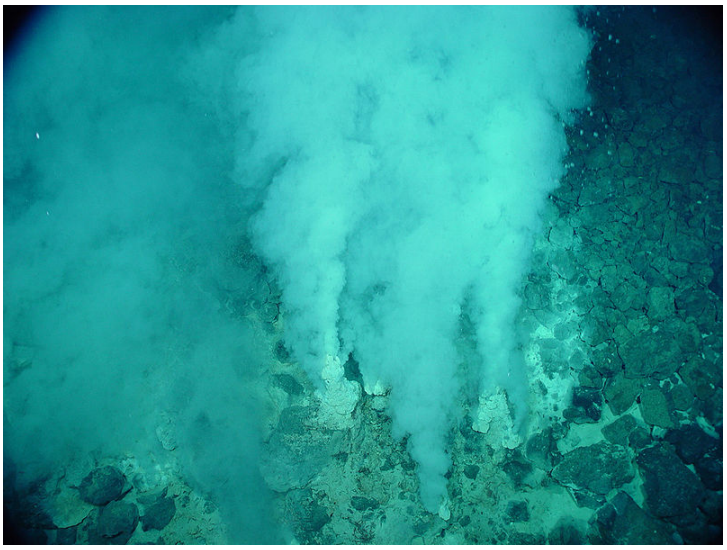


Figure 6.3.*c*: A hydrothermal vent. Image by NOAA (public domain).

The **benthic realm**, extends along the ocean bottom from the shoreline to the deepest parts of the ocean floor. It is comprised of sand, silt, and dead organisms. This is a nutrient-rich portion of the ocean because of the dead organisms that fall from the upper layers of the ocean. Because of this high level of nutrients, a diversity of sponges, sea anemones, marine worms, sea stars, fishes, and bacteria exist.

Coral Reefs

Coral reefs are characterized by high biodiversity and the structures created by invertebrates that live in warm, shallow waters within the photic zone of the ocean. They are mostly found within 30 degrees north and south of the equator. The Great Barrier Reef is a well-known reef system located several miles off the northeastern coast of Australia. The coral organisms are colonies of saltwater polyps that secrete a calcium carbonate skeleton. These calcium-rich skeletons slowly accumulate, forming the underwater reef (figure 6.3.*d*).



Figure 6.3.*d*: Coral reefs are formed by the calcium carbonate skeletons of coral organisms, which are marine invertebrates. (credit: Terry Hughes)

Corals found in shallower waters (at a depth of approximately 60 m or about 200 ft) have a mutualistic relationship with photosynthetic unicellular algae called dinoflagellates. The relationship provides corals with the majority of the nutrition and the energy they require. The waters in which these corals live are nutritionally poor, and, without this mutualism, it would not be possible for large corals to grow. Some corals living in deeper and colder water do not have a mutualistic relationship with algae; these corals attain energy and nutrients using stinging cells on their tentacles to capture prey. It is estimated that more than 4,000 fish species inhabit coral reefs. These fishes can feed on coral, other invertebrates, or the seaweed and algae that are associated with the coral.

Estuaries: Where the Ocean Meets Fresh Water

Estuaries are biomes that occur where a source of fresh water, such as a river, meets the ocean. Therefore, both fresh water and salt water are found in the same vicinity; mixing results in a diluted (brackish) saltwater. Estuaries form protected areas where many of the young offspring of crustaceans, mollusks, and fish begin their lives. Salinity is a very important factor that influences the organisms and the adaptations of the organisms found in estuaries. The salinity of estuaries varies and is based on the rate of flow of its freshwater sources. Once or twice a day, high tides bring salt water into the estuary. Low tides occurring at the same frequency reverse the current of salt water.

The short-term and rapid variation in salinity due to the mixing of fresh water and salt water is a difficult physiological challenge for the plants and animals that inhabit estuaries. Many estuarine plant species are **halophytes**, plants that can tolerate salty conditions. Halophytic plants are adapted to deal with the salinity resulting from saltwater on their roots or from sea spray. In some halophytes, filters in the roots remove the salt from the water that the plant absorbs. Other plants are able to pump oxygen into their roots. Animals, such as mussels and clams, have developed behavioral adaptations that expend a lot of energy to function in this rapidly changing environment. When these animals are exposed to low salinity, they stop feeding, close their shells, and stop using oxygen. When high tide returns to the estuary, the salinity and oxygen content of the water increases, and these animals open their shells, begin feeding, and return to using oxygen.

Freshwater Biomes

Freshwater biomes include lakes and ponds (standing water) as well as rivers and streams (flowing water). They also include wetlands, which will be discussed later. Humans rely on freshwater biomes to provide aquatic resources for drinking water, crop irrigation, sanitation, and industry. These various roles and human benefits are referred to as ecosystem services. Lakes and ponds are found in terrestrial landscapes and are, therefore, connected with abiotic and biotic factors influencing these terrestrial biomes.

Lakes and Ponds

Lakes and ponds can range in area from a few square meters to thousands of square kilometers. Temperature is an important abiotic factor affecting living things found in lakes and ponds. In the summer, thermal stratification of lakes and ponds occurs when the upper layer of water is warmed by the sun and does not mix with deeper, cooler water. Like oceans, lakes and ponds have photoic zones through which light can penetrate and aphotic zones without light. **Phytoplankton** (small photosynthetic organisms such as algae and photosynthetic bacteria that float in the water) are found here and carry out photosynthesis, providing the base of the food web of lakes and ponds. **Zooplankton** (very small animals that float in the water), such as rotifers and small crustaceans, consume these phytoplankton (figure 6.3.*e*). At the bottom of lakes and ponds, bacteria in the aphotic zone break down dead organisms that sink to the bottom.

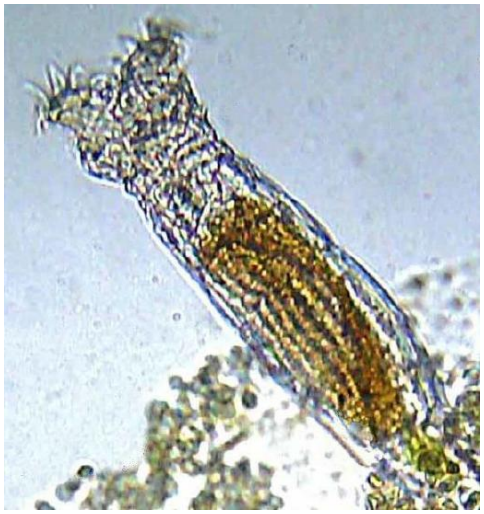


Figure 6.3.*e*: A rotifer is an example of the zooplankton found in lakes and ponds. Image by Bob Blaylock at English Wikipedia (CC-BY-SA).

Rivers and Streams

Rivers and streams are continuously moving bodies of water that carry large amounts of water from the source, or headwater, to a lake or ocean. The largest rivers include the Nile River in Africa, the Amazon River in South America (Figure 6.3.*f*), and the Mississippi River in North America. Abiotic features of rivers and streams vary along the length of the river or stream. Streams begin at a point of origin referred to as source water. The source water is usually cold, low in nutrients, and clear. The channel (the width of the river or stream) is narrower than at any other place along the length of the river or stream. Because of this, the current is often faster here than at any other point of the river or stream.



Figure 6.3.*f*: The Amazon River is the world's largest river. Image by Jason Hollinger (CC-BY)

The fast-moving water results in minimal silt accumulation at the bottom of the river or stream, therefore the water is clear. Photosynthesis here is mostly attributed to algae that are growing on rocks; the swift current inhibits the growth of phytoplankton. An additional input of energy can come from leaves or other organic material that falls into the river or stream from trees and other plants that border the water. When the leaves decompose, the organic material and nutrients in the leaves are returned to the water. Plants and animals have adapted to this fast-moving water. For instance, leeches have elongated bodies and suckers on both ends. These suckers attach to the substrate, keeping the leech anchored in place. Freshwater trout species are an important predator in these fast-moving rivers and streams.

As the river or stream flows away from the source, the width of the channel gradually widens and the current slows. This slow-moving water, caused by the gradient decrease and the volume increase as tributaries unite, has more sedimentation. Phytoplankton can also be suspended in slow-moving water. Therefore, the water will not be as clear as it is near the source. The water is also warmer. Worms and insects can be found burrowing into the mud. The higher order predator vertebrates include waterfowl, frogs, and fishes.

Wetlands

Wetlands are environments in which the soil is either permanently or periodically saturated with water. Wetlands are different from lakes because wetlands are shallow bodies of water that may periodically dry out. Emergent vegetation consists of wetland plants that are rooted in the soil but have portions of leaves, stems, and flowers extending above the water's surface. There are several types of wetlands including marshes, swamps, bogs, mudflats, and salt marshes (figure 6.3.*g*).



Figure 6.3.*g*: Located in southern Florida, Everglades National Park is vast array of wetland environments, including sawgrass marshes, cypress swamps, and estuarine mangrove forests. Here, a Great Egret walks among cypress trees. (credit: NPS)

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6.4: Data Dive- Biome Carbon Storage

Overview

Carbon sequestration is the process by which atmospheric carbon dioxide is taken up by trees, grasses, and other plants through photosynthesis and stored as carbon in biomass (trunks, branches, foliage, and roots). Carbon storage can also occur in soil formed from organic matter found in decomposing litter. Terrestrial carbon sequestration has been a recent topic of interest because of its implications for use in climate change mitigation. The carbon storage in terrestrial biomes helps to offset sources of carbon dioxide to the atmosphere, such as deforestation, wildfires, and fossil fuel emissions. As such, carbon storage in each biome can be altered by both natural and human caused events. The figure below indicates the estimated storage above (plants) and below (soil) ground by terrestrial biomes:

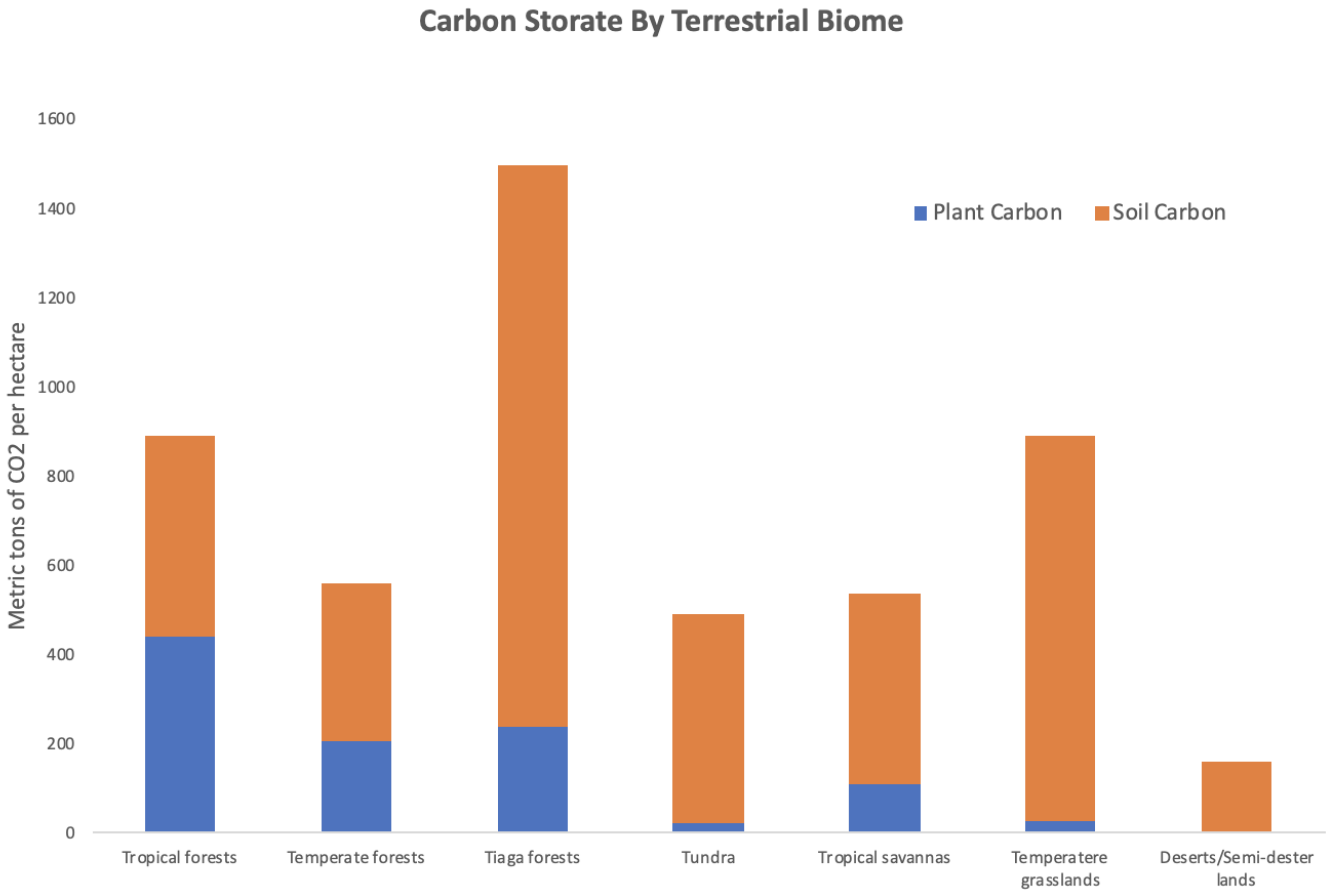


Figure 6.4.*a*: Carbon storage (in metric tons of CO2 per hectare) above (plant) and below (soil) ground in various biomes. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Islam KK, Sato N 2012.

Questions

1. What kind of graph is this?
2. What is the independent (explanatory) variable and the dependent (response) variable?
3. Which biome has the greatest storage in plants? What about soil?
4. What are the top three terrestrial biomes in terms of their carbon storage?
5. How can the results of this graph to inform future conservation efforts?
6. What do the results of this graph make you curious about?

Raw Data From Above Graph(s)

Table 6.4.*a***:** Raw data of carbon storage (in metric tons of CO2 per hectare) above (plant) and below (soil) ground in various biomes. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Islam KK, Sato N 2012.

Biome	Plant Carbon	Soil Carbon	Total Carbon
Tropical Forests	442	450	892
Temperate Forests	208	352	561
Taiga Forests	236	1260	1496
Tundra	23	467	490
Tropical Savannas	108	430	538
Temperate Grasslands	26	865	892
Deserts/Semi-Desert Lands	6	154	160

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6.5: Review

Summary

After completing this chapter you should be able to...

- Describe how latitude and altitude affect temperature and precipitation, which in turn, determine the distribution of biomes.
- Compare the eight major terrestrial biomes.
- Describe how light, temperature, flow, and salinity influence aquatic biomes.
- Distinguish between marine and freshwater biomes and describe examples of each.
- Explain the different realms and zones of the ocean.

Earth has **terrestrial biomes** and **aquatic biomes**. Temperature and precipitation, and variations in both, are key abiotic factors that shape the composition of animal and plant communities in terrestrial biomes. There are eight major terrestrial biomes: **tropical rainforests, savannas, deserts, chaparral, temperate grasslands, temperate forests, taiga,** and **Arctic tundra**.

Like terrestrial biomes, aquatic biomes are influenced by abiotic factors. In the case of aquatic biomes, the abiotic factors include light, temperature, flow regime, and dissolved solids. Aquatic biomes include both **marine biomes** and **freshwater biomes**. **Oceans**, **coral reefs**, and **estuaries** are marine biomes while **lakes**, **ponds**, **rivers**, **streams**, and **wetlands** are freshwater biomes.

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CHAPTER OVERVIEW

7: What is Biodiversity?

7.1: Introduction to What is Biodiversity?
7.2: Classification of Earth's Species
7.3: Origin of Biodiversity
7.4: Species Diversity
7.5: Genetic Diversity
7.6: Ecosystem Diversity and Services
7.7: Patterns of Biodiversity
7.7.1: Species Distribution
7.8: Summary
7.9: Topics for Discussion
7.11: Bibliography

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7.1: Introduction to What is Biodiversity?



A “silverback” mountain gorilla (*Gorilla beringei beringei*, EN) in Mgahinga Gorilla National Park, Uganda. Once thought to be one species, genetic analyses have shown that there are two gorilla species, each with two subspecies. Thanks to the efforts of dedicated conservationists and local communities in the Albertine Rift, the IUCN downlisted the mountain gorilla from Critically Endangered to Endangered in 2018. The three other subspecies are still considered Critically Endangered. Photograph by Nina R, https://www.flickr.com/photos/150102727@N06/31467129021, CC BY 2.0.

Conservation biology aims to improve the protection of biodiversity—that is, all the species, genetic diversity, and ecosystems on Earth. By this definition, the process of documenting life on Earth requires us to consider biodiversity on three different levels (Figure 7.1.1):

- **Species diversity**: The full variety of species, from single-celled organisms like bacteria to larger multicellular organisms like animals and everything in between.
- **Genetic diversity**: The full range of variability in genetic material within a species. This variation can occur spatially as differences between populations or as differences between individuals of the same population.
- **Ecosystem diversity**: The full variety of ecosystems—i.e., assemblages of species and the physical environments in which they live.

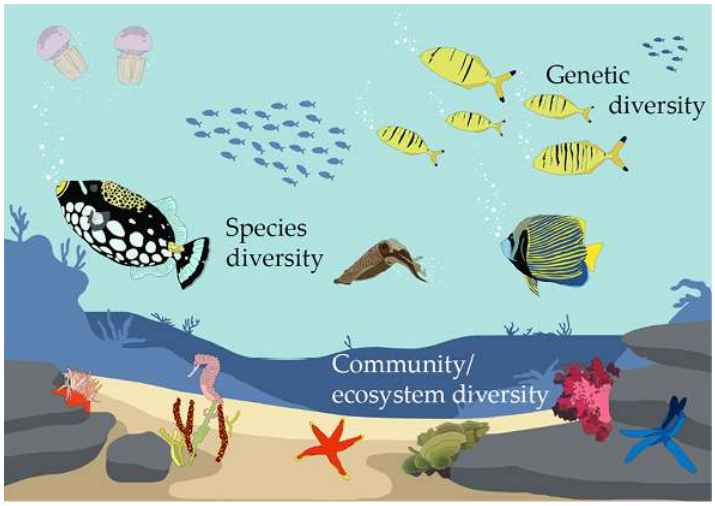


Figure 7.1.1 A region’s biodiversity includes the full complement of that area’s species diversity (all the area’s species), genetic diversity (the full range of genetic variation found within each of those species), and ecosystem diversity (the variety of ecosystems and ecological processes). CC BY 4.0.

The relationship between species, genetic, and ecosystem diversities is complex and interdependent. That is, a species cannot exist without genetic diversity or ecosystem diversity, and vice versa. For that reason, it is virtually impossible to affect one aspect of diversity without affecting the other. We can therefore think of species, genetic, and ecosystem diversities simply as different ways to measure the variety of life.

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7.2: Classification of Earth's Species

Earth is home to an impressive array of life forms. From single-celled organisms to creatures made of many trillions of cells, life has taken on many wonderful shapes and evolved countless strategies for survival. Recall that cell theory dictates that all living things are made of one or more cells. Some organisms are made of just a single cell, and are thus referred to as **unicellular**. Organisms containing more than one cell are said to be **multicellular.** Despite the wide range of organisms, there exists only two fundamental cell plans: prokaryotic and eukaryotic. The main difference these two cell plans is that eukaryotic cells have internal, membrane-bound structures called organelles (see chp 2.3). Thus, if you were to microscopically analyze the cells of any organism on Earth, you would find either prokaryotic or eukaryotic cells depending on the type of organism.

Biologists name, group, and classify organisms based on similarities in genetics and morphology. This branch of biological science is known as **taxonomy**. Taxonomists group organisms into categories that range from very broad to very specific (Figure 7.2.1). The broadest category is called **domain** and the most specific is **species** (notice the similarities between the words *specific* and *species*). Currently, taxonomists recognize three domains: Bacteria, Archaea, and Eukarya. All life forms are classified within these three domains.

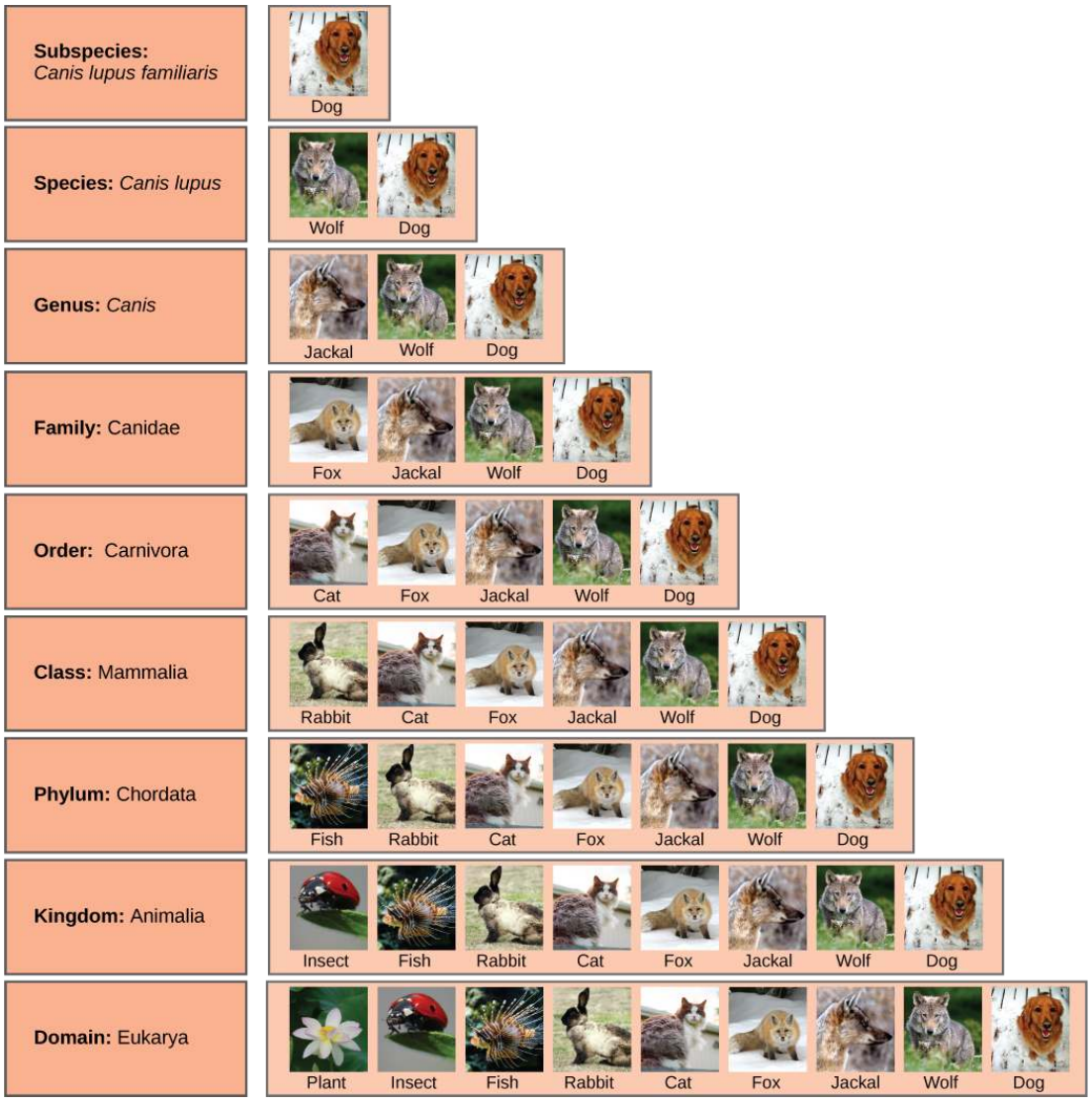


Figure 7.2.1. This illustration shows the taxonomic groups, in sequence, with examples. *This illustration by OpenStax is licensed under CC BY 4.0*

Domain Bacteria

Domain Bacteria includes prokaryotic, unicellular organisms (Figure 7.2.2). They are incredibly abundant and found in nearly every imaginable type of habitat, including your body. While many people view bacteria only as disease-causing organisms, most species are actually either benign or beneficial to humans. While it is true that some bacteria may cause disease in people, this is more the exception than the rule.

Bacteria are well-known for their metabolic diversity. **Metabolism** is a general term describing the complex biochemistry that occurs inside of cells. Many species of bacteria are **autotrophs**, meaning they can create their own food source without having to eat other organisms. Most autotrophic bacteria do this by using photosynthesis, a process that converts light energy into chemical energy that can be utilized by cells. A well-known and ecologically-important group of photosynthetic bacteria is **cyanobacteria**. These are sometimes referred to a blue-green algae, but this name is not appropriate because, as you will see shortly, algae are organisms that belong to domain Eukarya. Cyanobacteria play important roles in food webs of aquatic systems, such as lakes.

Other species of bacteria are **heterotrophs**, meaning that they need to acquire their food by eating other organisms. This classification includes the bacteria that cause disease in humans (*during an infection, the bacteria is eating you*). However, most heterotrophic bacteria are harmless to humans. In fact, you have hundreds of species of bacteria living on your skin and in your large intestine that do you no harm. Beyond your body, heterotrophic bacteria play vital roles in ecosystems, especially soil-dwelling bacteria that decompose living matter and make nutrients available to plants.

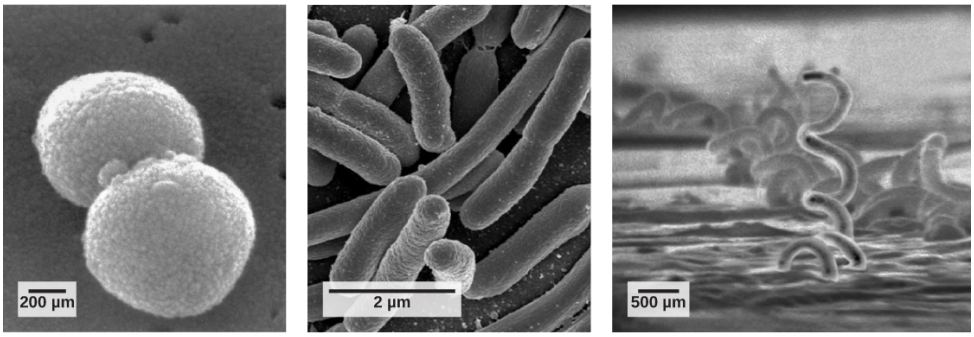


Figure 7.2.2. Many prokaryotes fall into three basic categories based on their shape: (a) cocci, or spherical; (b) bacilli, or rod-shaped; and (c) spirilla, or spiral-shaped. (credit a: modification of work by Janice Haney Carr, Dr. Richard Facklam, CDC; credit c: modification of work by Dr. David Cox, CDC; scale-bar data from Matt Russell). *This figure by OpenStax is licensed under CC BY 4.0*

Domain Archaea

Like bacteria, organisms in **domain Archaea** are prokaryotic and unicellular. Superficially, they look a lot like bacteria, and many biologists confused them as bacteria until a few decades ago. But hiding in their genes is a story that modern DNA analysis has recently revealed: archaeans are so different genetically that they belong in their own domain.

Many archaean species are found in some of the most inhospitable environments, areas of immense pressure (bottom of the ocean), salinity (such as the Great Salt Lake), or heat (geothermal springs). Organisms that can tolerate and even thrive in such conditions are known as **extremophiles**. (*It should be noted that many bacteria are also extremophiles*). Along with genetic evidence, the fact that a large percentage of archaeans are extremophiles suggests that they may be descendants of some of the most ancient lifeforms on Earth; life that originated on a young planet that was inhospitable by today's standards.

For whatever reason, archaeans are not as abundant in and on the human body as bacteria, and they cause substantially fewer diseases. Research on archaeans continues to shed light on this interesting and somewhat mysterious domain.

Domain Eukarya

This domain is most familiar to use because it includes humans and other animals, along with plants, fungi, and a lesser-known group, the protists. Unlike the other domains, **Domain Eukarya**contains multicellular organisms, in addition to unicellular species. The domain is characterized by the presence of eukaryotic cells. For this domain, you will be introduced to several of its kingdoms. **Kingdom** is the taxonomic grouping immediately below domain (see Figure 7.2.1).

Kingdom Animalia is comprised of multicellular, heterotrophic organisms. This kingdom includes humans and other primates, insects, fish, reptiles, and many other types of animals. **Kingdom Plantae** includes multicellular, autotrophic organisms. Except for a few species that are parasites, plants use photosynthesis to meet their energy demands.



Figure 7.2.3. The (a) familiar mushroom is only one type of fungus. The brightly colored fruiting bodies of this (b) coral fungus are displayed. This (c) electron micrograph shows the spore-bearing structures of Aspergillus, a type of toxic fungi found mostly in soil and plants. (credit a: modification of work by Chris Wee; credit b: modification of work by Cory Zanker; credit c: modification of work by Janice Haney Carr, Robert Simmons, CDC; scale-bar data from Matt Russell). *This work by OpenStax is licensed under CC BY 4.0.*

Kingdom Fungi includes multicellular and unicellular, heterotrophic fungi. Fungi are commonly mistaken for plants because some species of fungi grow in the ground. Fungi are fundamentally different from plants in that they do not perform photosynthesis and instead feed on the living matter of others. Another misconception is that all fungi are mushrooms. A mushroom is a temporary reproductive structure used by some fungal species, but not all. Some fungi take the form of molds and mildews, which are commonly seen on rotting food. Lastly, **yeast** are unicellular fungi. Many species of yeast are important to humans, especially baker's and brewer's yeast. Through their metabolism, these yeast produce CO2 gas and alcohol. The former makes bread rise and the latter is the source for all alcoholic beverages.

Protists refer to a highly disparate group that was formerly its own kingdom until recent genetic analysis indicated that it should be split in to many kingdoms (Figure 7.2.4). As a group, protists are very diverse and include unicellular, multicellular, heterotrophic, and autotrophic organisms. The term 'protist' was used as a catchall for any eukaryote that was neither animal, plant, or fungus. Examples of protists include macroalgae such as kelps and seaweeds, microalgae such as diatoms and dinoflagellates, and important disease-causing microbes such as *Plasmodium*, the parasite that causes malaria. Sadly, malaria kills hundreds of thousands of people every year.

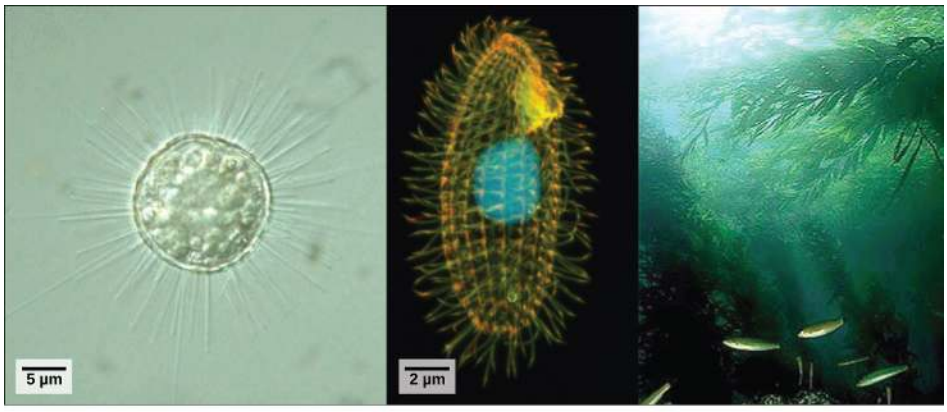


Figure 7.2.4. Protists range from the microscopic, single-celled (a) *Acanthocystis turfacea and the (b) ciliate Tetrahymena thermophilato the enormous, multicellular (c) kelps (Chromalveolata) that extend for hundreds of feet in underwater "forests." (credit a: modification of work by Yuiuji Tsukii; credit b: modification of work by Richard Robinson, Public Library of Science; credit c: modification of work by Kip Evans, NOAA; scale-bar data from Matt Russell). This work by OpenStax is licensed under CC BY 4.0*

With this cursory and fundamental understanding of biological diversity, you are now better equipped to study the role of biodiversity in the biosphere and in human economics, health, and culture. Each life form, even the smallest microbe, is a fascinating and and complex living machine. This complexity means we will likely never fully understand each organism and the myriad ways they interact with each other, with us, and with their environment. Thus, it is wise to value biodiversity and take measures to conserve it.

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7.3: Origin of Biodiversity

What biological process is responsible for biodiversity?

All species —from the bacteria on our skin to the birds outside—evolved at some point from a different species. Although it may seem that living things today stay much the same from generation to generation, that is not the case because evolution is ongoing. **Evolution** is the process through which the characteristics of a species change over time, which can ultimately cause new species to arise.



Figure 7.3.1. The diversity of life on Earth is the result of evolution, a continuous process that is still occurring. (credit "wolf": modification of work by Gary Kramer, USFWS; credit "coral": modification of work by William Harrigan, NOAA; credit "river": modification of work by Vojtěch Dostál; credit "protozoa": modification of work by Sharon Franklin, Stephen Ausmus, USDA ARS; credit "fish" modification of work by Christian Mehlführer; credit "mushroom", "bee": modification of work by Cory Zanker; credit "tree": modification of work by Joseph Kranak)

The theory of evolution is the unifying theory of biology, meaning it is the framework within which biologists ask questions about the living world. Its power is that it provides direction for predictions about living things that are borne out in experiment after experiment. The Ukrainian-born American geneticist Theodosius Dobzhansky famously wrote that "nothing makes sense in biology except in the light of evolution." He meant that the principle that all life has evolved and diversified from a common ancestor is the foundation from which we understand all other questions in biology.

Discovering How Populations Change

The theory of evolution by natural selection describes a mechanism for how species can change over time. That species change was suggested and debated well before Darwin. The view that species were unchanging was grounded in the writings of Plato, yet there were also ancient Greeks that expressed evolutionary ideas.

In the eighteenth century, ideas about the evolution of animals were reintroduced by the various naturalists. At the same time, James Hutton, the Scottish naturalist, proposed that geological change occurred gradually by the accumulation of small changes from processes (over long periods of time) just like those happening today. This contrasted with the predominant view that the geology of the planet was a consequence of catastrophic events occurring during a relatively brief past. Hutton's view was later popularized by the geologist Charles Lyell in the nineteenth century. Lyell became a friend to Darwin and his ideas were very influential on Darwin's thinking. Lyell argued that the greater age of Earth gave more time for gradual change in species, and the process provided an analogy for gradual change in species.

Charles Darwin and Natural Selection

Natural selection as a mechanism for evolution was independently conceived of and described by two naturalists, Charles Darwin and Alfred Russell Wallace, in the mid-nineteenth century. Importantly, each spent years exploring the natural world on expeditions to the tropics. From 1831 to 1836, Darwin traveled around the world on *H.M.S. Beagle*, visiting South America, Australia, and the

southern tip of Africa. Wallace traveled to Brazil to collect insects in the Amazon rainforest from 1848 to 1852 and to the Malay Archipelago from 1854 to 1862. Darwin's journey, like Wallace's later journeys in the Malay Archipelago, included stops at several island chains, the last being the Galápagos Islands (west of Ecuador). On these islands, Darwin observed species of organisms on different islands that were clearly similar, yet had distinct differences. For example, the ground finches inhabiting the Galápagos Islands comprised several species that each had a unique beak shape (Figure 7.3.2). He observed both that these finches closely resembled another finch species on the mainland of South America and that the group of species in the Galápagos formed a graded series of beak sizes and shapes, with very small differences between the most similar. Darwin imagined that the island species might be all species modified from one original mainland species. In 1860, he wrote, "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends."

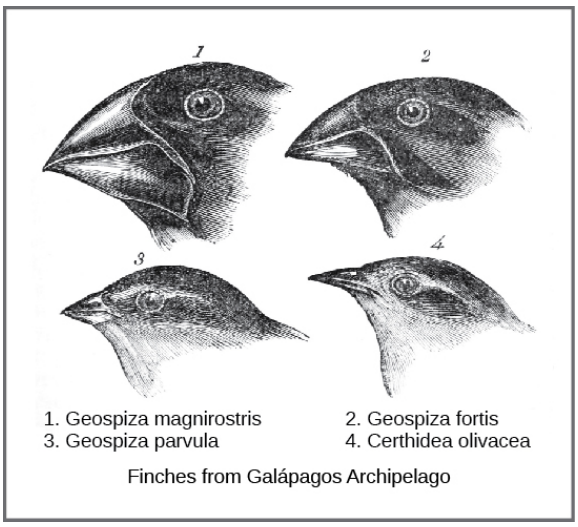


Figure 7.3.2. Darwin observed that beak shape varies among finch species. He postulated that the beak of an ancestral species had adapted over time to equip the finches to acquire different food sources. This illustration shows the beak shapes for four species of ground finch: 1. Geospiza magnirostris (the large ground finch), 2. G. fortis (the medium ground finch), 3. G. parvula (the small tree finch), and 4. Certhidea olivacea (the green-warbler finch).

Wallace and Darwin both observed similar patterns in other organisms and independently conceived a mechanism to explain how and why such changes could take place. Darwin called this mechanism natural selection. Natural selection, Darwin argued, was an inevitable outcome of three principles that operated in nature.

- First, there exists variation in traits among individuals within a population, and these traits are inherited, or passed from parent to offspring.
- Second, more offspring are produced than are able to survive; in other words, resources for survival and reproduction are limited.
- And lastly, there is a competition for those resources in each generation.

Out of these three principles, Darwin and Wallace reasoned that offspring with inherited characteristics that allow them to best compete for limited resources will survive and have more offspring than those individuals with variations that are less able to compete. Because characteristics are inherited, these traits will be better represented in the next generation. This will lead to change in populations over generations in a process that Darwin called "**descent with modification**." In sum, we can define **natural selection** as a process the causes beneficial traits to become more common in a population over time, causing the population to evolve.



(a) (b)

Figure 7.3.3. (a) Charles Darwin and (b) Alfred Wallace wrote scientific papers on natural selection that were presented together before the Linnean Society in 1858.

Papers by Darwin and Wallace (Figure 7.3.3) presenting the idea of natural selection were read together in 1858 before the Linnaean Society in London. The following year Darwin's book, *On the Origin of Species*, was published, which outlined in considerable detail his arguments for evolution by natural selection.

Natural selection can only take place if there is **variation**, or differences, among individuals in a population. Importantly, these differences must have some genetic basis, otherwise natural selection would not lead to change in the next generation because there would be no way to transmit those traits from one generation to the next.

Genetic diversity in a population comes from two main sources: mutation and sexual reproduction. **Mutation**, a permanent change in DNA sequence is the ultimate source of new genetic variation in any population. An individual that has a mutated gene might have a different trait than other individuals in the population. Without variation in traits, nature would not be able to select the traits that are best adapted for the organisms' environment at that particular time.

Evolutionary change in action

The development of antibiotic resistant bacteria is an example of evolution through natural selection and it has been directly observed by scientists. How does this happen? Imagine a person that has a bacterial infection: their body is being attacked by billions of bacteria. Because there is genetic variation in populations, some individual bacteria may already possess traits that allow them to tolerate antibiotic drugs. When the infected person is prescribed antibiotics, the drug attacks and kills the entire population, except for those bacteria that can resist the drug. These bacteria survive because they had a trait that was beneficial and thus nature selected for it. The surviving population will all be resistant to the drug and continue to reproduce, multiple, and pass down that beneficial trait to all offspring. The population has now evolved because all individuals have the antibiotic-resistant trait, whereas before it was rare. It is important to realize that evolution occurs at the population level and is reliant upon genetic variation that was already present. Without that variation, there is nothing for nature to select for. The rise and spread of antibiotic resistant bacteria is an emerging environmental issue and will be discussed in a later chapter.

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7.4: Species Diversity

In general, the first step in responding to the conservation need of a species or population is to know its identity. For this reason, one of the three main goals of conservation biology is to document all life on Earth or, in plain language, to give each species a name. The task of giving each species a (formal) name falls on specialist scientists known as **taxonomists**. Taxonomists (and the people assisting them) explore nature, collect specimens of plants, animals, and other organisms, describe/name those specimens, and store the specimens in permanent collections, such as natural history museums and **herbaria** (there are currently over 6,500 natural history museums in the world). These permanent collections, affectionally called “Libraries of Life”, provide the material and locations that taxonomists use to describe species and to develop systems for biodiversity classifications.

When a species is formally described, it is given a unique two-part name, known as a **binomial** name. For example, the binomial name for the lion is *Panthera leo*. The first part of the name, *Panthera*, identifies the generic epithet (or simply **genus**); in this case, the panthers or big cats. The second part of the name, *leo*, identifies a subset within the genus known as the specific epithet (or simply species); in this case, the lion. This binomial system thereby both identifies a lion as its own species and connects it to other closely-related species: Africa and Asia’s leopards (*P. pardus*, VU); Asia’s snow leopard (*P. uncia*, VU); Asia’s tigers (*P. tigris*, EN); and South America’s jaguars (*P. onca*, NT) (Figure 7.4.1).



Figure 7.4.1 The world’s large predatory cats: (A) tiger, (B) slow leopard, (C) leopard, (D) jaguar, and (E) lion. By looking at their binomial names one can immediately see the five species are closely related. CC BY 4.0.

Binomial species names, as well as the taxonomic relationships between different species, form the backbone of taxonomic databases, as compiled and organized by biodiversity informatics projects. Some biodiversity informatics projects focus on one group of species, while others focus on certain regions. For example, all known marine species are listed in the World Register of Marine Species (http://www.marinespecies.org), while the Catalogue of Afrotropical Bees (https://doi.org/10.15468/u9ezbh) collates information of only African bees. In some cases, multiple projects—each using different assumptions to suit different user groups better—may catalog the same group of species. For example, the world’s fungi, are listed both in Index Fungorum (http://www.indexfungorum.org) and MycoBank (http://www.mycobank.org), while bird names are indexed by at least seven different projects, each a little different from the other. There are even some biodiversity informatics projects that attempt to catalog all life on Earth; examples include Catalogue of Life (http://www.catalogueoflife.org), Encyclopaedia of Life (http://eol.org), and Wikispecies (https://species.wikimedia.org).

What is a species?

There are three rules of thumb that taxonomists use to describe a species:

- **Morphological definition of species:** Individuals that are distinct from other groups in their morphology, physiology, or biochemistry.
- **Biological definition of species:** Individuals that breed (or could breed) with each other in the wild, but do not breed with members of other groups.
- **Evolutionary definition of a species:** Individuals that share a common evolutionary past, usually indicated by genetic similarities.

In practice, conservation biologists generally rely on the morphological definition to identify species. The ability to recognize physical or morphological differences between organisms is handy even when the actual identity of specimens is unknown. In such cases, field biologists may refer to the unknown species as **morphospecies** (Figure 7.4.2), at least until an expert identifies the unknown individuals or a taxonomist gives them an official scientific name. In contrast, the biological definition of species relies on information that is difficult to obtain and thus not readily available. The biological definition also fails to recognize recent speciation, which can cause closely related but distinct species to interbreed. Similarly, it is generally impractical for fieldworkers to measure differences in genetic sequences to distinguish one species from another because these procedures currently require expensive, immovable laboratory equipment.

Taxonomists can use morphological, biological, and genetic information to identify species.

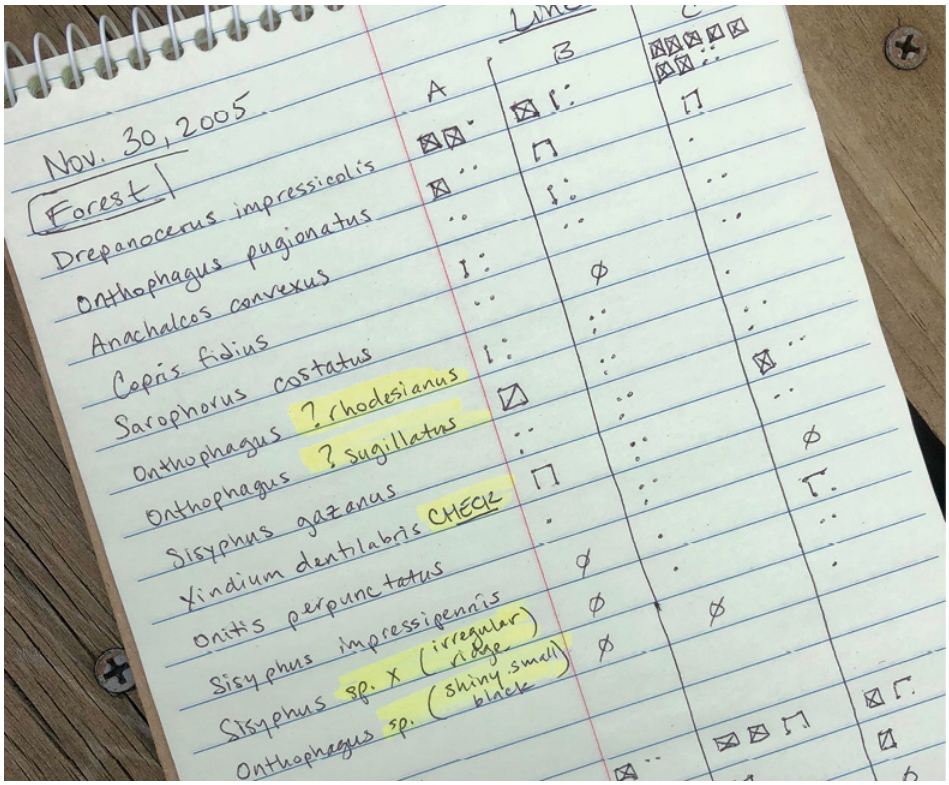


Figure 7.4.2 Field sheet showing application of the morphospecies concept during a dung beetle surveys in South Africa. Unidentified (and potentially misidentified) specimens are noted with a variety of descriptors (highlighted) and collected for identification at a later stage. Photograph by Lesley Starke, CC BY 4.0.

Despite the practical difficulties of applying the biological and evolutionary definitions in the field, both provide important guidelines for conservation efforts. The biological species definition allows us to better understand species **biogeography**, the geographical distribution of species, and the mechanisms that prevent two closely-related species to interbreed. The evolutionary species definition in turn allows us to better understand how and why the genetic makeup of populations change over time, through processes such as **random mutations, natural selection, emigration** (individuals leaving a population), and **immigration** (individuals joining a population). It is thus important for conservation biologists to acknowledge the importance of maintaining these dynamic processes in protecting natural systems, and where possible, include them in their fieldwork (Box 7.4.1).

Box 7.4.1 Finding a Needle in a Haystack: Monitoring Species Using eDNA

Tammy Robinson and Clova Mabin

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Trying to find threatened species in aquatic systems can be like trying to find a needle in a haystack. Traditionally, researchers have set off with nets, buckets, and even snorkels and scuba gear to painstakingly search for threatened species in ecosystems, ranging from streams to coral reefs. While searching in a small system, such as a pond, might not seem too difficult, it can be a real challenge to find tiny, inconspicuous organisms in and amongst the mud, stones, and plants, especially when they are trying their best to remain hidden. Things get even trickier when combing through large ecosystems like lakes or bays. These difficulties make it hard to reliably monitor the status or distribution of threatened aquatic species.

However, scientists have recently developed a new search tool called environmental DNA, (eDNA in short), where researchers collect and search water samples for the DNA of the species they are interested in. The eDNA technique was first developed by a biologist trying to detect organisms in sediment (Willerslev et al., 2003) but is now being used by conservationists working in all kinds of aquatic ecosystems. Organisms continually release small amounts of DNA into the water by sloughing off skin or other cells and releasing bodily wastes. This DNA then mixes in the surrounding environment, allowing those organisms to be detected through genetic analyses without actually sampling them directly.

Researchers have been testing just how useful eDNA is for finding threatened species in ponds and streams (Thomsen et al., 2012). They detected the eDNA of fish, shrimp, dragonflies, and amphibians in most ponds where the species were known to occur and found no trace of the eDNA of these species where they were absent. The most exciting development was their ability to detect eDNA evidence of threatened species in places where they had previously occurred but not been recently recorded by traditional search methods. Field observations and experiments also showed that eDNA can persist for up to two weeks in fresh water, and that concentrations can correspond to population sizes; this suggests that scientists may be able to monitor the abundance of rare aquatic species to a high degree of accuracy using this approach.

eDNA technology also holds considerable promise for the management of aquatic invasive species, if they could be detected as new arrivals before their numbers grow enough to be detected by conventional methods (Takahara et al., 2013). Early detection will give conservation managers a head-start and enable them to react quickly to invasions and increase their chances of preventing the environmental damage associated with invasive species. In a local twist to the tale, ongoing work in South Africa is applying eDNA as a tool for measuring the success of management efforts aimed at removing the invasive marine European shore crab (*Carcinus maenas*) (Figure 7.4.3) that could outcompete or threaten native African marine species. It is hoped that eDNA will be able to track the decline in crab numbers as the species is removed and then be used to monitor for any new arrivals should the crabs re-invade.



Figure 7.4.3 Researchers in South Africa have been using eDNA to monitor the success of a control program aimed at invasive European shore crabs. Photograph by Clova Mabin, CC BY 4.0.

This exciting new approach in detecting species is rapidly developing and improving our efficiency at monitoring threatened and invasive species. This makes the process less like looking for a needle in a haystack, and more like finding the millions of needles right under your nose.

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7.5: Genetic Diversity

Every extant species on Earth consists of at least one **population**, a group of individuals at a certain place that generally look alike and can potentially breed with each other to produce offspring. These population(s) can be very small (just a few individuals), very large (billions of individuals), or anything in-between. The individuals within each population generally differ genetically from one another to some degree. This **genetic variation**, a component of genetic diversity (Figure 7.5.1), exists because the **genes**—the functional units of hereditary information that provide the blueprint of an organism—in different individuals are made up of slightly different DNA sequences. Different forms of a gene, which arise through **mutations** that change DNA sequences, are known as **alleles**. The **gene pool**, in turn, consists of the total diversity of genes and alleles in a population or species. The particular mix of genes and alleles in an individual is its **genotype**. The expression of an individual's genotype, as determined by the environment where an organism has developed, is its **phenotype**—that is, the organism's morphology, anatomy, physiology, and biochemistry. Common characteristics to describe a person include height, hair color, and blood type, which taken together begin to describe that person's phenotype.

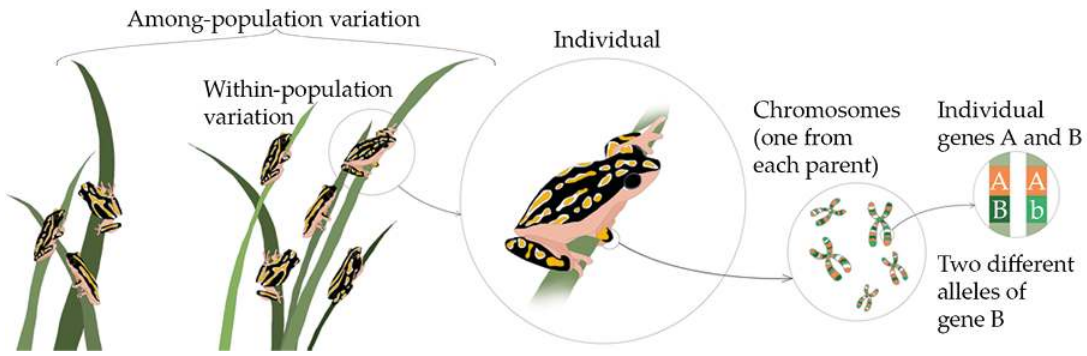


Figure 7.5.1 Genetic diversity arises due to variation in the alleles of individual genes and variation in chromosomes from different parents, which give rise to genetic variation between individuals, both within the same population and between different populations. CC BY 4.0.

In species which reproduce asexually, the potential for increased genetic diversity is limited to DNA mutations. However, sexual reproduction creates new genetic combinations by bringing together **chromosomes** from each parent. This process, called recombination, results in offspring that are genetically unique from their parents. Genetic mutations provide the foundation of genetic variation, but sexual reproduction dramatically increases genetic diversity by randomly mixing alleles in different combinations.

> Genetic diversity enables species to adapt to environmental change.

Two factors determine a species' genetic diversity: the number of genes that have multiple alleles (**polymorphic genes**) and the number of alleles present in a population for each polymorphic gene. If a gene is polymorphic, some individuals will have two different forms of the gene—that is, they will be **heterozygous** because they received different alleles of the same gene from their parents. Some individuals will have two of the same forms of the gene—they will be **homozygous** because each parent gave them the same allele. In general, the greater the genetic diversity in a population, especially the greater number of alleles present, the more capable a species will be to adapt to changing circumstances in their environment. Genetics also affect an individual organism's development, physiology, and **fitness**—the relative ability of individuals to survive and reproduce. This same principle gives humans the ability to select and breed crops and domestic animals with characteristics that benefit the production and quality of food (Davis et al., 2012). Many rare species have relatively low genetic diversity, especially in populations which have dwindled to small sizes. Low genetic diversity limits small populations' ability to adapt to changes in environmental conditions and leaves them at risk of extinction when conditions do change.

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7.6: Ecosystem Diversity and Services

Measuring biodiversity on a large scale involves measuring **ecosystem diversity**, the number of different ecosystems on Earth or in a geographical area as well as their relative abundances (figure 7.6.a). The loss of an ecosystem means the loss of the interactions between species and the loss of biological productivity that an ecosystem is able to create. An example of a largely extinct ecosystem in North America is the prairie ecosystem (figure 7.6.a). Prairies once spanned central North America from the boreal forest in northern Canada down into Mexico. They are now all but gone, replaced by crop fields, pasture lands, and suburban sprawl. Many of the species survive, but the hugely productive ecosystem that was responsible for creating our most productive agricultural soils is now gone. As a consequence, their soils are now being depleted unless they are maintained artificially at great expense.



Figure 7.6.a: The variety of ecosystems on Earth—from the coral reef (top) to prairie (bottom)—enables a great diversity of species to exist. Top image by Wise Hok Wai Lum (CC-BY-SA). Bottom image modified from Jim Minnerath, USFWS.

The soil productivity described above is an example of an **ecosystem service**. These are the products and processes associated with biological systems and are directly or indirectly of immense value to the well-being of people. Some ecosystem services are processes such as the regulation of climate, flooding, and disease. Nutrient cycling, pollination, and regulation of crop pests are ecosystem services important to food production (see the Food Production and Ecosystem Services box below). The water cycle provides fresh water, and photosynthesis adds oxygen to our air. Other ecosystem services are human provisions including food, fuel, and fiber (such as cotton for clothing or timber). Medicines are another important provision (see Importance of Species Diversity). Furthermore, healthy ecosystems allow for recreational activities, such as hiking, kayaking, and camping, and educational opportunities, such as field trips. Nature is also the basis for a significant part of aesthetic and spiritual values held by many cultures.

In 1997, Robert Costanza and his colleagues estimated to annual value of ecosystem services to be $33 trillion dollars ($53 trillion in 2019 dollars), and many consider this to be an underestimation. For comparison the gross domestic product of the United States

in 2020 was $21 trillion. Valuing ecosystem services can be difficult, particular for those services that are processes rather than provisions. One strategy is to calculate replacement cost. For example, how much would it cost to control a pest population if it was not regulated by natural processes? Figure 7.6.*b* illustrates the value of a few ecosystem services.

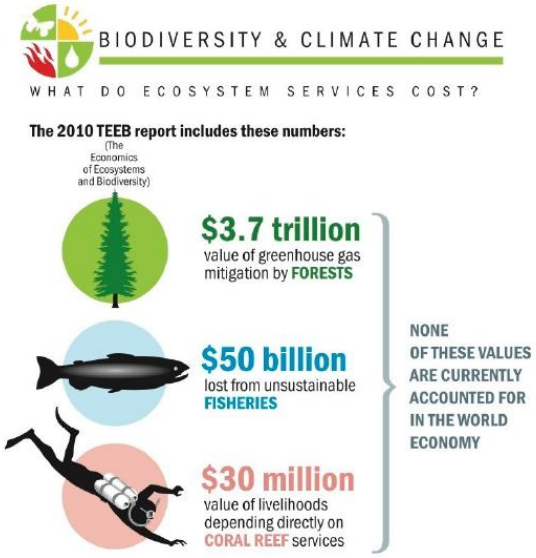


Figure 7.6.*b*: The value of three ecosystem services. The question, "What do ecosystem services cost?" is partially answered by the 2010 TEEB (The Economics of Ecosystems and Biodiversity) report. Greenhouse gas mitigation (which limits climate change) provided by forests is valued at $3.7 trillion. Unsustainable fisheries have compromised fish availability, costing $50 billion. Coral reef services, such as tourism, are valued at $30 million. Values are in 2010 dollars. None of these values are currently accounted for in the world economy. Data from The Economics of Ecosystems and Biodiversity Synthesis Report. Image by Future Challenges (CC-BY-SA).

Food Production and Ecosystem Services

Food production relies on several interacting ecosystem services. Most soils contain a huge diversity of organisms that maintain nutrient cycles, breaking down organic matter into nutrient compounds that crops need for growth. These organisms also maintain soil texture that affects water and oxygen dynamics in the soil that are necessary for plant growth. Replacing the work of these organisms in forming **arable** (farmable) soil is not practically possible. They occur within ecosystems, such as soil ecosystems, as a result of the diverse metabolic activities of the organisms living there, but they provide benefits to human food production, drinking water availability, and breathable air.

Other key ecosystem services related to food production are plant pollination and crop pest control. It is estimated that honeybee pollination within the United States brings in $1.6 billion per year; other pollinators contribute up to $6.7 billion. Over 150 crops in the United States require pollination to produce. Many honeybee populations are managed by beekeepers who rent out their hives' services to farmers. Honeybee populations in North America have been suffering large losses caused by a syndrome known as **colony collapse disorder**, a phenomenon with complex and interacting causes.

Other pollinators include a diverse array of other bee species and various insects and birds. Loss of these species would make growing crops requiring pollination impossible, increasing dependence on other crops. A 2002 study by Claire Kremen and colleagues found that **native** pollinators in Central California (those that historically occurred there; figure 7.6.*c* and d) provided full pollination to watermelon crops. This was only true on organic farms that were located near the natural habitat for these pollinators, highlighting the importance of sustainable farming practices and habitat conservation in preserving ecosystem services. Essentially, in a healthy ecosystem, native pollinators eliminated the need for rented honeybee hives. Note that while honeybees are valuable in an agricultural setting, they are not native to North America and can disrupt ecosystems by competing with native bees.



Figure 7.6.*c*: The California bumble bee (*Bombus californicus*) is one of several native insects that provided watermelon pollination in Kremen and colleagues' study. Image by Rhododendrites (CC-BY-SA).



Figure 7.6.*d*: Mason bees are efficient pollinators, and many are native to North America. Image by Robert Engelhardt (CC-BY-SA).

Finally, humans compete for their food with crop pests, most of which are insects. Pesticides control these competitors, but these are costly and lose their effectiveness over time as pest populations adapt. They also lead to collateral damage by killing non-pest species as well as beneficial insects like honeybees, and risking the health of agricultural workers and consumers. Moreover, these pesticides may migrate from the fields where they are applied and do damage to other ecosystems like streams, lakes, and even the ocean (see Industrial Agriculture and Environmental Toxicology). Ecologists believe that the bulk of the work in removing pests is actually done by predators and parasites of those pests, but the impact has not been well studied. A review found that in 74 percent of studies that looked for an effect of landscape complexity (forests and fallow fields near to crop fields) on natural enemies of pests, the greater the complexity, the greater the effect of pest-suppressing organisms. Another experimental study found that introducing multiple enemies of pea aphids (an important alfalfa pest) increased the yield of alfalfa significantly. This study shows that a diversity of pests is more effective at control than one single pest. Loss of diversity in pest enemies will inevitably make it more difficult and costly to grow food. The world's growing human population faces significant challenges in the increasing costs and other difficulties associated with producing food.

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7.7: Patterns of Biodiversity

Developing a strategy to conserve biodiversity requires a firm understanding of where **threatened species** and populations occur, why they are threatened, what their needs are, and what role they play in their respective ecosystems. By obtaining an understanding of species' distributions, biologists simultaneously gain an initial rough "estimate" of genetic diversity and ecosystem diversity. While addressing these questions is a critical task, finding appropriate answers can be complex, expensive, and take a long time to solve. This is in no small part because identifying species can, at times, be a very challenging endeavor.

Challenging species identifications

Before biologists can determine a species' distribution, needs, and population status, it is important to know the identity of the individuals being studied. While this may sound like a straightforward task, the process of identifying (and naming) a species can be deceptively hard, even for professional taxonomist. For example, a recent study found that 58% of 4,500 wild African ginger (*Aframomum* spp.) specimens that were deposited by professional biologists across 40 herbaria in 21 countries were given the wrong name (Goodwin et al., 2015)!

> Describing species can be difficult, in part, because the multiple methods used by biologists to separate species do not always give the same results.

Identifying species can be hard, in part because the three tests biologists use to separate different species—morphology, biology, and evolution—do not always give the same results. That is because the methods and assumptions of each test are different. For example, some species have several varieties with easily observed morphological differences but are biologically and genetically similar enough that all those varieties are still considered a single species. A well-known example is the single species *Canis familiaris*, or domestic dog, whose wildly variable and numerous breeds can interbreed despite their large morphological differences. In contrast, some butterflies are considered distinct species because they cannot interbreed and have a characteristic genetic makeup, even though they cannot be separated by the naked eye.

Another important aspect complicating species identifications is that **speciation**—whereby one species evolves into another—is a slow and gradual process; for some species, it may take many thousands of years. Consequently, much controversy exists about where to draw the "new species" line; in other words, when is a species distinct enough to be considered a separate species? Similarly, biologists often struggle to **split** and identify **cryptic species**—undescribed species that are wrongly grouped with other similar-appearing species. A recent study estimated that 60% of newly discovered species are cryptic (Ceballos and Ehrlich, 2009).

To complicate matters even further, some species are closely related enough that they sometimes mate and produce **hybrids**. These hybrids blur the distinction between species, particularly those that may be early in the process of speciation. For some taxa, hybridization naturally occurs in areas where the distribution ranges of related species overlap (e.g. de Jong and Butynski, 2010). Such natural hybridization plays an important role in speciation (the evolution of new species). But hybridization can also be detrimental to conservation efforts, particularly when it involves rare species and/or human disturbance. For example, when humans reduce one species' populations so much that they struggle to find reproductive partners of their own kind (e.g. vaz Pinto et al., 2016), when humans remove dispersal barriers that kept related species apart (e.g. Mondol et al., 2015), or when humans force related species that naturally occupy separate distributions to live together through **translocations** (e.g. Grobler et al., 2011; Benjamin-Fink and Reilly, 2017; van Wyk et al., 2017). While some hybrids may be sterile and thus unable to reproduce, at other times the resulting offspring can be quite strong in an evolutionary sense—a condition known as **hybrid vigor** (or heterosis)—and may outcompete their parent species. The Cuban Crocodile (Figure 7.7.1), endemic to Cuba and critically endangered under the IUCN Red List, is restricted mainly to the Zapata Swamp where it coexists with the more widely distributed American Crocodile. Evidence of hybridization between these two species in the wild has been collected through DNA analysis. This hybridization further threatens the existence of the Cuban Crocodile. (Milian-Garcia et al., 2014)

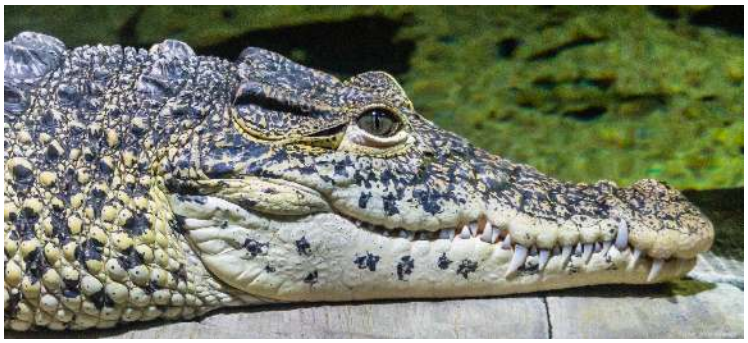


Figure 7.7.1: Critically Endangered Cuban Crocodile (*Crocodylus rhombifer)*. (Photo by Iain A. Wanless, Flickr, CC-BY-2.0)

Because the demand for expert taxonomists outstrips their availability, there is also a need to train and employ more taxonomists, particularly in the tropics and other species-rich areas. The public can help in this endeavor. In 2015, **citizen scientists**—volunteers participating in scientific projects—discovered 51 of 60 new dragonfly species from Africa that were described that year (Dijkstra et al., 2015).

Measuring species diversity

Species diversity is the number of different species in a particular area and their relative abundance. The area in question could be a habitat, a biome, or the entire biosphere. Areas with low species diversity, such as the glaciers of Antarctica, still contain a wide variety of living organisms, whereas the diversity of tropical rainforests is so great that it cannot be accurately assessed. **Species richness**, the number of species living in a habitat or other unit, is one component of biodiversity. **Species evenness** is a component of species diversity based on **relative abundance** (the number individuals in a species relative to the total number of individuals in all species within a system). Foundation species (see Ecosystem Types and Dynamics) often have the highest relative abundance of species. Two locations with the same richness do not necessarily have the same species evenness. For example, both communities in figure 7.7.2 have three different trees species and thus a species richness of three. However, there is a dominant species (represented by six individuals) in community #1. In community #2, there are three of individuals of each species. Therefore, community #2 has a greater species evenness and greater species diversity overall.



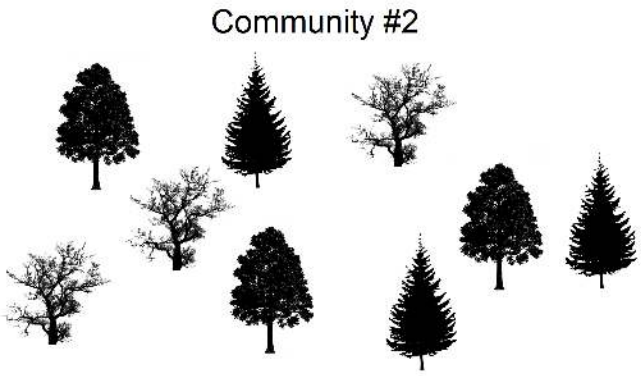


Figure 7.7.2: Two hypothetical tree communities have the same species richness, but community #2 (bottom) has a greater species evenness. Both communities have nine trees and three tree species. In community #1, one species is dominant, represented by six individuals. There are two individuals of a conifer species, and only one individual of the final species. In community #2, there are three individuals from each species. Images compiled by Melissa Ha from Alone tree George Hodan, Old Tree Silhouette, and Tree (all public domain).

Biologists have developed three quantitative measures of species diversity as a means of measuring and comparing species diversity (Figure 7.7.3):

- **Alpha diversity** (or **species richness**), the most commonly referenced measure of species diversity, refers to the total number of species found in a particular biological community, such as a lake or a forest.
- **Gamma diversity** describes the total number of species that occur across an entire region, such as a mountain range or continent, that includes many ecosystems.
- **Beta diversity** connects alpha and gamma diversity. It describes the rate at which species composition changes across a region. For example, if every wetland in a region was inhabited by a similar suite of plant species, then the region would have low beta diversity; in contrast, if several wetlands in a region had plants communities that were distinct and had little overlap with one another, the region would have high beta diversity. Beta diversity is calculated as gamma diversity divided by alpha diversity.

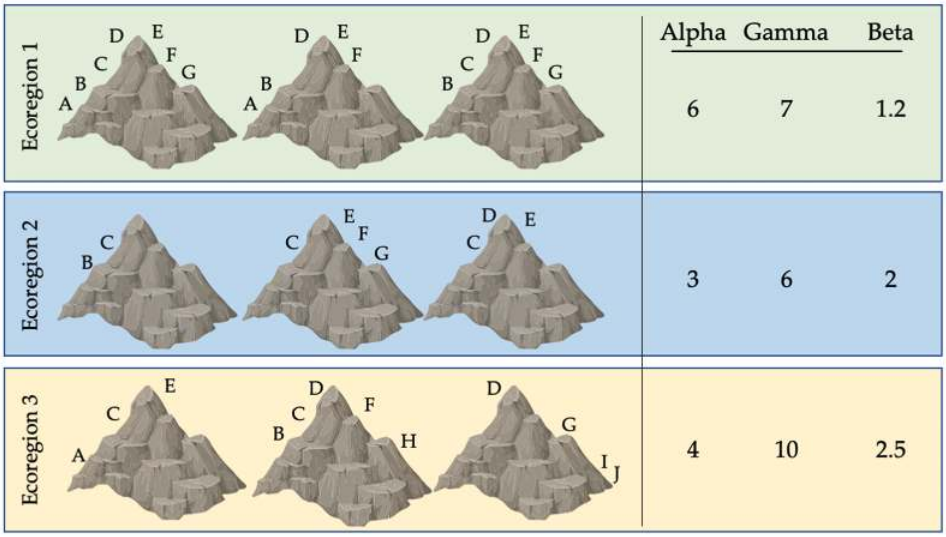


Figure 7.7.3 Biodiversity indices for nine mountain peaks across three ecoregions. Each symbol represents a different species; some species have populations on only one peak, while others are found on two or more peaks. The variation in species richness on each peak results in different alpha, gamma, and beta diversity values for each ecoregion. This variation has implications for how we divide limited resources to maximize protection. If only one ecoregion can be protected, ecoregion 3 may be a good choice because it has high gamma (total) diversity. However, if only one peak can be protected, should a peak in ecoregion 1 (with many widespread species) or ecoregion 3 (with several unique, range-restricted species) be protected? After Primack, 2012, CC BY 4.0.

It is important to note that alpha, beta, and gamma diversity describe only part of what is meant by biodiversity. For example, none of these three terms completely account for genetic diversity, which allows species to adapt as conditions change. It also neglects the importance of ecosystem diversity, which results from the collective response of species to their dynamic environment. However, these diversity measures are useful for comparing different regions, and identifying locations with high concentrations of **native species** that should be protected.

How many species exist?

To date, taxonomists have described about 1.5 million species that share this planet with us (Costello et al., 2012). While this total may seem impressive, available evidence suggests that this estimate vastly underestimates the true extent of Earth's biodiversity. In fact, even now, after all the exploration in years gone by, several thousand new species are being described each year.

The most exciting and newsworthy discoveries of new species generally involve higher-level taxa, especially living fossils. For example, in 1938, biologists across the world were stunned by the report of a strange fish caught in the Indian Ocean off South Africa. This fish, subsequently named coelacanth (*Latimeria chalumnae*, CR), belongs to a group of marine fishes that were common in ancient seas but were thought to have gone extinct 65 million years ago. Coelacanths are of interest to evolutionary biologists because they show certain features of muscles and bones in their fins that are comparable to the limbs of the first vertebrates that crawled onto land. Following the initial discovery, coelacanths have been found along Africa's Indian Ocean coast from South Africa to the Comoros and through to Kenya. Unfortunately, the entire coelacanth population, estimated at fewer than 500 individuals, is currently highly threatened because of ongoing fishing pressures (Musick, 2000).

> Estimates suggest there are somewhere between 1–6 billion distinct species on Earth. The most diverse group of species is bacteria.

The presence of so many undiscovered species and communities makes precise estimates of species diversity incredibly difficult, especially in locations that remain scientifically unexplored. Our most recent estimates, combining genetic analysis of well-known groups with mathematical patterns, suggests there are between 1–6 billion distinct species on Earth (Table 7.7.1) of which there are only about 163 million animals and 340 thousand plants (Larsen et al., 2017)—this is obviously much greater than the current catalog of 1.5 million species! Given the amount of new species that continue to hide in plain sight, so to speak, there is no doubt that a great number of species and communities are waiting to be discovered over the next several decades. A 2011 study suggests that only 13% of **eukaryotic** species (such as plants, animals, fungi, and algae) have been named. Estimates of numbers of **prokaryotic** species (such as bacteria) are largely guesses, but biologists agree that science has only just begun to catalog their diversity. Given that Earth is losing species at an accelerating pace, science knows little about what is being lost.

Table 7.7.1 Estimated living biomass and number of species for each kingdom of life, following the seven-kingdom system (Ruggiero et al., 2015). Note how plants weigh the most, but bacteria have the most species.

Kingdom	Weight (Gt)	Number of species (in million)	% of all species	Number of described species	% of described species
Animals	2	163	7	1,205,336	< 1
Fungi	12	165	7	135,110	< 0.1
Plants	450	0.382c	< 0.5	364,009	95
Chromista	Unknown	0.025c	< 0.5	23,428	94
Protozoans	4	163	7	2,686	0.1
Archaea	7	0.0005	< 0.5	377	75
Bacteria	70	1,746	78	9,982	0.1

a As gigatonnes of carbon, from Bar-On et al., 2018

b From Larsen et al. (2017)'s Table 1, Scenario 1

c From http://www.catalogueoflife.org

There are various initiatives to catalog described species in accessible and more organized ways, and the internet is facilitating that effort. Nevertheless, at the current rate of species description, which according to the State of Observed Species reports is 17,000–20,000 new species a year, it would take close to 500 years to describe all of the species currently in existence. The task, however, is becoming increasingly impossible over time as extinction removes species from Earth faster than they can be described.

Naming and counting species may seem an unimportant pursuit given the other needs of humanity, but it is not simply an accounting. Describing species is a complex process by which biologists determine an organism's unique characteristics and whether or not that organism belongs to any other described species. It allows biologists to find and recognize the species after the initial discovery to follow up on questions about its biology. That subsequent research will produce the discoveries that make the species valuable to humans and to our ecosystems. Without a name and description, a species cannot be studied in depth and in a coordinated way by multiple scientists.

Where are most species found?

Because it is so hard to obtain accurate estimates of species numbers, many conservation biologists have recently started to focus their efforts on understanding and planning around patterns of species diversity. This makes sense: regions with many species of one taxon tend to also have many species of other taxa, so protecting one diverse group of species will likely also protect many other species, even if those other species are not well understood.

By examining all these patterns of species diversity across the world, biologists have discovered at least two general frameworks governing species richness. The first framework is that stable ecosystems usually have many species, while ecosystems that were subjected to more recent glaciation usually have fewer species. This observation explains why tropical ecosystems are generally considered the world's most species-rich environments. While tropical grasslands, wetlands, and other ecosystems all hold relatively high species diversity, species richness of tropical forests are particularly noteworthy; even though these areas occupy only about 7% of Earth's land surface, they contain over half of the world's species (Corlett and Primack, 2010). This is, in a large part, due to the relatively large global distribution of the tropical forests and the diversity of geological history between these areas of South and Central America, Africa, Asia, and Australia, which has resulted in unique assemblages of species that have evolved in isolation from each other.

Tropical forests are not the only species-rich tropical ecosystem. Tropical coral reefs, colonies of tiny aquatic invertebrates that form entire ecosystems (Figure 7.7.4), are the marine equivalent of tropical forests both in terms of species richness and complexity. These areas not only provide homes for corals, but also for huge numbers of fish, molluscs, and marine mammals that find shelter in these highly productive and sheltered ecosystems.



Figure 7.7.4 Coral reefs such as this one at Zanzibar's Mnemba Atoll, off the north coast of Tanzania, are highly diverse underwater ecosystems composed of the accumulated skeletons of billions of tiny marine invertebrates. These underwater landscapes provide habitat for at least 25% of all marine species. Photograph by Kamal Karim, https://www.flickr.com/photos/118534047@N06/22449100152, CC BY 2.0.

High levels of species diversity, especially among plants, can also be found in ecosystems with a Mediterranean climate, such as southwestern Africa, as well as southwestern Australia, California, central Chile, and the Mediterranean Basin of southern Europe and North Africa. The climate of a Mediterranean-type ecosystem is characterized by cool, moist winters, hot, dry summers, resulting in distinctive plant adaptations such as short twigs and stiff leaves. A combination of special environmental factors, including a considerably old geological age, complex site characteristics (such as varied topography and soils), and frequent fires facilitated rapid speciation and helped to prevent any one species from dominating. Today, although regions with a Mediterranean climate cover only 2% of Earth's surface, 20% of all plant species are found here (Underwood et al., 2009).

The second framework governing pattern of species diversity is that locations with high numbers of species usually hold many endemic species.

Biogeographic transition zones—also known as **ecotones**—regions where different ecosystems meet and overlap, are a special case of areas that contain great species diversity and high levels of endemicity. These areas share environmental factors of two or more environments, allowing for the mixture of biodiversity from those component environments, while unique features within these areas often also give rise to unique species.

Today is an exciting time of biological exploration. Methods and technologies for exploration are improving rapidly, and we are learning more about the value and function the diversity of life on Earth. As genetic techniques advance and become more accessible, an increasing number of people are participating in recording the presence of species in locations around the world; this includes amateur **naturalists** and citizen scientists who contribute to bird surveys, plant walks, and other **natural history** activities. With this increased knowledge of biodiversity also comes an acute awareness that human activities damage ecosystems and reduce diversity. Hopefully this broader awareness will spur more people to take responsibility to protect and restore that biodiversity.

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7.7.1: Species Distribution

Biodiversity is not evenly distributed on the planet. For example, Lake Victoria in Africa (figure 7.7.1.*a*) contained almost 500 species from a family of fishes called cichlids before the introduction of the **invasive** Nile Perch in the 1980s and 1990s caused a mass extinction. (Note that this number does not include species of other fish families.) Lake Huron, the second largest of North America's Great Lakes, contains about 79 species of fish, all of which are found in many other lakes in North America. What accounts for the difference in diversity between Lake Victoria and Lake Huron? Lake Victoria is a tropical lake, while Lake Huron is a temperate lake. Lake Huron in its present form is only about 7,000 years old, while Lake Victoria in its present form is about 15,000 years old. These two factors, latitude and age, are two of several hypotheses biogeographers have suggested to explain biodiversity patterns on Earth.



Figure 7.7.1.*a*: Lake Victoria in Africa, shown in this satellite image, was the site of one of the most extraordinary evolutionary findings on the planet, as well as a casualty of devastating biodiversity loss. (credit: modification of work by Rishabh Tatiraju, using NASA World Wind software)

Biogeography is the study of the distribution of the world's species both in the past and in the present. The work of biogeographers is critical to understanding our physical environment, how the environment affects species, and how changes in environment impact the distribution of a species. There are three main subfields of biogeography: ecological biogeography, historical biogeography (called paleobiogeography), and conservation biogeography. **Ecological biogeography** studies the current factors affecting the distribution of plants and animals. **Historical biogeography**, as the name implies, studies the past distribution of species. **Conservation biogeography**, on the other hand, is focused on the protection and restoration of species based upon the known historical and current ecological information.

The Tropics Have High Biodiversity

One of the oldest observed patterns in ecology is that biodiversity typically increases as latitude declines. In other words, the greatest species richness occurs near the equator and the lowest richness occurs near the poles (figure 7.7.1.*b*).

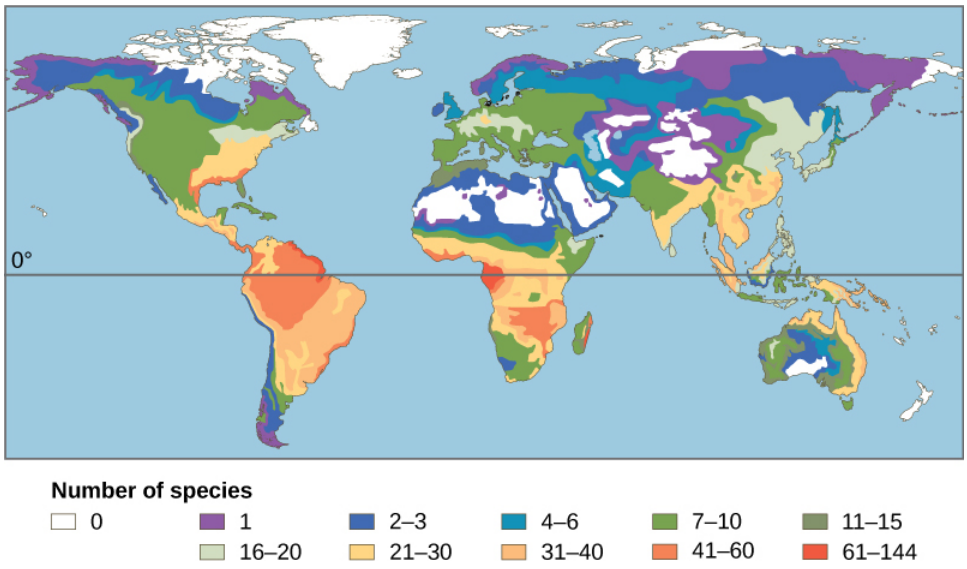


Figure 7.7.1.*b*: This map illustrates the number of amphibian species across the globe and shows the trend toward higher biodiversity at lower latitudes. A similar pattern is observed for most taxonomic groups. The greatest number of species, 61-144, are found in the Amazon region of South America and in parts of Africa. Between 21 and 60 species are found in other parts of South America and Africa, and in the eastern United States and Southeast Asia. Other parts of the world have between 1 and 20 amphibian species, with the fewest species occurring at northern and southern latitudes.

It is not yet clear why biodiversity increases closer to the equator, but hypotheses include the greater age of the ecosystems in the tropics versus temperate regions, which were largely devoid of life or drastically impoverished during the last ice age. The greater age provides more time for **speciation,** the evolutionary process of creating new species. Another possible explanation is the greater energy the tropics receive from the sun, but scientists have not been able to explain how greater energy input could translate into more species. The complexity of tropical ecosystems may promote speciation by increasing the habitat complexity, thus providing more **ecological niches** (see Communities chapter). Lastly, the tropics have been perceived as being more stable than temperate regions, which have a pronounced climate and day-length seasonality. The stability of tropical ecosystems might promote speciation. Regardless of the mechanisms, it is certainly true that biodiversity is greatest in the tropics. There are also high numbers of endemic species.

Biodiversity Hotspots

In 1988, British environmentalist Norman Myers developed a conservation concept to identify geographical areas rich in species and at significant risk for species loss: **biodiversity hotspots**. The original criteria for a hotspot included the presence of 1500 or more endemic plant species and 70 percent of the area disturbed by human activity. **Endemic species** are found in only one location. For example, all of cichlid species found in Lake Victoria only occurred there. The blue jay is endemic to North America, while the Barton Springs salamander is endemic to the mouth of one spring in Austin, Texas. Endemic species with highly restricted distributions, like the Barton Springs salamander, are particularly vulnerable to extinction. If a population of a widespread species declines in one region, individuals from another region may be able to recolonize the first location, but this is not possible for endemic species. Endemic species are particularly common in isolated regions, such as mountaintops or islands. Endemism is especially likely on islands that are large and far from the mainland. Identifying biodiversity hotspots aids with conservation efforts, a kind of conservation triage. By protecting hotspots, governments are able to protect a larger number of species. There are now 36 biodiversity hotspots (figure 7.7.1.*c*) containing large numbers of endemic species, which include half of Earth's endemic plants.

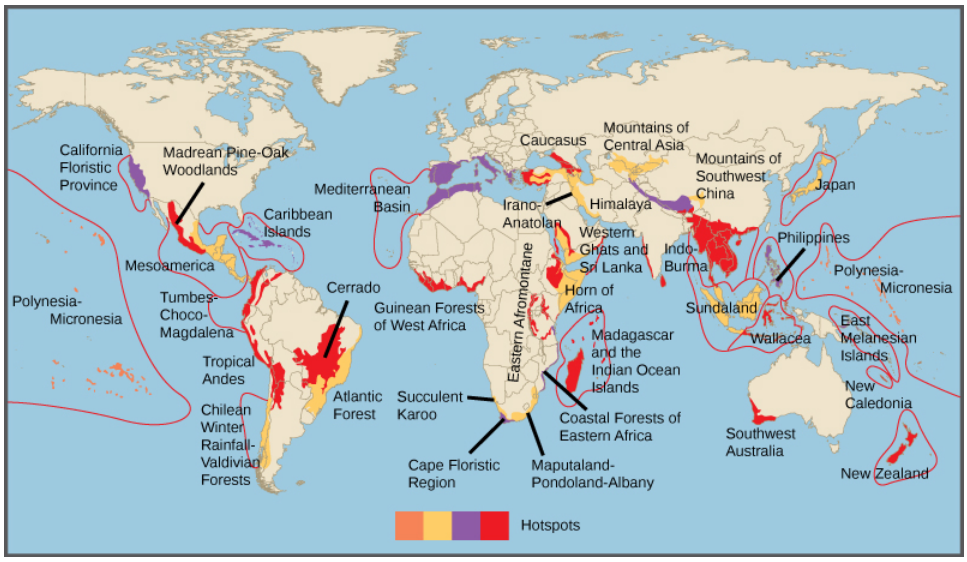


Figure 7.7.1.*c*: Conservation International has identified 36 biodiversity hotspots, which cover only 2.5 percent of the Earth's surface but have endemic to them 42 percent of the terrestrial vertebrate species and 50 percent of the world's plants. Hotspots are shaded in red, purple, yellow, or orange. Examples include the California Floristic Province, Tropical Andes, Mediterranean Basic, Cape Floristic Province, and Polynesia-Micronesia.

Biodiversity Hotspots in South Africa

A rich species diversity is found in South Africa. With a land surface of approximately 148,000 km^2 (about 57,000 square miles), representing approximately 1% of the Earth's total surface, South Africa contains 10% of the world's total known bird, fish and plant species, and 6% of the world's mammal and reptile species.

This natural wealth is threatened by the expansion of the human population and the increasing demand this places on the environment. The Karoo (figure 7.7.1.*d*) and the Cape are biodiversity hotspots in South Africa. South Africa has a wide range of climatic conditions and many variations in landscape, creating a variety of ecological niches, which can promote species diversity. These various landscapes give rise to the biomes which allow a wide variety of life to survive.



Figure 7.7.1.*d*: Map of South Africa, illustrating the Karoo, a dry region with hot summers and cold winters. Image by (WT-shared) NJR ZA at wts wikivoyage (CC-BY-SA).

More than 20,300 species of flowering plants occur in South Africa (figure 7.7.1.*e*). One of the six most important areas of plant growth in the world is in the Western Cape. Most of the 2,000 threatened species of plants are found in the **fynbos** in South-West Cape (figure 7.7.1.*f*).



Figure 7.7.1.*e*: Vegetation of the Karoo in near Willowmore, Eastern Cape, South Africa. Image by Winfried Bruenken (CC-BY-SA).



Figure 7.7.1.*f*: Vegetation of the fynbos in Western Cape, South Africa. Image by Joachim Huber (CC-BY-SA).

South Africa is home to 243 mammal species. Among the 17 threatened species in South Africa are the black rhino, pangolin, and giant golden mole. The blue antelope and quagga (figure 7.7.1.*g*) have become extinct. Of more than 800 bird species, 26 are threatened, including the penguin, Cape vulture, martial eagle (figure 7.7.1.*h*), and Cape parrot. In total 370 reptiles and amphibians occur in the region of which 21 are threatened. Six of these are endangered. Of the 220 freshwater fishes in South Africa, 21 are threatened. There are more than 2,000 marine fish species. While many insect species remain unidentified, 80,000 insects are known to occur.

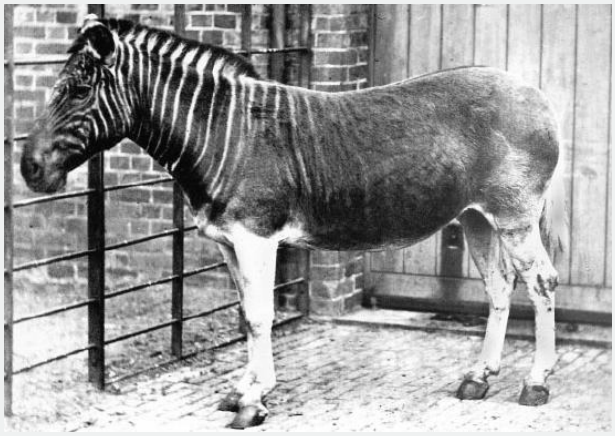


Figure 7.7.1.*g*: The quagga (*Equus quagga quagga*), now extinct, is technically a subspecies of the plains zebra. Image by Stanford Woods (public domain).



Figure 7.7.1.*h*: The Martial Eagle (*Polemaetus bellicosus*) is one of the threatened bird species found in South Africa. Image by Charles J. Sharp (CC-BY-SA).

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Spatial and Temporal Heterogeneity Promote Biodiversity

Environmental heterogeneity refers to the lack of uniformity in an area. Regions that are spatially heterogeneous are composed of smaller areas with contrasting vegetation, water and nutrient availability, soils and rocks, or other features. In regions that are temporally heterogeneous, conditions fluctuate over time. Heterogeneity promotes species richness by increasing the number of ecological niches, and heterogenous regions are thus priorities with respect to conserving biodiversity. Some regions are more hetergeneous than others. For example, a wetland consists of many microhabitats that differ in soil type and water availability, and water levels change over the seasons. Other regions, like the temperate grasslands in the midwestern United States, are relatively homogenous (uniform). Just as biodiversity can be assessed at a variety of scales, heterogeneity can be measured at large scales (such as within an entire biome) or small scales (such as within a single meadow).

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7.8: Summary

1. Earth's biodiversity includes the entire range of living species (species diversity), the genetic variation that occurs among individuals within a species (genetic diversity), and, at a higher level, the biological communities in which species live and their associations with the physical and chemical environment (ecosystem diversity).
2. For practical purposes, most ecologists and conservationists identify species in the field according to their morphology, although improvements in genetic techniques are allowing more species to be identified according to their evolutionary past, revealing many cryptic species that people did not realise were there.
3. There are several ways to measure and compare biodiversity. The most popular measurement is species richness in a particular community, such as a forest or grassland (alpha diversity), species richness across a larger landscape, such as a mountain range (gamma diversity), and the rate of change of species composition as one crosses a large region (beta diversity).
4. It is estimated that there may be as many as 2 billion species on Earth. Most species already described are insects, while the best-known species include birds and mammals. The majority of species still need to be discovered.
5. Variation in climate, topography, and geological age are all factors that affect patterns of species richness. Geological age and complexity provide environmental variation, which in turn allows opportunities for genetic isolation, local adaptation, and speciation, given enough time. Tropical forests, coral reefs, and Mediterranean-type ecosystems host a disproportionately large amount of the world's biodiversity.

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7.9: Topics for Discussion

1. Think of any group of species (birds, trees, or maybe insects) that can be found in the area where you live. Do you think it is important to be able to identify these species? Why? How many species can you personally identify at this moment? What steps would you take to learn to identify more species?
2. Which ecosystems in your country are particularly species-rich, and which are species-poor? Describe some factors that make ecosystems species-rich or species-poor.
3. Which biomes on Earth do you think most undescribed species are lurking? Explain your answer.

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CHAPTER OVERVIEW

8: Importance of Biodiversity

8.1: Introduction to the Importance of Biodiversity
8.2: Material Contributions
8.3: Regulating Services
8.4: Nonmaterial Contributions
8.5: Option Values
8.6: Environmental Economics
8.7: Summary
8.8: Topics for Discussion
8.9: Bibliography

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8.1: Introduction to the Importance of Biodiversity

All of us depend on nature for survival, whether we live off the land, or in a city where we can buy natural resources, transported to us from a distance, at the market. When we do not take care of nature, our quality of life suffers. To illustrate this point, in the book, *Collapse* (2011), prize-winning author Jared Diamond describes how, throughout history, ineffective responses to ailing environments have contributed to human conflicts.



The charismatic baobab (*Adansonia digitata*) standing tall outside Dakar, Senegal. Sometimes called the "Tree of Life" for its enormous value to humans, the baobab is also a keystone species. In addition to providing food for a great number of species, baobabs also provide an important refuge for several bat and bird species that exclusively use these trees for roosting, nesting, and breeding. Photograph by Mattia Menchetti, https://www.inaturalist.org/photos/24373230, CC BY-SA 4.0.

Between 1950 and 2000, 80% of the world's armed conflicts occurred within the boundaries of the world's 36 **Global Biodiversity Hotspots** (Hanson et al., 2009)—areas with high levels of biodiversity that also suffer from substantial environmental degradation. Even today, environmental degradation continues to play a major role in fueling ongoing conflicts, such as those of the Middle East (Gleick, 2014), West Africa's Sahel region (Benjaminsen, 2008), and the Horn of Africa (Markakis, 1995). Preventing these conflicts, which also impact biodiversity negatively (Nackoney et al., 2014; Brito et al., 2018; Daskin et al., 2018), from escalating and new conflicts from developing requires political and societal changes. People in government and local communities must recognize the value of **healthy ecosystems** and become their champions. After all, complex and adaptive ecosystems provide jobs, food, and other resources, thereby contributing to our overall well-being.

> A healthy environment improves our overall wellbeing by enabling us to live healthy and prosperous lives. In other words, it is our life support system.

But what exactly are we losing when we fail to protect biodiversity? Why should we care if a species goes extinct, or an ecosystem becomes degraded? What evidence do we have that the natural world is our life support system? To better understand the importance of biodiversity for human well-being and quality of life, and the variety of benefits people freely gain from biodiversity, the UN brought together a group of leading scientists to study **nature's contributions to people (NCP**, Díaz et al., 2018), more commonly referred to as **ecosystem services**. This group, called the **Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)**, recognizes three categories of ecosystem services, namely material contributions, regulation services, and nonmaterial contributions. Note that there are broad overlaps and interdependence among the three categories; consequently, some contributions and services can easily fit under more than one category.

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8.2: Material Contributions

Nature's material contributions to people, also called provisioning services, commodity values or **direct use values**, represent contributions derived from the direct extraction and physical consumption of natural resources (Figure 8.2.1). This category is often the most visible and marketed of all ecosystem services. Also, because of their important contribution to the economy, economists are often interested in calculating the values of material contributions and associated services, which they do by monitoring the cost of each product at several points along its life cycle, as well as the behaviors of target groups of people.



Figure 8.2.1 (Top) A Mandari fisherman from South Sudan carrying smoked fish to the local market. Photograph by Leonard Tedd/DFID, https://www.flickr.com/photos/dfid/8379215187, CC BY-SA 2.0. (Bottom) A lady from Burkina Faso returns to her village with a bundle of firewood for cooking. Photograph by Jose Navarro, CC BY 4.0.

Material contributions can be subdivided into four subcategories. The first subcategory is energy resources, such as firewood and biofuels. The second is food resources, such as drinking water, bushmeat, and edible fruit. The third is materials, companionship, and labor, which include natural products used to make clothes, ornamental resources used for decorations, and animals used for biomedical research, as pets, and for labor. The fourth is medicinal, biochemical, and genetic resources, which include medicinal plants used to cure ailments, psychoactive fungi used in spiritual ceremonies, and genetic stocks used to improve crops.

Many people, especially those in rural areas, obtain many of the material contributions they need for survival from the surrounding environment. These products, which include bushmeat, perfumes from aromatic plants, and firewood, are often assigned to **consumptive use values**. According to the IPBES 2019 Global Assessment Report on Biodiversity and Ecosystem Services, more than two billion people worldwide rely on wood for their primary energy source (IPBES 2019). In contrast, material contributions that are sold at commercial markets, whether locally or internationally, are assigned to **productive use values**. Because of material contributions' importance in sustaining people's material assets and health, it is important to ensure that these products are sustainably harvested.

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8.3: Regulating Services

Regulating services maintain nature's ability to provide material contributions, usually in indirect ways. For example, our ability to obtain food indirectly depends on a variety of subtle yet important ecosystem processes (e.g. energy cycling), as well as more observable services (e.g. pollination). For that reason, regulation services are sometimes called **indirect use values**. Regulating services (together with nonmaterial contributions, discussed below) are also sometimes referred to as **non-consumptive use values** because they provide economic benefits without needing to be collected, harvested, consumed, converted, or destroyed during use.

> The economic benefits we gain from regulating services are estimated to be larger than all the different kinds of material contributions together.

The economic benefits we gain from regulating services are estimated to be larger than all the different kinds of material contributions together, especially in areas where ecosystems are intact (Costanza et al., 2014). Over 75% of global food crops rely on animal pollination (IPBES 2019). Even so, these benefits do not always appear in descriptions of national economies because those statistics generally focus on material contributions. Nonetheless, maintaining regulating services is very important. When damaged ecosystems cannot provide these benefits, substitute resources must be found—often at great expense—to avoid economic collapse. Later in the text, we discuss one such example, by considering the value and replacement costs of water maintenance services obtained from forests.

Regulating services can be subdivided into many different subcategories depending on context, each overlapping to varying degrees with one another. Following is a discussion of some prominent subcategories of regulating services.

Maintaining ecosystem stability

Perhaps the most important indirect contribution we gain from biodiversity is its ability to maintain conditions that enable life on Earth to persist. This principle complements the **Gaia hypothesis**, which proposes that all the biological, physical, and chemical properties on Earth interact to form a complex, self-regulating superorganism, and that these interactions maintain the conditions and processes necessary for life to persist (Lovelock, 1988).

There are two complementary theories that explain the importance of maintaining a variety of different species if one is to conserve this superorganism (Ehrlich and Walker, 1998). Originally proposed by American ecologist Paul Ehrlich, the **rivet-popper hypothesis** compares biodiversity to the rivets (some of which may be redundant) that hold an airplane together. Just as an airplane can only lose so many rivets before it falls apart, so will the progressive loss of species systematically weaken an ecosystem until the entire system collapses. A well-known example of the rivet-popper hypothesis is the **mutualistic relationships** many plants have with all the various pollinators and **seed dispersers**, in this context representing the rivets holding the system together. We might not immediately notice the systematic loss of pollinators we are currently experiencing (Gallai et al., 2008; Dirzo et al, 2014), but eventually these losses will catch up with us, perhaps in the form of food insecurity.

The **species redundancy hypothesis**, proposed by African ecologist Brian Walker, holds that biodiversity and ecosystem stability is best maintained not by focusing on preserving individual species, but by preserving redundancy in ecosystem functioning, by ensuring that each ecosystem is composed of a variety of (seemingly redundant) species performing similar roles. In other words, we should not focus our efforts on protecting just one or two important pollinating species, but a variety of them, to ensure that a variety of plants (and hence entire ecosystems) can also continue to survive. In this way, if one pollinator is lost due to an environmental disturbance or disease, the system will not collapse because other pollinating species will be able to compensate for the loss of that one species.

It is important to note that there are some individual species that provide such an outsized contribution to ecosystem functioning that their loss will greatly alter ecosystem composition and functioning. These "pilots" of natural ecosystems are generally known as **keystone species** (Figure 8.3.1). The keystone species concept was originally proposed after scientists observed that removing sea stars from intertidal zones allowed their prey (mussels) to increase uncontrollably which, in turn, pushed species, such as sea urchins and other shellfish, away, leaving an overall poorer ecosystem (Paine, 1969). Apex predators, such as lions (*Panthera leo*, VU) and cheetahs (*Acinonyx jubatus*, VU), are also keystone species because of their role in keeping herbivore populations under control. If these apex predators were to disappear, increasing herbivore populations would lead to overgrazing, and ultimately also

herbivore declines. This top-down control predators exert on herbivores also answers one of modern ecology's oldest questions: "why is the world green?" (Hairston et al., 1960).

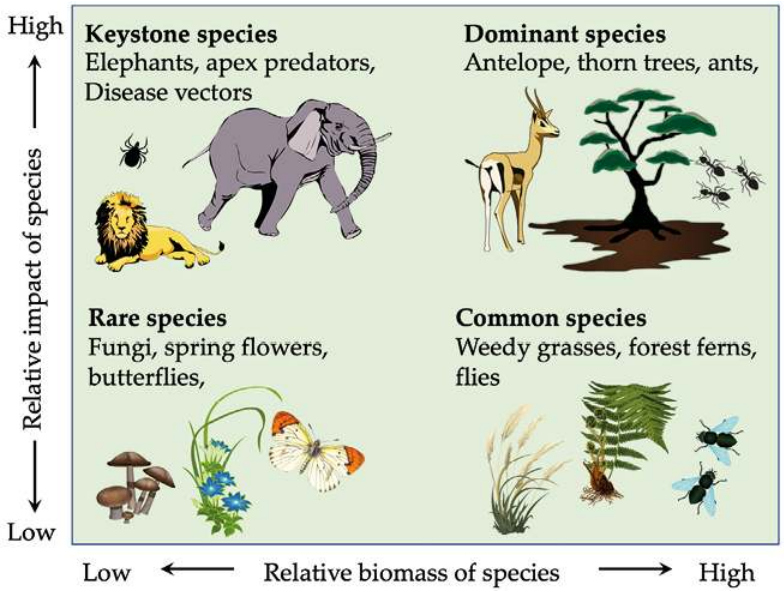


Figure 8.3.1 Although keystone species constitute only a small proportion of their ecosystem's overall living biomass, they have such disproportionately important roles that their disappearance would lead to drastic environmental changes. This contrasts with rare species that constitute a low proportion of overall biomass and have a minimal impact on their ecosystems' organization. Like keystone species, dominant species have a significant impact on their environment; however, they also make up a large proportion of an area's living biomass. Common species, in turn, have a relatively minimal impact on their communities despite making up a large proportion of the living biomass. After Power et al., 1996, CC BY 4.0.

An **ecosystem engineer** is a special type of keystone species that extensively modifies the physical environment, thereby creating and maintaining habitats for other species. Mound-building termites are important ecosystem engineers in the grassland and savanna ecosystems of Africa, Asia, and South America because their activities alter physical, chemical, and biological soil properties (Jouquet et al., 2011), and their massive mounds (some mounds are 10 m high, 20 m across, and may be over 2,000 years old) (Figure 8.3.2) support distinctive ecological communities and serve as refuges for a large variety of animals and even plants (Loveridge and Moe, 2004; van der Plas et al, 2013). Elephants are also ecosystem engineers; their dramatic foraging habit of pushing over trees provides suitable habitats to countless small animals (Pringle, 2008). Elephants also open up dense vegetation, which allows grasses to thrive, in turn providing food for grazing antelope (Valeix et al., 2011). Holes dug by elephants sometimes make water more accessible, while elephant dung provides food for butterflies and dung beetles and creates an important germination environment for seeds and fungi. But too many elephants can also damage ecosystems by reducing the number of large trees on which other species depend (Cumming et al., 1997). It is important to remember that water is an important limiting resource for elephants (Chamaillé-Jammes et al., 2008), so there is a greater risk for elephants to become overly destructive in areas where humans artificially increase aboveground water availability.



Figure 8.3.2: Termite mound in Ghana. (CC-BY-4.0; Kelby Boateng, Wikimedia commons)

Because so many species depend on ecosystem engineers and other keystone species for survival, their disappearance from an ecosystem can create an **extinction cascade**—a series of linked extinction events following one another. A related phenomenon known as a **trophic cascade** describes the situation where one keystone species' loss has rippling effects at other trophic levels. Some of the best-studied trophic cascades involve apex predators and their role in suppressing prey populations (Estes et al., 2011), but disease pathogens can also be a keystone species that leads to trophic cascades. For example, the introduction of rinderpest from Asia to Africa in the late 1800s caused catastrophic ungulate population declines in East Africa through the early 1900s. With no primary consumers, grasslands were encroached by woody plants; these changes in the primary producer community also increased the intensity and frequency of wildfires, leading to cascading impacts throughout these savannah communities. An extensive vaccination program finally saw the disease eradicated in the 1960s, allowing ungulate population and grasslands to recover; and wildfires to become less destructive (Holdo et al., 2009).

> The loss of keystone species from an ecosystem may create an extinction cascade—a series of linked extinction events following one another.

Maintaining ecosystem productivity

Plants and algae—in this context known as primary producers—use photosynthesis to capture and store energy from sunlight in their living tissue. This ability of ecosystems to generate living biomass, starting with plants trapping the sun's energy, is known as **ecosystem productivity**. Primary consumers (i.e. herbivores) can then harvest this captured energy by eating plant material. The energy (and nutrition) obtained from plants enable herbivores to generate their own living biomass, in the form of growth and reproduction, before they, themselves, are consumed by secondary consumers (e.g. carnivores, predators, **omnivores**). This cycle ends (or starts, depending on one's perspective) when **decomposers** and **detritivores** (e.g. fungi, earthworms, and millipedes) that break down complex plant and animal tissues into simple compounds such as nitrates, and phosphates. These simple compounds are then released into the soil and water, from where primary producers can take them up again.

Climate regulation

Many of us were taught from a young age that plants are the "lungs of the planet" (Figure 8.3.3) because they convert carbon dioxide (CO_2) into breathable oxygen (O_2) during photosynthesis. This contribution, whereby plants regulate the atmosphere's CO_2/O_2 balance through carbon absorption and storage (termed **carbon sequestration**) forms part of the atmospheric carbon cycle and plays a major role in regulating global climate patterns. The reduction in plant life through deforestation or other human activities is thus of major concern because of the reduced capacity of plants to sequester atmospheric carbon dioxide, a greenhouse gas that contributes to climate change. The important role of plant communities in the atmospheric carbon cycle is now even being recognized by global markets. For example, the carbon-storing capacity of the Congo Basin's forests has an estimated value at over US $2.5 billion per year (Hughes, 2011). As part of the worldwide effort to reduce carbon dioxide emissions and address climate

change, industrial countries and corporations have started paying some landowners to preserve and restore ecosystems that store significant amounts of carbon.



Figure 8.3.3 A very visual advertisement campaign used emotion and guilt to raise awareness of deforestation. It shows a forest as a pair of lungs, rivers symbolizing veins and arteries, and water representing blood. The left lung is healthy, but the right one is partially cut down, symbolic of a cancer, to remind us that ongoing deforestation will increase our own personal discomfort. Image by TBWA\Paris, CC BY 4.0.

Plants are also important in regulating regional climate conditions by influencing both the water cycle via transpiration, and local heating and cooling via solar radiation absorption. For example, forests and other vegetation often absorb more heat than bare soil due to their respective **albedos**. Because heat rises, heat absorbed by vegetation enables water vapor released by plants via transpiration to rise higher into the atmosphere, where it subsequently condenses and falls as rain. In contrast, the loss of vegetation is often associated with reduced rainfall (Garcia-Carreras and Parker, 2011), which can in turn reduce agricultural productivity and biodiversity (Lawrence and Vandecar, 2015).

Lastly, trees keep local areas cool by providing shade and releasing water vapor into the atmosphere (Morakinyo et al., 2013; Kardan et al., 2015). This cooling effect increases people's comfort and work efficiency, and reduces the need for fans or air conditioners, leading to higher productivity and cost savings (Balogun et al., 2014; Ogueke et al., 2017). Trees also act as windbreaks, thereby reducing evaporation and erosion in agricultural areas, and reducing the loss of heat from homes and other buildings in cold weather. The value of shade trees is also recognized in agro-ecosystems, as a strategy for coffee and cacao farmers to increase crop yields and to adapt to increasing temperatures due to climate change (Jaramillo et al., 2011).

Conserving soil and water quality

> Wetlands play a prominent role in flood control. They are also very effective in immobilizing pathogens and toxic pollutants released into the environment by human activities.

Wetlands play a prominent role in regulating soil and water quality, as well as flood control. During heavy rains, wetlands slow the speed of rushing floodwater, which lowers flood height and reduces erosion. Wetlands also act as natural sponges: they absorb vast amounts of floodwater during heavy rains, which is then released more slowly and evenly afterwards, thereby maintaining water sources used for drinking, irrigation, hydropower generation, and transport. Wetlands are also very effective in breaking down and immobilizing pathogens, toxic pollutants, and excess nutrients released into the environment from agricultural activities, sewage, industrial wastes, and pesticides.

Wetlands are, however, not the only ecosystem that maintain soil and water quality and quality. In fact, maintaining complex and adaptive ecological communities of all kinds are of vital importance in buffering ecosystems against flooding and drought, protecting fertile soils, and maintaining water quality. In intact ecosystems, plant foliage and dead leaves intercept rain, which slows the flow of water from upper reaches of **catchment areas** into streams and rivers; this allows for a slow release of water for days or even weeks after rains have ceased. Soil is anchored in place by plant roots and aerated by soil organisms; this combination increases the soil's capacity to absorb water and hold nutrients. All these aspects together reduce flooding and limit erosion of fertile topsoil which, in turn, limits loss of essential nutrients that would otherwise occur after heavy rains.

The economic benefits of water quality maintenance services provided by intact plant communities are enormous. In the late 1980s, the New York City administration paid US $1.5 billion to local authorities in rural New York State to protect their water supplies by maintaining forests in the catchment area that surrounded the city's reservoirs, and by improving agricultural practices in the catchment area. While US $1.5 billion may seem like a lot of money, at the time it was considered a pittance compared to the US $9 billion that the man-made water filtration systems—doing the same job—would have cost over just the first 10 years in operation (NRC, 2000).



Figure 8.3.4 Logging, fire, and agriculture reduced the Mau Forest Complex, Kenya's most important catchment, to a quarter of its original size, in the process damaging the region's hydroelectric, tea, and tourism industries. Restoration plans are currently underway to reverse the destruction through extensive reforestation projects. Photograph by Patrick Shepherd/CIFOR, https://www.flickr.com/photos/cifor/36978973483, CC BY 4.0.

Pollination and seed dispersal

Pollination describes the transfer of pollen grains from male parts of a flower to female parts to allow fertilization and production of offspring. Some plants can be pollinated by wind, but others require animals to pollinate their flowers; examples include birds, bats, bees, flies, butterflies, and other insects (Figure 8.3.5). These pollination services are important for the persistence of many wild plants, as well as for many fruit, seed, and vegetable crops that we utilize as food (Box 8.3.1). Work done in Zambia, Mozambique, and Uganda showed that pollinator collapse could increase malnutrition rates by over 50% which, in turn, could increase death rates among children and mothers during childbirth (Ellis et al., 2015). Given the dependency on animal-assisted pollination in many agricultural systems, it is critical to maintain or expand pollinator-friendly practices. Our ability to continue benefiting from these services will depend on our ability to maintain and expand on pollinator-friendly activities.

Box 8.3.1 Are Wild Pollinators Important in African Agriculture?

Abraham J. Miller-Rushing

Acadia National Park, US National Park Service, Bar Harbor, ME, USA.

Pollinators and food security are so closely tied to one another they should almost be considered synonymous terms. But when people think of pollination, they often only think of honeybees, which people domesticated more than 8,500 years ago for honey production. However, wild pollinators, which include a variety of insects, birds, and mammals, are often more effective at pollinating than honeybees are. One estimate suggests wild pollinators can double fruit production compared to honeybees (Garibaldi et al., 2013). This is most likely because the morphological and behavioral diversity of wild pollinators allow for more specialized pollination relationships with plants. For example, some wild pollinators have longer proboscis (i.e. insect tongues) that enable them to pollinate deeper flowers (Figure 4.A), something honeybees cannot do. African crops rely even more on wild pollinators than do crops in other areas of the world because it can be difficult to maintain aggressive African honeybee hives and prevent them from being damaged by wild animals (African Pollinators Initiative, 2007).



Figure 8.3.5 With their long proboscis, wild pollinators, such as this white barred hawk moth (Leucostrophus alterhirundo) from Mozambique, are highly efficient pollinators. Photograph by Celesta von Chamier, https://www.inaturalist.org/observations/1124702, CC BY 4.0.

Eggplant, papaya, coffee, and palm oil—crops of huge economic and cultural importance—highlight the value of wild pollinators to local and global economies. Eggplants are hermaphroditic; in other words, they can self-pollinate. Even so, pollination from two wild bee species, namely the doubleband carpenter bee (Xylocopa caffra) and a type of sweat bee (Lipotriches rufipes), increase fruit production far beyond that of self-pollination (Gemmil-Herren and Ochieng, 2008). In contrast, papaya trees are dioecious (i.e. they have separate male and female trees) and thus depend on crosspollination (i.e. pollinators take pollen grains from male flowers on one tree to female flowers on another tree) to produce fruit. While a wide variety of wild bees and butterflies visit papaya flowers, only some hawkmoths and skipper butterflies are effective papaya pollinators, probably because they have long proboscises that can penetrate the deep papaya flowers (African Pollinators Initiative, 2007). A healthy and diverse pollinator community also help coffee plants (which relies on a variety of pollinators, Samnegård et al., 2014) and oil palm (which requires cross pollination by specialist oil palm weevils, African Pollinators Initiative, 2007) produce more fruits, thereby increasing their economic value.

Despite their value to natural ecosystems and food security, wild pollinator populations are declining worldwide (Gallai et al., 2008; Dirzo et al., 2014). To avoid losing them forever, it is important to preserve wild pollinators through the conservation and restoration of native ecosystems, sustainable agricultural practices, such as the reduced use of pesticides and herbicides, and by communicating the value of pollinators to the general public, land managers, and politicians. Additionally, monitoring and research programs aimed at pollinators could enhance our understanding of their value, ecology, and conservation.



Figure 8.3.4 (Left) A Cape sugarbird (*Promerops cafer*, LC) feeding on a pincushion (*Leucospermum sp.*), and in the process pollinating the plant. Photograph by Rafael Tosi, https://macaulaylibrary.org/asset/118353841, CC BY 4.0. (Right) A scoliid wasp (Scoliidae) pollinating a creeping foxglove (*Asystasia gangetica*) flower. Photograph by Peter Vos, https://www.inaturalist.org/observations/10965989, CC BY 4.0.

Many fruit and seed-bearing plants also depend on a process called **seed dispersal** to reproduce, colonize vacant habitats, and avoid competing with parent plants for limiting resources. Seed dispersal describes the physical movement of seeds by fruit-eating and seed-eating birds, large herbivores, primates, and a range of other animals away from the parent plant. Due to specialized features, some seeds can stick to animals' fur, allowing them to be carried along much further distances than wind could, and different directions than water could. Many animals also consume seeds and fruits, providing opportunities for dispersal when the consumer moves off looking for more food, a resting spot, or mates to interact with. For some plants, seed dispersal involves a critical step required for germination, namely **seed scarification**. One method of scarification involves an animal breaking the seed's hard coat by biting it. Alternatively, stomach acids may weaken the consumed seed's hard coat while it passes through the animal's digestive tract. Without this step, seeds requiring scarification may not be able to germinate; those plants' persistence thus depends upon the animals that consume them. While the importance of pollination for food security is well known, the importance of seed dispersal should not be underestimated. A study from Côte d'Ivoire found that primates provided necessary seed dispersal services for at least 25 fruiting plant species important to humans (Koné et al., 2008).

Hazard detection and mitigation

When intact, nature is our first line of defence against many natural disasters. Consider, for example, the contribution of **mangrove swamps** in protecting us from cyclones/hurricanes (van Bochove et al., 2014), or the contribution of wetlands in flood control. In contrast, degrading the natural environment can have severe consequences. It is thus critical to prevent ecosystem degradation in the first place, rather than having to resort to costly restoration projects.

In addition to keeping us safe, biodiversity can also be used to help track environmental changes. Species used for this purpose, called **indicator species** or environmental monitors are, by definition, associated with unique environmental conditions or sets of ecosystem processes. Tracking changes in their population sizes, distributions, and behavior of can thus serve as a substitute for expensive detection equipment. Aquatic filter feeders, such as mussels and clams are particularly useful in this regard because their tissues accumulate chemical pollutants. A study from Senegal's mangrove swamps detected heavy metal pollution using clams, mussels, and snails after tests barely detected those pollutants in the area's sediments (Bodin et al., 2013). But even common everyday species can serve as indicator species: for example, conservation authorities around the world are using bird abundances and behaviors to better understand the impact of climate change (http://climatechange.birdlife.org).

Sentinel species are a special type of indicator species that can act as an early warning system for environmental hazards because they are more sensitive to certain conditions than humans are. Lichens are particularly well-known sentinel species. Being sensitive to air pollution and chemicals in rainwater, some lichens cannot survive in polluted areas. Thus, their presence is generally a sign of good air quality, while their absence may signal air pollution (Bako et al., 2008). Another example is seabirds, whose declining populations can serve as an early-warning system for overfishing (Paiva et al., 2015). Some sentinel species can even be used

directly for human health purposes. For example, the non-profit NGO APOPO has been taking advantage of the incredibly fine sense of smell of southern giant pouched rats (Cricetomys ansorgei LC)—affectionately called HeroRATs—to detect landmines (Figure 8.3.5), tuberculosis (Reither et al., 2015), salmonella infections (Mahoney et al., 2014), and even people trapped under collapsed structures (LaLonde et al., 2015).



Figure 8.3.6 With the help of specially trained southern giant pouched rats, over 80,000 landmines and other unexploded remnants of war were found and destroyed in Mozambique starting in 2008; the country was declared landmine free in 2015. Photograph by APOPO, CC BY 4.0.

Lastly, some species can be used to mitigate various sources of pollution. For example, through a process called **biosorption**, the superior absorption capabilities of some lichens, plants, fungi, and microorganisms offer some of the cheapest and most effective methods for removing toxic heavy metals (Fosso-Kankeu and Mulaba-Bafubiandi, 2014) from the environment. Scientists also recently discovered a plastic-eating fungus (Khan et al., 2017) that may provide a potential solution to plastic pollution.

Pest and disease control

Every day, predators, such as owls and bats, keep us healthy by controlling populations of disease vectors, such as rats and mosquitoes. This process, where predatory (and parasitic) species regulate populations of pests and other nuisance species, is known as **biological control**, or biocontrol in short. The use of insectivores (i.e. insect-eating species), such as bats and birds, to control crop pests is well established in traditional farming systems (Abate et al., 2000). But even on commercial crop farms, natural enemies, such as bats and birds, play an important role in keeping pests under control (Taylor et al., 2018). Some plants also play a part in biocontrol efforts: recent research found that some native plants used for intercropping in traditional agricultural systems emit chemical signals that kill and drive pest species away from crops (Khan et al., 2010). With an increasing number of studies illustrating the significant benefits gained from natural pest control systems, enhanced farming practices that facilitate greater ecosystem complexity will hopefully play a bigger role in food security in future.

Most people are familiar with scavengers, such as jackals and vultures, that work as nature's clean-up crew, picking at food scraps left in the field by large predators. Together with the range of flesh-eating insects, detritivores, and decomposers, scavengers play a crucial role in keeping us healthy by sanitizing the environment (O'Bryan et al., 2018). While it is all too easy to take these activities for granted, some people actively welcome these services. For example, in northern Ethiopia, spotted hyenas (*Crocuta crocuta*, LC) are tolerated in urban settlements because they consume livestock carcasses and sometimes even human corpses, which pose a disease risk (Yirga et al., 2015).

Recent experiences have shown that without proper care, the sanitary services provided by wildlife can collapse over a very short time. For example, during what is known as the Asian vulture crisis of the 1990s, vulture populations in India, Pakistan, and Nepal declined precipitously in a matter of years from **secondary poisoning** after eating carcasses of dead animals treated with the anti-inflammatory drug diclofenac. With nothing else available to remove carcasses of dead animals as efficiently as vultures, rotting flesh contaminated drinking water and allowed populations of rats and **feral** dogs (Canis familiaris) to proliferate. While vultures have stomach acids which kill pathogens, dogs and rats do not and thus became major pathogen vectors, spreading deadly diseases such as rabies, anthrax, and plague. The estimated healthcare costs in the face of Asia's vulture crisis amounted to over US $1

billion per year (Markandya et al., 2008). Today, Africa is facing its own vulture crisis. But instead of one threat, Africa's vultures face a multitude of human-made threats, making solving this crisis much more complex (Box 8.3.2).

Scavengers such as vultures and jackals are nature's clean-up crew; they keep us healthy by sanitizing the environment.

Box 8.3.2 Conservation Lessons from the Asian and African Vulture Crises

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A common perception among laypeople and conservationists alike is the idea of safety in numbers for wildlife species. After all, is a widely distributed and abundant species not safe from the threats of extinction? The answer is a firm no! As the collapse of central Asia's vulture populations (Oaks et al., 2004) demonstrates, species numbering in the millions can disappear in the space of just a few years.

The Asian vulture crisis shares some similarities with the demise of the passenger pigeon (*Ectopistes migratorius*, EX) in North America a century ago. This pigeon was once the most abundant bird on Earth; yet, despite numbering in the billions, it was driven to extinction in a short span of time, primarily due to hunting over a 20-year period in the late 1800s. In the case of Asian vultures, the threat was not hunting, but rather a nonsteroidal anti-inflammatory drug (NSAID)—diclofenac—which is fed to sick cattle and then ingested by vultures when they feed on dead livestock. As diclofenac is deadly toxic to vultures, the widespread use of this treatment on the Indian subcontinent (which includes India, Nepal, and Pakistan) has seen catastrophic vulture population declines. With one of Asia's major natural trash disposal systems gone, the area experienced a human health crisis from widespread drinking water contamination and increased incidence of diseases carried by ubiquitous and increasing rat and feral dog populations (Markandya et al., 2008).

The Asian vulture crisis is instructive on several grounds. First, it took a long time to detect and confirm the vulture declines because regular and standardized monitoring of the three affected vulture species had not been conducted. Second, the extent of the decline was extreme, with vulture numbers declining by over 95% within a decade. Third, the declines were due to a single threat—contamination from diclofenac, which were subsequently found to be deadly-poisonous to vultures (Oaks et al., 2004). Thanks to the concerted efforts of conservationists and politicians, and the rapid reactions of the governments of India, Pakistan, and Nepal, diclofenac was removed from the market in 2006. Vulture populations in Asia have since stabilized, with even a cautious suggestion of an increase.

Now, Africa faces its own vulture crisis (Ogada et al., 2015). However, in contrast to the Asian crisis, Africa's crisis involves a greater number of species, and spans a larger geographical area. Importantly, it also includes a greater number of threats, including poisoning, harvesting for traditional medicine and for food, and electrocution following contact with power lines. Many vultures also die when they scavenge on poisoned carcasses meant to kill problem predators (Figure 8.3.7). To this list of lethal causes, one should also add the universal threats of habitat loss and persecution of birds of prey.



Figure 8.3.7 Conservation biologists inspect several white-backed vultures that were poisoned at South Africa's Kruger National Park. Poachers across Africa intentionally kill vultures for traditional medicine, and unintentionally kill them while setting traps for large predators. Photograph by Andre Botha, CC BY 4.0.

Thanks to long-term monitoring, the collapse of African vulture populations has been well documented. Of the 95 vulture populations being monitored, 89% were either extirpated or experienced severe declines. Across eight study species, the mean rate of decline is estimated at 4.6% per year (i.e. one out of 20 birds that are dying per year are not being replaced). The charismatic Rüppell's vulture (*Gyps rueppellii*, CR) has declined by 85% across its range; consequently, this species is now considered highly threatened by the IUCN, as are the hooded vulture (*Necrosyrtes monachus*, CR), white-headed vulture (*Trigonoceps occipitalis*, CR), and African white-backed vulture (Gyps africanus, CR). Only slightly better off, at least for now, are the lappet-faced vulture (*Torgos tracheliotos*, EN) and Egyptian vulture (*Neophron percnopterus*, EN), the Cape vulture (Gyps coprotheres, VU), and the bearded vulture (*Gypaetus barbatus*, NT).

The collapse of Africa's vulture populations is cause for serious concern among conservation biologists, wildlife and livestock managers, and public health officials. Unlike in Asia, however, workable solutions to Africa's vulture crisis have not yet been found. This may be due to the multitude of threats, and the complexity of the problem exacerbated by the involvement of individual poachers, local communities, and government structures across more than 40 countries. If conservationists and governments can work together, as they did in Asia, then perhaps Africa's vultures and the ecosystem services that they provide can still be saved.

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8.4: Nonmaterial Contributions

Nonmaterial contributions from nature, also called cultural services, include the subjective and psychological aspects of nature that influence our perceptions about quality of life. These contributions can be divided into three subcategories: inspiration and learning support, supporting psychological and physical experiences, and supporting individual and group identities.

Inspiration and learning support

Nature has inspired artists and writers throughout history. Consequently, many books, television programs, movies, and websites produced for entertainment purposes are based on natural themes. This infusion of nature into popular culture is worth billions of dollars per year. To take one example, the 1994 Disney blockbuster *The Lion King*, based on the lives of a variety of African savannah animals, generated revenues estimated at just under US $1 billion from theater attendances alone. It was so successful that three movie sequels, an animated television series, and several video games and books followed. A musical based on *The Lion King* movie plot continues to be a top-earning title in box-office history for both stage productions and films.

Movies featuring stunning natural landscapes and charismatic wildlife often increase the desire of moviegoers to visit natural areas where they can see these landscapes and animals first-hand. But it can also raise awareness of environmental issues in new audiences. While many documentaries are created with this purpose in mind, such benefits can also extend to blockbuster movies meant for broader audiences (Silk et al., 2018). For example, Disney's *Happy Feet* (2006) highlighted the threat of overfishing and plastic pollution to penguins; *Avatar* (2009) raised awareness of **habitat loss** and overharvesting; and *The Jungle Book* (2016) exposed audiences to the plight of pangolins. Such exposure can even lead to environmentally conscious behavioural changes. For example, moviegoers were willing to donate 50% more money to climate mitigation after watching the apocalyptic movie *The Day After Tomorrow* (2004) (Balmford et al., 2004). Perhaps, in part, due to the influence of environmentally-orientated movies, an increasing number of movie stars (and other celebrities) have started using their stardom as a platform from where they promote biodiversity conservation efforts in Africa (Duthie et al. 2017; see also https://wildfor.life).

Scientists and engineers also sometimes turn to nature to seek inspiration for new technologies or to solve innovation challenges. For example, the water-vapor collecting capacity of the racing stripe darkling beetle (*Stenocara gracilipes*) from the Namib Desert in Namibia (Figure 8.4.1) inspired engineers who developed self-filling water bottles (Clark, 2012), irrigation systems to overcome drought conditions (Scott, 2011), fog-free windows and mirrors (Parker and Lawrence, 2011), and methods for controlling condensation and frost on aircraft surfaces (Boreyko et al., 2016). While these and other scientific endeavors, collectively known as **biomimicry**, provide many social and economic benefits, their primary value comes from new knowledge, improved education, and enriched human experiences.



Figure 8.4.1 The racing stripe darkling beetle is endemic to one of the world's most arid regions, Namibia's Namib Desert. To survive, it collects water from early-morning fog with the bumps on its back. In a classic case of biomimicry, creative entrepreneurs are copying these features to create self-filling water bottles and fog-free windows. Photograph by Alex Rebelo, https://www.inaturalist.org/observations/11086737, CC BY 4.0.

Supporting psychological and physical experiences

While the economic benefits gained from nature incentivizes biodiversity protection, many people believe that the aesthetic values of nature provide an even greater incentive for conservation. This principle rests on the fact that nearly everyone enjoys wildlife and landscapes aesthetically. Even city-dwellers who are superficially removed from nature find a sense of relief and well-being when they have opportunities to come in close contact with the natural world. But what if dragonflies and butterflies disappeared? What if our favorite sports team's mascot ceased to exist in nature? What if there were no more forests filled with bird flocks or monkey troops?

The intangible but desirable aesthetic values people attach to certain aspects of nature are known as **amenity values**. Amenity values are becoming increasingly important in many local and national economies, in the form **ecotourism**. At any one time, there are millions of tourists traveling and spending money to see particular species or to experience unique ecosystems. This includes scuba divers approaching a coral reef (Figure 8.4.2), birdwatchers visiting a rare species' stakeout, and people on a safari to view **flagship species.**



Figure 8.4.2 Scuba divers on vacation at Ponta do Ouro, Mozambique, appreciating a large potato bass (*Epinephelus tukula*, LC). The income to be gained from ecotourism activities often outweighs the profits from unsustainable harvesting, and thus provides a strong economic justification for biodiversity conservation. Photograph by Derek Keats, https://www.flickr.com/photos/dkeats/36684179721, CC BY 2.0.

> *The revenue and jobs generated by ecotourism provides a strong and immediate justification to protect biodiversity and restore areas that have been degraded.*

The revenue and jobs generated by ecotourism provides a strong and immediate justification to protect areas rich with biodiversity or to restore areas that have been degraded. Ecotourism can even be integrated directly in plans for future development, protection, and restoration. The revenue obtained from ecotourism also allows local people to move away from unsustainable hunting, fishing, or grazing practices towards lifestyles that can be maintained in the long term.

Supporting individual and group identities

Many people care deeply about biodiversity. The thought of a charismatic animal or a special landscape (Figure 8.4.3) may elicit a strong emotional response, which leads to a desire to protect plants, animals, and natural places. For some people, this desire is associated with a hope to someday see those unique species or landscapes in person. Others do not expect or even desire to see these species and landscape themselves, yet they value their existence. In either case, these individuals recognize the **existence values** of wildlife and nature—the benefit people receive from simply knowing that an ecosystem or species exists. **Bequest values** (also known as beneficiary values) is a component of existence values, defined as the perceived benefit people receive from preserving a natural resource or species for future generations.



Figure 8.4.3 Each year, after the spring rains, California's central valley comes alive with a rich tapestry of color, attracting wildflower enthusiasts from all over the world. Photo by Mike Ostrovsky on Unsplash

The desire to ensure the protection of biodiversity has prompted a wide range of people to establish, join, or otherwise contribute to conservation organizations. For many people involved in these organizations, their participation stems from the ethical premise that wildlife are equal to human life, and that biodiversity conservation offers genuine and long-lasting well-being. This environmental philosophy is often described as **deep ecology**, the ethical premise that species and biodiversity have a right to exist independent of their possible benefits to humans, and that humans have an inherent responsibility to protect species and biodiversity. Deep ecology holds that social structures (including politics, economics, technology, and ideology) must change radically to reduce the destruction of Earth's biodiversity and to enhance people's quality of life. It emphasizes and prioritizes the natural environment, aesthetics, religion, and culture, rather than material consumption. Although the ethical appreciation of biodiversity is similar in deep ecology and conservation biology, deep ecology includes broader goals for personal, social, and political change.

> *Biodiversity forms the basis of spiritual, celebratory, and other social-cohesion experiences for many people.*

Biodiversity also forms the basis of spiritual, celebratory, and other social-cohesion experiences for many people. It ensures people experience a sense of place and belonging, reminds them of childhood experiences, and gives a sense of connection when they experience natural sights, sounds and smells. All these factors play a major role in people's sense of who we are—our identity.

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8.5: Option Values

The **option values** of biodiversity describe nature's potential to provide currently unknown or unrealized benefits at some point in the future. For example, while many species may not currently have any realized material contributions, a small number of taxa may have enormous potential to support new industries or prevent major agricultural crops from collapsing. For this reason, scientists continuously search for species with hidden uses: entomologists search for insects that can control pest species, microbiologists search for bacteria useful in biochemical manufacturing, and agricultural scientists search for genetic varieties of plants that can produce more food to feed a growing human population. As fears of antibiotic resistance become reality, archaea (widespread single-celled microorganisms with no nucleus which are also thought to be the oldest life forms on Earth) may be used to develop new classes of antibiotic medicine (Metcalf et al., 2014). Some researchers also hope that studying primates—the likely original source of diseases such as HIV/AIDS, Ebola, and malaria (Martin et al., 2005)—may allow us to one day find cures for these diseases. It is worth noting that the effectiveness of using animals to study human diseases remains highly controversial (Archibald and Clotworthy, 2007; Festing and Wilkinson, 2007; Rollin, 2007), and that many people believe that the suffering and death of animals during biomedical research is unethical.

This continuous search for valuable or useful natural products, called **bioprospecting**, has already contributed a great amount to global **economic development**, and is expected to become even more important in the coming decades. This is particularly true in the rush to find replacements for climate sensitive crops that may be threatened by climate change. For example, researchers hope that the genetic diversity in wild coffee populations can act as an insurance policy in case our warming planet damages currently popular commercial strains (Davis et al., 2012). There is also much hope that plants from Africa will lead to new medical treatments, for diseases such as malaria, cancer, and high blood pressure (Gurib-Fakim, 2017). It is for reasons such as these that losing even small portions of expansive ecosystems concerns scientists. The extinction of even one valuable species or gene can represent a tremendous loss to humanity, even if many other species are preserved.

> Bioprospecting, the search for valuable or useful natural products, has already contributed greatly to global economic development.

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8.6: Environmental Economics

It should be clear from reading this chapter that the well-being of people around the world is fundamentally linked to opportunities for biodiversity to survive and prosper. That means that when we destroy an ecosystem or let a species go extinct, we also put at risk our own ability to survive and prosper. To fully account for these risks, decisions that negatively affect biodiversity must account for all the costs and benefits (hidden or otherwise), including the impacts on ecosystem services, before the decision is implemented.

One of the most popular methods for accounting for potential harm to biodiversity, especially when weighing public policy and commercial decisions, is to attach market (or monetary) values to the ecosystem services. For some ecosystem services, it is rather straightforward to estimate a market value. For example, how much would it cost to replace a natural pollination service with hand pollination by farm workers? But for many services, estimating a monetary value is much more difficult. Where do we even start to estimate the value of breathing clean air, or knowing that dolphins exists?

To examine these kinds of complex questions, conservation biologists look to a sub-discipline within economics called **environmental economics**. Environmental economics broadly examines the contribution of ecosystem services to global economies. An important component of this examination involves estimating the market value of all the different ecosystem services we benefit from, but it also includes studying the environmental costs of economic transactions, environmental policies, and other decisions that impact the environment.

8.6.1 Placing a price on the natural world

Approximating the market values of ecosystem services is no small feat, in part because nature's contributions to people vary by location and perspective (Díaz et al., 2018). There also continue to be technical (e.g. Kling et al., 2012) and ethical (e.g. McCauley, 2006; Silvertown, 2015) disagreements about the need and methods used to translate nature's services into monetary terms. Nevertheless, including such estimates has become a widely accepted norm in economics models and conservation activities (Guerry et al., 2015). To accomplish this task, economists rely on seven main methods to estimate the market values of ecosystem services (Farber et al., 2002):

- *Market value*: The price a person is willing to pay for a specific product or service. For example, how much is a person willing to pay for a bundle of firewood at a local market?
- *Avoidance cost*: The cost society avoids paying because a specific ecosystem service exists. For example, how much does society avoid paying for water filtration service otherwise provided by a region's forests and wetlands?
- *Replacement cost*: The cost society would have incurred if a specific ecosystem service had to be replaced. For example, how much would society have to pay in extra healthcare costs and in clean-up costs for diseased carcasses to replace the sanitation services provided by vultures?
- *Factor income*: The additional income generated by the enhancement of an ecosystem service. For example, how much would a reduction in water pollution increase the income of fishermen through healthier fish populations?
- *Travel cost*: The additional travel cost a person is willing to pay to experience an ecosystem service otherwise not available to them. For example, how much extra is a person willing to pay for transport to participate in recreational activities at a cleaner lake?
- *Hedonic pricing*: The additional expense a person is willing to pay to experience an ecosystem service. For example, how much extra is someone willing to pay for a house with an ocean view, compared to an inland house?
- *Contingent valuation*: The additional expenses a person is willing to pay for an alternative hypothetical scenario. For example, how much is someone willing to pay for cleaner air, or the right to catch more fish?

> The combined value of all of Earth's ecosystem services may be double the current value of the global economy.

Using a combination of these methods, a range of ecosystem services have been valued in recent years. For example, the services offered by pollinating insects around the world have been valued at US $153 billion per year (Gallai et al., 2008). The replacement cost of tropical forests is also increasingly appreciated in carbon sequestration markets, where heavy greenhouse gas emitters pay huge sums of money to conserve forests to become more **carbon neutral**. For example, the **United Nations Environmental**

Programme (UNEP) has estimated that their forests are worth 4.2 times more intact than the value that could be earned through logging. One ambitious study estimated the value of all of Earth's ecosystem services at US $145 trillion annually (Costanza et al., 2014), which is almost double the current US $78 trillion value of the global economy. By comparing the value of ecosystem services over time, Costanza et al. (2014) also estimated that we are losing US $4.3–20.2 trillion per year in ecosystem services through land degradation.

8.6.2 Environmental economics' biggest contributions

Since its development, environmental economics has contributed to conservation biology in several very important ways. Perhaps the most important contribution is that it has enabled conservation biologists to better communicate the value of ecosystem goods and services to audiences like government officials and business leaders, who often base decisions on economic considerations. By doing this, environmental economics has also focussed our attention on the wide range of goods and services that biodiversity provides and has elevated these topics into corridors where they were not previously discussed.

> Environmental economics enable us to better communicate the value of biodiversity to those who base decisions on economic considerations.

Environmental economics also enabled conservation biologists to better account for environmental impacts of environmental damaging activities. In doing so, the field highlighted how activities that appear profitable are running at an economic loss when properly accounting for otherwise ignored environmental (and social) damages. While such calculations have traditionally focused on imbalances in overharvesting of material contributions, recent developments have also started accounting for damages inflicted on regulating services and nonmaterial contributions, such as the loss of nature's contribution to climate regulation (Auffhammer et al., 2017; Hsiang et al., 2017).

8.6.3 Environmental economics' biggest challenges

Despite all the direct and indirect contributions of environmental economics to biodiversity conservation, there are also several challenges facing the field. Some of these challenges relate to methodological complexities of valuing ecosystem services, but many challenges also have their roots in governance failures. Following is a discussion of the most important challenges facing environmental economics.

Accounting for negative externalities

Modern economics is built on the principle of **voluntary transactions**—that is, a transaction occurs only when it benefits all the stakeholders involved. However, environmental (and social) harm often arises when some hidden costs are passed on to people not directly involved in the transactions. The unregulated use of **open-access resources**—resources such as water, air, and fish populations that are freely used by many different groups of people—provide many opportunities for this kind of abuse. Consider a company that dumps chemical waste into a river instead of properly disposing of it. While the company may benefit from this cost-cutting measure, people further downstream bear the environmental and social costs of the company's "free" waste disposal by having to contend with polluted drinking water, loss of swimming and other recreational opportunities, and loss of fish as a safe food source. Damage inflicted on rivers and other open-access resources also represent a classic example of the **tragedy of the commons**—while some people initially benefit from abusing the "free" ecosystem services, those values are gradually lost to all of society, including those who abused it (NRC, 2002).

The hidden costs of economic transactions that are passed on to people not directly involved are generally known as negative **externalities** (Figure 8.6.3). Because negative externalities allow a small number of people to benefit at the expense of the rest of society, they often lead to **market failures**, characterized by transactions that do not lead to optimal outcomes for all stakeholders. Governments may correct for these kinds of market failures by imposing taxes on activities that are harmful to the environment. Carbon taxes imposed on greenhouse gas emitters is a common example. But many times, governance structures fail, or even exacerbate, the impact of negative externalities, by artificially maintaining destructive activities with tax incentives, direct payments, and price regulations. The financial incentives governments provide to maintain destructive activities are more often referred to as **perverse subsidies** (Myers and Kent, 2001). The size of perverse subsidies is often very large, regularly dwarfing conservation spending. For example, US $26 billion in subsidies were provided to the Africa's **fossil fuel** industry just in 2015

(Whitley and van der Burg, 2015), compared to just US $381 million spent annually to secure Africa's protected areas with lions (Lindsey et al., 2018).

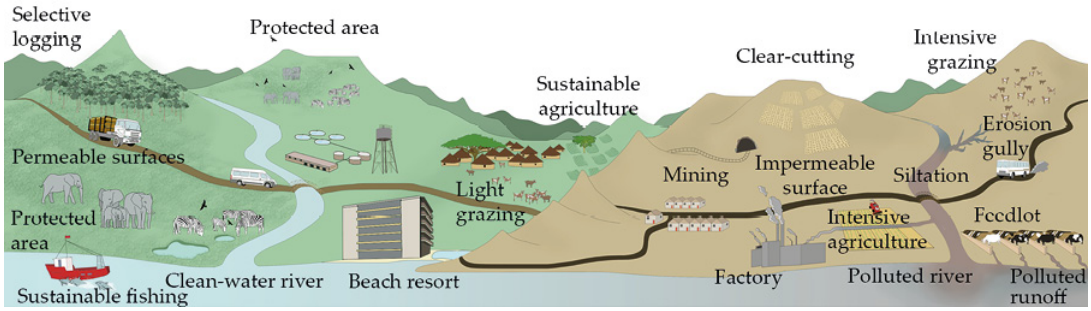


Figure 8.6.3 Politicians, developers, and industries all too often fail to account for negative externalities (right side of figure) when they consider the contribution of destructive economic activities to society. Accounting for these negative externalities—and redistributing perverse subsidies to activities that provide public benefits (left side of figure)—will help us transition to more sustainable lifestyles. CC BY 4.0.

There are many reasons why governance structures continue to fail nature and allow market failures to occur. For example, due to the prevailing mindset of pursuing economic growth at all costs, politicians, developers, and industries often skew their cost-benefit analyses by prioritizing the short-term benefits gained from destructive sectors over long-term societal well-being and sustainability. Another factor is intense lobbying by industries benefiting from perverse subsidies, which leads to corruption and other questionable decisions. Solving these challenges will rely on a society that prioritizes economic development and establishes structures (i.e. passing and enforcing environmental laws, Chapter 12) that fully account for negative externalities.

Determining ownership

Another problem that plagues environmental economists and other stakeholders is deciding who owns the commercial rights to biodiversity. In the past, corporations and scientists (generally from wealthier countries) traveled extensively (often to poorer countries in the tropics) to collect species from which commercially valuable products might be obtained. These new products were then sold, but all profits were kept by the corporations while the people in the poorer source countries received little to no financial benefit.

To combat this unfair exploitation, called **biopiracy**, many developing countries now require scientists and corporations to obtain permits before they can collect biological material for commercial or research purposes. Also, at the international level, nearly 100 countries have agreed to the fair sharing of benefits arising from the use of biological resources, through the Nagoya Protocol. Through these and similar laws and agreements, the hope is that a greater portion of the profits gained from biodiversity will be allocated to people who protect biodiversity and who live in the areas from where it is extracted.

A more inclusive approach

The valuation of ecosystem services has traditionally relied on generalized principles of economics and natural sciences. While this focus enabled scientists to develop broadly applicable themes and metrics in ecosystem evaluation, it also neglected the role of context and culture in understanding nature's role in people's lives. Many people have also remained uneasy about commodifying nature (i.e. giving it a market value), because some of the most important contributions of biodiversity are not easily converted into monetary metrics. Consequently, many feared that the transactional approach to ecosystem services would lead to social inequity concerns and alienate people offended by the idea that nature's metaphysical properties must compete against commercial interests.

To address these concerns, the valuation and classification of ecosystem services are currently undergoing several major transformations. Prominently, the UN's most recent classification scheme (Díaz et al., 2018) has given a more prominent voice to a wider range of stakeholders, including the social sciences, and recognizes the importance of culture and context in nature's contributions to people. Figure 8.6.4 depicts global trends in eighteen categories of nature's contribution to humans. This exciting area of research is actively developing, and readers are encouraged to track developments and reactions associated with 2019 IPBES Global Assessment at https://www.ipbes.net/news/ipbes-global-assessment-preview.

	Nature's contribution to people	50-year global trend	Directional trend across regions	Selected indicator
REGULATION OF ENVIRONMENTAL PROCESSES	1 Habitat creation and maintenance	↓	○	• Extent of suitable habitat
		↓	○	• Biodiversity intactness
	2 Pollination and dispersal of seeds and other propagules	↓	○	• Pollinator diversity
		↓	○	• Extent of natural habitat in agricultural areas
	3 Regulation of air quality	↘	⇅	• Retention and prevented emissions of air pollutants by ecosystems
	4 Regulation of climate	↘	⇅	• Prevented emissions and uptake of greenhouse gases by ecosystems
	5 Regulation of ocean acidification	→	⇅	• Capacity to sequester carbon by marine and terrestrial environments
	6 Regulation of freshwater quantity, location and timing	↘	⇅	• Ecosystem impact on air-surface-ground water partitioning
	7 Regulation of freshwater and coastal water quality	↘	○	• Extent of ecosystems that filter or add constituent components to water
	8 Formation, protection and decontamination of soils and sediments	↘	⇅	• Soil organic carbon
	9 Regulation of hazards and extreme events	↘	⇅	• Ability of ecosystems to absorb and buffer hazards
	10 Regulation of detrimental organisms and biological processes	↓	○	• Extent of natural habitat in agricultural areas
		↘	○	• Diversity of competent hosts of vector-borne diseases
MATERIALS AND ASSISTANCE	11 Energy	↗	⇅	• Extent of agricultural land—potential land for bioenergy production
		↘	⇅	• Extent of forested land
	12 Food and feed	↗	⇅	• Extent of agricultural land—potential land for food and feed production
		↓	⇅	• Abundance of marine fish stocks
	13 Materials and assistance	↗	⇅	• Extent of agricultural land—potential land for material production
		↘	⇅	• Extent of forested land
	14 Medicinal, biochemical and genetic resources	↘	○	• Fraction of species locally known and used medicinally
		↓	○	• Phylogenetic diversity
NON-MATERIAL	15 Learning and inspiration	↓	○	• Number of people in close proximity to nature
		↓	○	• Diversity of life from which to learn
	16 Physical and psychological experiences	↘	○	• Area of natural and traditional landscapes and seascapes
	17 Supporting identities	↘	○	• Stability of land use and land cover
	18 Maintenance of options	↓	○	• Species' survival probability
		↓	○	• Phylogenetic diversity

DIRECTIONAL TREND

Decrease ← → Increase

Global trends: ↓ ↘ → ↗ ↑

Across regions: ○ Consistent ⇅ Variable

LEVELS OF CERTAINTY

- Well established
- Established but incomplete
- Unresolved

Figure 8.6.4: Analysis of nature's contribution to people from the IPBES Global Assessment Report. Over 2,000 studies were reviewed in the analysis which shows a decline for 14 of the 18 categories. (IPBES Global Assessment Report, 2019)

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8.7: Summary

1. People value biodiversity in many ways. The reasons vary from person to person, and from region to region. But generally, nature's contributions to people, also called ecosystem services, are divided into three overlapping and interdependent categories, namely material contributions, regulating services, and nonmaterial contributions.
2. Material contributions include benefits people get from consuming natural resources (e.g. drinking water or burning wood for cooking) or using natural resources in production and trade (e.g. timber to build homes or other structures).
3. Biodiversity also provides a large variety of regulating services that enable people to benefit from nature's material contributions. Some of these contributions include ecosystem productivity, water and soil protection, climate regulation, pollination, seed dispersal, and disaster prevention and detection.
4. People attach nonmaterial values to biodiversity which are difficult to quantify, and thus to account for, in modern economic systems. These values include support for inspiration and learning, support for psychological and physical experiences, and support for personal and group identities.
5. Environmental economics studies the implications of economic transactions, environmental policies, and other decisions that impact the environment. This field has highlighted how damage to the environment, such as pollution caused by industry, are not always fully considered when making political and development decisions, leading to unsustainable economic practices and market failure. Accounting for negative externalities and perverse subsidies can help policymakers design incentives that promote sustainable practices.

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8.8: Topics for Discussion

1. Think of a recent infrastructure development near where you live, such as a recently-built road or dam. Try to come up with a list of ecosystem services that were damaged by this development. Who carries the costs of these lost services? Do you think the benefits from the development were worth the costs? Explain your answer.
2. Do individual organisms, populations, species, and biological communities have rights? What about physical features such as lakes, rivers, and mountains? While explaining your answer, also think about where we should draw the line of moral responsibility in how we care for nature.
3. A European botanist on holiday visits your area. During a short hike, you show this botanist a plant used as a traditional treatment for malaria. The botanist takes samples of this plant back to Europe, where subsequent testing shows that it can be used to develop an effective anti-malarial drug. Who do you think should receive the profits from this new drug? The botanist who undertook the trip, and you because you showed the botanist the plant? What about the organization that funded the drug's development, and the scientists who synthesised the new drug? What about all the people who educated you and your family in the plant's value? If the profits belong to multiple entities, how should it be divided?

Allsopp, M.H., W.J. de Lange, and R. Veldtman. 2008. Valuing insect pollination services with cost of replacement. PLoS ONE 3: e3128. https://doi.org/10.1371/journal.pone.0003128 A study estimating the economic value of local pollination services.

Costanza, R., R. de Groot, P. Sutton, et al. 2014. Changes in the global value of ecosystem services. Global Environmental Change 26: 152–58. https://doi.org/10.1016/j.gloenvcha.2014.04.002 An attempt to value all ecosystem services.

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Isbell, F., V. Calcagno, A. Hector, et al. 2011. High plant diversity is needed to maintain ecosystem services. Nature 477: 199–202. https://doi.org/10.1038/nature10282 Maintaining ecosystem services requires protecting a diversity of species.

Koné, I., J.E. Lambert, J. Refisch, et al. 2008. Primate seed dispersal and its potential role in maintaining useful tree species in the Taï region, Côte d'Ivoire: Implications for the conservation of forest fragments. Tropical Conservation Science 1: 293–306. https://doi.org/10.1177%2F194008290800100309 Maintaining primate populations is important also for humans who rely on forest resources.

Markandya, A., T. Taylor, A. Longo, et al. 2008. Counting the cost of vulture decline—an appraisal of the human health and other benefits of vultures in India. Ecological Economics 67: 194-204. https://doi.org/10.1016/j.ecolecon.2008.04.020 A study illustrating the value of vultures.

Naidoo, R., B. Fisher, A. Manica, et al. 2016. Estimating economic losses to tourism in Africa from the illegal killing of elephants. Nature Communications 7: 13379. https://doi.org/10.1038/ncomms13379 Africa loses US $25 million annually from elephant poaching.

Peterson, G.D., Z.V. Harmackova, M. Meacham, et al. 2018. Welcoming different perspectives in IPBES: "Nature's contributions to people" and "Ecosystem services". Ecology and Society 23: 39. https://doi.org/10.5751/ES-10134-230139 Addressing shortcomings of the ecosystem services concept

Schleicher, J., M. Schaafsma, N.D. Burgess, et al. 2018. Poorer without it? The neglected role of the natural environment in poverty and wellbeing. Sustainable Development 25: 83–98. https://doi.org/10.1002/sd.1692 The environment and human well-being are intricately linked.

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CHAPTER OVERVIEW

9: Habitat Destruction and Fragmentation

9.1: Introduction to Habitat Destruction and Fragmentation
9.2: Habitat Loss Overview
9.3: What is Habitat Loss?
9.4: Habitat Loss' Impact on Select Ecosystems
9.5: Population Growth and Consumption
9.6: Summary
9.7: Topics for Discussion
9.9: Bibliography

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9.1: Introduction to Habitat Destruction and Fragmentation

The right to shelter, food, and association are basic human needs recognized in many international charters and country constitutions. Like humans, wildlife also needs areas where they can find protection, nourishment, and mates to have any hope of survival. The area where a species can survive and meet their basic needs is known as its **habitat**. It is often useful to think of a habitat as a multi-dimensional space, characterized by suitable levels of many different environmental variables. These variables include factors such as soil moisture, light availability, temperature, structures for nesting/denning, prey abundance, etc. Some species, including humans, are highly tolerant of changes in their environmental conditions; consequently, such **generalist species** find it relatively easy to move to a new area in the unfortunate event that their "home" is destroyed. In contrast, **specialist species** —those that can only survive within a narrow range of environmental conditions—often do not have anywhere else to go when their habitat is lost, and consequently they go extinct.



Mount Nimba Strict Nature Reserve, which straddles the border region of Guinea and Côte d'Ivoire, is a World Heritage Site situated in the Guinean Forest of West Africa Biodiversity Hotspot. The ecosystem, which supports chimpanzees that use stone tools, is threatened by iron mining, agriculture, and deforestation. Photograph by Guy Debonnet, http://whc.unesco.org/en/documents/123989, CC BY-SA 3.0 IGO.

In a world where intact natural ecosystems are increasingly being altered by the activities of an ever-increasing human population and its consumptive needs, habitat loss has emerged as the number one threat facing biodiversity today. The expansion of human activity causes massive disturbances to natural ecosystems by altering, degrading, and outright destroying wildlife habitats. A number of specialist species have already been pushed to extinction. But even generalist species are increasingly falling victim to habitat loss: pushed out of their shrinking habitats, they come into conflict with humans while trying to meet their needs near urban centres and on agricultural land. Eventually our own lives will suffer, whether through lost ecosystem services, or sorrow for all the wonderful landscapes and species that have disappeared under our watch. In this chapter we delve into the causes and consequences of this increased competition for space between man and wildlife.

> The primary threat to biodiversity today is habitat loss and degradation.

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9.2: Habitat Loss Overview

Humans rely on technology to modify their environment and make it habitable. Other species cannot do this. Elimination of their habitat—whether it is a forest, coral reef, grassland, or flowing river—will kill the individuals in the species. Remove the entire habitat, and the species will become extinct, unless they are among the few species that do well in human-built environments. Habitat loss includes habitat destruction and habitat fragmentation.

Habitat Destruction

Habitat destruction occurs when the physical environment required by a species is altered so that the species can no longer live there. Human destruction of habitats accelerated in the latter half of the twentieth century. Land conversion for agriculture has been the main driver of habitat loss since 1970. Figure 9.2.1*a* depicts commodities produced on previously forested land, with the greatest proportion from cattle and palm oil. Figure 9.2.1*b* illustrates the differences in land requirements for various crops.

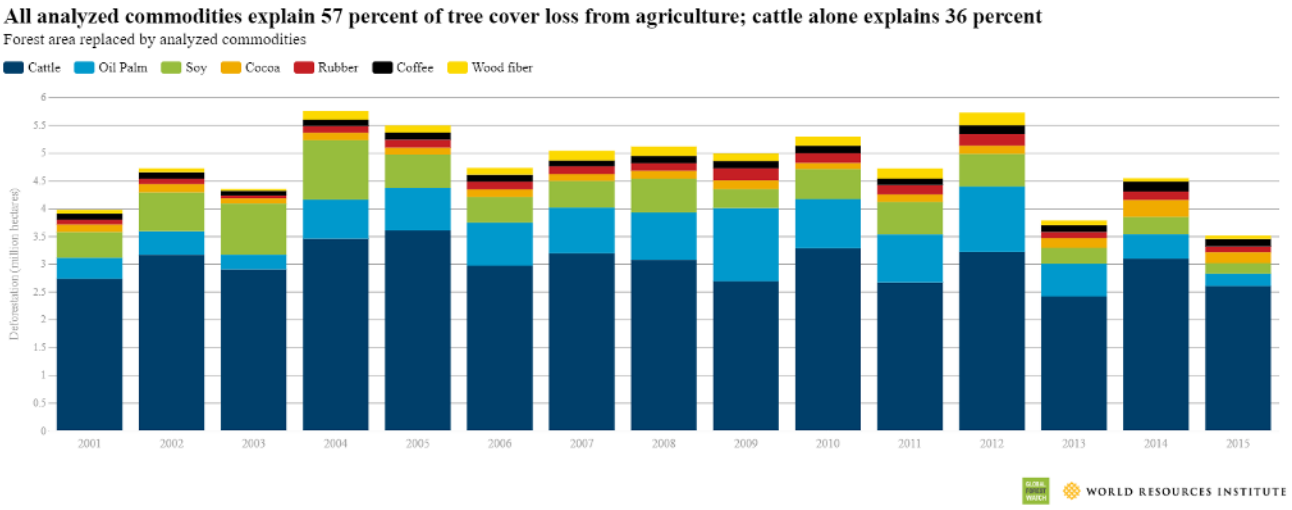


Figure 9.2.1*a*: Land conversion from forested land to agriculture for select commodities. (World Resources Institute/Global Forest Review)

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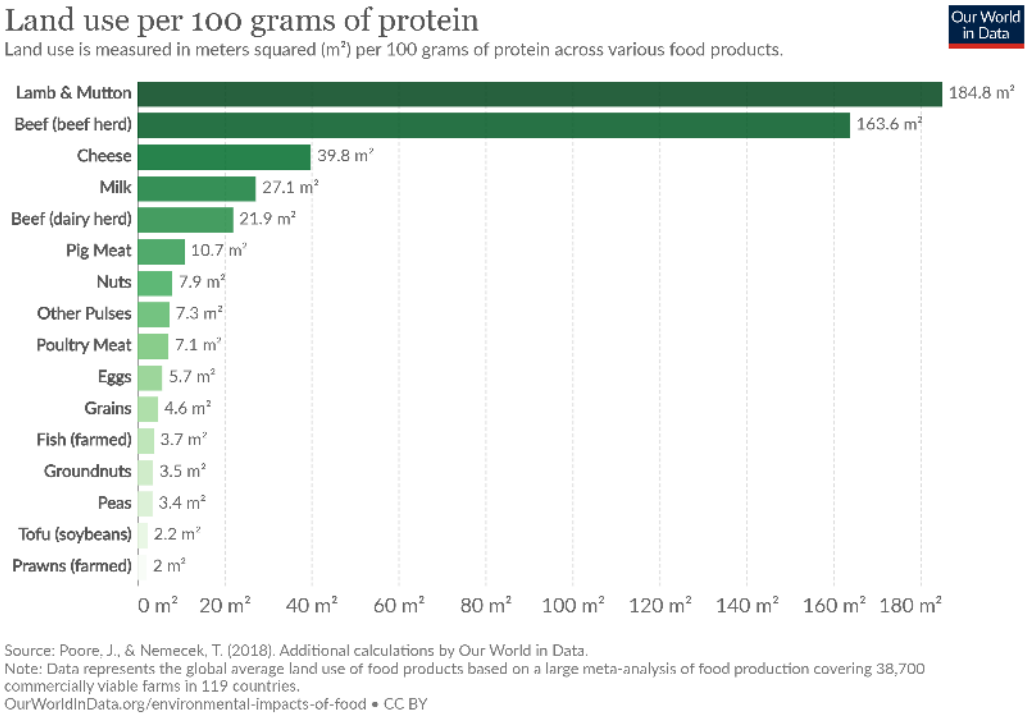


Figure 9.2.1*b*: Land use per 100 grams of protein

Consider the exceptional biodiversity of Sumatra: it is home to one species of orangutan, a species of critically endangered elephant, and the Sumatran tiger, but half of Sumatra's forest is now gone. The neighboring island of Borneo, home to the other species of orangutan, has lost a similar area of forest. Forest loss continues in protected areas of Borneo. The orangutan in Borneo is listed as endangered by the International Union for Conservation of Nature (IUCN), but it is simply the most visible of thousands of species that will not survive the disappearance of the forests of Borneo. The forests are removed for timber and to plant palm oil plantations (figure $9.2.a$). Palm oil is used in many products including food products, cosmetics, and biodiesel in Europe. According to Global Forest Watch, 9.7% of tree cover was lost globally from 2002 to 2019, and 9% of that occurred in Indonesia and Malaysia (where Sumatra and Borneo are located). Figure $9.2.b$ shows the average annual change in forest area around the world from 1990 to 2015.



(a) (b)



(c)



(d) (e)

Figure 9.2.a: (a) One species of orangutan, *Pongo pygmaeus*, is found only in the rainforests of Borneo, and the other species of orangutan (*Pongo abelii*) is found only in the rainforests of Sumatra. These animals are examples of the exceptional biodiversity of (c) the islands of Sumatra and Borneo, which are located in the south Pacific, just northwest of Australia. Sumatra is in the country of Indonesia. Half of Borneo is in Indonesia, and half is in Malaysia. Other species include the (b) Sumatran tiger (*Panthera tigris sumatrae*) and the (d) Sumatran elephant (*Elephas maximus sumatranus*), both critically endangered species. Rainforest habitat is being removed to make way for (e) oil palm plantations such as this one in Borneo's Sabah Province. (credit a: modification of work by Thorsten Bachner; credit b: modification of work by Dick Mudde; credit c: modification of work by U.S. CIA World Factbook; credit d: modification of work by "Nonprofit Organizations"/Flickr; credit e: modification of work by Dr. Lian Pin Koh)

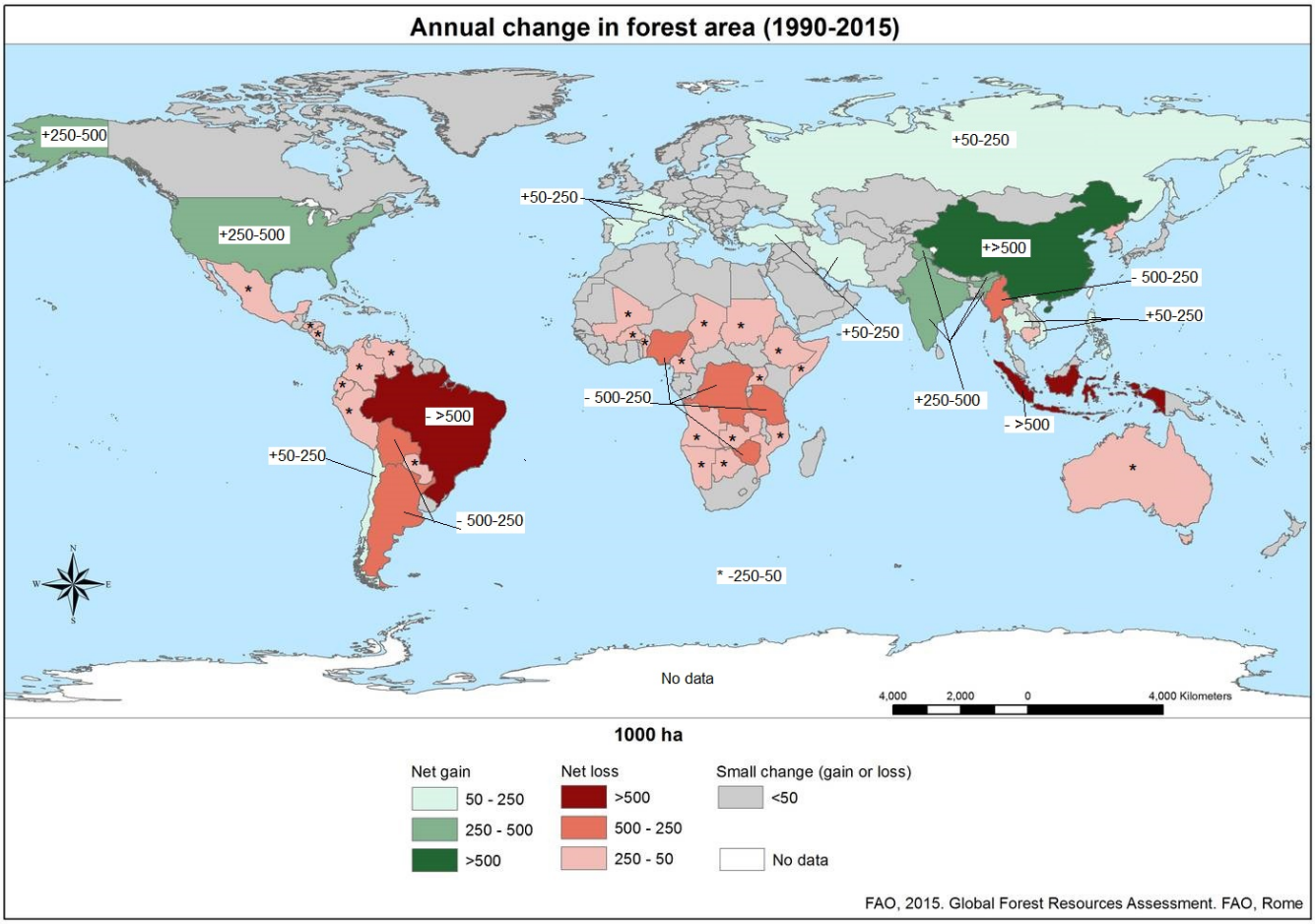


Figure 9.2.*b*: Average annual change in forest area globally from 2005 to 2015. China is dark green, indicating that have gained more than 500 "kilohectares" (kha) of forest. Medium green indicates countries that have gained 250-500 kha, including the the United States, India, Ghutan, and Bangladesh. Light green indicates countries that have gained 50-250 khA, including Chile, Spain, France, Italy, Turkey, Iran, Russia, Vietnam, and Thailand. Indonesia and Brazil lost more than 500 kha of forest (marked with dark red). Countries that lost 500-250 kha are marked with medium red, including Bolivia, Argentina, Nigeria, Democratic Republic of the Congo, Tanzania, Zimbabwe, and Myanmar. Countries that lost 250-50 kha are marked with light red and an asterisk (*). These include Mexico, Honduras, Nicaragua, Venezuela, Colombia, Ecuador, Peru, Paraguay, Mali, Burkina Faso, Benin, Cameroon, Chad, Sudan, Ethiopia, Somalia, Uganda, Angola, Namibia, Botswana, Zimbabwe, Mozambique, Cambodia, North Korea, and Australia. No data has been collected for Antarctica. All other regions have had lost or gained less than 50 kha in forest area. Image by FAO, 2015. Global Forest Resources Assessment. FAO. Rome (Open Access Policy).

Preventing Habitat Destruction with Wise Wood Choices

Most consumers do not imagine that the home improvement products they buy might be contributing to habitat loss and species extinctions. Yet the market for illegally harvested tropical timber is huge, and the wood products often find themselves in building supply stores in the United States. One estimate is that up to 10% of the imported timber in the United States, which is the world's largest consumer of wood products, is illegally logged. A 2012 United Nations and Interpol report estimated that the illegal timber trade is worth $30-100 billion each year. Most of the illegal products are imported from countries that act as intermediaries and are not the originators of the wood.

How is it possible to determine if a wood product, such as flooring, was harvested sustainably or even legally? The Forest Stewardship Council (FSC) certifies sustainably harvested forest products (figure 9.2.*c*). Looking for their certification on flooring and other hardwood products is one way to ensure that the wood has not been taken illegally from a tropical forest. There are certifications other than the FSC, but these are run by timber companies, thus creating a conflict of interest. Another

approach is to buy domestic wood species. While it would be great if there was a list of legal versus illegal woods, it is not that simple. Logging and forest management laws vary from country to country; what is illegal in one country may be legal in another. Where and how a product is harvested and whether the forest from which it comes is being sustainably maintained all factor into whether a wood product will be certified by the FSC. It is always a good idea to ask questions about where a wood product came from and how the supplier knows that it was harvested legally.



Figure 9.2.*c*: The sawmill in Uaxactun, Guatamala is Forest Stewardship Council (FSC) certified and provides good income from a sustainable resource for not only the saw operators but also many others who help keep the operation running. Image by Jason Houston for USAID (public domain).

Habitat Destruction of Rivers and Streams

Habitat destruction can affect ecosystems other than forests. Rivers and streams are important ecosystems and are frequently the target of habitat modification. Damming of rivers affects flow and access to habitat. Altering a flow regime can reduce or eliminate populations that are adapted to seasonal changes in flow. For example, an estimated 91% of riverways in the United States have been modified with damming or stream bank modification. Many fish species in the United States, especially rare species or species with restricted distributions, have seen declines caused by river damming and habitat loss. Research has confirmed that species of amphibians that must carry out parts of their life cycles in both aquatic and terrestrial habitats are at greater risk of population declines and extinction because of the increased likelihood that one of their habitats or access between them will be lost. This is of particular concern because amphibians have been declining in numbers and going extinct more rapidly than many other groups for a variety of possible reasons.

Habitat Fragmentation

Habitat fragmentation occurs when the living space of a species is divided into discontinuous patches. For example, a mountain highway could divide a forest habitat into separate patches. This is especially problematic for consumers at the top of the food chain, which require large ranges to find adequate prey. Additionally, habitat fragmentation separates individuals from potential mates. **Wildlife corridors** mitigate the damage of habitat fragmentation by connecting patches with suitable habitat. For example, the bridge over a highway could allow animals to move between habitat patches (figure 9.2.*d*). Riparian areas, areas of land adjacent to bodies of water, such as streams, can serve as natural wildlife corridors when left intact.



Figure 9.2.*d*: This overpass on the Trans-Canada Highway between Banff and Lake Louise, Alberta, serves as a wildlife corridor. Image by WikiPedant at Wikimedia Commons (CC-BY-SA).

References

Global Forest Watch. 2020. World Resources Institute. Accessed 2020-07-29.

Illegal logging nets organized crime up to 100 billion dollars a year, INTERPOL–UNEP report reveals. 2012. Interpol. Accessed 2020-07-29.

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9.3: What is Habitat Loss?

Habitat loss is defined as the outright destruction of natural ecosystems, an inevitable consequence of expanding human populations and human activities. The theory of **island biogeography** (MacArthur and Wilson, 1967) offers a good explanation for why habitat loss drives species extinctions. Using oceanic islands as a model system, one of the theory's main predictions is that large islands have more species than small ones because they can accommodate more individuals, which causes those species to be better buffered against extinctions (Figure 9.3.1). Empirical evidence offers strong support for this observation, also known as the **species-area relationship**. For example, large African islands generally hold more bird species than small islands (Figure 9.3.2). In addition, 62 of the 79 (63%) Sub-Saharan Africa's species that went extinct over the past few centuries (IUCN, 2019) have been confined to oceanic islands, rather than the continental mainland which in effect functions like one very big island.

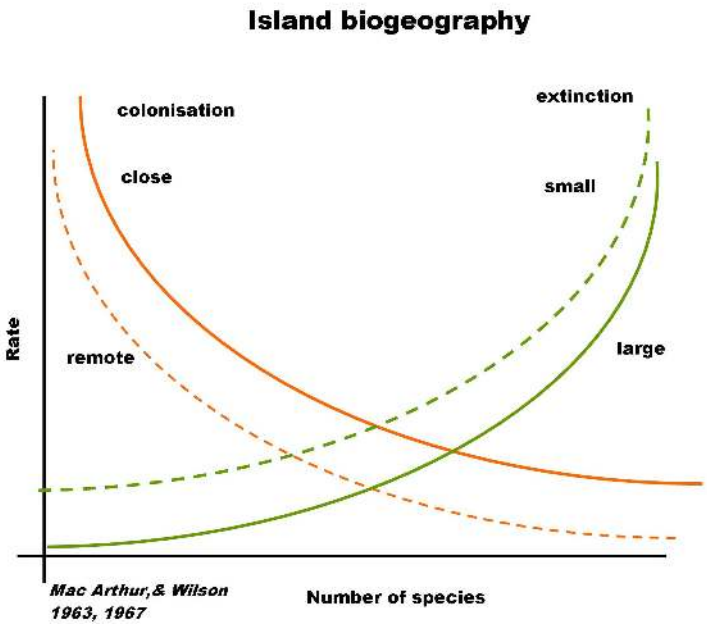


Figure 9.3.1: Mac Arthur and Wilson's theory of island biogeography in a diagram. (F.W. own work, CC BY 3.0 Wikimedia Commons)

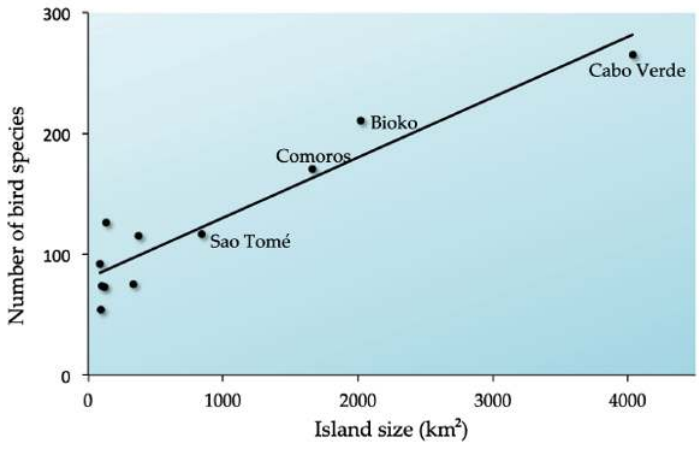


Figure 9.3.2 Area size greatly influences species richness, as evidenced by the bird species richness on several prominent volcanic islands around Africa. This observation, known as the species-area relationship, explains why habitat loss is so devastating to biodiversity—the more we reduce the amount of habitat left for species to live in, the more extinctions we will see in the coming years. Source: Avibase (https://avibase.bsc-eoc.org), following BirdLife International 2018 taxonomy, CC BY 4.0

The species-area relationship underpins much of conservation biology today. By applying the relationship's principles to "islands" of suitable habitat surrounded by a "sea" of damaged or unsuitable habitat (the "matrix"), conservation biologists know that conserving large areas of suitable habitat is much more effective in protecting biodiversity (Box 9.3.1). This is especially true when

trying to protect species that have large home ranges, and/or occur in low densities: they can only live in habitat patches that are large enough to maintain viable populations. Observations of extirpations in differently sized habitat patches support this application.

Box 9.3.1 The Importance of Liberia's Forest Network to the Survival of the Pygmy Hippopotamus

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Remaining populations of the pygmy hippopotamus (*Choeropsis liberiensis*, EN) are found predominately within transboundary West African rainforests spanning Côte d'Ivoire, Guinea, Liberia, and Sierra Leone (Ransom et al., 2015). Liberia contains the largest intact blocks (over 40%) of this Upper Guinean rainforest, a Global 200 ecoregion (Olson et al., 2002). An elusive animal, little is known about the pygmy hippo's distribution, population status, and ecology. Pygmy hippo numbers are currently estimated at fewer than 2,500 individuals across its range, with the expectation of further decline as a result of agricultural expansion, logging, development, and hunting (Ransom et al., 2015).

Within Liberia, pygmy hippopotamus populations are found in the major forest blocks of the southeast and northwest (Figure 9.3.3), which are separated by an area of degraded land with high human densities (FFI and FDA, 2013). The southeastern forest block is made up of several large chunks of national, communal, and protected forests fragmented by logging routes and concessions. Although populations are well documented within protected areas, recent reports indicate that populations also exist outside formally protected forests (Hillers et al., 2017). The establishment and management of forest corridors linking key habitats is therefore a conservation priority.

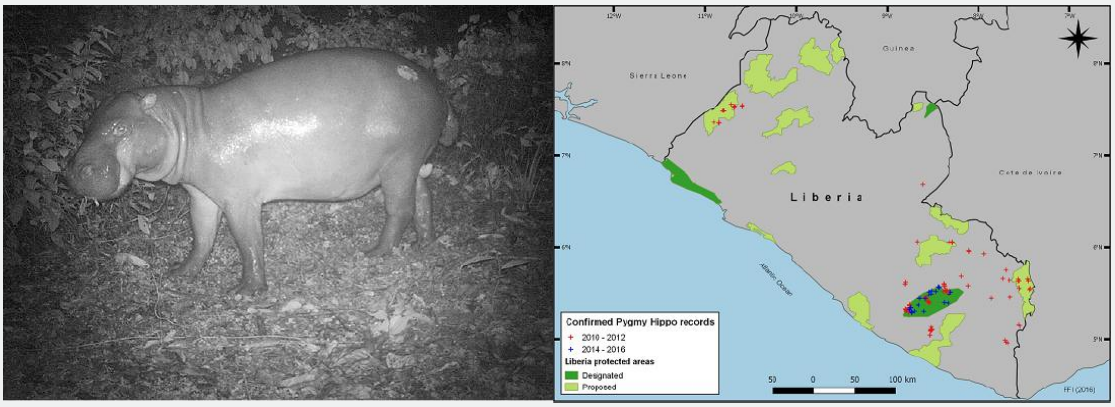


Figure 9.3.3 (Top) Night-time camera trap image of the pygmy hippopotamus taken in Sapo National Park, Liberia. Photograph by FFI, CC BY 4.0. (Bottom) Distribution of pygmy hippopotamus in Liberia based on confirmed records from 2010-2016. Map by Benedictus Freeman/FFI, CC BY 4.0.

It is important to understand that species living in ecosystems that are not conspicuously destroyed may also experience the effects of habitat loss, and hence suffer population declines. This is because habitat loss often manifests itself, at least initially, through less visible but equally threatening **habitat degradation**. For example, disturbances such as overgrazing do not immediately change the organization of dominant plants and other structural features of an ecological community. First, barely noticeable, a few sensitive habitat specialists disappear, being unable to cope with high levels of grazing. Soon, **invasive species** that can tolerate trampling start occupying the niches left open by the extirpated sensitive species. Eventually, when livestock eat the last remaining edible morsels of palatable plants not choked out by invasive species, all that is left of the once productive grassland is a field full of dense, unpalatable, invasive shrubbery.

9.3.2 What is habitat fragmentation?

As governments and industries implement measures to accelerate economic growth, ecosystems that formerly covered large, continuous swathes of land are being increasingly subdivided into smaller parcels by roads, farm fields, towns, and other human constructs. This process, known as **habitat fragmentation**, divides once large and widespread wildlife populations—many already suffering from habitat loss—into several increasingly smaller subpopulations. Habitat fragmentation thereby hastens extinctions, as each of these fragmented **subpopulations** are more exposed to a range of deleterious genetic effects than the previously large and connected population.

As if they are victims of double jeopardy, habitat fragmentation also impedes these smaller subpopulations' dispersal and colonization abilities. Most species, especially those that occur in low densities, have large home ranges and/or live in ephemeral habitats, and must be able to move freely across the landscape to find shelter, food, water, and mates. A recent global review found that habitat fragmentation has already reduced the average distance of animal movements by two-thirds—from 22 km to 7 km—over the past few decades (Tucker et al., 2018). If they cannot move freely, these individuals cannot fulfill their needs and are at risk of extinction. **Habitat interior** specialists are particularly vulnerable to habitat fragmentation, as they are often reluctant to disperse over degraded or cleared areas, even if only a few meters wide (Blake et al., 2008; van der Hoeven et al., 2010).

Physical barriers that impede the ability of wildlife to move freely across the landscape also represent a form of habitat fragmentation. Dispersal impeded by human-constructed barriers, such as railways; dams; water-filled ditches; roads; and fences (Figure 9.3.4), can have disastrous consequences for biodiversity. Consider, for example, Africa's seasonal drylands. These areas were historically characterized by vast herds of **migratory** herbivores constantly moving from one area to another after fresh pasture. But as land management systems changed over time, the construction of roads and erection of fences to mark property boundaries impeded the ability of these herds to move freely after the resources they needed to stay alive (Durant et al., 2015; Hopcraft et al., 2015; Stabach et al., 2016). Restricted to only small parts of their range, these once-migratory animals were forced to overgraze the areas they already exploited, leading to extensive population declines.



Figure 9.3.4 Common wildebeest (*Connochaetes taurinus*, LC) at Kenya's Maasai Mara that died after a fence stopped them from continuing their migration. Photograph by Teklehaymanot G. Weldemichel, CC BY 4.0.

Habitat loss and habitat fragmentation may even threaten the survival of species that are not as obviously dependent on large-scale movements for survival. As discussed previously, many plants cannot persist without seed dispersal. Unfortunately, many seed dispersers, including forest primates (Estrada et al., 2017) as well as frugivorous birds, such as parrots, orioles, turacos, and hornbills (Lehouck et al., 2009), are sensitive to habitat fragmentation. In one of the few studies looking at this issue in Africa, researchers found that valuable timber trees in Tanzania's East Usambara Mountains are being extirpated as forest fragments become too small to support viable populations of fruit-eating birds (Cordeiro et al., 2009). The loss of these important seed dispersers will therefore have knock-on effects on the plants that depend on them for survival. Eventually, if enough seed dispersers, or perhaps even a single keystone species, disappear because of habitat fragmentation, entire ecosystems may eventually collapse.

9.3.3 What are edge effects?

> Edge effects exacerbate the impact of habitat fragmentation by reducing the functional size of habitat patches.

Edge effects are closely associated with, and exacerbate, the negative effects of habitat loss and fragmentation by altering environmental conditions in the habitat interiors. Dense woodlands, thickets, and forests are especially vulnerable to edge effects. Imagine a tropical forest, especially its large trees forming a continuous leafy canopy. These continuous canopies regulate the **microclimate** of a forest's understory by blocking sunlight and wind and maintaining humidity during the day, but also trapping heat rising from the forest floor at night. When the forest's trees are felled, the continuous canopy is fragmented, which in turn compromises the canopy's ability to regulate the forest's microclimate. Cleared areas, as well as forested areas directly adjacent to the cleared areas, will consequently be sunnier, warmer, windier, and dryer during the day, and cooler at night; these climatic changes also disturb nutrient cycles and biomass balances (Haddad et al., 2015). All of these changes further reduce the size of the forest patch to be smaller than the remaining canopy might indicate (Figure 9.3.5) as the new conditions prevent forest specialists such as shade-loving mosses, seedlings of late-successional trees, and humidity-sensitive amphibians from living in forest edges, leaving them with less interior forest habitat for which they must compete. Importantly, these microclimatic changes can penetrate a forest patch over much greater distances than one might expect.

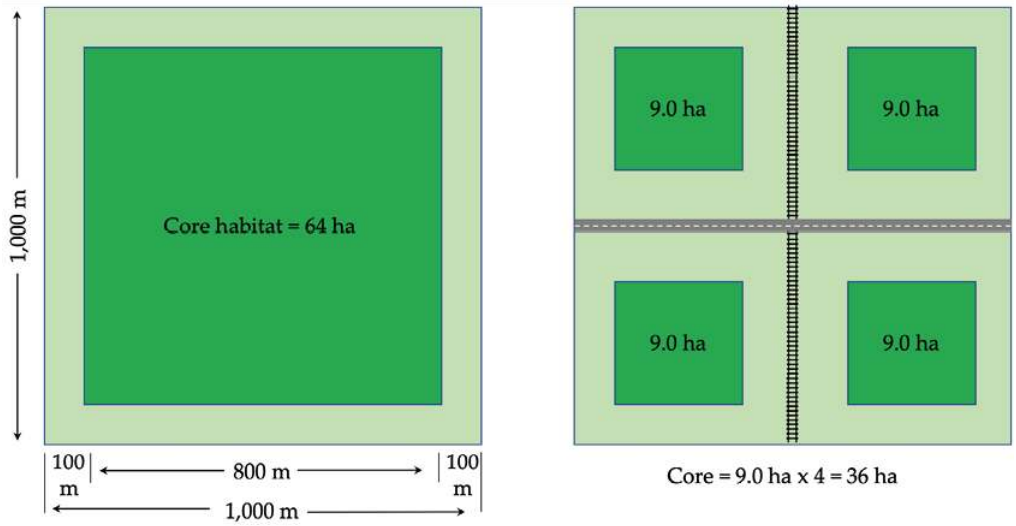


Figure 9.3.5 An illustration showing how habitat fragmentation and edge effects reduce habitat area. (A) A 100-ha forest patch, where edge effects (grey) penetrate 100 m into the forest: approximately 64 ha of the forest is still core habitat suitable for forest interior species. (B) The same 100-ha forest patch now bisected by a road and a railway. Although the road and railway take up very little area, it increases the patch's perimeter: area ratio. The resulting edge effects leave more than half of the forest unsuitable for interior species. After Primack, 2012, CC BY 4.0.

Edge effects also create several additional threats to the forest species already suffering from altered microclimates. Notably, disturbed edge conditions present a favorable environment for colonization by fast growing and fast reproducing invasive species. Those forest species that are not displaced by the altered microclimates and invasive species also face elevated predation risk. That is because trees that have died due to altered edge conditions provide suitable perches with clear views from which predatory birds can hunt (Sedláček et al., 2014). The degraded forest edge, sometimes resembling a savannah structure, also provides opportunities for woodland species such as snakes to enter the forests, pushing the remaining forest species even deeper into the forest (Freedman et al., 2009). For this reason, forest edge communities generally consist of widespread generalist species and invasive species, while specialist species that can hang on are, literally and figuratively, living on the edge.

> Edge effects beget further edge effects in a positive feedback loop leading to a rapidly disappearing ecosystem.

The most devastating impact of edge effects is that edge effects beget further edge effects in a positive feedback loop leading to a rapidly disappearing ecosystem. First, expanding invasive (and generalist) species populations at habitat edges can easily overwhelm more sensitive habitat specialists. As habitat specialists are displaced at the contact zones, microclimatic conditions change, which allows for invasions even deeper into the fragmented habitat patch. In this way, invasions systematically penetrate deeper and deeper into the forest as microclimates are disturbed, habitat specialists are displaced, and new contact zones are created. The forest plants that die in the process also increase fuel loads, which, combined with drier and windier edge conditions,

create an environment increasingly favorable for fire disturbance. Whether from lightning strikes or human activities, subsequent fires burn hotter and over a larger area (van Wilgen et al., 2007), disturbing and destroying more and more habitat each time. Through these mechanisms, edge effects can degrade entire ecosystems over time, harming both the native species and human livelihoods that depend on those areas.

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9.4: Habitat Loss' Impact on Select Ecosystems

9.4.1 Tropical forests

Occupying about 7% of all land surfaces (Figure 9.4.1), tropical forests are estimated to contain over 50% of the world's terrestrial species (Corlett and Primack, 2010). Due to these high levels of biodiversity, the complexity of biological interactions in tropical forests is unparalleled in other ecosystems, and consequently also their importance to humans. Tropical forests also have regional importance including protecting catchment areas and moderating climate. Lastly, as reservoirs of carbon, tropical forests play a globally important role in mitigating the negative effects of anthropogenic climate change. 4.2 million hectares of humid tropical primary forest were lost in 2020 (Figure 9.4.3). In addition to biodiversity loss, the resulting carbon emissions from this amount of tropical forest loss is equivalent to the annual emissions from 570 million cars (Global Forest Watch).

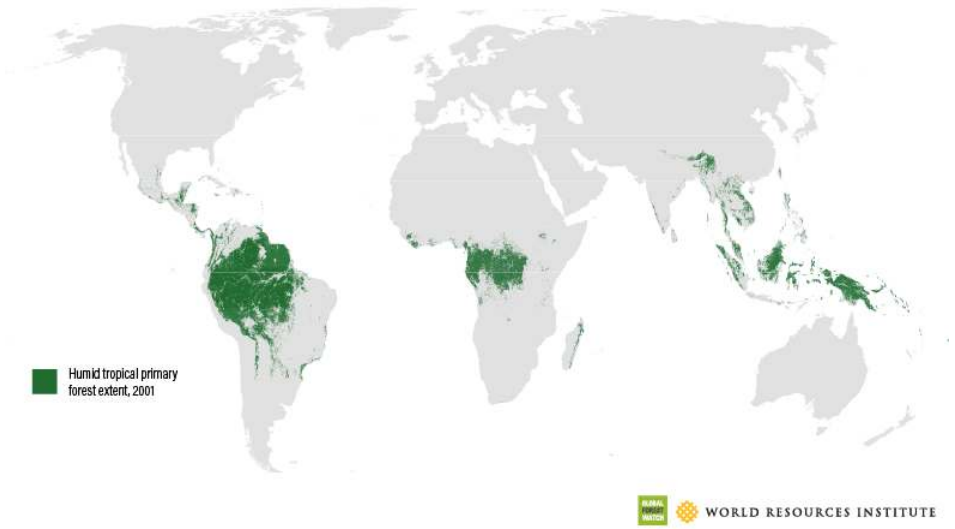


Figure 9.4.1: Distribution of tropical primary forest in 2001

Top 10 countries for humid tropical primary forest loss by extent (2020)

Country	Humid tropical primary forest loss, 2002-20 (million hectares)	Humid tropical primary forest extent, 2001 (million hectares
Brazil	26.2	343.2
Indonesia	9.7	93.8
Democratic Republic of the Congo	5.3	104.6
Bolivia	3	40.8
Malaysia	2.7	15.9
Peru	2.2	69.1
Colombia	1.7	54.8
Cambodia	1.3	4.3
Paraguay	1.1	3.5
Madagascar	0.9	4.8

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Figure 9.4.2: Leading countries in tropical primary forest loss 2020

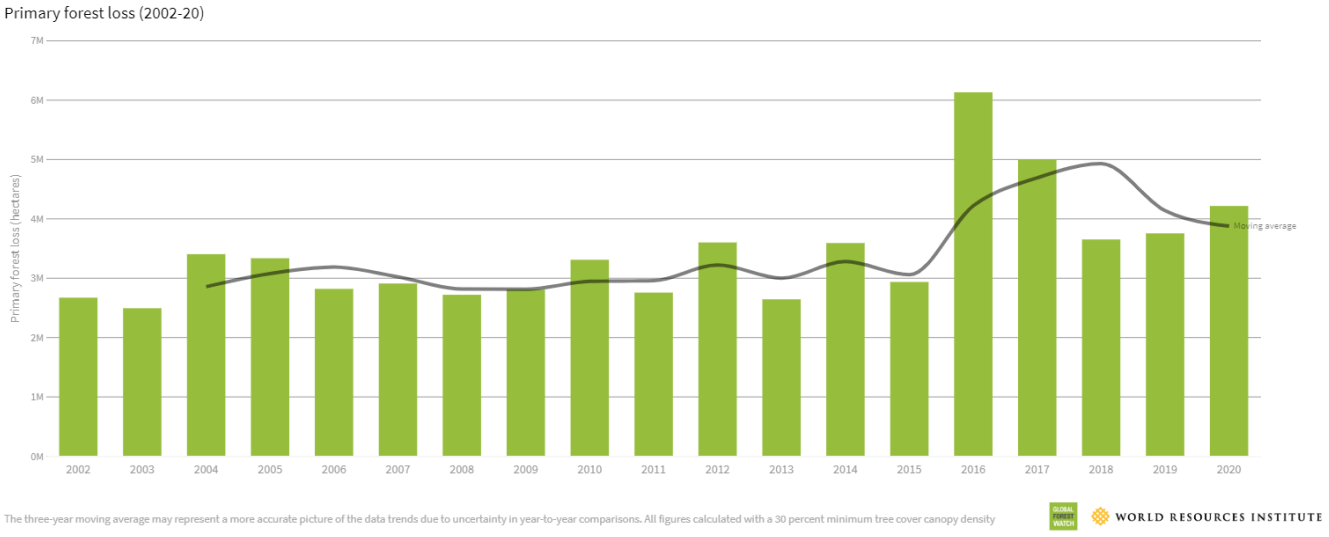


Figure 9.4.3: Loss of tropical primary forest between 2002 and 2020

Despite the importance of tropical forests, their destruction has become synonymous with the rapid loss of biodiversity (Figure 9.4.4). Africa had already lost over 65% of its original tropical forests by 1990 (Sayer, 1992); human activities destroyed an additional 308,000 km2 (an area larger than Italy) between 1990 and 2010 (Achard et al., 2014). Losses were particularly severe in Burundi, Benin, and Mozambique, with each country holding less than 5% of its original forest cover (Sayer, 1992). Retaining about half of its original forest cover, the DRC is relatively better off, but current deforestation rates in this country are currently second highest globally (Weisse and Goldman, 2019). Current deforestation rates are so severe in Equatorial Guinea that this country will lose all its forests within the next 20 years if current trends hold (Potapov et al., 2017). Despite these alarming trends —the destruction continues nonstop, particularly in Ghana and Côte d'Ivoire, which saw a 60% and 26% rise in forest loss (the highest rise globally), respectively, between 2017 and 2018 (Weisse and Goldman, 2019). Across Africa, logging is currently the dominant driver of tropical forest loss (causing 77% of total losses over the past decade), followed by agriculture (Potapov et al., 2017).

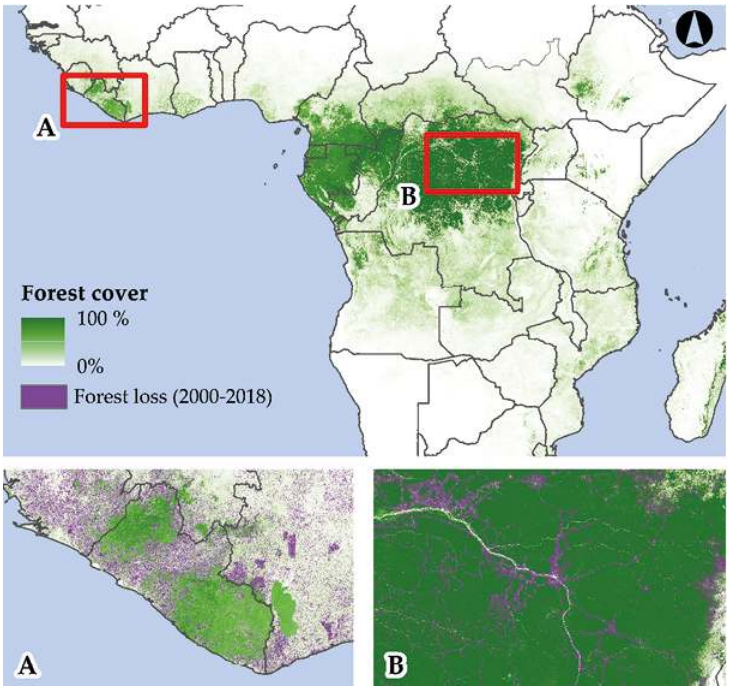


Figure 9.4.4 The extent of Sub-Saharan Africa's tropical forests in 2018, and the extent of tropical forests loss (A) around Liberia and (B) in the north-eastern part of the Congo Basin between 2000 and 2018. Note in (A) how deforestation follows country borders, and in (B) how deforestation follows road networks. Source: Hansen et al., 2013. Map by Johnny Wilson, CC BY 4.0.

9.4.2 Rivers and deltas

Due to our dependence on freshwater, humans have always preferred to live near rivers, streams, and lakes. Consequently, these aquatic environments have been destroyed at a scale at least equal to that of terrestrial environments. Rivers have taken a particularly hard hit from human activities, being polluted by industries and dammed to ensure a reliable, year-round supply of water for consumption and irrigation, and to generate hydroelectricity.

Dam construction holds several negative consequences for biodiversity and people. Aquatic organisms that cannot survive the altered river conditions downstream (reduced flow and dissolved oxygen, higher temperatures, and increased turbidity) are most vulnerable. Lastly, dams reduce connectivity in freshwater ecosystems, preventing freshwater organisms from exchanging genetic material, migrating between upsteam and downstream areas, and adapting to changing conditions.

Terrestrial ecosystems also suffer from dam construction. Of concern is the direct loss of riverine and **palustrine ecosystems** downstream from the dam due to reduced waterflow. Dams may cause the drying of large wetlands and floodplains downstream, displacing people who depend on the river's now-compromised seasonal flood cycles (Drijver and Marchand, 1985). Flooding of upland areas next to dammed rivers also displaces terrestrial wildlife and people. For example, construction of Mali's Manalati Dam flooded 430 km2 of savannah and 120 km2 of forest, which fractured the migration routes of the region's **nomadic**

pastoralists, leading to overgrazing and soil erosion of the remaining grazing lands (deGeorges and Reilly, 2006), in addition to a 90% loss of fisheries downstream (Acreman, 1996).

9.4.3 Wetlands

Wetlands are being mined for valuable peat, or drained and/or filled in for development and agriculture. This is a major concern because wetlands serve as spawning grounds and nurseries for aquatic and amphibious wildlife and stop-over sites for migratory birds (Box 9.4.1). Wetlands also provide multiple important ecosystem services. For example, they prevent erosion and runoff by capturing large volumes of floodwater, which is then released slowly over time. This process also allows sediments and nutrients kicked up during flood events to settle out, creating fertile habitats for a wide diversity of animals and plants, as well as for agriculture. Water that leaves after this settling period is cleaner than when it entered, having been filtered by the soil, plants, and microbes of wetlands. This water purification and filtration service is generally cheaper and much more efficient than man-made filtration systems. The loss of any wetlands, but especially at such large scales, is thus a grave concern not only because of the countless animals and plants threatened with extinction, but also the people that depend on all the valuable ecosystem services they offer.

Box 9.4.1 Migratory Birds of Africa: The Largest of the Last Great Migrations?

Abraham J. Miller-Rushing and John W. Wilson

Acadia National Park, US National Park Service, Bar Harbor, ME, USA.

How are Africa's bird migrations, the biggest in the world, faring in a rapidly changing world? Each year, about 2.1–5 billion birds (mostly songbirds, but also raptors, waterbirds, and many others) travel back and forth between their wintering grounds in Africa and breeding grounds in Europe and Asia (Figure 9.4.3). Of the 126 species involved in this migration, over 40% have continuously decreased in abundance since 1970 (Vickery et al., 2014). At first, populations that overwintered in open dry savannahs declined: examples include the Ortolan bunting (E*mberiza hortulana*, LC) and European turtle dove (*Streptopelia turtur*, VU) which decreased by 84% and 69% between 1980 and 2009, respectively. More recently, species overwintering in the humid Afrotropics also started declining: this includes songbirds, such as the common nightingale (*Luscinia megarhynchos*, LC) and river warbler (*Locustella fluviatilis*, LC)—populations of both declined by 63%—and waterbirds such as the black-tailed godwit (*Limosa limosa*, NT), which declined by 45%.

To survive their long journeys, migratory birds need favorable weather conditions, adequate food sources, and intact habitat not only at the end points where they breed or overwinter, but also along their routes where the migratory animals can rest and refuel (Runge et al., 2015). Disturbances in any of these places can lead to sharp population declines. For example, recent research showed that the habitat quality of a single stop-over site can determine whether a migration is successful or not (Gómez et al., 2017). Illustrating this point, a drought in the Sahel, an important migratory stop-over site, led to food shortages that killed 77% of the world's common whitethroats (*Sylvia communis*, LC); even today, this population has not yet fully recovered (Vickery et al., 2014).

Human activities have greatly contributed to the declines of Africa's migratory birds (Kirby et al., 2008; Vickery et al., 2014). For example, each year thousands of hectares of wetlands, forests, grasslands, and savannahs are being converted into farmlands and urban areas or polluted by rampant use of pesticides and herbicides. Migratory birds also need to deal with hunters and trappers, and an increasing number of human-made structures, such as high-rise buildings, wind turbines, and power lines that represent collision and electrocution hazards (e.g. Rushworth et al., 2014). Then there is the threat of inconsistent rainfall, which causes food shortages and direct mortality, and climate change, which causes temporal mismatches between migratory movements and abundance of key food resources (Both et al., 2006; Vickery et al., 2014).

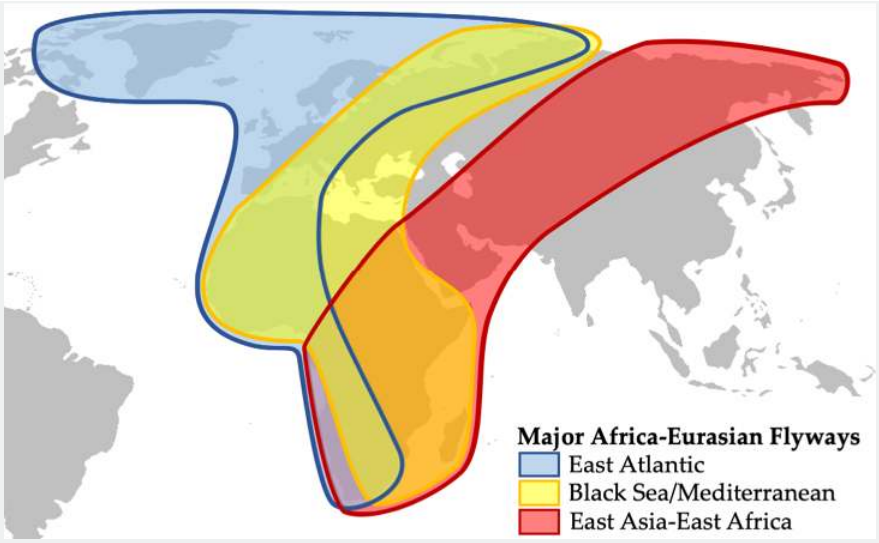


Figure 9.4.5 The three major migratory flyways that African birds use to travel back and forth between their wintering grounds in Africa and breeding grounds in Europe and Asia each year. After BirdLife International, 2019, CC BY 4.0.

Mangrove swamps (sometimes called mangrove forests, though technically a wetland because their function and structure are primarily determined by hydrology, Lewis, 2005; Gopal, 2013) are one of Earth's most threatened wetland ecosystems. Characterized by woody plants that can tolerate saltwater, mangrove swamps occupy brackish waters in tropical coastal areas, typically where there are muddy bottoms. These areas are sparsely distributed; globally, mangrove swamps cover only 53,000 km2 of land scattered across 118 countries (Dybas, 2015). In addition to holding many unique species, mangrove swamps also protect coastal cities and villages from cyclone/hurricane and tsunami damage and provide important breeding and feeding grounds for marine shellfish and fish. One study estimated that mangrove swamps provide an estimated US $57,000 worth of ecosystem services per hectare (van Bochove et al., 2014). A large percentage of mangrove swamps have been destroyed or damaged by agriculture, urban expansion, pollution, and commercial shellfish farming (Giri et al., 2011). With so much destruction, it should come as little surprise that about 40% of vertebrate species endemic to mangrove swamps are currently threatened with extinction (Luther and Greenberg, 2009).

9.4.4 Seasonal drylands

Semi-arid savannahs, scrublands, and grasslands are being lost through conversion to agriculture and **desertification**—the systematic degradation of formerly complex and adaptive seasonal drylands into barren wastelands (Figure 9.4.6). When human populations were low, nomadic pastoralism and shifting cultivation enabled people to utilize seasonal drylands in a sustainable way. Today however, population growth, combined with restrictions placed on free movement by administrative borders and competition for land, forces people and animals living on drylands to be more sedentary. While these areas may initially support some agriculture and livestock, unsustainable techniques, such as overgrazing and excessive tilling, lead to soil erosion and the depletion of soil nutrients and natural **seed banks**. With the cover vegetation gone, the unprotected topsoil is easily lost to wind and flooding, leaving behind the deeper, infertile, and compact subsoil layers with little capacity to hold water. The result is something that closely resembles a man-made desert. However, rather than a functional ecosystem characterized by species adapted to life in the desert, these wastelands have lost their original productivity and biological communities, only to be revived through expensive and/or time-consuming **land reclamation** methods.



Figure 9.4.6 Desertification, the degradation of formerly complex and adaptive seasonal drylands into barren wastelands, is a growing threat to Africa's natural environment, its wildlife, and its people. It is a prominent problem in the Sahel region, such as the area pictured, in Burkina Faso. Photograph by Jose Navarro, https://www.flickr.com/photos/53871588@N05/5630241115, CC BY 4.0.

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9.5: Population Growth and Consumption

Until about 150 years ago, the rate of human population growth had been relatively slow, with the birth rate only slightly exceeding the death rate. Modern medical achievements and more reliable food supplies have changed this balance; they have reduced mortality rates while birth rates remain high. Consequently, the human population has grown to 7.9 billion as of 2021.

Simple math suggests that more people leads to less space for biodiversity (Figure 9.5.1), because humans and wildlife compete for the same resources, broadly speaking. With many countries already facing social, economic, and developmental challenges such as malnutrition, crime, and unemployment, one can almost understand why politicians prioritize socio-economic upliftment over biodiversity conservation. This is a grave mistake; as previously discussed, biodiversity and human well-being are intricately linked. It is one of conservation biologists' most important tasks: to make the link between conservation and human welfare clear to policy scholars and politicians.



Figure 9.5.1 Night lights of Montreal, Canada. To have more people leads to more competition for space, leaving less space to maintain biodiversity and ecosystem services. It also means more natural resources extracted, more pollution, and more greenhouse gas emissions. Photo by David Iliff. License: CC BY-SA 3.0, Wikimedia Commons

In recent years, there has been an increasing tendency of economists, scientists, and politicians to shift the focus from population growth to consumption as the more important underlying driver of biodiversity loss. For many, the emphasis on consumption avoids politically charged topics, such as population control, which most people oppose on ethical or moral grounds, and because it is associated with divisive topics such as xenophobia, racism, and eugenics (Kolbert and Roberts, 2017). Others highlight that it is not the number of people per se, but how natural resources are consumed that is the main cause of environmental decline. Indeed, affluent people and affluent countries have a disproportionate impact on the natural environment because they consume a disproportionately large share of the world's natural resources. To use one example, the USA accommodates only 5% of the world's human population but uses 25% of the world's harvested natural resources each year (WRI, 2019). In fact, decorative Christmas lights in the USA alone use more energy than the annual energy usage of the entirety of Ethiopia or Tanzania (Moss and Agyapong, 2015). And yet, the average USA citizen uses less than half of the energy (measured as carbon emissions) that an average citizen of Qatar uses (World Bank, 2019; see also Figure 9.5.2), Qatar being a small but wealthy Middle Eastern country.

The major threats to biodiversity are all rooted in expanding human populations and unsustainable consumption patterns.

Another important aspect to consider in the consumption argument is that, through increased **globalization**, the impacts of consumption in industrialized countries are felt over much greater distances than before (Moran and Kanemoto, 2017). For instance, chocolate consumed in Europe was most likely made with cacao produced in West Africa (Gockowski and Sonwa, 2011); other crops, such as coffee and tea, produced in Africa are similarly enjoyed all over the world. In the best-case scenario, African farmers are satisfying a demand in a global market; at worst, foreign companies are establishing croplands with little benefit trickling down to local people. Supporters of the consumption argument rightfully point out that it would be very unjust to blame the local farmers for cleared forests when they simply produce commodity crops that the international market demands.

As with many other complex challenges, both sides of the population-consumption debate are correct. One method to link the impact (I) of a human population on the environment is through the formula

$(I = P \times A \times T]$

This is the IPAT in short, where P is population size, A is Affluence (e.g. per capita GPD), and T is technology (e.g. per capita energy use) (Ehrlich and Goulder, 2007). The IPAT equation is similar in concept to the **ecological footprint** (Figure 9.5.2): both illustrate that human populations and consumption patterns interact to exacerbate human impacts on the environment. In other words, many poor Africans can have the same impact on the environment as just a few wealthy Americans, and vice versa.

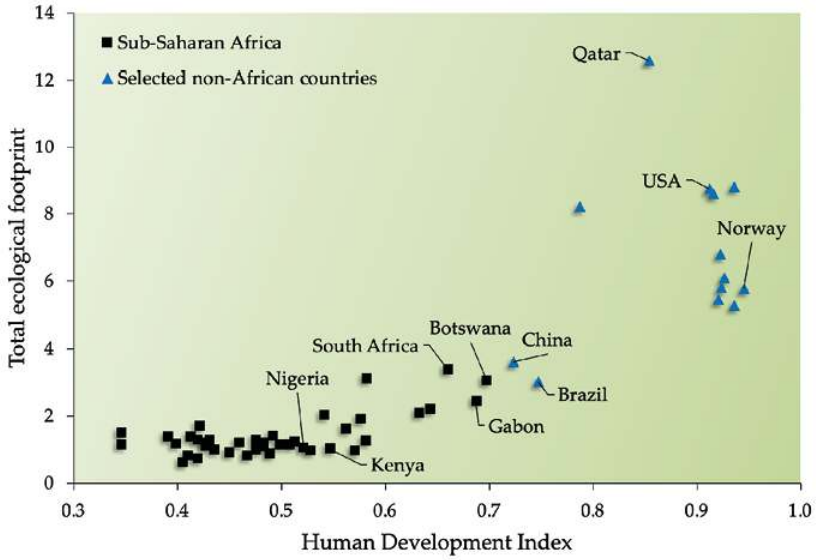


Figure 9.5.2 A nation's ecological footprint is calculated by estimating the amount of land needed to support the average resident of that nation. Although there is some disagreement as to the exact methods for these calculations, the overall message is clear: people in more developed nations use a disproportionately large amount of natural resources. However, the overall impacts of countries with huge populations, such as China, are also huge because of the cumulative impact from so many people. Source: GFN, 2017, CC BY 4.0.

Both the IPAT equation and ecological footprint concept are insightful as to the challenges facing ecosystems and people. Today, people in less developed nations are increasingly aspiring to attain the same levels of high consumption as industrial countries. These patterns generally lead to an inefficient, wasteful, and unsustainable use of natural resources (i.e. overconsumption). Population growth rates in many industrial countries are currently slowing; some countries are even experiencing long-term population declines, which allow conservation-minded individuals in those countries to focus their efforts on addressing consumption patterns. The situation is quite different in less developed countries, where we are faced with increasing per capita consumption and fast population growth. While conservation biologists differ in terms of how strongly they argue for addressing the population size issue, most also agree that conservation goals benefit from education, the empowerment of women, and wider access to family planning and reproductive health services.

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9.6: Summary

Summary

1. One of the primary threats to biodiversity today are habitat loss and habitat fragmentation. Many species living in tropical forests, freshwater ecosystems, the marine environment, and seasonal drylands are at risk of extinction due to habitat loss.
2. The theory of island biogeography and the species-area relationship can be used to predict the numbers of species that will go extinct due to habitat loss. Both theories predict that large habitat patches are better able to maintain wildlife populations because they accommodate populations better buffered against extinction.
3. Habitat fragmentation describes the process when once large and widespread habitats (and hence wildlife populations) are divided into several increasingly smaller and isolated units. This process leads to extinctions because it impedes dispersal, colonisation, foraging, and reproduction.
4. Edge effects reduce the functional size of habitats because they alter microclimates and expose habitat specialists to displacement by invasive species, predators, and other disturbances.
5. Habitat loss and fragmentation are rooted in expanding human populations and excessive consumption of natural resources. The >IPAT equation illustrates how population size, wealth, and technology together determine our impact on the environment.

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9.7: Topics for Discussion

1. Why does oil palm (>Elaeis guineensis, LC) cultivation represent a significant threat to biodiversity?
2. Read Harris et al. (2009) on the decline of the world's mass wildlife migrations. Which lost African migration appeals to you most and why? What species were involved? What numbers of animals were involved? How do you think this migration can be revived?
3. Which ecosystem in your region would you consider the most damaged, and which would you consider the most pristine? Can you explain why these two ecosystems have such different fates?
4. Do you agree with the idea that human population growth is the primary driver of extinctions today? Why? How do we balance protecting biodiversity with providing for a growing human population, and the right of people to have children?

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CHAPTER OVERVIEW

10: Impacts of Climate Change

10.1: Introduction to the Impacts of Climate Change

10.2: Climate Change

10.2.1: Climate vs. Weather

10.2.1.1: The Greenhouse Effect and Climate Change

10.3: Drivers of Climate Change

10.5: The Impact of Climate Change

10.6: Beneficiaries of Climate Change

10.7: The Overall Impact of Climate Change

10.8: Summary

10.9: Topics for Discussion

10.11: Bibliography

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10.1: Introduction to the Impacts of Climate Change

Life-threatening heatwaves, drowning coastal towns, tens of thousands of displaced refugees… These words may very well describe a scene from the latest horror movie. But they also describe the nightmare scenario facing us humans in just a few decades if we continue to leave the threat of climate change under-addressed. This term, climate change (which is shorthand for **anthropogenic climate change**), refers to the complete set of climate characteristics—temperature; precipitation; pressure systems; wind patterns; and oceanic currents—that are changing both locally and regionally due to human influences. It is closely related to **global warming**, also called global heating, which describes the general trend of increasing global temperatures we see under climate change.



Figure 10.1.1: UN secretary general Ban Ki-moon introduces the Momentum for Change initiative at the UN Climate Change Conference, also known as COP17, held in Durban, South Africa in 2011. Photograph by UNFCCC, https://www.flickr.com/photos/unfccc/6470741719, CC BY 2.0.

Climate change has the potential to render Earth unrecognizable from what any human has ever experienced. These changes will have an immense impact on ecosystem services, global economies, and our own quality of life. Yet, while there is much talk about these risks, there is too little action addressing its main causes. Some of the lack of action may be attributed to “climate change” and “future” often being used in the same sentence, giving politicians and industries a false impression that we can deal with climate change once we achieved sufficient economic growth. The reality could however not be further from the truth, as we already see signs of the changes to come here today, including near-annual crop-failures, record-high temperatures, and record-strength coastal storms.



Figure 10.1.2: Rate of sea level rise from 1900 - 2018

(Data source: Frederikse et al. (2020)
Credit: NASA’s Goddard Space Flight Center/PO.DAAC)

Thankfully, with the increase in understanding that our activities are creating a global crisis of epic proportions, the impacts of climate change are now being actively debated in the corridors of governments and major corporations. Politicians, the media, and others are also increasingly replacing “climate change” with more vivid language, like “climate crisis” and “climate emergency” (e.g. Carrington, 2019). This will hopefully encourage even more governments and industries to come to the table and cooperate like never before to address the fundamental drivers of climate change. Solving this global crisis requires an international multi-pronged approach that should include ecosystem protection and restoration, direct species management, and legislative action. But before we consider the solutions, we will first investigate why climate change is happening, and how it will impact biodiversity over the coming decades.

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10.2: Climate Change

Global **climate change** is also a consequence of human population needs for energy, and the use of fossil fuels to meet those needs. Essentially, burning **fossil fuels**, including as oil, natural gas, and coal, increases carbon dioxide concentrations in the atmosphere. Carbon dioxide traps heat energy from the sun, resulting not only in an average increase in global temperature but also in changing precipitation patterns and increased frequency and severity of extreme weather events, such as hurricanes. Scientists overwhelmingly agree the present warming trend is caused by humans. See the Climate Change chapter for a detailed description its cause and impacts. A few examples of how climate change impacts biodiversity are described in the paragraphs below.

Climate change is recognized as a major extinction threat, particularly when combined with other threats such as habitat loss. Scientists disagree about the likely magnitude of the effects, with extinction rate estimates ranging from 15 percent to 40 percent of species committed to extinction by 2050. By altering regional climates, it makes habitats less hospitable to the species living in them. The warming trend will shift colder climates toward the north and south poles, forcing species to move (if possible) with their adapted climate norms. For example, one study indicates that European bird species ranges have moved 91 kilometers (56.5 miles) northward, on average. The same study suggested that the optimal shift based on warming trends was double that distance, suggesting that the populations are not moving quickly enough. Range shifts have also been observed in plants, butterflies, other insects, freshwater fishes, reptiles, amphibians, and mammals.

The shifting ranges will impose new competitive regimes on species as they find themselves in contact with other species not present in their historic range. One such unexpected species contact is between polar bears and grizzly bears (figure $10.2.a$). Previously, these two species had separate ranges. Now, their ranges are overlapping and there are documented cases of these two species mating and producing viable offspring.



Figure 10.2.*a*: Historically, grizzly bear habitat extended from Mexico through the western United States and into the mid-latitudes of Canada. Since 2008, grizzly bears (*Ursus arctos horribilis*) have been spotted farther north than their historic range, a possible consequence of climate change. Their range now extends to the northern tip of Canada and throughout Alaska. As a result, grizzly bear habitat now overlaps polar bear (*Ursus maritimus*) habitat. The two kinds of bears, which are capable of mating and producing viable offspring, are considered separate species as historically they lived in different habitats and never met. However, in 2006 a hunter shot a wild grizzly-polar bear hybrid known as a grolar bear, the first wild hybrid ever found.

Climate gradients will also move up mountains, eventually crowding species higher in altitude and eliminating the habitat for those species adapted to the highest elevations. Some climates will completely disappear. The rate of warming appears to be accelerated in the arctic, which is recognized as a serious threat to polar bear populations that require sea ice to hunt seals during the winter months. Seals are a critical source of protein for polar bears. A trend to decreasing sea ice coverage has occurred since observations began in the mid-twentieth century. The rate of decline observed in recent years is far greater than previously predicted by climate models.

Changing climates also throw off the delicate timing adaptations that species have to seasonal food resources and breeding times. Scientists have already documented many contemporary mismatches to shifts in resource availability and timing. For example, pollinating insects typically emerge in the spring based on temperature cues. In contrast, many plant species flower based on daylength cues. With warmer temperatures occurring earlier in the year, but daylength remaining the same, pollinators ahead of peak flowering. As a result, there is less food (nectar and pollen) available for the insects and less opportunity for plants to have their pollen dispersed. For migrating birds, timing is everything – they must arrive at their summer breeding grounds when food supplies are at their peak, so that they can rebuild their body fat and reproduce successfully. In some areas, birds are showing up early, before flowers open or insects hatch, and finding very little to eat.

Ocean levels rise in response to climate change due to meltwater from glaciers and the greater volume occupied by warmer water. Shorelines will be inundated, reducing island size, which will have an effect on some species, and a number of islands will disappear entirely. Additionally, the gradual melting and subsequent refreezing of the poles, glaciers, and higher elevation mountains—a cycle that has provided freshwater to environments for centuries—will be altered. This could result in an overabundance of salt water and a shortage of freshwater.

Finally, increased carbon dioxide levels in the atmosphere react with ocean water to form carbonic acid, a phenomenon called **ocean acidification**. In combination with warmer temperatures, ocean acidification is responsible for coral bleaching, the process by which coral expel the algae that typically conduct photosynthesis within the corals. Ocean acidification can also dissolve the calcium carbonate skeletons formed by the coral. Overall, climate change plays a major role in the loss of nearly one third of coral reefs.

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10.2.1: Climate vs. Weather

Section Hook

The iconic Grand Canal of Venice, Italy, doesn't need high quality instruments to note effects of climate change. The Grand Canal was built in a way that the water levels are directly correlated with the sea level. As such, the steps leading into the canal have become rulers for sea level changes over the hundreds of years of their existence. The last step leading into the canal directly reflected the sea level at the time of creation and currently, the water level is 3 feet above this. In the last quarter century, sea levels have been rising much faster than previously measured. This puts Venice in a difficult position moving into a future where scientists predict the sea level to continue to rise, estimating that the city will be underwater by 2100, along with many other coastal cities. Unfortunately, rising seas are only one of the many predicted outcomes of global climate change.



Figure 10.2.1.*a*: Flooding in Venice, Italy. Image by WorldIslandInfo.com in Wikimedia Commons (CC-BY2.0).

Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer. **Global warming** refers to the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of greenhouse gases in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change.

A common misconception about global climate change is that a specific weather event occurring in a particular region (for example, a very cool week in June in central Indiana) is evidence of global climate change. However, a cold week in June is a weather-related event and not a climate-related one. These misconceptions often arise because of confusion over the terms climate and weather.

Climate refers to the long-term, predictable atmospheric conditions of a specific area. The climate of a biome is characterized by having consistent temperature and annual rainfall ranges. Climate does not address the amount of rain that fell on one particular day in a biome or the colder-than-average temperatures that occurred on one day. In contrast, weather refers to the conditions of the atmosphere during a short period of time. Weather forecasts are usually made for 48-hour cycles. Long-range weather forecasts are available but can be unreliable.

To better understand the difference between climate and weather, imagine that you are planning an outdoor event in northern Wisconsin. You would be thinking about *climate* when you plan the event in the summer rather than the winter because you have long-term knowledge that any given Saturday in the months of May to August would be a better choice for an outdoor event in Wisconsin than any given Saturday in January. However, you cannot determine the specific day that the event should be held on because it is difficult to accurately predict the weather on a specific day. Climate can be considered “average” weather.

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10.2.1.1: The Greenhouse Effect and Climate Change

Earth's Temperature is a Balancing Act

Earth's temperature depends on the balance between energy entering and leaving the planet. When incoming energy from the sun is absorbed, Earth warms. When the sun's energy is reflected back into space, Earth avoids warming. When energy is released from Earth into space, the planet cools. Many factors, both natural and human, can cause changes in Earth's energy balance, including:

- Changes in the greenhouse effect, which affects the amount of heat retained by Earth's atmosphere;
- Variations in the sun's energy reaching Earth;
- Changes in the reflectivity of Earth's atmosphere and surface.

Scientists have pieced together a picture of Earth's climate, dating back hundreds of thousands of years, by analyzing a number of indirect measures of climate such as ice cores, tree rings, glacier size, pollen counts, and ocean sediments. Scientists have also studied changes in Earth's orbit around the sun and the activity of the sun itself.

The historical record shows that the climate varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s can be explained by natural causes, such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. Recent changes in climate**,** however, cannot be explained by natural causes alone. Research indicates that natural causes are very unlikely to explain most observed warming, especially warming since the mid-20th century. Rather, human activities, especially our combustion of fossil fuels, explains the current warming (figure 10.2.1.1.*a*). The scientific consensus is clear: through alterations of the carbon cycle, humans are changing the global climate by increasing the effects of something known as the greenhouse effect.

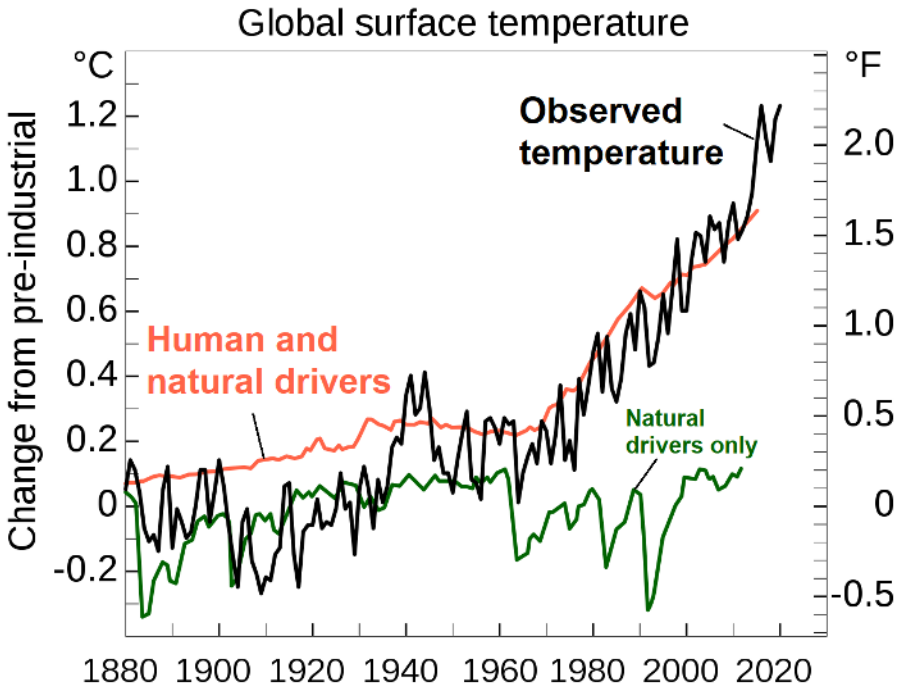


Figure 10.2.1.1.*a*: This graph shows the predicted temperatures from two climate models and observed temperatures from 1880 to 2020. The first model considered only natural factors that could influence temperature and is represented by the green line (bottom). It shows some fluctuations in temperature by no overall increase or decrease. The second model considered both human and natural factors and is represented by the orange line (top). It shows an overall increase in temperature. Actual observations (black, jagged line; middle) more closely match the second model. Overall, temperature has increased about 1.2 degrees Celsius (2.1 degrees Fahrenheit) since pre-industrial times. Image relabeled from Efbrazil (CC-BY-SA).

The Greenhouse Effect Causes the Atmosphere to Retain Heat

Gardeners that live in moderate or cool environments use greenhouses because they trap heat and create an environment that is warmer than outside temperatures. This is great for plants that like heat, or are sensitive to cold temperatures, such as tomato and

pepper plants. Greenhouses contain glass or plastic that allow visible light from the sun to pass. This light, which is a form of energy, is absorbed by plants, soil, and surfaces and heats them. Some of that heat energy is then radiated outwards in the form of infrared radiation, a different form of energy. Unlike with visible light, the glass of the greenhouse blocks the infrared radiation, thereby trapping the heat energy, causing the temperature within the greenhouse to increase.

The same phenomenon happens inside a car on a sunny day. Have you ever noticed how much hotter a car can get compared to the outside temperature? Light energy from the sun passes through the windows and is absorbed by the surfaces in the car such as seats and the dashboard. Those warm surfaces then radiate infrared radiation, which cannot pass through the glass. This trapped infrared energy causes the air temperatures in the car to increase. This process is commonly known as the **greenhouse effect**.

The video below made for kids, but provides a clear and simple introduction to the greenhouse effect.



The greenhouse effect also happens with the entire Earth. Of course, our planet is not surrounded by glass windows. Instead, the Earth is wrapped with an atmosphere that contains **greenhouse gases** (GHGs). Much like the glass in a greenhouse, GHGs allow incoming visible light energy from the sun to pass, but they block infrared radiation that is radiated from the Earth towards space (figure 10.2.1.1.*b*). In this way, they help trap heat energy that subsequently raises air temperature. Being a greenhouse gas is a physical property of certain types of gases; because of their molecular structure they absorb wavelengths of infrared radiation, but are transparent to visible light. Some notable greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4). GHGs act like a blanket, making Earth significantly warmer than it would otherwise be. Scientists estimate that average temperature on Earth would be -18° C without naturally-occurring GHGs.

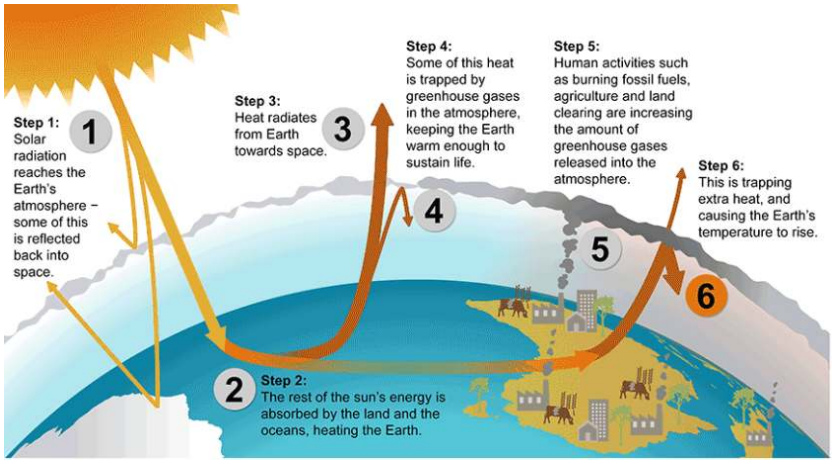


Figure 10.2.1.1.*b*: The enhanced greenhouse effect. Step 1: Some solar radiation reaches the Earth's surface, and some is reflected back into space. Step 2: The rest of the sun's energy is absorbed by the land and the oceans, heating the Earth. Step 3: Heat radiates from Earth towards space. Step 4: Some of the heat is trapped by greenhouse gases in the atmosphere, warming the Earth. Step 5: Human activities such as burning fossil fuels, agriculture, and land clearing have increased the concentrations of greenhouse gases in the atmosphere. Step 6: This is trapping extra heat, causing the Earth's temperature to rise.

What is Global Warming?

Global warming refers to the recent and ongoing rise in global average temperature near Earth's surface. It is caused mostly by increasing concentrations of greenhouse gases in the atmosphere. Global warming is causing climate patterns to change. However, global warming itself represents only one aspect of climate change.

What is Climate Change?

Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer.

The Main Greenhouse Gasses

The most important GHGs directly emitted by humans include CO_2 and methane. **Carbon dioxide** (CO_2) is the primary greenhouse gas that is contributing to recent global climate change. CO_2 is a natural component of the carbon cycle, involved in such activities as photosynthesis, respiration, volcanic eruptions, and ocean-atmosphere exchange. Human activities, primarily the burning of fossil fuels and changes in land use, release very large amounts of CO_2 to the atmosphere, causing its concentration in the atmosphere to rise.

Atmospheric CO_2 concentrations have increased by 50% since pre-industrial times, from approximately 280 parts per million (ppm) in the 18th century to 424 ppm in 2024 (figure 10.2.1.1.c). The current CO_2 level is higher than it has been in at least 800,000 years, based on evidence from ice cores that preserve ancient atmospheric gases (figure 10.2.1.1.$d-f$). Human activities currently release over 30 billion tons of CO_2 into the atmosphere every year. While some volcanic eruptions released large quantities of CO_2 in the distant past, the U.S. Geological Survey (USGS) reports that human activities now emit more than 135 times as much CO_2 as volcanoes each year. This human-caused build-up of CO_2 in the atmosphere is like a tub filling with water, where more water flows from the faucet than the drain can take away.

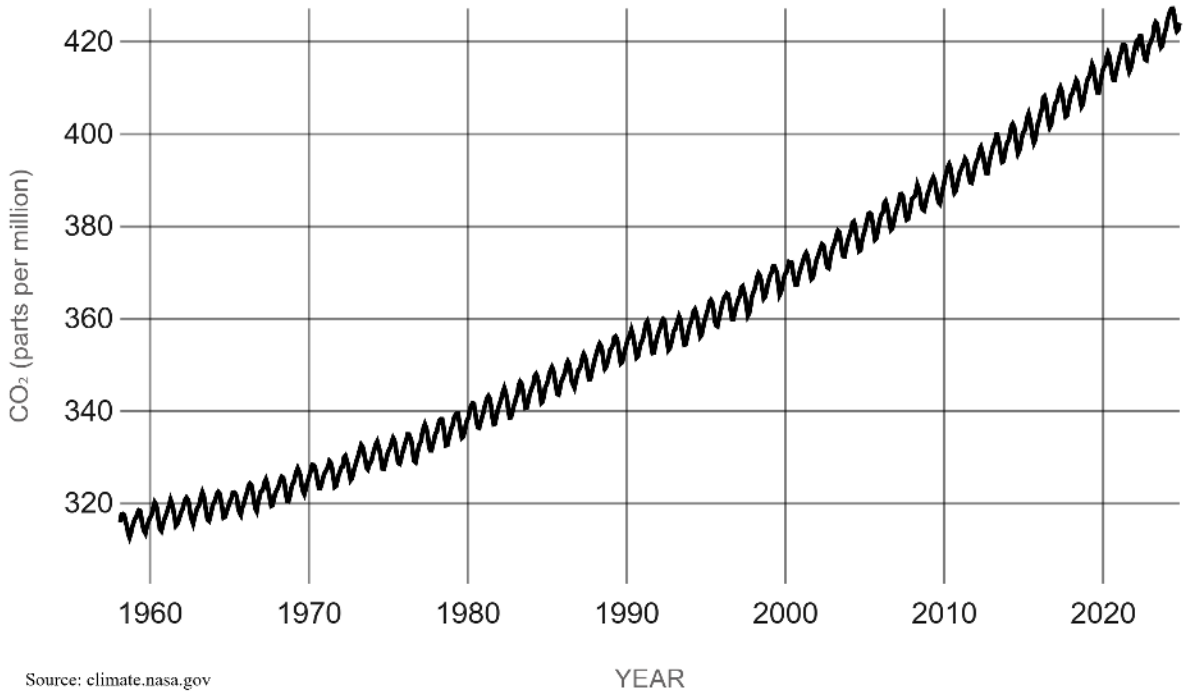


Figure 10.2.1.1.c: Monthly mean carbon dioxide concentration in parts per million (ppm) measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. Carbon dioxide concentrations dip every summer due to increased photosynthesis. Data source NOAA, image by NASA, public domain.

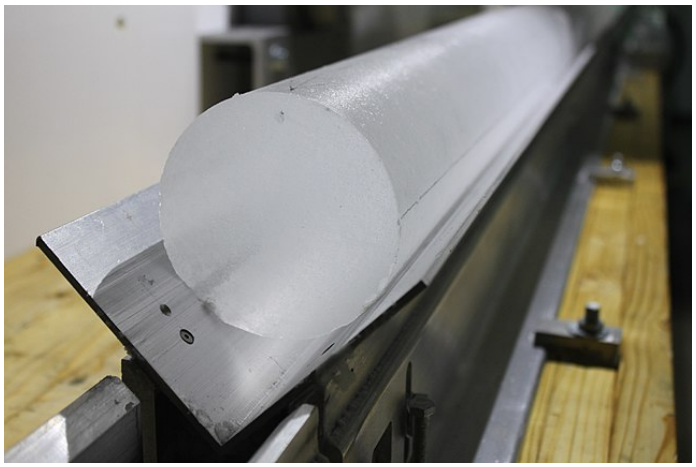


Figure 10.2.1.1.*d*: The EastGRIP ice core, which was drilled from the Greenland Ice Sheet. You can read more here. Image by Helle Astrid Kjær (CC-BY).

Figure 10.2.1.1.*e*: This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO2 has increased since the Industrial Revolution. On the x-axis are the years before today (0 = 2024). It begins 800,000 years prior to 2024. On the y-axis is the carbon dioxide level in parts per million. Carbon dioxide levels have fluctuated over the years, but they never exceeded 300 parts per million until 1950. In 2024, carbon dioxide levels reached 424 ppm. Ice core data, NOAA graph retrieved from NASA website)

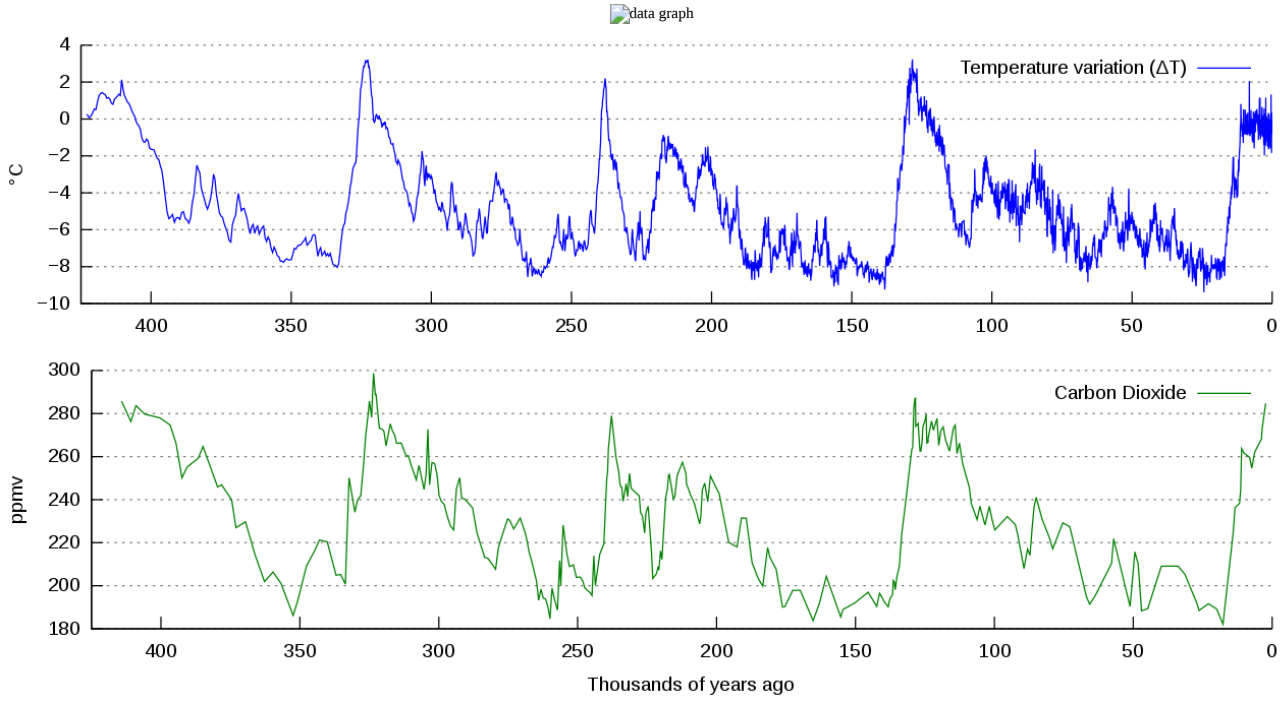


Figure 10.2.1.1.*f*: Graph of change in temperature in degrees Celsius (top, blue line) and carbon dioxide concentration in parts per million by volume (bottom, green line) measured from the Vostok, Antarctica ice core. These have been associated for over 400,000 years. As carbon dioxide concentration increased, so did temperature. As carbon dioxide concentration decreased, so did temperature. These data were collected in 1999. Since then, carbon dioxide concentrations have increased to 409.8 ppm (2019 average). Image and caption (modified) by NOAA/Autopilot (CC-BY-SA)

Other Greenhouse Gasses

Although this concentration is far less than that of CO_2, **methane** (CH_4) is 28 times as potent a greenhouse gas. Methane is produced when bacteria break down organic matter under anaerobic conditions and can be released due to natural or anthropogenic processes. Anaerobic conditions can happen when organic matter is trapped underwater (such as in rice paddies) or in the intestines of herbivores. Anthropogenic causes now account for 60% of total methane release. Examples include agriculture, fossil fuel extraction and transport, mining, landfill use, and burning of forests. Specifically, raising cattle

releases methane due to fermentation in their rumens produces methane that is expelled from their GI tract. Methane is more abundant in Earth's atmosphere now than at any time in at least the past 650,000 years, and CH_4 concentrations increased sharply during most of the 20th century. They are now more than two and-a-half times pre-industrial levels (1.9 ppm), but the rate of increase has slowed considerably in recent decades.

Water vapor is the most abundant greenhouse gas and also the most important in terms of its contribution to the natural greenhouse effect, despite having a short atmospheric lifetime. Some human activities can influence local water vapor levels. However, on a global scale, the concentration of water vapor is controlled by temperature, which influences overall rates of evaporation and precipitation. Therefore, the global concentration of water vapor is not substantially affected by direct human emissions.

Ground-level ozone (O_3), which also has a short atmospheric lifetime, is a potent greenhouse gas. Chemical reactions create ozone from emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight (as discussed in section 10.1). In addition to trapping heat, ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Changes in the Sun's Energy Affect how Much Energy Reaches Earth

Climate can be influenced by natural changes that affect how much solar energy reaches Earth. These changes include changes within the sun and changes in Earth's orbit. Changes occurring in the sun itself can affect the intensity of the sunlight that reaches Earth's surface. The intensity of the sunlight can cause either warming (during periods of stronger solar intensity) or cooling (during periods of weaker solar intensity). The sun follows a natural 11-year cycle of small ups and downs in intensity, but the effect on Earth's climate is small. Changes in the shape of Earth's orbit as well as the tilt and position of Earth's axis can also affect the amount of sunlight reaching Earth's surface.

Changes in the sun's intensity have influenced Earth's climate in the past. For example, the so-called "**Little Ice Age**" between the 17th and 19th centuries may have been partially caused by a low solar activity phase from 1645 to 1715, which coincided with cooler temperatures. The Little Ice Age refers to a slight cooling of North America, Europe, and probably other areas around the globe. Changes in Earth's orbit have had a big impact on climate over tens of thousands of years. These changes appear to be the primary cause of past cycles of ice ages, in which Earth has experienced long periods of cold temperatures (ice ages), as well as shorter interglacial periods (periods between ice ages) of relatively warmer temperatures.

Changes in solar energy continue to affect climate. However, solar activity has been relatively constant, aside from the 11-year cycle, since the mid-20th century and therefore does not explain the recent warming of Earth. Similarly, changes in the shape of Earth's orbit as well as the tilt and position of Earth's axis affect temperature on relatively long timescales (tens of thousands of years), and therefore cannot explain the recent warming.

Changes in Reflectivity Affect How Much Energy Enters Earth's System

When sunlight energy reaches Earth it can be reflected or absorbed. The amount that is reflected or absorbed depends on Earth's surface and atmosphere. Light-colored objects and surfaces, like snow and clouds, tend to reflect most sunlight, while darker objects and surfaces, like the ocean and forests, tend to absorb more sunlight. The term **albedo** refers to the amount of solar radiation reflected from an object or surface, often expressed as a percentage. Earth as a whole has an albedo of about 30%, meaning that 70% of the sunlight that reaches the planet is absorbed. Sunlight that is absorbed warms Earth's land, water, and atmosphere.

Albedo is also affected by aerosols. **Aerosols** are small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight. Unlike greenhouse gases (GHGs), the climate effects of aerosols vary depending on what they are made of and where they are emitted. Those aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect.

Natural changes in albedo, like the melting of sea ice or increases in cloud cover, have contributed to climate change in the past, often acting as feedbacks to other processes. Volcanoes have played a noticeable role in climate. Volcanic particles that reach the upper atmosphere can reflect enough sunlight back to space to cool the surface of the planet by a few tenths of a degree for several years. Volcanic particles from a single eruption do not produce long-term change because they remain in the atmosphere for a much shorter time than GHGs.

Human changes in land use and land cover have changed Earth's albedo. Processes such as deforestation, reforestation, desertification, and urbanization often contribute to changes in climate in the places they occur. These effects may be significant regionally, but are smaller when averaged over the entire globe.

Scientific Consensus: Global Climate Change is Real

The **Intergovernmental Panel on Climate Change** (IPCC) was created in 1988 by the United Nations Environment Programme and the World Meteorological Organization. It is charged with the task of evaluating and synthesizing the scientific evidence surrounding global climate change. The IPCC uses this information to evaluate current impacts and future risks, in addition to providing policymakers with assessments. These assessments are released about once every every six years. The most recent report, the 5th Assessment, was released in 2013. Hundreds of leading scientists from around the world are chosen to author these reports. Over the history of the IPCC, these scientists have reviewed thousands of peer-reviewed, publicly available studies. The scientific consensus is clear: global climate change is real and humans are very likely the cause for this change.

Additionally, the major scientific agencies of the United States, including the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), also agree that climate change is occurring and that humans are driving it. In 2010, the US National Research Council concluded that "Climate change is occurring, is very likely caused by human activities, and poses significant risks for a broad range of human and natural systems". Many independent scientific organizations have released similar statements, both in the United States and abroad. This doesn't necessarily mean that every scientist sees eye to eye on each component of the climate change problem, but broad agreement exists that climate change is happening and is primarily caused by excess greenhouse gases from human activities. Critics of climate change, driven by ideology instead of evidence, try to suggest to the public that there is no scientific consensus on global climate change. Such an assertion is patently false.

Current Status of Global Climate Change and Future Changes

Greenhouse gas concentrations in the atmosphere will continue to increase unless the billions of tons of anthropogenic emissions each year decrease substantially. Increased concentrations are expected to do the following:

- Increase Earth's average temperature (figure 10.2.1.1.g),
- Influence the patterns and amounts of precipitation,
- Reduce ice and snow cover, as well as permafrost,
- Raise sea level (figure 10.2.1.1.h),
- Increase the acidity of the oceans.

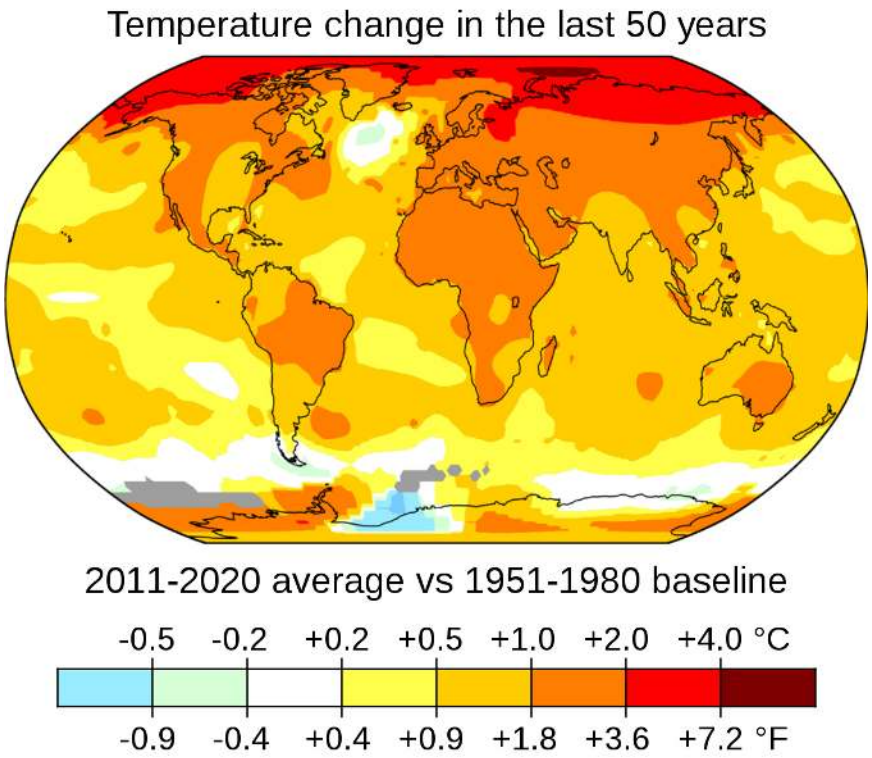


Figure 10.2.1.1.*g*: Temperature increases have been most pronounced in northern latitudes and over land masses. The colors represent the temperature difference between the 2011-2020 average and the 1951-1980 baseline, with warmer colors (yellow, orange, red) representing increases, and cool colors (green, blue) representing decreases. The image uses longer term averages of at least a decade to smooth out climate variability due to factors such as El Niño. Grey areas in the image have insufficient data for rendering. Image and caption (modified) from NASA's Scientific Visualization Studio/Eric Fisk (public domain).

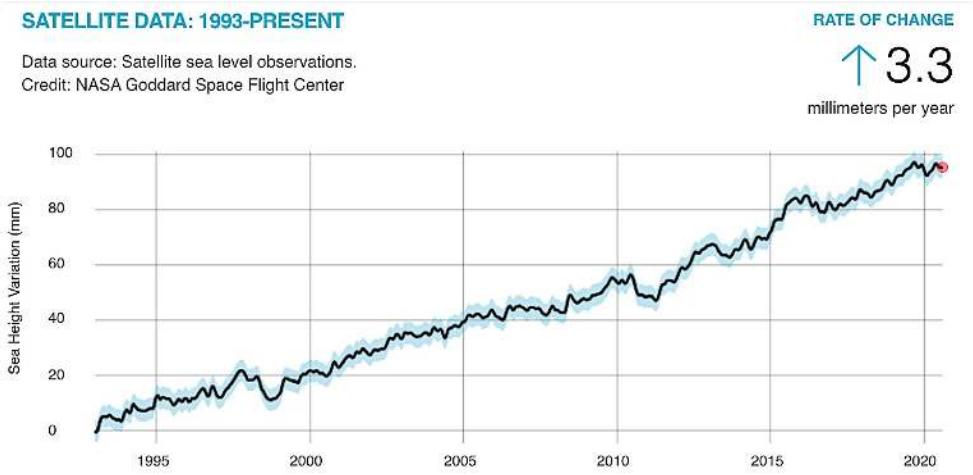


Figure 10.2.1.1.*h*: Sea height variation (mm) over time. Sea height has increased about 3.3 millimeters per year on average since 1993. Data is from satellite sea level observations by the NASA Goddard Space Flight Center. Image by NASA (public domain).

These changes will impact our food supply, water resources, infrastructure, ecosystems, and even our own health. The magnitude and rate of future climate change will primarily depend on the following factors:

- The rate at which levels of greenhouse gas concentrations in our atmosphere continue to increase,
- How strongly features of the climate (e.g., temperature, precipitation, and sea level) respond to the expected increase in greenhouse gas concentrations,

- Natural influences on climate (e.g., from volcanic activity and changes in the sun's intensity) and natural processes within the climate system (e.g., changes in ocean circulation patterns).

Past and Present-day GHG Emissions Will Affect Climate Far into the Future

Many greenhouse gases stay in the atmosphere for long periods of time. As a result, even if emissions stopped increasing, atmospheric greenhouse gas concentrations would continue to remain elevated for hundreds of years. Moreover, if we stabilized concentrations and the composition of today's atmosphere remained steady (which would require a dramatic reduction in current greenhouse gas emissions), surface air temperatures would continue to warm. This is because the oceans, which store heat, take many decades to fully respond to higher greenhouse gas concentrations. The ocean's response to higher greenhouse gas concentrations and higher temperatures will continue to impact climate over the next several decades to hundreds of years.

Future Temperature Changes

Climate models project the following key temperature-related changes:

- Average global temperatures are expected to increase by 2°F to 11.5°F by 2100, depending on the level of future greenhouse gas emissions, and the outcomes from various climate models.
- By 2100, global average temperature is expected to warm at least twice as much as it has during the last 100 years.
- Ground-level air temperatures are expected to continue to warm more rapidly over land than oceans.
- Some parts of the world are projected to see larger temperature increases than the global average.

Future Precipitation and Storm Events

Patterns of precipitation and storm events, including both rain and snowfall are likely to change. However, some of these changes are less certain than the changes associated with temperature. Projections show that future precipitation and storm changes will vary by season and region. Some regions may have less precipitation, some may have more precipitation, and some may have little or no change. The amount of rain falling in heavy precipitation events is likely to increase in most regions, while storm tracks are projected to shift towards the poles. Climate models project the following precipitation and storm changes:

- Global average annual precipitation through the end of the century is expected to increase, although changes in the amount and intensity of precipitation will vary by region.
- The intensity of precipitation events will likely increase on average. This will be particularly pronounced in tropical and high-latitude regions, which are also expected to experience overall increases in precipitation.
- The strength of the winds associated with tropical storms is likely to increase. The amount of precipitation falling in tropical storms is also likely to increase.
- Annual average precipitation is projected to increase in some areas and decrease in others.

Future Ice, Snowpack, and Permafrost

Arctic sea ice is already declining drastically. The area of snow cover in the Northern Hemisphere has decreased since 1970. Permafrost temperature has increased over the last century, making it more susceptible to thawing. Over the next century, it is expected that sea ice will continue to decline, glaciers will continue to shrink, snow cover will continue to decrease, and permafrost will continue to thaw.

For every 2°F of warming, models project about a 15% decrease in the extent of annually averaged sea ice and a 25% decrease in September Arctic sea ice. The coastal sections of the Greenland and Antarctic ice sheets are expected to continue to melt or slide into the ocean. If the rate of this ice melting increases in the 21st century, the ice sheets could add significantly to global sea level rise. Glaciers are expected to continue to decrease in size. The rate of melting is expected to continue to increase, which will contribute to sea level rise.

Future Sea Level Change

Warming temperatures contribute to sea level rise by expanding ocean water, melting mountain glaciers and ice caps, and causing portions of the Greenland and Antarctic ice sheets to melt or flow into the ocean. Since 1870, global sea level has risen by about 8 inches. Estimates of future sea level rise vary for different regions, but global sea level for the next century is expected to rise at a greater rate than during the past 50 years. The contribution of thermal expansion, ice caps, and small glaciers to sea level rise is relatively well-studied, but the impacts of climate change on ice sheets are less understood and represent an active area of research.

Thus, it is more difficult to predict how much changes in ice sheets will contribute to sea level rise. Greenland and Antarctic ice sheets could contribute an additional 1 foot of sea level rise, depending on how the ice sheets respond.

Regional and local factors will influence future relative sea level rise for specific coastlines around the world (figure 10.2.1.1.*i*). For example, relative sea level rise depends on land elevation changes that occur as a result of subsidence (sinking) or uplift (rising), in addition to things such as local currents, winds, salinity, water temperatures, and proximity to thinning ice sheets. Assuming that these historical geological forces continue, a 2-foot rise in global sea level by 2100 would result in the following relative sea level rise:

- 2.3 feet at New York City
- 2.9 feet at Hampton Roads, Virginia
- 3.5 feet at Galveston, Texas
- 1 foot at Neah Bay in Washington state



Figure 10.2.1.1.*i*: The United States government paid for the residents of Isle De Jean Charles, an island south of Louisiana (that is also part of Louisiana), to relocate when it became inhabitable due to sea level rise. Image by Karen Apricot (CC-BY-SA).

Future Ocean Acidification

Ocean acidification is the process of ocean waters decreasing in pH. Oceans become more acidic as carbon dioxide (CO_2) emissions in the atmosphere dissolve in the ocean. This change is measured on the pH scale, with lower values being more acidic. The pH level of the oceans has decreased by approximately 0.1 pH units since pre-industrial times, which is equivalent to a 25% increase in acidity. The pH level of the oceans is projected to decrease even more by the end of the century as CO_2 concentrations are expected to increase for the foreseeable future. Ocean acidification adversely affects many marine species, including plankton, mollusks, shellfish, and corals. As ocean acidification increases, the availability of calcium carbonate will decline. Calcium carbonate is a key building block for the shells and skeletons of many marine organisms. If atmospheric CO_2 concentrations double, coral calcification rates are projected to decline by more than 30%. If CO_2 concentrations continue to rise at their current rate, corals could become rare on tropical and subtropical reefs by 2050.

Mismatched Interactions

Climate change also affects phenology, the study of the effects of climatic conditions on the timing of periodic lifecycle events, such as flowering in plants or migration in birds. Researchers have shown that 385 plant species in Great Britain are flowering 4.5 days sooner than was recorded earlier during the previous 40 years. In addition, insect-pollinated species were more likely to flower earlier than wind-pollinated species. The impact of changes in flowering date would be mitigated if the insect pollinators emerged earlier. This mismatched timing of plants and pollinators could result in injurious ecosystem effects because, for continued survival, insect-pollinated plants must flower when their pollinators are present.

Likewise, migratory birds rely on daylength cues, which are not influenced by climate change. Their insect food sources, however, emerge earlier in the year in response to warmer temperatures. As a result, climate change decreases food availability for migratory bird species.

Spread of Disease

This rise in global temperatures will increase the range of disease-carrying insects and the viruses and pathogenic parasites they harbor. Thus, diseases will spread to new regions of the globe. This spread has already been documented with dengue fever, a disease the affects hundreds of millions per year, according to the World Health Organization. Colder temperatures typically limit the distribution of certain species, such as the mosquitoes that transmit malaria, because freezing temperatures destroy their eggs.

Not only will the range of some disease-causing insects expand, the increasing temperatures will also accelerate their lifecycles, which allows them to breed and multiply quicker, and perhaps evolve pesticide resistance faster. In addition to dengue fever, other diseases are expected to spread to new portions of the world as the global climate warms. These include malaria, yellow fever, West Nile virus, zika virus, and chikungunya.

Climate change does not only increase the spread of diseases in humans. Rising temperatures are associated with greater amphibian mortality due to chytridiomycosis (see Invasive Species). Similarly, warmer temperatures have exacerbated bark beetle infestations of coniferous trees, such as pine an spruce.

Climate Change Affects Everyone

Our lives are connected to the climate**.** Human societies have adapted to the relatively stable climate we have enjoyed since the last ice age which ended several thousand years ago. A warming climate will bring changes that can affect our water supplies, agriculture, power and transportation systems, the natural environment, and even our own health and safety.

Carbon dioxide can stay in the atmosphere for nearly a century, on average, so Earth will continue to warm in the coming decades. The warmer it gets, the greater the risk for more severe changes to the climate and Earth's system. Although it's difficult to predict the exact impacts of climate change, what's clear is that the climate we are accustomed to is no longer a reliable guide for what to expect in the future.

We can reduce the risks we will face from climate change**.** By making choices that reduce greenhouse gas pollution, and preparing for the changes that are already underway, we can reduce risks from climate change. Our decisions today will shape the world our children and grandchildren will live in.

You can take steps at home, on the road, and in your office to reduce greenhouse gas emissions and the risks associated with climate change. Many of these steps can save you money. Some, such as walking or biking to work, can even improve your health! You can also get involved on a local or state level to support energy efficiency, clean energy programs, or other climate programs.

Suggested Supplementary Reading

Intergovernmental Panel on Climate Change. 2013. 5th Assessment: Summary for Policymakers.

NASA. 2018. Global Climate Change: Vital Signs of the Planet. This website by NASA provides a multi-media smorgasbord of engaging content. Learn about climate change using data collected by NASA satellites and more.

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10.3: Drivers of Climate Change

The climate change we are experiencing today is driven by human activities that increase greenhouse gas concentrations in Earth's atmosphere. Although we mainly hear about **greenhouse gases** in the context of their contribution to climate change, they are in fact essential for life on Earth. Consider for a moment carbon dioxide's (CO_2) critical role in photosynthesis, and water vapor's role in the formation of rain. Both of these gases are greenhouses gases. Greenhouse gases earn their name because they function much like the glass covering a greenhouse; they allow sunlight to easily pass through the atmosphere but trap the reflected heat energy so that it stays close to Earth's surface. This **greenhouse effect** allows all the organisms on Earth, even us humans, to flourish. Without greenhouse gases, temperatures would drop, and our planet would be too cold to sustain life. However, high concentrations of greenhouse gases can also be harmful. Think for a moment of greenhouse gases as "blankets" covering the Earth's surface: more "blankets" will trap more heat, giving rise to higher temperatures. This is exactly what is happening today—human activities are currently increased greenhouse gas concentrations in the atmosphere so much, and at such a fast pace, that Earth is heating up too fast for biodiversity to adapt to the changes.

> Greenhouse gases are essential for life on Earth. But too much of them cause Earth to heat up too much too fast, leading to climate change.

At present, the single biggest cause of increased greenhouse gas concentrations is the burning of fossil fuels. Since the **Industrial Revolution** about 200–250 years ago, humans have become heavily dependent on the energy captured in these fuels—coal, oil, and natural gas—for activities such as transportation, heating, manufacturing, and electricity generation. Fossil fuels contain a high percentage of carbon, so when it is burned, that carbon is released into the atmosphere, generally as CO_2. Consequently, since human populations started exploding and have been using fossil fuels at increased rates, the greenhouse effect has been significantly amplified.

While fossil fuel burning is currently the biggest overall driver of climate change, the destruction of carbon sinks, such as tropical forests (Box 10.3.1) and peatlands is also a large contributor. Destroying these ecosystems contributes to rising atmospheric CO_2 concentrations directly through burning of vegetation that releases carbon, and indirectly through the loss of vegetation that would otherwise extract CO_2 from the atmosphere if they were still alive. The contribution of ecosystem loss to climate change is substantial: 13% of today's global carbon emissions can be accounted for by tropical deforestation (IPCC, 2014).

The link between human-induced climate change and atmospheric CO_2 concentrations was first highlighted in the late 19th century (Arrhenius, 1896). However, it was not until the mid-1950s (e.g. Kaempffert, 1956) that scientists started to raise concerns about increasing CO_2 concentrations in the atmosphere. By the 1980s, as global annual mean temperatures started to rise, consensus about climate change linked to CO_2 began to spread among the broader public. Yet concrete steps to curb CO_2 emissions would only be initiated decades later. In the meantime, CO_2 emissions continue to accelerate (Figure 10.3.2): more than 37 billion tonnes of carbon, a new record, were released into the atmosphere in 2018 (Jackson et al., 2018; Le Quéré et al., 2018). To put it in another way, during 2018, humans released on average over 100 million tonnes of CO_2 into the atmosphere every day.

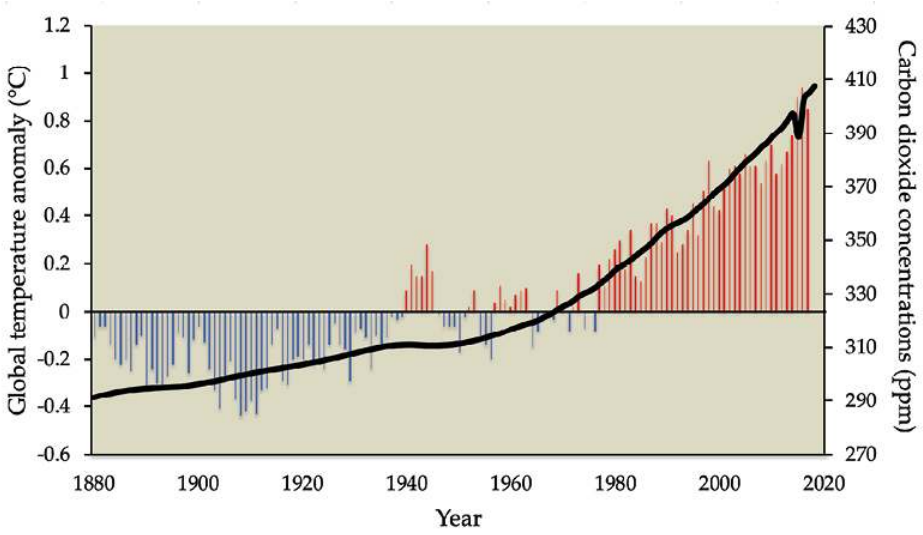


Figure 10.3.2 Human activities, notably the burning of fossil fuels and deforestation, have drastically increased atmospheric CO2 concentrations over the past century. As a result, average annual global temperatures are now much higher than they have been in the past. Temperatures are reported in terms of difference (anomaly) from average annual temperature from 1910–2000. Source for climate data: NOAA, 2018a. Sources for CO2 data: NASA, 2018 (before 2006); NOAA, 2018b (after 2005), CC BY 4.0.

The second-most important greenhouse gas that drives climate change is methane (CH4). Methane is a natural by-product emitted from decaying organic matter, most notably from wetlands that inhibit the speed of decomposition. These important ecosystem processes release methane into the atmosphere, albeit in relatively low concentrations. However, human activities have boosted methane emissions significantly over the past few centuries, through wasted food decaying at landfills, leaks from natural gas wells, an increase of industrial-scale cattle and dairy farms, and large-scale destruction of swamps and peatlands. Warmer temperatures also result in the drying of wetlands and peatlands; this drying speed up decomposition of organic material, which increases the rate of methane release. Methane currently constitutes 16% of all global greenhouse gas emissions released by humans (IPCC, 2014). This may not seem to be a major contribution; however, methane is 72 times more effective than CO2 in trapping radiation over a 20-year period (Forster et al., 2007), so even small increases in atmospheric methane can have dramatic effects.

The third important greenhouse gas that drives climate change is nitrous oxide (N2O), also known as laughing gas. Nitrous oxide is a by-product of synthetic fertilizers used in agriculture, burning of fossil fuels, and several industrial processes, and accounts for 6% of all human-caused greenhouse emissions (IPCC, 2014). However, it is even more potent than methane, and stays in the atmosphere for about 114 years, so the impact of one tonne of N2O is equivalent to 310 tons of CO2 over 100 years (Forster et al., 2007).

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10.5: The Impact of Climate Change

Climate change is not a new phenomenon. During the past 2 million years, there have been at least 10 cycles of global warming and cooling. When the polar ice caps melted during warming periods, sea levels rose to well above their earlier levels, and a larger portion of Earth experienced tropical climates. During cooling periods, the polar ice caps expanded, sea levels dropped, and tropical species' ranges contracted. Sometimes these changes occurred gradually, which enabled the affected species to adapt. But the onset of some climate change periods was abrupt, causing major ecosystem disruptions and global mass extinction events. Yet, nature recovered every time; many of the species we see today are survivors of previous climate change events. It is thus fair to ask why today's climate change is of such concern to us.

10.5.1 Climate change's impact on people

History provides us with many lessons to illustrate the impact of climate change on human societies. These lessons start with the earliest well-documented example of a societal collapse—that of the Middle East's Natufian communities roughly 10,000 years ago—which has been attributed to climatic changes (Weiss and Bradley, 2001). Since then, climate change has regularly contributed to the collapse of complex human societies across the world. Notable examples of such collapses include the Akkadian Empire (the world's first empire) of the Middle East (Carolin et al., 2019), Egypt's Old Kingdom (who constructed the pyramids), Central America's Classic Mayan civilisation, the USA's first English colony (deMenocal, 2001), several Chinese dynasties (Wang et al., 2010), and the Late Bronze Age societies along the Mediterranean Sea (Kaniewski et al., 2013). Also, in Southern Africa, the fall of the Mapungubwe Kingdom has been attributed to crop failures and declining grazing lands due to regional droughts and warming cycles (O'Connor and Kiker, 2004).

Unlike the unavoidable natural climatic shifts that led to the historical societal collapses discussed above, we have brought today's climatic change impacts upon ourselves. Because of our general lack of response in addressing the drivers of climate change, thousands of people will suffer the consequences. Prominently, many parts of the world are already seeing higher temperatures and longer droughts (Engelbrecht et al., 2009). These conditions are compromising our quality of life (Watts et al., 2017) by leading to more intense wildfires (Jolly et al., 2015; Strydom and Savage, 2016), increased incidences of malaria (Siraj et al., 2014), increased crop failures (Myers et al., 2014; Medek et al., 2017), and increased competition for water (Flörke et al., 2018). Many coastal areas are also seeing storms increasing in intensity and frequency, exposing people living near large rivers, deltas, and estuaries to more frequent flooding (Figure 10.5.1) and storm surges (Fitchett and Grab, 2014). **Sea level rise** is expected to leave many low-lying oceanic islands uninhabitable within a few decades (Storlazzi et al., 2018). With all these impacts expected to increase the competition for space under an increasing human population, it would be wise for the world's governments to start preparing for thousands of climate refugees that would need to be relocated in the near future (Merone and Tait, 2018).

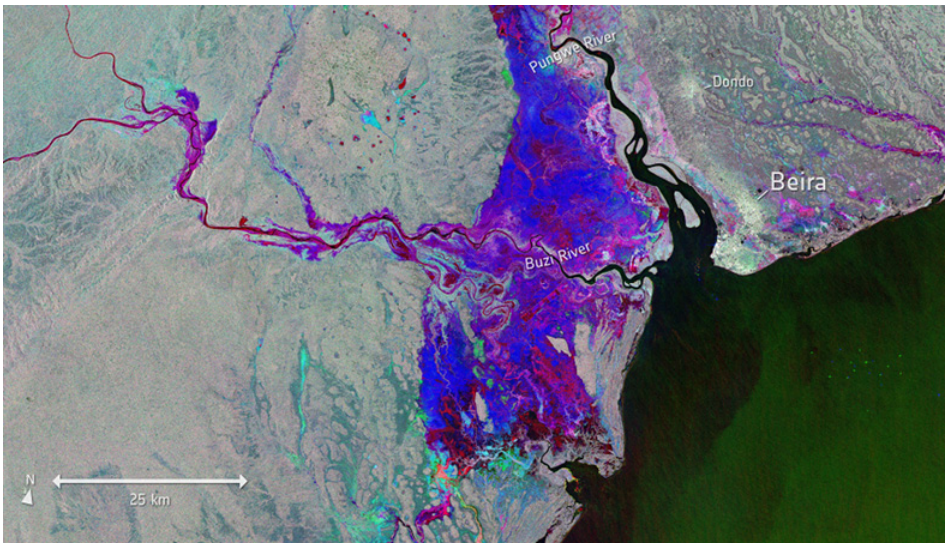




Figure 10.5.1 (Top) A Copernicus Sentinel-1 satellite image showing the extent of flooding (areas shown in blue) in central Mozambique after Cyclone Idai made landfall on 15 March, 2019. Photograph by European Space Agency, https://www.flickr.com/photos/europeanspaceagency/47477652401, CC BY-SA 2.0. (Bottom) People in Beira, Mozambique, taking refuge on rooftops to escape flooding brought by Cyclone Idai. Photograph by World Vision, https://www.flickr.com/photos/dfid/46570320385, CC BY 2.0. More than a thousand people died during this, one of the worst storms on record to have hit Africa. While no single flooding event can be attributed to climate change, it is undeniable that warmer oceans create conditions for hurricanes and cyclones to be stronger, bigger, and more frequent.

To combat climate change, politicians of several countries have started to enact laws to reduce greenhouse gas emissions and habitat destruction. Many industries are also hard at work developing "greener" technologies to enable us to live more sustainable lives. Conservation biologists also play a crucial role in mitigating the negative impacts of climate change. In addition to highlighting the plight of the natural world to society at large, we could work towards reducing the loss of ecosystem services and preventing species extinctions. To accomplish this task, we need to identify which species and ecosystems are most sensitive to climate change and develop strategies that will ensure the continued persistence of as many sensitive species and their habitats as possible. The rest of this chapter is dedicated to methods we can employ to understand which species are sensitive, and how they may respond to climate change.

10.5.2 Climate change's impact on terrestrial ecosystems

Aside from regional variations in temperature and precipitation, Earth's surface will be a few degrees warmer in future than the temperatures we experience today. In effect, that means that today's climatic zones will generally shift upslope in mountainous areas and towards the poles on lowlands, plains, and plateaus. To survive, climate-sensitive plants and animals will need to track these shifts so that they remain within their suitable climatic envelopes of temperature and precipitation. By altering regional climates, it makes habitats less hospitable to the species living in them. While increased carbon dioxide levels can help plants conduct photosynthesis more efficiently, they are threatened by harsh temperatures and extreme weather events. Additionally, with warmer conditions, moisture from snow melt arrives earlier in the season, lengthening the fire season.

In response to changing conditions, range shifts have also been observed in plants, butterflies, other insects, freshwater fishes, reptiles, amphibians, and mammals. Because individual plants cannot physically move to cooler regions, plant range shifts result from seed dispersal. Seeds are often dispersed in all directions away from a parent plant, but more of the seedlings that establish in northern locations or higher elevations survive, resulting in a gradual shift towards the poles or up mountains (Figure 10.5.2). However, species that cannot adapt to new conditions or shift their ranges quickly enough face extinction.



Figure 10.5.2: In a 2015 study by Monleon and Lintz, seedlings of the Pacific dogwood (*Cornus nuttallii*) were found at elevations 347 m (379 yards) higher than mature trees. Image by J Bres (CC-BY-SA).

Climate change on mountains

Species that live on mountains are at particular risk from climate change. Because temperatures decrease by roughly 0.65°C for every 100 m in elevation rise (known as temperature lapse rates), a 1°C increase suggests that climate-sensitive species living on a mountain would be displaced by at least 150 m (1.5 m/year) upslope between the years 2000 and 2100. Species that live on the lower slopes of mountains and are mobile enough to make such an adjustment may have opportunities to move to higher ground. However, species that live on or near peaks may have nowhere else to go as the world heats up, resulting in what biologists call **mountain-top extinctions**. It is only a matter of time before vulnerable mountain specialists will follow the example of Costa Rica's once abundant Monteverde golden toad (*Bufo periglenes*, EX), the first known amphibian extinction attributed to climate change (Crump et al., 1992).

> Species that live on mountain peaks are vulnerable to climate change because they may have nowhere else to go as the world heats up.

Climate change in the lowlands

The response of species living in lowlands and on plains tend be more variable and complex than those living on mountains. While some species may only need to make minor range adjustments, researchers estimate that some taxa may need to move 500 km (Barbet-Massin et al., 2009)—maybe even 1,000 km (Hsiang and Sobel, 2016)—to keep up with climate shifts. For species that have already shifted their distributions by 200–300 km (Beale et al., 2013), adapting seems relatively easy thanks to their mobility and largely intact ecosystems. Unfortunately, the rate of climate change will likely outpace the ability for most species to adapt (Jezkova and Wiens, 2016; Wiens, 2016).

Species of tropical lowland forests and deserts are also highly vulnerable to shifting climates. Many tropical species have narrow tolerances for temperature and rainfall variation, while desert specialists may be at the limits of their physiological heat and desiccation tolerances (Figure 10.5.2). Consequently, even small changes in the climate of these two ecosystems may have major effects on reproduction, species distributions, and hence ecosystem composition (Box 10.5.1). One species already impacted is the

nocturnal aardvark (Orycteropus afer, LC): a study in Southern Africa's Kalahari Desert found over 80% mortality rates in this species during recent summers (Rey et al., 2017). The high levels of mortality in this species was attributed to above average temperatures, which subjected the animals to heat stress, leading to behavioral disruptions, declining body conditions, and eventually starvation. The impact of climate change on the aardvark is of concern because it is an ecosystem engineer: their burrows provide denning and refuge sites for multiple other species (Whittington-Jones et al., 2011).

Box 10.5.1 Desert Birds and Climate Change

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Deserts, with their extreme temperatures and scarce and unpredictable rainfall, are among the most inhospitable environments on the planet. To survive and breed in arid regions, organisms must minimize their energy and water requirements, and avoid exposure to potentially lethal temperatures. Birds are generally small and diurnal; and are therefore among the groups of animals most vulnerable to even small increases in air temperatures associated with climate change. Studies of the effects of temperature on arid-zone birds can thus be highly informative in terms of identifying new conservation challenges posed by global warming, developing mitigation measures, and understanding the management interventions that may become necessary during the 21st Century.

Daytime temperatures in many deserts regularly exceed avian body temperature, creating conditions under which birds can avoid lethal heat stroke only by dissipating heat via evaporation. But rapid rates of evaporation increase the risk of birds becoming lethally dehydrated. Desert birds thus face life-or-death decisions between avoiding hyperthermia by evaporative cooling versus avoiding lethal dehydration by minimizing water losses. Mass mortality events occasionally take place during extreme heat waves when air temperatures exceed birds' physiological tolerance limits. In Australia, for example, there are both historic and contemporary accounts of die-offs sometimes involving millions of birds. As Earth heats up under climate change, the risk of such die-offs in desert birds is expected to increase dramatically for the deserts of Australia and North America during the 21st Century (McKechnie and Wolf, 2010; Albright et al., 2017).

Arid regions are also experiencing significant temperature increases which are predicted to continue over the next several decades (Conradie et al., 2019). Under these conditions, the impact of air temperature on avian physiology can be mediated by behavior. Birds employ a trio of behavioral adjustments to manage heat load and keep their body temperatures within safe limits. These include shade-seeking, reducing activity to minimize metabolic heat production, and gaping the beak (panting, sometimes accompanied by gular flutter) to facilitate respiratory evaporative cooling (Figure 10.5.2). Although these behaviors can buffer birds against physiological costs of high temperature, they carry subtle but important costs of the own, notably via their impact on birds' ability to forage.

For desert birds, foraging is critically important for maintaining both energy and water balance, as most species obtain all their water from food. Reduced activity almost inevitably means reduced food intake via impacts on time available for foraging. Seeking shade also carries costs: for some species, returns on foraging effort in shaded locations are significantly lower than in the sun (e.g. Cunningham et al., 2013). Finally, respiratory evaporative cooling can severely restrict the ability of actively-foraging birds to acquire food due to mechanical constraints on simultaneously gaping the bill and using it for prey capture and handling (e.g. du Plessis et al., 2012).

Under climate change, the implications of these behavioral trade-offs between foraging and thermoregulation are non-trivial. Inability to balance water and energy budgets mean birds progressively lose body condition during heat waves (du Plessis et al., 2012). Compromised foraging also affects birds' capacity to provision offspring, resulting in reduced nest success and/or

smaller, lighter fledglings which may struggle to survive and recruit into the breeding population (e.g. Cunningham et al., 2013, Wiley and Ridley, 2016).

Successfully balancing the trade-offs between foraging and thermoregulation, and between hyperthermia and dehydration, is the secret to success for birds in hot places. As the climate warms, achieving this balance will become ever more challenging. Sublethal behavioral costs of keeping cool kick in at temperatures cooler than those promoting mass mortalities. In some parts of the world, the loss of birds from desert ecosystems may therefore occur through the insidious whittling away of fitness and weakening of populations (Conradie et al., 2019) before we even witness the dramatic die-off events for which Australia is already infamous.



Figure 10.5.3 A pair of southern pied babblers (*Turdoides bicolor*, LC), an endemic of Southern Africa's arid savannahs, gaping their beaks to facilitate respiratory evaporative cooling during a particularly hot summer afternoon. Photograph by Nicholas Pattinson, CC BY 4.0.



Figure 10.5.4 The Namib sand gecko (*Pachydactylus rangei*), endemic to Namibia's Namib Desert, survives the scorching heat by being nocturnal and burrowing into loose sand with its webbed toes. Warmer conditions under climate change may make it much harder for the gecko and other desert species, operating at the limits of their physiological tolerances, to survive. Photograph by Marije Louwsma, https://www.inaturalist.org/observations/18594993, CC BY 4.0.

An additional concern for lowland ecosystems is that climate change will likely lead to the creation of novel (i.e. hotter) ecosystems unlike any others currently on Earth (Williams et al., 2007). These changes will lead to **biotic attrition**. The gradual impoverishment of biological communities of lowland ecosystems as species either go extinct or move away while tracking their climatic envelopes. What is not clear is how the niches left open by the net loss of species, and newly created niches in the novel ecosystems, will be filled. The most likely scenario is that more tolerant, generalist species will fill the empty niches. However, with the inevitable loss of some species, combined with the decoupling of important biological interactions (discussed below), some functions and services associated with lowland ecosystems are likely to eventually collapse. It is important to note that tropical lowland forests and deserts are by no means the only ecosystems vulnerable to biotic attrition.

Climate change and dispersal limitations

Across many diverse ecosystems, a great number of species are threatened by climate change because of their poor dispersal abilities. Because they lack appropriate dispersal mechanisms, species, such as slow maturing plants (Foden et al., 2007), mosses, and flightless insects may simply not be able to keep up with changing climatic conditions. The impacts of climate change on Africa's dispersal-limited species can already be seen. For example, the once abundant Aldabra banded snail (*Rhachistia aldabrae*, CR) is today so rare that this Lazarus species (Figure 10.5.5) was once believed to be extinct due to climate change (Battarbee, 2014). Dispersal limitations will also greatly affect terrestrial species living on oceanic islands, which will find it near impossible to track their climatic niches as it moves over the ocean.



Figure 10.5.5 The Seychelles' Aldabra banded snail was once thought to be one of the world's first species pushed to extinction by climate change. Luckily, a small isolated population has been discovered, offering conservation biologists a second chance to ensure this species' survival. Photograph by Catherina Onezia/Seychelles Islands Foundation, CC BY 4.0.

Climate change and biological interactions

Species that are highly mobile are not entirely spared from the negative impacts of climate change. Consider migratory species for a moment. The same way the musicians of an orchestra rely on a conductor to remain synchronized, migratory species rely on environmental cues, such as daylength and temperature, to decide when they need to start moving from one area to the next. But because different species rely of different environmental cues to time their life cycles (e.g. breeding), not all species will adjust to climate change at the same rate. There is consequently a high likelihood that climate change will disrupt these synchronous movements that the animal kingdom has developed over thousands of years (Renner and Zohner, 2018). This disruption of timed aspects of species' life cycle, such as migration and breeding, is called **phenological mismatch** or trophic asynchrony. Researchers have already seen signs of phenological mismatch: some migratory birds have started to migrate to their breeding grounds at earlier dates than before (Both et al., 2006; Vickery et al., 2014). If these trends hold, they may soon start breeding before peak food availability, which could lead to lower fitness of offspring.

Resident species are also vulnerable to phenological mismatch. While these species might not be known for large-scale movements around the globe, they may still have to adjust their ranges to keep track of their climatic niches. Considering the improbability of different species will adapt at the same pace, there is thus a danger that important mutualistic relationships might be pulled apart these during range adaptations. This is of concern for species with specialized feeding niches, as seen in some pollinators. Extinctions arising from this decoupling of mutualistic relationships are referred to as coextinction (Koh et al., 2004), while a series of linked coextinctions is called an extinction cascade.

Climate change and reptiles

One may think that reptiles—often seen basking on sun-drenched rocks to obtain active body temperatures—may benefit from climate change. Yet, as a group, they are also expected to suffer under climate change. One reason is because many reptiles will also have to adapt their ranges to shifting climates (Houniet et al., 2009). Even more important, climate change will increase reptiles' vulnerability to **demographic stochasticity**. Many reptiles—and some fish—have their sex determined by temperature during embryonic development, with warmer temperatures often leading to more females (Valenzuala and Lance, 2004). In general, females regulate their offspring's sex ratios by fine-scale breeding site selection. Under climate change, however, it might be harder

for the females to find breeding sites with suitable microclimates. Those species unable to adopt new mechanisms to control for offspring sex ratio bias may eventually go extinct, even under relatively small temperature shifts (Sinervo et al., 2010).

10.5.3 Climate change's impact on freshwater ecosystems

With the world's freshwater ecosystems already strained by the demands of a growing human population, freshwater biodiversity will face several additional stressors associated with climate change. Climate change will impact water temperature, flow volume, and flow variability. Because these variables are three primary predictors of freshwater ecosystem composition (van Vliet et al., 2013; Knouft and Ficklin, 2017), it is expected that climate change will greatly affect freshwater ecosystem composition and functioning in the coming decades.

Warmer rivers and streams

Climatologists and hydrologists predict that freshwater ecosystems will generally experience temperature increases under climate change. Like their terrestrial counterparts, many freshwater species are sensitive to temperature shifts (e.g. Reizenberg et al., 2019). Warmer water also holds less dissolved oxygen, and increased pollutant toxicity (Whitehead et al., 2009). In addition, longer growing seasons and higher water temperatures will lead to a general increase in **primary productivity** and decomposition rates, which in turn will lead to increased nutrient loads, algae blooms, and **eutrophication** (Whitehead et al., 2009). All these factors will force many freshwater species—even those not sensitive to temperature shifts—to adjust their ranges to keep track of suitable conditions. Many of these adjustments will be impeded by habitat fragmentation, notably by dams and other human constructs that block suitable dispersal pathways. As an additional complication, many aquatic organisms cannot travel overland, so are naturally limited to adjust their ranges along the rivers and streams in which they live. But the orientation of these rivers and streams may not follow suitable thermal isolines: consider a cold-water species that needs to disperse to higher elevation—and hence upstream—as its climate niche moves higher up a mountain. For some freshwater species, the impediments to adjusting their ranges as necessary may be insurmountable.

> Climate change will alter water temperature, flow volume, and flow variability, the three primary predictors of freshwater ecosystem composition.

Changing flow regimes

Changing precipitation levels will have several impacts on freshwater ecosystems, particularly as it relates to changes in their flow regimes (Thieme et al., 2010; Knouft and Ficklin, 2017). For example, areas that are undergoing decreased precipitation will experience decreased runoff and increased drying of wetlands and small streams, while areas with increased precipitation will experience increased storm surges and flushing. These changes, together with the impacts of increased water extraction rates and evapotranspiration under a warmer world, will cause significant changes in water levels, flow rates, sediment loads, water turbidity, and the structure of the physical environment.

Given these multiple stressors, there is a reasonable expectation that many freshwater species will go extinct or face significant population declines and range shifts over the next decades. These changes are of major concern especially in regions where so many people depend on fish and related natural resources for their livelihoods.

10.5.4 Climate change's impact on marine ecosystems

Like tropical forests, the world's oceans have historically provided a relatively stable environment in which marine organisms have evolved. While this stability promotes species diversity, it also leaves marine species more vulnerable to environmental changes. In fact, a recent study found that cold-blooded marine species are twice as vulnerable to the impacts of warmer oceans than their terrestrial counterparts (Pinsky et al., 2019). In addition to the impacts of storm surges (Figure 10.5.6) and **ocean warming** (which leads to rising sea levels and ocean deoxygenation), marine organisms also must deal with **ocean acidification**. These threats will likely have impacts like those faced in terrestrial and freshwater ecosystems, including range adjustments, biotic attrition, and decoupling or important interactions. Below we discuss the mechanisms that will lead to some of these changes in more detail.



Figure 10.5.6 Many species living in low-lying coastal regions may be pushed to extinction by more frequent cyclones/hurricanes, storm surges, and sea level rise resulting from climate change. One such example is the Knysna seahorse (*Hippocampus capensis*, EN); biologists have attributed the deaths of thousands of these unique animals to temperature fluctuations and flooding events that altered parts of their highly restricted range in South Africa (Pollom, 2017). Photograph by Brian Gratwicke, https://www.flickr.com/photos/briangratwicke/7108174613, CC BY 2.0.

Ocean acidification

As discussed earlier, human activities release massive amounts of CO2 into the atmosphere each day. Although forests and other plant communities get considerable attention for CO2 sequestration, the world's oceans also play a key role in keeping Earth's carbon balance in check. In fact, the world's oceans absorb an estimated 20–25% of our current CO2 emissions (Khatiwala et al., 2009). Now, with more atmospheric CO2 available, oceans absorb more carbon, which dissolves in seawater as carbonic acid. While this absorption may slow climate change, it also increases the acidity (i.e. lowing the pH levels) of the world's oceans. This process—known as **ocean acidification**—has several consequences that may directly and indirectly kill marine organisms. For example, it inhibits the ability of coral animals to deposit the calcium used to build their reefs' structure (Mollica et al., 2018), and prevents shellfish from accumulating adequate amounts of calcium carbonate to develop shells strong enough for survival (Branch et al., 2013). Ocean acidification also disturbs predator-prey dynamics by impairing the senses of prey species (Leduc et al., 2013), and compromising the ability of marine creatures to communicate with conspecifics (Roggatz et al., 2016).

> Climate change is causing sea level rise and increased seawater temperatures, with broad implications for marine ecology and people living in coastal areas.

Sea level rise

Over the past 30–40 years, ocean surface temperatures have warmed by about 0.64°C (NOAA, 2016, Figure 10.5.7).Ocean warming has several implications, the most well-known being **sea level rise**, caused by the thermal expansion of ocean water combined with the released water from melting glaciers and polar ice caps. As the oceans creep further inland, the extent of low-lying coastal ecosystems such as rocky shores or sandy beaches will shrink, and so also the sizes of the wildlife populations living in those areas. The extinction of Australia's Bramble Cay melomys (*Melomys rubicola*, EX)—the world's first documented mammalian extinction caused by anthropogenic climate-change—has been attributed to sea level rise (Gynther et al., 2016).

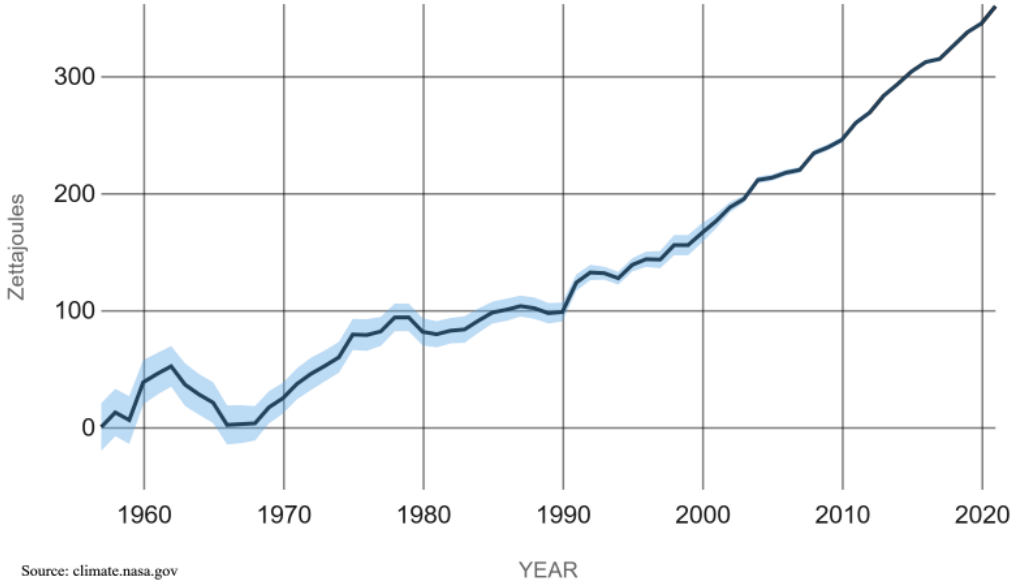


Figure 10.5.7 Ocean heat content changes since 1955 (NOAA/NCEI World Ocean Database). Annual estimates for the first 2,000 meters of ocean depth. Each data point is a five year average. Latest measurement December 2023. One-third to one-half of global sea level rise is due to ocean warming.

Coral bleaching

The incredible diversity of corals reef ecosystems is attributable to the relative stability of tropical oceans. Because of this stability, individual coral species have adapted to very specialized niches. Many corals thus tolerate only narrow ranges in temperature, sunlight levels, water opacity, and nutrient loads. Climate change is disrupting this stability, by changing the temperature (ocean warming), depth (sea level rise), sediment and nutrient loads (increased erosion and runoff) of the environments where corals live. These changes are leading to a breakdown of critical mutualistic relationships between photosynthetic algae and corals. In the process, corals also lose their vibrant colors, revealing the corals' ghostly white skeletons, hence the name **coral bleaching** (Figure 10.5.8). This relationship breakdown deprives the corals of essential carbohydrates they obtain from the algae, causing the corals to starve to death if the stressful conditions continue for a prolonged time.



Figure 10.5.8 A marine biologist surveys bleached corals in Curieuse Marine National Park, Seychelles. Bleaching events occur when heat stress kills corals, leaving only white skeletons where a once-vibrant coral reef community existed. Photograph by Emma Camp, CC BY 4.0.

Ocean deoxygenation

Marine fish and invertebrates rely on dissolved oxygen that enters the water either through the atmosphere, or by photosynthetic plankton. But because warmer water absorbs less oxygen, scientists predict that some areas of the ocean will see a 3–6% drop in dissolved oxygen concentrations under climate change (IPCC, 2014). This process, known as **ocean suffocation** or ocean deoxygenation (Ito et al., 2017), will leave parts of the ocean unsuitable for marine fishes and invertebrates. The impact of ocean deoxygenation will also be felt by economically important fisheries.

10.5.5 Climate change interacts with habitat loss

Habitat loss and climate change each cause negative impacts on biodiversity; however, these threats also interact to have an overall larger negative impact than the sum of these threats independently. Prominently, because of habitat loss, many species will be unable to adequately adjust their ranges to keep track of their shifting climatic niches. For example, some species might not be able to adapt their ranges because suitable habitat in their future ranges will be destroyed by human activity.

> Climate change interacts with habitat loss, by impeding species' ability to adapt, and by bringing dispersing wildlife into conflict with humans.

Range-shift gaps describes a habitat gap that prevents a species from dispersing from its current to future ranges (Figure 10.5.9). These gaps, which may occur naturally or because of habitat fragmentation, may also impede range adjustments under climate change. While the impact of range-shift gaps is an active area of research, it is expected that mountain-top species may be inherently vulnerable to range-shift gaps, particularly if they are unable to first disperse downslope before they can reach climatically suitable locations at higher elevation elsewhere.

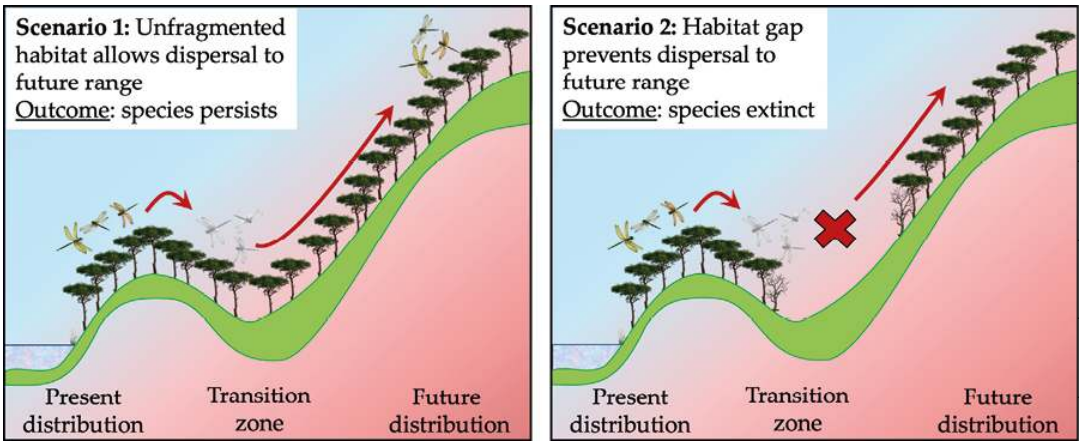


Figure 10.5.9 Hypothetical example of a species adjusting its range to climate change along unfragmented habitat (Scenario 1) and a species unable to adjust its range due to a range-shift gap (Scenario 2). In Scenario 1, the species persists; in Scenario 2 the species goes extinct because a gap in available habitat prevents dispersal into suitable areas. CC BY 4.0.

Habitat loss and climate change are also expected to exacerbate human-wildlife conflicts. Losses of arable land will see even more natural ecosystems converted for agriculture which, in turn, will further increase competition among and between humans and wildlife for resources such as food, water, and suitable habitat (Serdeczny et al., 2017). As the human footprint expands across Earth, agriculture and infrastructure will impede the ability of specialist species to find food and adapt to changing conditions, while generalist species will be forced into agricultural lands and nearby human habitation as they search for resources and/or disperse across the landscape. Such a scenario will likely exacerbate human-wildlife conflict where predators living in fragmented ecosystems with diminishing natural prey populations are increasingly prone to wandering beyond protected area boundaries into ranching areas in search of food (Tuqa et al., 2014).

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10.6: Beneficiaries of Climate Change

To be clear, not all species will suffer equally from climate change. In fact, there are some species that will be **resilient**, and others that will even benefit from a warming world. Primary among the beneficiaries are plants in the northern areas of Europe, Asia, and North America (Zabel et al., 2014), and to a lesser extent in southern South America and New Zealand. In these areas, plants will benefit from longer growing seasons (earlier springs and shorter winters) and increased CO2 concentrations (which will increase photosynthesis rates).

> Generalist species with high genetic diversity and that reproduce quickly are likely to benefit from climate change. Many species that exhibit these traits carry diseases and are agricultural pests.

Some tropical species may thrive as their habitats become hotter and wetter. Species with high genetic diversity that reproduce quickly (allowing for rapid adaption to environmental changes) are also likely to benefit. Unfortunately, many species that exhibit these traits carry diseases (Box 10.6.1) and are agricultural pests (Serdeczny et al., 2017). For example, populations of the coffee berry borer (*Hypothenemus hampei*)—Africa's most notorious coffee pest—are expected to greatly increase in a warmer world (Jaramillo et al., 2011). This growing threat is particularly worrying given that higher temperatures have already reduced coffee harvests in countries such as Tanzania by as much as 50% (Craparo et al., 2015).

Box 10.6.1 Habitat Alteration, Climate Change, and Mosquito-Borne Diseases

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With unprecedented climate change looming, mosquito-borne diseases, including malaria and dengue fever, will impact humans and wildlife in novel and unpredictable ways. While climate change is global in nature, changes due to habitat alteration are occurring more rapidly on a local scale, and are having significant effects on mosquito-borne diseases (Figure 1.6.1). For example, destruction of Peruvian rainforests unleashed more than 120,000 cases of malaria in the late 1990s, compared to fewer than 150 nine years earlier (Vitor et al., 2006).





Figure 10.6.1 (Top) Trucks transporting recently logged trees in Gabon. Photograph by David Stanley, https://www.flickr.com/photos/davidstanleytravel/46170117302, CC BY 2.0. (Bottom) *Anopheles funestus*, one of the most important vectors of malaria in Africa. Photograph by USCDCP, CC0.

The rainforests of the Congo Basin harbor roughly 20% of all known plant and animal species on Earth. Yet, habitat alteration continues at an alarming rate (Harris et al., 2012). Exacerbating these threats is the fact that Africa (Boko et al., 2007), and Central Africa in particular (McClean et al., 2006), are predicted to be some of the most severely affected by climate change. Predicted temperature increases would lead to longer seasons of malaria transmission and a 5–7% extension of the disease into higher latitudes (Craig et al., 1999, Boko et al., 2007). Coupled with projected population growth, climate change would nearly double the number of people at risk of infection from dengue fever by 2080. This is concerning because Africa is particularly vulnerable to environmental changes due to its limited adaptive capacity, widespread poverty, and low levels of development.

How then, will habitat alteration and climate change affect mosquito-borne diseases such as malaria? The relationship between disease transmission, habitat alteration, and climate change is complex. Though deforestation increases the risk of disease transmission (Vitor et al., 2006), different malaria-carrying mosquitoes (*Anopheles* spp.) are adapted to different microclimates. Ironically, our multi-faceted ecosystems both play the role of maintaining transmission cycles with cross-infections to humans and regulating those cycles while controlling spill-over into human populations. The balance between these factors is influenced by the availability of suitable habitat for mosquitoes and of reservoir hosts of infection. In an ideal world, transmission cycles are regulated by density-dependent processes such as acquired immunity to infectious diseases, and by limits on the carrying capacity of the environment to support insects and hosts.

Altered natural habitats and possible increases in disease transmission from animals to people also increase potential risks of new pathogens adapting to human hosts. Only about 2,000 of an estimated 1 million unique viruses carried by wild vertebrate species with potential zoonotic threats have been described. For example, when a lentivirus of chimpanzees first jumped into humans in the 1930s, not many people died. But the disease carved a foothold in the rapidly growing African city of Kinshasa in DRC and evolved into a form that efficiently preyed upon humans. More than 78 million people were infected between 1981 and 2015. To date, the disease it causes, AIDS, has killed more than 39 million people, while another estimated 37 million people are living with HIV.

Today, habitat alteration, such as deforestation, is not only driving species extinct and emitting lots of climate-changing carbon dioxide, it is also increasing opportunities for mosquito-borne diseases, such as malaria and dengue, to infect more humans in new places. Technological advances, including mathematical and computer modeling, genomics, and satellite tracking, will hopefully allow us to predict future disease outbreaks better. But we can also reduce outbreak opportunities by taking better care of our environment.

One group of species currently threatened with extinction that may benefit from a warmer world is marine turtles. Researchers working on Cabo Verde speculate that the island nation's loggerhead turtle (*Caretta caretta* VU) populations will benefit from an increasing female-biased sex ratio (as expected under warmer conditions) given that a single male can breed with several females (Laloë et al., 2014). However, the researchers note that this population requires continued monitoring as insurance against demographic stochasticity (Section 8.7.2) that may become a larger threat under climate change.

> Climate change has the potential to greatly restructure the world's ecosystems, ecosystem services, and national economies.

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10.7: The Overall Impact of Climate Change

It should be clear to anyone that climate change has the potential to greatly restructure the world's ecosystems, ecosystem services, and national economies. Many coastal areas will experience rising sea levels and increased flooding, while inland areas may experience desertification and less favorable crop growing conditions.

If we are to mitigate the far-reaching impacts of climate change, we must carefully monitor and study changes in biological communities and ecosystem functioning, and how they relate to changes in climate and other stressors. While we may lose some species in a warmer world, we can also prevent many extinctions with pro-active wildlife management. It is likely that many existing protected areas will no longer preserve some of the rare and threatened species that currently live in them (Hole et al., 2009; Smith et al., 2016, but see Beale et al., 2013), necessitating careful planning when establishing new protected areas. Even if climate change is not as severe as predicted, the steps we take now to safeguard biodiversity can only help in future.

In 2007, the world economy was close to collapse because of the misdeeds of the financial services industry. Considering climate change's record in causing societal disruption and suffering, and our increasingly globalized world (in which regional disruptions are felt much wider than before), politicians are rightfully concerned about our ability to adapt to a widespread restructuring of the world's natural resources (Dietz et al., 2016). While the consequences of climate change are closely associated with the environmental sciences, it is truly, at its core, a human rights concern.

The widespread and dramatic impacts of climate change rightfully deserve much attention. But it is also important to remember that we continue to destroy habitat at a massive scale and increasing pace, and this loss of habitat is currently the main cause of species extinctions. The highest priorities for conservation must continue to be the preservation of healthy, intact, and connected ecosystems, and the restoration of degraded ecosystems. These actions will simultaneously reduce the impacts of climate change, by reducing carbon emissions, increasing carbon sequestration, and giving wildlife more opportunities to adjust their ranges, in their own time, as the world's climate changes.

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10.8: Summary

1. While climate change is often thought of as a future challenge, we can already see its impacts today, as shown by record-high temperatures and changing rainfall patterns. These changes are happening because human activities release large amounts of greenhouse gases into the atmosphere on a daily basis.
2. Habitat loss contributes to climate change directly through the destruction of complex ecosystems (i.e. carbon sinks) which releases stored CO2, and indirectly through the loss of vegetation that would otherwise sequester CO2 from the atmosphere.
3. Some climatic shifts are predicted to be so rapid in coming decades that many species will be unable to adjust their ranges to keep up with environmental changes. Species with dispersal limitations, special habitat requirements, and important mutualistic relationships are at especially high risk of extinction.
4. Mitigating the negative impacts of climate change will require an international multi-pronged approach that includes ecosystem protection and restoration, direct species management, and legislative action.
5. Species are seldom exposed to only one threat; rather, different threats interact with climate change so that their combined impact is greater than their individual effects. A successful conservation strategy needs to deal with these threats collectively.

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10.9: Topics for Discussion

1. Think of any particular ecosystem in your region. How do you think climate change will impact that ecosystem? What single measure do you think can be implemented to reduce the impact of climate change on that ecosystem? Can you think of the resources you will need to implement that measure?
2. Which groups of people and wildlife do you think will benefit the most from climate change and why? Who do you think will suffer the most and why?
3. How should we deal with species that have nowhere to go under climate change? Should we let them go extinct? What if it is an economically important species, like one that supports an important fishery or ecotourism industry? What do you think are our best options to save such species?

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10.11: Bibliography

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CHAPTER OVERVIEW

11: Pollution, Overharvesting, Invasive Species, and Disease

- 11.1: Introduction to Pollution, Overharvesting, Invasive Species, and Disease
- 11.2: Pollution in Its Many Forms
  - 11.2.1: Water Pollutants and Their Sources
  - 11.2.2: Mitigating Water Pollution
  - 11.2.3: Air Pollution
    - 11.2.3.1: Acid Deposition
  - 11.2.4: Section Review
  - 11.2.5: Solid Waste Management
    - 11.2.5.1: Waste Generation
    - 11.2.5.2: Waste Disposal
    - 11.2.5.3: Solid Waste and Marine Life
    - 11.2.5.4: Data Dive- Plastic in World Oceans
    - 11.2.5.5: Waste Reduction
    - 11.2.5.6: Data Dive- "Flushable" Wipes
    - 11.2.5.7: Review
- 11.3: Impacts of Industrial Agriculture
- 11.4: Overharvesting
- 11.5: Persecution
- 11.6: Invasive Species and GMOs
  - 11.6.1: Overview of Invasive Species
- 11.7: Parasites and Diseases
- 11.8: Data Dive- Threats to Biodiversity
- 11.9: Summary
- 11.10: Topics for Discussion
- 11.12: Bibliography

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11.1: Introduction to Pollution, Overharvesting, Invasive Species, and Disease

Conservation biologists aim to preserve all the components, interactions, and processes within and between ecosystems, natural communities, species, and populations. The main obstacle to accomplishing this goal is habitat loss, while climate change will also play an increasingly important role. But let us for a moment consider widespread species and migratory populations. These species and populations typically live in different habitats and encounter different climates as they move across the landscape. We might think that tolerance for variety would make these groups robust against habitat loss and climate change. And yet, they are also declining, even in seemingly intact ecosystems and protected areas (Craigie et al., 2010; Lindsey et al., 2014). How can it be that populations apparently buffered from the two main extinction drivers are also subjected to population declines and extirpations?



A pair of southern white rhinoceros (*Ceratotherium simum simum*, NT) in Tshukudu Private Game Reserve, adjacent to South Africa's Kruger National Park. Once nearly extinct due to uncontrolled hunting, this species rebounded to over 20,000 individuals. Now, poaching is taking a toll again, even in premier protected areas such Kruger, where at least 662 rhinos were lost in 2016. Rangers have cut off the horn of one of the rhinos in the photo in a desperate attempt to prevent poaching. Photograph by Jan Fleishmann, https://commons.wikimedia.org/wiki/File:Nw_9302_white_rhinos_Tshukudu_JF.jpg, CC BY-SA 4.0.

> Comprehensive conservation efforts must recognize that biodiversity faces multiple threats that need to be dealt with at different scales.

While habitat loss and climate change are the most prominent threats facing biodiversity at present, they are not alone. Nearly all human activities place additional pressures on populations, even those that already suffer from habitat loss and climate change. These additional pressures are primarily from pollution, overharvesting, **persecution**, invasive species, and disease (Maxwell et al., 2016). Because these threats are associated with and/or exacerbated by human activities, they can be dynamic in their nature, develop rapidly, and persist at such large scales that wildlife populations have little opportunity to adapt or move to safer areas. Moreover, these threats may interact with each other, as well as with climate change and habitat loss, so that their combined impact is greater than their individual effects. In this chapter, we explore how each of these threats impact wildlife and natural communities, and how they could push populations and species to extinction.

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11.2: Pollution in Its Many Forms

Rachel Carson's 1962 book, *Silent Spring*, described the dangers of pollution—pesticide pollution in particular—with a clarity that captured the public's attention for many years afterwards. Carson, an American biologist, was particularly successful in drawing attention to **biomagnification** (also called bioaccumulation), a process through which pesticides and other toxins accumulate and become more concentrated in animals at higher levels of the **food chain** (Figure 11.2.1). Her work drew on research that found that dichlorodiphenyltrichloroethane (DDT), sprayed on crops to kill pest insects and on water bodies to kill malaria mosquito (*Anopheles* spp.) larvae, was also harming non-target organisms that consumed insects and fish exposed to DDT. Of note is that non-target organisms high on food chains, particularly fish-eating birds, such as eagles, pelicans, and egrets, often had high levels of DDT concentrated in their tissues. The affected birds were generally weakened, and the shells of their eggs were thin and prone to cracking during incubation. Consequently, bird populations declined dramatically in areas where DDT was used, as adults died and failed to raise young.

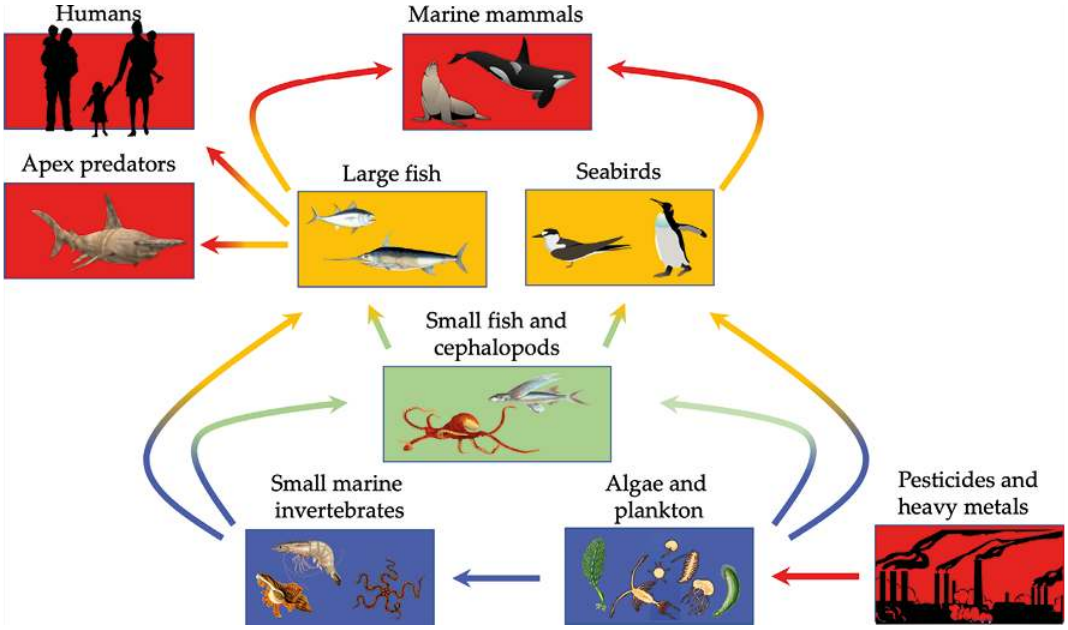


Figure 11.2.1 A simplified marine food web showing how sharks, marine mammals, seabirds, and even humans are all vulnerable to health problems associated with bioaccumulation where pesticides, heavy metals, and other harmful chemicals become concentrated at higher trophic levels. After Ross and Birnbaum, 2003, CC BY 4.0.

In the 1970s, many industrialized countries recognized the dire situation and banned the use of DDT, which eventually allowed for the partial recovery of the affected bird populations. Unfortunately, while some countries have switched to safer alternatives (e.g. Hargrove, 2003), DDT continues to be widely used in Africa and other countries to control malaria mosquito, tsetse fly (*Glossina* spp.), and other disease vectors. Researchers recently observed complete absences of breeding fish-eating birds in some African wetlands, and some of the highest-ever recorded DDT levels in seed-eating birds (Bouwman et al., 2013). This is cause for concern, not only for wildlife, but also for the long-term effects on people, particularly the consumers of the food products exposed to these chemicals (e.g. Manaca et al., 2011) and the workers who handle these chemicals in the field.

DDT is however not the only form of pollution we battle today. With the impacts of a growing human population becoming gradually more pervasive, pollution is compromising water, soil, and air quality at rates faster than ever before. Some forms of pollution can be highly visible, and with dramatic consequences (Figure 11.2.2). But importantly, there are many less detectable forms of pollution. While it may not always lead to immediate mortality, these insidious forms of pollution have sublethal impacts that compromise organisms' fitness over time, with early death and population declines still being the end result. Responding to the silent threats of subtle and easily-overlooked pollution is often delayed, especially when the negative effects are felt only years after exposure. In their totality, pesticides and other pollutants claim 9 million human lives globally each year, which is over three times more than the total impact of AIDS, malaria, and tuberculosis, together (Landrigan et al., 2018). Yet we continue to tolerate these threats, in part because the impact of pollution on our health is not always that apparent, especially when pollution deaths are expressed as a stroke, heart disease, respiratory infections, diarrhoea, or cancer, among other health issues.



Figure 11.2.2 A young boy next to an open sewer in Nairobi, Kenya. In addition to the dangers to human welfare and livelihoods, polluted waterways kill millions of native animals and plants each year, and harm countless number of ecosystems. Photograph by Eoghan Rice/Trócaire, https://commons.wikimedia.org/wiki/File:A_young_boy_sits_over_an_open_sewer_in_the_Kibera_slum,_Nairobi.jpg, CC BY 2.0.

One of the most challenging aspects when trying to prevent pollution is identifying the source. Many forms of pollution can easily be transported away from their source through the air, via rivers, even in groundwater. This transport of pollutants (called **pesticide drift** in the case of pesticides) means that a substantial burden (perhaps as much as 95%, Miller, 2004) of impacts are being felt by non-target species, including economically important non-target organisms. For example, pesticide drift from cotton fields in Benin has caused extirpations of freshwater fish (Agbohessi et al., 2015), while beneficial pollinating insects are also often negatively impacted (Pettis et al., 2013). Studies on fish (Adeogun et al., 2016), large mammals (Bornman et al., 2010), and frogs (Hayes and Menendez, 1999) have shown that beneficial organisms that survive this secondary pesticide exposure have disrupted reproductive and endocrine systems, and hence reduced fitness. Even humans may be exposed to secondary poisoning from pesticides, as toxic pesticide levels have been found in edible oysters and mussels (Dodoo et al., 2013), prawn (Roche and Tidou, 2009), and even chickens (Barnhoorn et al., 2009).

To make matters worse, many pollutants take many years to **biodegrade** (i.e. break down in nature), and thus continue to pose a threat to wildlife and humans long after entering the environment. One important class of such long-lived pollutants is **persistent organic pollutants** (POP). Several types of pesticides qualify as POPs, which are prone to bioaccumulation and drift. The most famous POP is DDT; in the USA, biologist continue to see eggshell thinning and bird deaths, nearly 50 years after DDT was banned in that country (Burnett et al., 2013). More information on POPs, many which are banned from use by signatories of the Stockholm Convention on Persistent Organic Pollutants, can be found on the Stockholm Convention website (http://pops.int).

There are also many types of persistent inorganic pollutants that find their way into the environment on a daily basis. One important class of persistent inorganic pollutants that also bioaccumulate is heavy metals; these include mercury, cobalt, copper, lead, and arsenic. Some everyday products can also persist in the environment. For example, an aluminium can takes about 200 years to break down, while a plastic bag takes between 100–1,000 years to break down. The continued use of these products should thus raise alarm to anyone concerned about the environment and human health. But it also provides opportunities for any person to contribute to conservation by reducing use of these products and reusing/recycling those products that find their way into the supply chain.

Water pollution

Water pollution, the accidental or intentional dumping of pesticides; herbicides; oil products; fertilizers; sewage; industrial waste; detergents; and other foreign chemicals and objects into aquatic environments, is a current pollution concern in many parts of the world (Prüss-Ustün et al., 2016; Landrigan et al., 2018).

The dumping of products containing heavy metals into aquatic environments is particularly concerning because heavy metals are toxic even in small concentrations, and likely to biomagnify. When aquatic organisms process contaminated water, they absorb or ingest the heavy metals along with other essential nutrients. With each additional step along the food chain, organisms ingest and accumulate increasingly higher concentrations of these toxic elements (see Figure 11.2.1). In this way, even small amounts of

heavy metals can become lethal across several levels of the **food web** over time. Biomagnification is especially a concern with long-lived predatory marine fishes that people consumed as food, such as swordfish (*Xiphias gladius*, LC), marlins, sharks, and some tunas and sea basses.

> Because of biomagnification, many long-lived predatory marine fishes are now considered unsafe for human consumption.

Oil pollution involves the release of petroleum products into the environment, which can originate from damaged ships, failed drilling rigs, leaking offshore platforms, or other unexpected events. The released oil causes mammals and birds to lose the insulating abilities of their fur and feathers, leaving those animals vulnerable to hypothermia and drowning. Other aquatic animals, including fish and shellfish, may ingest oil products, causing them to sicken and die. Because of the way oil is extracted and transported, marine ecosystems are particularly at risk. Furthermore, because of the massive amount of oil that are involved in oil extraction and transport, an oil pollution event often represents a serious ecological disaster (Figure 11.2.3).

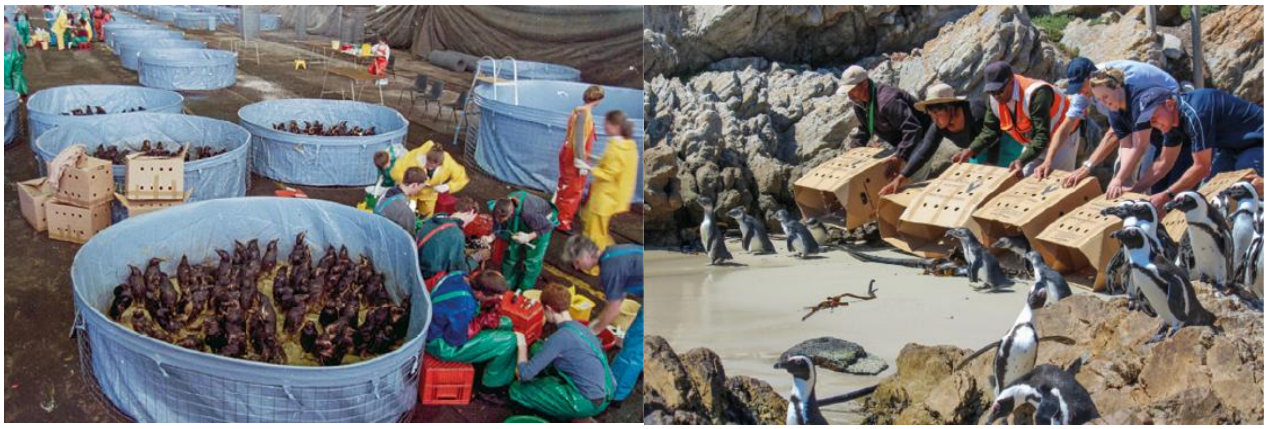


Figure 11.2.3 (Top) Staff and volunteers from the seabird rescue centre SANCCOB are caring for some of the 19,000 African penguins (Spheniscus demersus, EN) that were rescued after a stricken iron ore carrier spilled 1,400 tonnes of oil off South Africa in June 2000 (Wolfaardt et al., 2009). (Bottom) SANCCOB volunteers releasing a group of African penguins that were rescued from the oil spill. Photographs by SANCCOB, CC BY 4.0.

Plastic pollution is fast becoming a ubiquitous threat to the environment. To visualize the magnitude of the problem, consider that there are more than 1.6 trillion pieces of plastic, collectively weighing over 70,000 tons, currently floating in the Atlantic and Indian Oceans surrounding Africa (Eriksen et al., 2014). While many of these plastic items were dumped directly in the ocean, many also have a terrestrial origin. For example, if someone throws a plastic wrapper on a sidewalk, there is a good chance that the wrapper will find its way into a nearby stream at some point, carried by wind or rain runoff. From here, the wrapper will float along various streams and rivers until it reaches the ocean. A recent review found that 88–95% of plastics floating into the world's oceans originated from just 10 rivers (Schmidt et al., 2017; Lebreton et al., 2017). In the process, thousands of seabirds, dolphins, whales, turtles, seals and fish die each year from suffocation or starvation after ingesting plastics and other pieces of trash that they confused with food (Wilcox et al., 2015). This plastic pollution also impacts humans: researchers recently found microfibers (many of which are plastic) in over 80% of tap water samples from Uganda (Kosuth et al., 2017), as well as food-grade commercial sea salt originating from South Africa (Karami et al., 2017).

Some of the biggest impacts from plastic pollution are caused not by visible scraps of plastic, but by microplastics, the collective name for plastic particles smaller than 1 mm (some are microscopic). **Microplastics** may originate from the breakdown of larger pieces of plastic and polystyrene products, or they may be manufactured intentionally small, such as beads added to cosmetics and other personal care products that are flushed down drains after use. Because microplastics are so small, they easily pass through the standard filters used at sewage treatment plants. Consequently, microplastics generally end up in the aquatic environment, where they are unintentionally consumed by crustaceans (crabs, lobsters, and krill), molluscs (mussels, oysters, and clams), echinoderms (sea stars, sea urchins, sea cucumbers), and baby fish. This consumption can block or damage the victim's digestive and respiratory systems, cause reduced food uptake by creating a false sense of satiation, or even poison animals through leeching of synthetic chemicals. Each of these threats increases death rates and lowers reproductive rates (Sussarellu et al., 2016). Just as with the biomagnification we discussed earlier, the consumption of microplastics also affects other consumers (including humans), because

the small organisms that ingest the microplastics are often food for other animals, allowing plastic pollution to move through an entire food chain. For example, a recent study from Lake Victoria found microplastics imbedded in the digestive tracts of perch and tilapia bought at a local market and meant for human consumption (Biginagwa et al., 2016). Because microplastics are so hard to remove once in an ecosystem, the best method for their containment may be to reduce plastic use, to ban products containing microplastics, or to develop microplastics that are biodegradable within a reasonable timeframe. But for this to happen, there is a need to educate the public and lawmakers (Galloway and Lewis, 2016) about the dangers posed by this threat to the environment and local economies.

> Nutrient pollution, caused in part by excessive fertilizer use, can led to eutrophication, famous for causing algae blooms, aquatic dead zones, and fish kills.

Nutrient pollution represents another growing threat to aquatic environments. Many lakes, streams, and other freshwater and marine environments naturally contain low concentrations of essential nutrients, such as nitrates and phosphates. In order to survive, the species living in these nutrient-poor waters must then be adapted to this natural nutrient scarcity. However, raw sewage, agricultural fertilizers, concentrated animal feeding operations, and industrial processes release large amounts of additional nitrates and phosphates into the environment, which are washed into the aquatic environment. Minor additions of essential nutrients stimulate plant growth, providing more food for organisms at higher trophic levels. However, at high concentrations, the system become subjected to nutrient pollution.

One of the worst outcomes of nutrient pollution is **eutrophication**. During eutrophication, surface algae grow so rapidly (known as an algae bloom) that it starts blocking sunlight from reaching aquatic organisms below the surface (Figure 11.2.4). Because each individual alga is short-lived, their rapid growth also adds large amounts of decaying matter to the environment. In response, decomposers that feed on the dead algae can become so abundant that they consume most of the water's dissolved oxygen. Without oxygen and sunlight, aquatic plant and animal life may die off in large numbers. The resultant dead zones are sometimes visibly in the form of fish kills, with large numbers of dead fish floating on the surface of the affected water body. The organisms that die during this process is generally also toxic to humans because of bacteria build-up and other imbalances. Eutrophication is an increasingly common problem.



Figure 11.2.4: Eutrophication of a stream in China. (Felix Andrews, own work, CC BY 3.0 Wikimedia commons)

Groundwater pollution—the release of pollutants into aquifers and other sources of groundwater—is also becoming a serious issue in many parts of the world. This type of pollution generally originates from landfills, on-site sanitation systems, leaking sewage systems, mining leachate, **agriculture runoff** (fertilizer, pesticides, animal waste, etc.), and other types of waste dumping.

The pollutants may sometimes be released directly into aquifers; however, more often the contaminants and pathogens leak into the soil, from where it seeps into groundwater.

One of the most important emerging threats to groundwater is **hydrological fracturing** or fracking, in short. During this process, pressurized liquids that contain suspended particles and thickening agents are blasted into rock formations deep underground to break them open. When the pressure and liquids are removed, the suspended particles keep the fractures open, which enables extraction of natural gas and petroleum. While fracking was initially hailed as a method to access previously inaccessible fossil fuels, scientists subsequently found that it poses a wide variety of very serious environmental and health risks. Most importantly, the liquids used in fracking contain toxic chemicals which pose a high risk for groundwater pollution (Osborne et al., 2011), which in turn lead to miscarriages and birth defects (McKenzie et al., 2014), cancer (McKenzie et al., 2012), as well as skin and respiratory diseases (Rabinowitz et al. 2015). In addition, fracking increases greenhouse gas emissions (Howarth, 2014) and induces infrastructure-damaging earthquakes (Ellsworth, 2013). Because of these myriad serious risks, several national governments in Europe, and several local governments in the USA, UK, Canada, and Australia have banned the practice from their lands (https://keeptapwatersafe.org/global-bans-on-fracking). In contrast, and despite opposition from civil society, several countries in Africa (e.g. South Africa: Roelf, 2016; Botswana: Barbee, 2015) recently approved this harmful practice.

Air pollution

In the past, people and industries thought that the atmosphere was so vast that any gases or particles released into the air would disperse and dilute to the point that they would post no ill effects. But as air quality has diminished over time, scientists have documented that air pollution can cause irreparable harm to ecosystems and human health, often far from the original sources. A striking example comes from West Africa's Lake Chad, which shrank by 95% between 1963 and 1998 (Figure 11.2.5). Experts generally thought that the shrinkage was caused by unsustainable water use in the region, but recent evidence suggests that air pollution from Europe which reduced rainfall in the Lake's catchment area may also have contributed to this ecological disaster (Hwang et al., 2013). The Lake's water level has risen since 2007, likely due, in part, to clean air regulations implemented by the European Union. Despite this positive turn around, air pollution continues to be a serious problem (Amegah and Agyei-Mensah, 2017) that threatens both humans and wildlife.

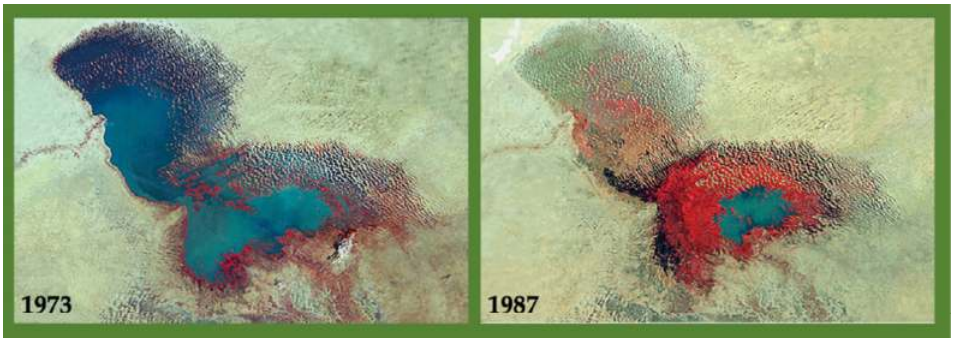


Figure11.2.5 Changing rainfall patterns attributed to air pollution may have contributed to West Africa's Lake Chad shrinking by 95% between 1963 and 1998. An ecological disaster ensued, as the 68 million people whose livelihoods were at risk put additional strains on the environment while trying to replace the natural resources the lake previously provided. Images by NASA/GSFC, https://svs.gsfc.nasa.gov/2065, CC BY 4.0.

Burning fossil fuels also releases sulphur oxides (SOx) and nitrogen oxides (NOx) into the atmosphere, where they combine with water vapor to produce nitric and sulphuric acids. These acids later return to the ground as acid rain, with dramatically low pH relative to normal rainwater. Prevailing winds can transport acid rain clouds over long distances, so the effects of acid rain may occur hundreds of kilometers from its sources. Because the acid rain is closely tied to the water cycle, aquatic and soil organisms are particularly vulnerable to the negative effects of acid rain. Plants exposed to acid rain, either directly or after absorbing contaminated water from the ground, are often left severely weakened or even killed: it has even caused plant extirpations. (UNEP, 2006).

Soil pollution

Soil pollution occurs when soil meets foreign chemicals and other pollutants. This type of pollution is often associated with industrial activities that extract resources from the earth, agricultural runoff, pesticide use, oil spills, acid rain, improper treatment

of sewage, and improper disposal of waste. People and wildlife can then become sick through direct contact with contaminated soils, or through secondary contamination via polluted groundwater or eating food grown in contaminated soil.

The improper disposal of electronic waste (or e-waste in short) is a particularly serious form of soil pollution. Because electronic products contain toxic heavy metal contaminants that are expensive to recycle, discarded electronic products usually end up in dump yards (Figure 11.2.6). Here, open burning of electronic and other waste materials releases the toxic compounds into the soil, as well as the air and water (Robinson, 2009), from where it also accumulates in the environment.



Figure 11.2.6 Nearly all electronic goods contain parts with toxic chemicals that are expensive to recycle. Instead, such components end up in dump yards such as this one in Ghana, from where the toxic compounds pollute the air, water, and soil, posing many human and environmental risks. Photograph by Agbogbloshie Makerspace Platform, https://www.flickr.com/photos/qampnet/14937188796, CC BY-SA 2.0.

Light pollution

Light pollution describes the addition of excessive, ill-timed, or poorly designed artificial light to the natural world. A consequence of an increasingly industrialized world (Falchi et al., 2016), light pollution has increased dramatically over the past decades as more people have gained greater access to electricity and cities continue to grow (Figure 11.2.7). Behavioral disruption is perhaps the most well-known consequence of increased light pollution—consider all the moths and other nocturnal insects (and insect predators, such as bats and geckos) attracted to artificial night lights. Light pollution also interferes with the navigation abilities of nocturnal species, which often use the stars, moon, and light reflectance from water surfaces to orientate themselves. For example, work in Gabon has shown how artificial lights disorientate sea turtle hatchlings trying to reach the sea (Bourgeois et al., 2009), while others have highlighted the significance of light-induced seabird mortality (Black, 2005). These and other behavioral disruptions—which include attraction to and repelling away from artificial light—may seem to only affect a small number of individuals around a few lights in your home. But the systemic impact of thousands of lights every night has wide-ranging ecosystem impacts when considering the cumulative impact of reduced reproductive performance (Firebaugh and Haynes, 2016), disrupted predator-prey dynamics (Minnaar et al., 2015) and disturbed night-time pollination services (Knop et al., 2017) on the many thousands of organisms impacted every night.



Figure 11.2.7: A comparison of nighttime lights in the Great Lakes area, USA captured by NASA's Visible Infrared Imaging Radiometer Suite (VIRS) from 2012 - 2016. Orange indicates a reduction for the time period, white indicates no change and purple indicates new light in 2016. (NASA, public domain)

Light pollution also disrupts the natural day-night cycles with which most species evolved. These disruptions interfere with **circadian rhythms**, which negatively affect living organisms' physiology. For example, one study showed that night-time light pollution disrupted natural sleep patterns in birds, leaving the affected individuals more susceptible to malaria infections (Ouyang et al., 2017). Circadian rhythm disruptions from light pollution (especially from high frequency "blue" light) also impact humans by increasing stress, fatigue, and anxiety, and susceptibility to obesity (Rybnikova et al., 2016) and cancer (Haim and Portnov, 2013). It is important to note that light pollution does not mean that the use of light is inherently bad—light has and will continue to play an important role in our daily lives. However, it does mean that we need to be more thoughtful about the consequences of light pollution and put measures in place to mitigate its impacts on the natural world and our own lives.

Noise pollution

Many people find a sense of freedom when they are in natural surroundings, with peace and quiet facilitating a much-needed connection to nature. These experiences are increasingly being threatened by **noise pollution**. However, noise pollution (also called acoustic pollution)—caused by human activities, such as industrial, military, and transportation systems—affects more than just the appealing tranquility of nature. It also prevents animals from hearing each other, predators, and prey, all which could interfere with feeding, reproduction, navigation, and predator-avoidance behaviors. One study that did investigate the topic found that traffic noise increased dwarf mongooses' (Helogale parvula, LC) alertness but also reduced responsiveness to alarm calls (Kern and Radford, 2016). Such responses could leave the affected individuals less fit and more vulnerable to predators.

> Noise pollution prevents interferes with communication, feeding, reproduction, navigation, and predator-avoidance behaviors; it may even contribute to mass strandings of whales.

One would think that marine organisms living in the vast oceans may be spared from noise pollution, but this is not the case (Koper and Plön, 2012; Kunc et al., 2017). Sound carries much further in salt water than air, so noises from ship propellers; military sonar; seismic activities, and construction have significantly increased the level of ambient noise levels marine organisms experience. This increased level of ambient noise not only disrupts communication in sea animals (e.g. Cerchio et al., 2014), but can even lead to death (some mass whale strandings have been attributed to noise pollution: Morell et al., 2017; Williams et al., 2017). As with light pollution, there is a general need to be more thoughtful about the consequences of sound pollution on the natural world and to put measures in place (see e.g. Koper and Plön, 2012) to mitigate its impacts.

Thermal pollution

Thermal pollution describes localized human-induced temperature changes to the natural world. Aquatic ecosystems represent one of the ecosystems most vulnerable to thermal pollution. For example, when water is released from big dams, it comes from the colder middle and lower strata of the reservoir, leading to rapid cooling of aquatic ecosystems further downstream. The opposite is true at power plants that use river water as a coolant; turbines release their heat to the circulating water and then the warmed water is released back into the environment. These abrupt releases of thermally discordant water often lead to thermal shock which can be lethal to fish and other aquatic organisms.

The **urban heat island effect** represents a terrestrial form of thermal pollution. Urban and other developed areas are generally covered with large swaths of man-made surfaces (e.g. asphalt roads, pavement surfaces, and building roofs), which absorb solar energy rather than reflect it. This absorbed heat, in combination with heat outputs from industrial activities, cause urban areas to function like "islands of heat" that are several degrees warmer (Figure 11.2.8) than surrounding rural areas (Feyisa et al., 2014; Chakraborty and Lee, 2018). The urban heat island effect reduces the quality of life for people and wildlife by reducing comfort and water availability (due to increasing evaporation). It also increases energy consumption to offset the heat increases which, in turn, contributes to air pollution and climate change.

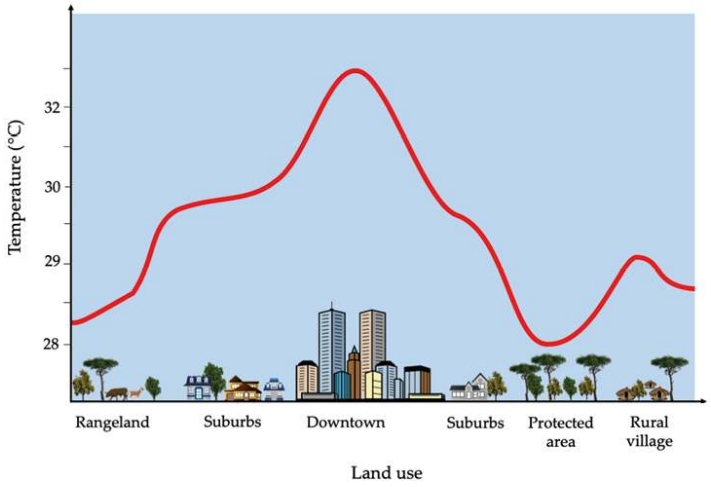


Figure 11.2.8 (Top) Man-made surfaces such as roofs, roads, and pavements do not reflect, but rather absorb solar energy as heat, causing built-up areas to be warmer than the surrounding rural areas, CC BY 4.0.

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11.2.1: Water Pollutants and Their Sources

Although natural processes such as volcanic eruptions or evaporation sometimes can cause water pollution, most pollution is derived from human, land-based activities. Pollutants can spread through different water reservoirs, as the water carrying them progresses through stages of the water cycle (figure 11.2.1.*a*). **Residence time** (the average time that a water molecule spends in a reservoir) is key to pollution problems because it affects pollution potential. Water in rivers has a relatively short residence time, so pollution usually is there only briefly. Of course, pollution in rivers may simply move to another reservoir, such as the ocean, where it can cause further problems. Groundwater is typically characterized by slow flow and longer residence time, which can make groundwater pollution particularly problematic. Finally, **pollution residence time** can be much greater than the water residence time because a pollutant may be taken up for a long time within the ecosystem or absorbed onto sediment.

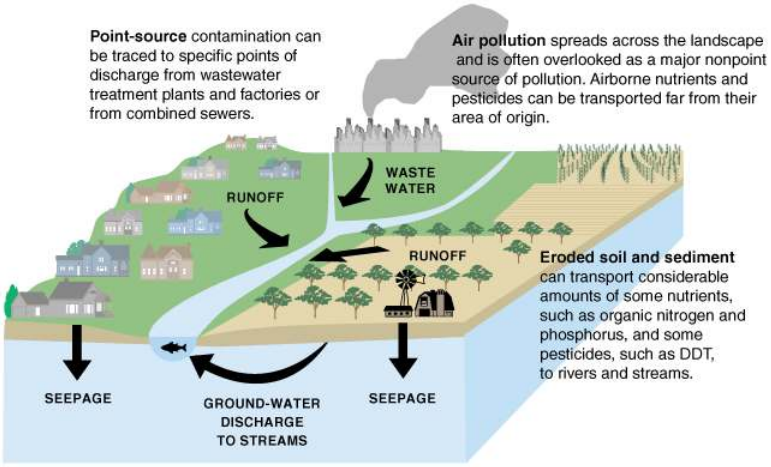


Figure 11.2.1.*a*: Sources of some water pollutants and movement of pollutants into different water reservoirs of the water cycle (such as rivers and aquifers). Point source contamination can be traced to specific points of discharge. Air pollution is an example of nonpoint source contamination because contaminants are throughout the air and landscape, ultimately entering the water from multiple locations. Eroded soil and sediment are another source of nonpoint source pollution. Image by USGS (public domain).

Water can be contaminated by various human activities or by existing natural features, like mineral-rich geologic formations. Agricultural activities, industrial operations, landfills, animal operations, and small and large scale sewage treatment processes, among many other things, all can potentially contribute to contamination. As water runs over the land or infiltrates into the ground, it dissolves material left behind by these potential contaminant sources. The risks and type of remediation for a contaminant depend on the type of chemicals present.

Point source pollution can be attributed to a single, definable origin. For example, animal factory farms (figure 11.2.1.*b*) raise a large number and high density of livestock such as cows, pigs, and chickens. Combined sewer systems that have a single set of underground pipes to collect both sewage and storm water runoff from streets for wastewater treatment can also be major point sources of pollutants. During heavy rain, storm water runoff may exceed sewer capacity, causing it to back up. This spills untreated sewage directly into surface waters (figure 11.2.1.*c*). Other examples include pipes from factories, waste disposal sites, storage tanks, and chemical spills.



Figure 11.2.1.*b*: Large animal farms are often referred to as concentrated feeding operations (CFOs). These farms are considered potential point sources of pollution because untreated animal waste may enter nearby waterbodies as untreated sewage. Credit: ehp.gov

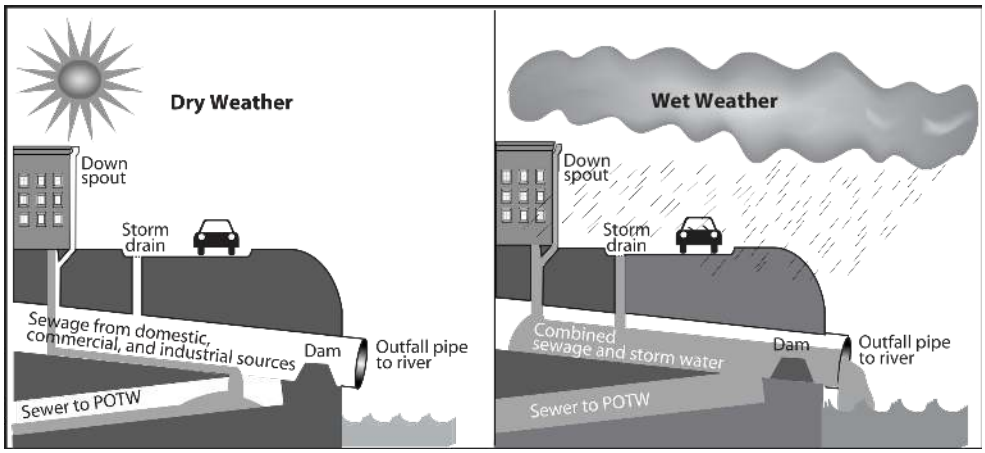


Figure 11.2.1.*c*: A combined sewer system is a possible major point source of water pollution during heavy rain due to overflow of untreated sewage. Sewage from domestic, commercial, and industrial sources enter the system through the down spout and storm water enters through the storm drain. During dry weather (and small storms), all sewage is handled by the publicly owned treatment works (POTW). A dam prevents raw sewage from flowing into a water body through the outfall pipe. During wet weather (large storms), the relief structure allows some of the combined sewage and storm water to be discharged untreated to an adjacent water body. Image by U.S. Environmental Protection Agency (public domain).

Nonpoint source pollution is from multiple dispersed sources. The whole of the contribution of pollutants is harmful, but the individual components may not reach harmful concentrations. Nonpoint sources of pollution include agricultural fields, cities, and abandoned mines. Rainfall runs over the land and through the ground, picking up pollutants from throughout the **watershed** (including areas of land and smaller streams that drain into a particular body of water). These pollutants might include herbicides, pesticides, and fertilizer from agricultural fields and lawns; oil, antifreeze, animal waste, and road salt from urban areas; and acid and toxic elements from abandoned mines. Then, this pollution is carried by runoff into surface water bodies and groundwater. Nonpoint source pollution, which is the leading cause of water pollution in the U.S., is usually much more difficult and expensive to control than point source pollution because of its low concentration, multiple sources, and much greater volume of water.

According to a 2016 report, there were 20,912 cases of impaired water bodies in the United States, which means they could neither support a healthy ecosystem nor meet water quality standards (table 11.2.1.*a*). Selected causes of impairment (water pollutants) are discussed below, categorized according to whether they arise from chemical, biological, or physical processes.

Table 11.2.1.*a*: The leading causes of impaired bodies of water in the United States in 2016. Data from EPA (public domain).

Cause of Impairment	Number of Impaired Bodies of Water
Polychlorinated biphenyls (PCBs)	3,712
Pathogens	2,248
Nutrients	2,228
Mercury	2,138
Metals (other than mercury)	2,075
Cause unknown- impaired biota	1,852
Organic enrichment/oxygen depletion	1,281
Turbidity	1,175
Pesticides	795
Salinity/total dissolved solids/chlorides/sulfates	576
pH/acidity/caustic conditions	489
Sediment	453
Temperature	358
Total toxics	282
Algal growth	174
Cause unknown	159
Dioxins	136
Toxic organics	127
Toxic inorganics	99

Chemical Pollutants

Chemical pollution from agriculture, industry, cities, and mining threatens global water quality. Air pollutants from these activities can also enter bodies of water (and become water pollutants) through dry deposition, precipitation, and runoff. Some chemical pollutants have serious and well-known health effects, whereas many others have poorly known long-term health effects.

Any natural water contains dissolved chemicals, some of which are important human nutrients while others can be harmful to human health. The concentration of a water pollutant is commonly given in very small units such as parts per million (**ppm**) or even parts per billion (**ppb**). An arsenic concentration of 1 ppm means 1 part of arsenic per million parts of water. This is equivalent to one drop of arsenic in 50 liters of water. To give you a different perspective on appreciating small concentration units, converting 1 ppm to length units is 1 cm (0.4 in) in 10 km (6 miles) and converting 1 ppm to time units is 30 seconds in a year. **Total dissolved solids** (TDS) represent the total amount of dissolved material in water. Average TDS values for rainwater, river water, and seawater are about 4 ppm, 120 ppm, and 35,000 ppm, respectively.

Organic Pollutants

Organic pollutants include herbicides and pesticides, pharmaceuticals, fuel (such as oil spills), industrial solvents and cleansers, and synthetic hormones associated with pharmaceuticals. These synthetic hormones can act as **endocrine disruptors**. Many are **persistent organic pollutants** (POPs), which are long-lived in the environment, biomagnify through the food chain, and can be toxic. As previously mentioned, DDT (pesticide), dioxin (herbicide by-product), and PCBs (polychlorinated biphenyls, which were used as a liquid insulator in electric transformers), are all POPs.

An example of organic chemical contamination is the Love Canal, in Niagara Falls, New York (Figure 11.2.1.*d*). From 1942 to 1952, the Hooker Chemical Company disposed of over 21,000 tons of chemical waste, including chlorinated hydrocarbons, into a canal and covered it with a thin layer of clay. Chlorinated hydrocarbons are a large group of organic chemicals that have chlorine functional groups, most of which are toxic and carcinogenic to humans (DDT and PCBs are an examples.) The company sold the land to the New York School Board, who developed it into a neighborhood. After residents began to suffer from serious health ailments and pools of oily fluid started rising into residents' basements, the neighborhood had to be evacuated. This site became a U.S. Environmental Protection Agency **Superfund Site**, a site with federal funding and oversight to ensure its cleanup.



Figure 11.2.1.*d*: The Love Canal in Niagra Falls, New York. Image by Environmental Protection Agency (public domain).

Inorganic Pollutants

Inorganic pollutants (figure 11.2.1.*e*) include nutrients like nitrate (NO_3^-) and phosphate (PO_4^{3-}), heavy metals, chloride (Cl^-), and radioactive isotopes released from mining or nuclear accidents (such as cesium, iodine, uranium, and radon gas). Nutrients can be from geologic material, like phosphorus-rich rock, but are most often sourced from fertilizer and animal and human waste. Untreated sewage and agricultural runoff concentrate nitrogen and phosphorus which are essential for the growth of microorganisms. Nutrients like nitrate and phosphate in surface water can promote the growth of microbes, like blue-green algae (cyanobacteria), which in turn deplete dissolved oxygen (O_2) and produce toxins. This process is known as **eutrophication** (discussed below as well as previously in Biogeochemical Cycles, Threats to Biodiversity, and Industrial Agriculture).



Figure 11.2.1.*e*: This scientist demonstrates how to test water quality, and part of this involves measuring levels of inorganic pollutants. Image by Erin Gleeson (CC-BY).

Examples of heavy metals include arsenic, mercury, lead, cadmium, and chromium, and they can bioaccumulate and biomagnify through the food chain. Arsenic (As) enters the water supply naturally from weathering of arsenic-rich minerals and from human activities such as coal burning and smelting of metallic ores. The worst case of arsenic poisoning occurred in the densely populated impoverished country of Bangladesh, which had experienced 100,000s of deaths from diarrhea and cholera each year from drinking surface water contaminated with pathogens due to improper sewage treatment. In the 1970s the United Nations provided aid for millions of shallow water wells, which resulted in a dramatic drop in pathogenic diseases. Unfortunately, many of the wells produced water naturally rich in arsenic. Tragically, there are an estimated 77 million people (about half of the population) who inadvertently may have been exposed to toxic levels of arsenic in Bangladesh as a result. The World Health Organization has called it the largest mass poisoning of a population in history.

Mercury enters the water supply naturally from weathering of mercury-rich minerals and, like mercury, from human activities such as coal burning and metal processing. A famous mercury poisoning case in Minamata, Japan involved methylmercury-rich industrial discharge that caused high mercury levels in fish. People in the local fishing villages ate fish up to three times per day for over 30 years, which resulted in over 2,000 deaths. During that time the responsible company and national government did little to mitigate, help alleviate, or even acknowledge the problem.

Salt, typically sodium chloride, is a common inorganic contaminant. It can be introduced into groundwater from natural deposits or from anthropogenic sources like the salts applied to roads in the winter to keep ice from forming (figure 11.2.1.*f*). Salt contamination can also occur from **saltwater intrusion**, where cones of depression around fresh groundwater pumping near ocean coasts induce the encroachment of saltwater into the freshwater body.



Figure 11.2.1.*f*: A snow plow and road salt application truck that is used to clear snow and ice from roadways for improving traffic and pedestrian safety. The use of salt to deice pavement can be harmful to aquatic life in urban streams. Image and caption (modified) from USGS (public domain).

The acidity or alkalinity of a body of water can also impact its quality. **pH** is a measure of the concentration of hydrogen ions (protons) in a solution, which determines how acidic or basic (alkaline) a solution is. Acidic solutions have a high hydrogen ion concentration and a pH less than 7, and basic solutions have a pH of greater than 7. The pH of freshwater usually ranges from 5 to 9, and saltwater is slightly basic (pH = 8.2) in a healthy ecosystem. When conditions are too acidic, some aquatic animals cannot reproduce, and calcium carbonate structures (clams, snails, corals, etc.) dissolve. Acid deposition is further discussed later in this chapter, and ocean acidification is discussed in the next chapter.

Hard water contains abundant calcium and magnesium, which reduces its ability to develop soapsuds and enhances scale (calcium and magnesium carbonate minerals) formation on hot water equipment. Water softeners remove calcium and magnesium, which allows the water to lather easily and prevent the minerals from precipitating on surfaces (figure 11.2.1.*g*). Hard water develops naturally from the dissolution of calcium and magnesium carbonate minerals in soil; it does not have negative health effects in people.



Figure 11.2.1.*g*: Overly hard water (high calcium content) can cause film on glassware. Image by Liz Meimann/Iowa State Univ. (public domain).

Biological Pollutants

Pathogens (infectious microorganisms or viruses) enter water primarily from human and animal fecal waste due to inadequate sewage treatment. In many underdeveloped countries, sewage is discharged into local waters either untreated or after only rudimentary treatment. In developed countries untreated sewage discharge can occur from overflows of combined sewer systems, poorly managed livestock factory farms, and leaky or broken sewage collection systems. Water with pathogens can be remediated by adding chlorine or ozone (O_3), by boiling, or by treating the sewage in the first place.

Physical Sources of Pollution

Trash, sediments, and thermal pollution arise from physical sources of pollution (figure 11.2.1.*h*). Trash was discussed extensively in Solid Waste Management. Excess sediments enter bodies of water when various land uses, such as mining, deforestation, and agriculture increases erosion. Sediments can carry toxins or excess nutrients with them, and they cloud the water (resulting in **turbidity**). Turbidity obstructs aquatic plants from accessing sufficient sunlight. Thermal pollution occurs when water temperature exceeds its natural range. Many power plants (such as coal, natural gas, nuclear, etc.) rely on water from the environment for cooling. This water is released back into bodies of water at a higher temperature than usual. High temperature disrupt aquatic organisms for several reasons; one is that warmer waters cannot hold as much dissolved oxygen (see below; figure 11.2.1.*i*). Dams can also raise water temperature to the detriment or the organisms that live there.



Figure 11.2.1.*h*: Water Pollution. Obvious water pollution in the form of floating debris; invisible water pollutants sometimes can be much more harmful than visible ones. Image by Stephen Codrington (CC-BY).

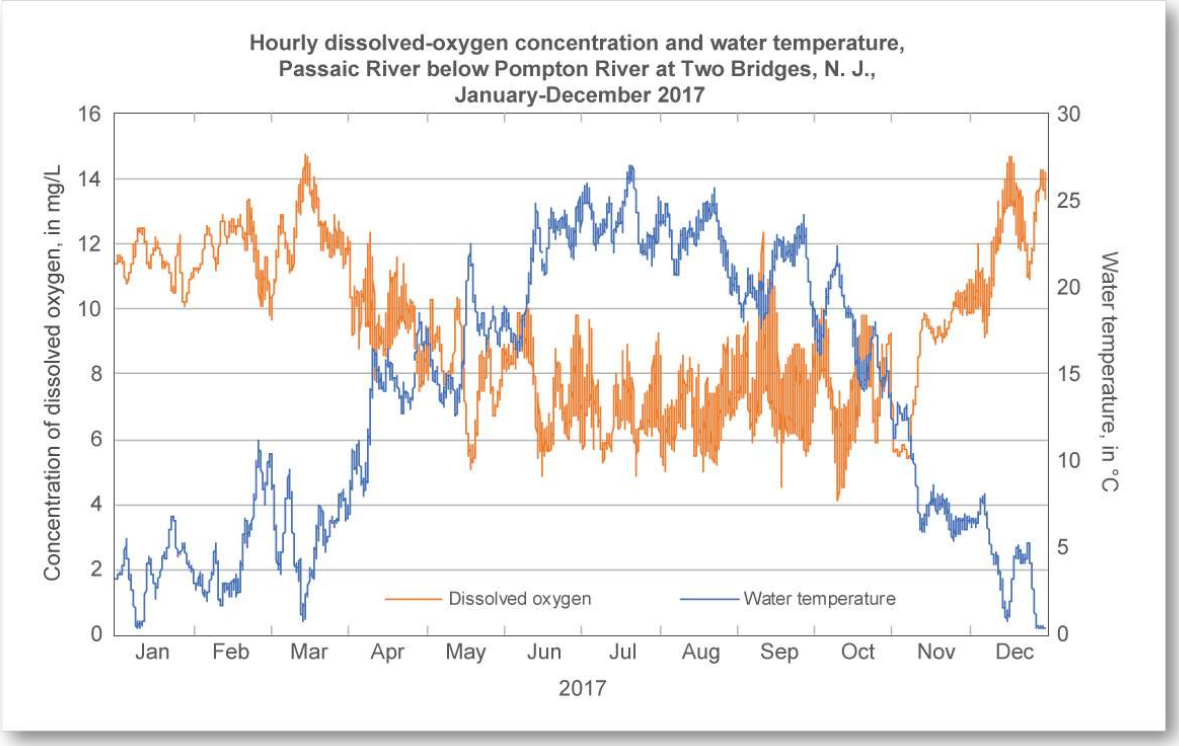


Figure 11.2.1.*i*: Water temperature affects dissolved oxygen concentrations in bodies of water. From January to December 2017, water temperature (blue) increases in summer months and then decreases. Dissolved oxygen levels (orange) dips in the summer when temperature increases. Image and caption (modified) from USGS (public domain).

Biochemical Oxygen Demand, Hypoxia, and Eutrophication

Oxygen-demanding waste is an extremely important pollutant to ecosystems. Most surface water in contact with the atmosphere has a small amount of dissolved oxygen, which is needed by aquatic organisms for cellular respiration. Decomposers, such as bacteria and fungi, also conduct cellular respiration and consume oxygen as they break down dead organic matter.

Too much decaying organic matter in water is a pollutant because it removes oxygen from water, which can kill fish, shellfish, and aquatic insects. The amount of oxygen used by **aerobic** (in the presence of oxygen) decomposition of organic matter is called **biochemical oxygen demand** (BOD). The major source of dead organic matter in many natural waters is sewage; grass and leaves are smaller sources.

An unpolluted water body with respect to BOD is a turbulent river that flows through a natural forest. Turbulence continually brings water in contact with the atmosphere where the dissolved oxygen content is restored. The dissolved oxygen content in such a river ranges from 10 to 14 ppm. When biological oxygen demand is low, clean-water fish such as trout thrive (figure 11.2.1.*j*).



Figure 11.2.1.*j*: Left: Fish like rainbow trout thrive under low biological oxygen demand and ample levels of dissolved oxygen. Right: Fish like carp thrive under high biological oxygen demand and low dissolved oxygen levels. Left image by Engbretson Eric/U.S. Fish and Wildlife Service (public domain). Right image by X posid (public domain).

A polluted water body with respect to BOD is a stagnant, deep lake in an urban setting with a combined sewer system. This system favors a high input of dead organic carbon from sewage overflows and limited chance for water circulation and contact with the atmosphere. In such a lake, the dissolved oxygen content is ≤ 5 ppm. Biological oxygen demand is high, and fish tolerant to low oxygen levels, such as carp and catfish dominate (figure 11.2.1.*k*).

Excessive nutrients, particularly nitrogen (N) and phosphorous (P), are pollutants closely related to oxygen-demanding waste. Plants and algae require 15-20 nutrients for growth, most of which are plentiful in water. Nitrogen and phosphorus are called **limiting nutrients**, however, because they usually are present in water at low concentrations and therefore restrict the total amount of plant growth. This explains why nitrogen and phosphorus are major ingredients in most fertilizer.

High concentrations of limiting nutrients, particularly nitrogen (N) and phosphorous (P), from human sources (mostly agricultural and urban runoff including fertilizer, sewage, and phosphorus-based detergent) can cause cultural **eutrophication**, which leads to the rapid growth of aquatic producers, particularly algae. Thick mats of floating algae or rooted plants lead to a form of water pollution that damages the ecosystem by clogging fish gills and blocking sunlight (figure 11.2.1.*k*). A small percentage of algal species produce toxins that can kill animals, including humans. Exponential growths of these algae are called **toxic algal blooms**.



Figure 11.2.1.*k*: A cyanobacteria (blue-green algae) bloom in Lake Erie resulting from fertilizer pollution. Image by NASA (public domain).

When the prolific algal layer dies, it becomes oxygen-demanding waste, which can create very low oxygen concentrations in the water (< 2 ppm), a condition called **hypoxia.** This results in a dead zone because it causes death from asphyxiation to organisms that are unable to leave that environment (figure 11.2.1.*l*). Approximately 50% of lakes in North America, Europe, and Asia are negatively impacted by eutrophication. Eutrophication and hypoxia are difficult to combat because they are caused primarily by nonpoint source pollution, which is difficult to regulate, and nitrogen and phosphorus are difficult to remove from wastewater. Figure 11.2.1.*m* provides a comparison of eutrophying emissions from various agricultural sources.

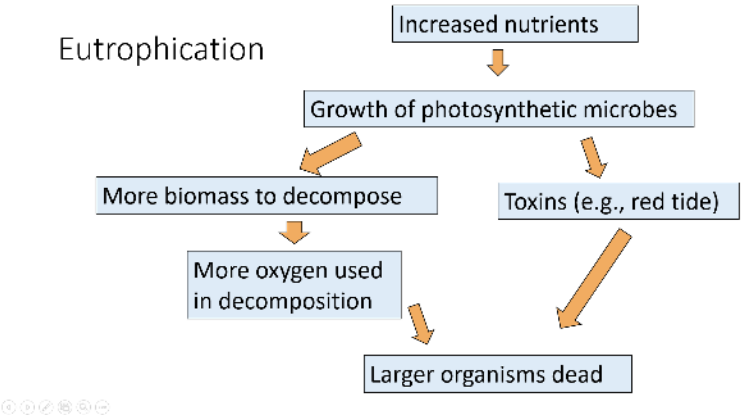


Figure 11.2.1.*l*: The process of eutrophication. During eutrophication, increased nutrients causes the growth of photosynthetic microbes resulting in more biomass to decompose. More oxygen is used in decomposition, resulting in the death of larger organisms. The growth of photosynthetic microbes also leads to toxins (for example, those produced during red tides), which also leads to the death of larger organisms.

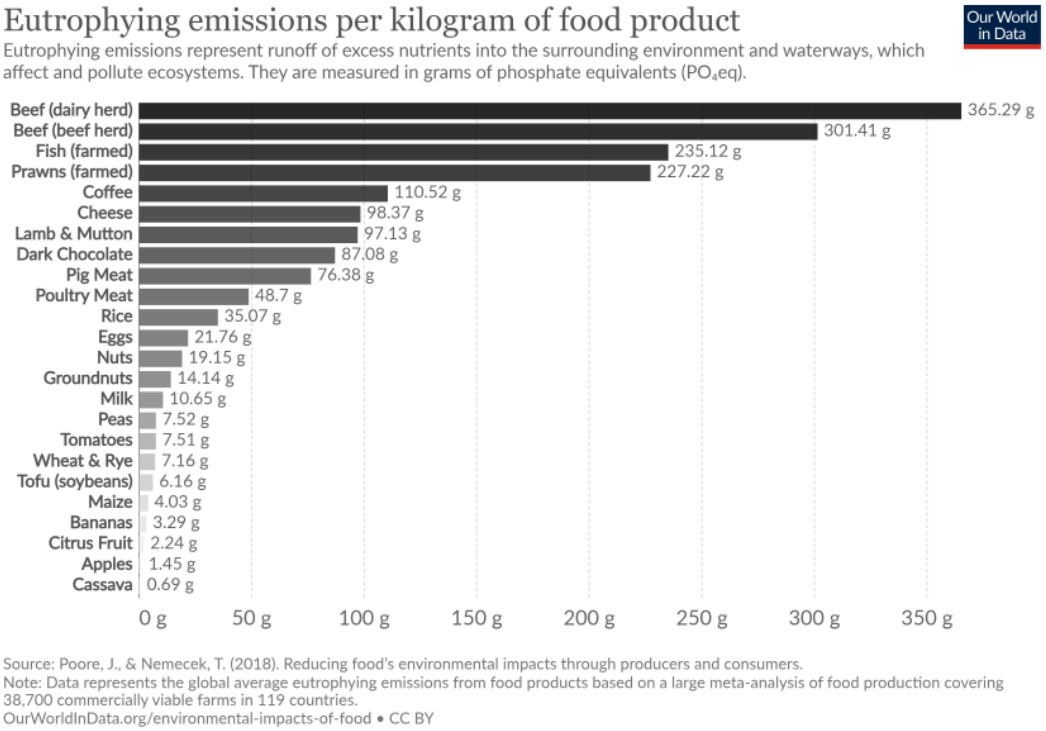


Figure 11.2.1*m*: A compariaon of eutrophying emissions per kg of food product. (CC-BY; Our World in Data from Poore and Nemecek 2018)

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- The Industrialization of Nature: A Modern History (1500 to the present) from *Sustainability: A Comprehensive Foundation* by Tom Theis and Jonathan Tomkin, Editors. Download for free at CNX. (licensed under CC-BY)

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11.2.2: Mitigating Water Pollution

Water pollution can be mitigated through regulation, bioremediation, and watershed management.

Regulation

During the early 1900s, rapid industrialization in the U.S. resulted in widespread water pollution due to free discharge of waste into surface waters. The Cuyahoga River in northeast Ohio caught fire numerous times, including a famous fire in 1969 that caught the nation's attention (figure 11.2.2.a). In 1972 Congress passed one of the most important environmental laws in U.S. history, the Federal Water Pollution Control Act, which is more commonly called the **Clean Water Act** (CWA). The purpose of the Clean Water Act and later amendments is to maintain and restore water quality, or in simpler terms to make our water swimmable and fishable. It became illegal to dump pollution into surface water unless there was formal permission. The CWA regulates pollution from a single source such as that from industry or sewage treatment plants by setting pollution standards (maximum levels of each pollutant that can be in bodies of water or released at a time). United States water quality improved significantly as a result, but as there is still more work to be done.



Figure 11.2.2.a: Cuyahoga River on fire in 1969. Image from USEPA Environmental-Protection-Agency (public domain).

Remediation

Remediation is the act of cleaning contamination. Biological remediation (**bioremediation**) is a waste management technique that involves the use of organisms such as plants, bacteria, and fungi to remove or neutralize pollutants from a contaminated site. According to the United States EPA, bioremediation is a "treatment that uses naturally occurring organisms to break down hazardous substances into less toxic or nontoxic substances". This type of remediation is usually used on organic chemicals but also works on reducing or oxidizing inorganic chemicals like nitrate. **Phytoremediation** is a type of bioremediation that uses plants to absorb the chemicals over time.

Bioremediation is widely used to treat human sewage and has also been used to remove agricultural chemicals (pesticides and fertilizers) that leach from soil into groundwater. Certain toxic metals, such as selenium and arsenic compounds, can also be removed from water by bioremediation. Mercury is an example of a toxic metal that can be removed from an environment by bioremediation. Several species of bacteria can carry out the biotransformation of toxic mercury into nontoxic forms. These bacteria, such as *Pseudomonas aeruginosa*, can convert a charged form of mercury (Hg^{2+}) to an uncharged form (Hg), which is less toxic to humans.

Probably one of the most useful and interesting examples of the use of prokaryotes for bioremediation purposes is the cleanup of oil spills. To clean up these spills, bioremediation is promoted by adding inorganic nutrients that help bacteria already present in the environment to grow. Hydrocarbon-degrading bacteria feed on the hydrocarbons in the oil droplet, breaking them into inorganic compounds. Some species, such as *Alcanivorax borkumensis*, produce surfactants that break the oil into droplets, making it more accessible to the bacteria that degrade the oil. In the case of oil spills in the ocean, ongoing, natural bioremediation tends to occur, inasmuch as there are oil-consuming bacteria in the ocean prior to the spill. Under ideal conditions, it has been reported that up to 80 percent of the nonvolatile components (those that do not readily evaporate) in oil can be degraded within one year of the spill.

Researchers have genetically engineered other bacteria to consume petroleum products; indeed, the first patent application for a bioremediation application in the U.S. was for a genetically modified oil-eating bacterium.



(a) (b)

Figure 11.2.2.a: (a) Cleaning up oil after the Exxon Valdez spill in Alaska (1989), the workers hosed oil from beaches and then used a floating boom to corral the oil, which was finally skimmed from the water surface. Some species of bacteria are able to solubilize and degrade the oil. (b) One of the most catastrophic consequences of oil spills is the damage to fauna. (credit a: modification of work by NOAA; credit b: modification of work by GOLUBENKOV, NGO: Saving Taman)

There are a number of cost/efficiency advantages to bioremediation, which can be employed in areas that are inaccessible without excavation. For example, hydrocarbon spills (specifically, oil spills) or certain chlorinated solvents may contaminate groundwater, which can be easier to treat using bioremediation than more conventional approaches. This is typically much less expensive than excavation followed by disposal elsewhere, incineration, or other off-site treatment strategies. It also reduces or eliminates the need for "pump and treat", a practice common at sites where hydrocarbons have contaminated clean groundwater. Using microorganisms for bioremediation of hydrocarbons also has the advantage of breaking down contaminants at the molecular level, as opposed to simply chemically dispersing the contaminant.

Chemical remediation uses the introduction of chemicals to remove the contaminant or make it less harmful. One example is reactive barriers, a permeable wall in the ground or at a discharge point that chemically reacts with contaminants in the water. Reactive barriers made of limestone can increase the pH of acid mine drainage, making the water less acidic and more basic, which removes dissolved contaminants by precipitation into a solid form. **Physical remediation** consists of removing the contaminated water and either treating it (aka pump and treat) with filtration or disposing of it. All of these options are technically complex, expensive, and difficult, with physical remediation typically being the most costly.

Watershed Management

Watershed management involves reducing chemicals applied to land in the watershed (which will drain into a body of water) and runoff of those chemicals (figure 11.2.2.$b-c$). This strategy is more effective for nonpoint source pollution than setting pollution standards (as the CWA does) because it does not require each source of pollution be identified.



Figure 11.2.2.*b*: While some watersheds are relatively small, others encompass thousands of square miles and may contain streams, rivers, lakes, reservoirs, and underlying groundwater that are hundreds of miles inland. Shown here is an aerial view of Drakes Bay, part of California's Tomales-Drake watershed. Image and caption (modified) from Brian Cluer, NOAA Fisheries West Coast Region, California Coastal Office (public domain).

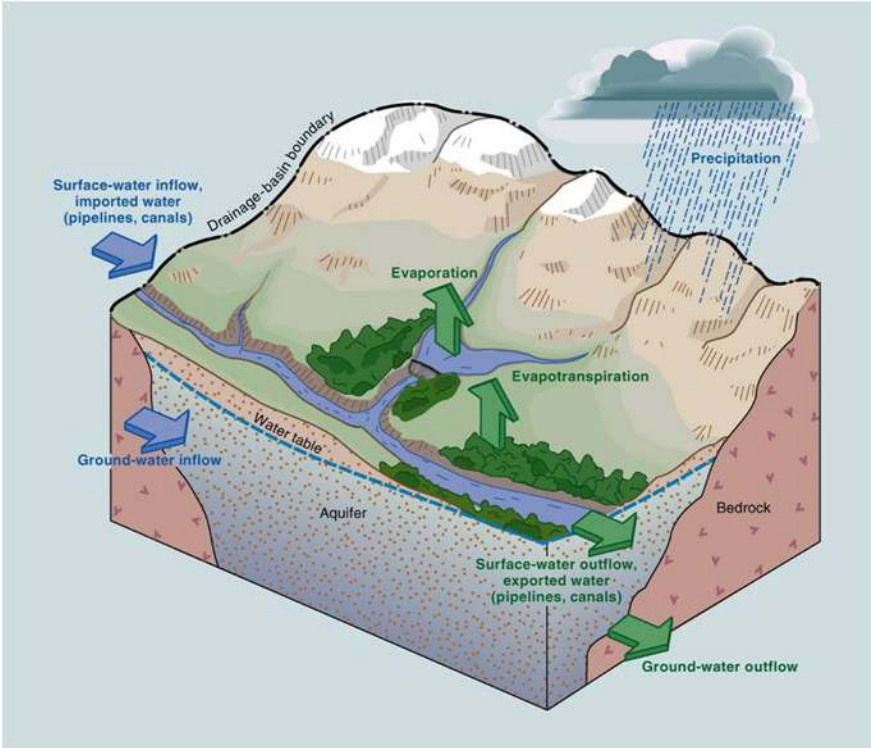


Figure 11.2.2.*c*: Diagram of a watershed, the area that drains into a body of water. The drainage-basin boundary defines the edges of the watershed. Precipitation falls on the watershed. Some reenters the atmosphere through evaporation or evapotranspiration. The water collects into smaller streams, which drain into a larger river. Additionally, surface water can enter the watershed (surface-water inflow) as water imported through pipelines or canals. Surface water exits the watershed (surface-water outflow) as water exported through pipelines canals. Similarly, ground-water inflow enters the system, and ground-water outflow exits the system. Ground water is stored in the aquifer underground, and the water table marks upper level of groundwater in the aquifer. Image from Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, : Water budgets: Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308.

Maintaining or restoring **riparian areas** (riparian zones) is key to watershed management (figure 11.2.2.*d*). These are areas of land close enough to a body of water to be affected by that body of water, for example, the lush region of vegetation surrounding a river. Riparian areas provide many ecosystem services that promote water quality and limit pollution. The vegetation absorbs nutrients that could otherwise cause eutrophication. It also provide shade, keeping the water cool and increasing its capacity to hold dissolved oxygen. The roots of the vegetation cling to soil, combating erosion. Additionally, roots and low-lying plants slow the flow of run-off, promoting infiltration. High infiltration rates have several benefits: (1) less runoff is available to bring pollution to the river, lake, or bay, (2) pollutants will be filtered from the runoff as it soaks into the ground, and (3) aquifers are replenished.



Figure 11.2.2.*d*: Riparian areas reduce water pollution by absorbing nutrients, keeping water cool, limiting erosion, and promoting infiltration. Image by BLM (public domain).

Watershed management plans typically leave undisturbed riparian vegetation directly adjacent to a body of water (figure 11.2.2.*e*). Next (moving away from the water), could be managed forest followed by agriculture. The most intensive agriculture should be farthest from the body of water, particularly when pesticides and fertilizers are in use.

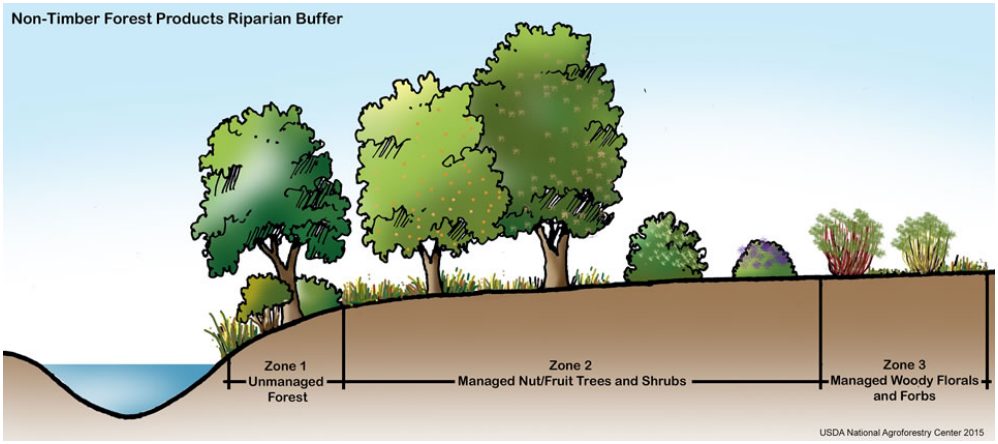


Figure 11.2.2.*e*: Although riparian forest buffers are often designed primarily for water quality benefits, these practices can also include woody species that provide products such as nuts, fruit, and decorative woody florals. These are examples of non-timber forest products. Zone 1, which is closest to the river, is unmanaged forest. Zone 2 contains managed nut or fruit trees and shrubs. Zone 3 contains managed woody florals and forbs. (Forbs are non-woody plants excluding grasses.) Image and caption by USDA National Agroforestry Center (public domain).

In urban areas can also be carefully structured to limit water pollution. Rain gardens next to buildings are areas with soil and vegetation that promote infiltration. Permeable pavement, which allows water to pass through it, also promotes infiltration, and reduces runoff, creating fewer opportunities for the water to acquire pollutants from washing over a dirty street.

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SECTION OVERVIEW

11.2.3: Air Pollution

Air pollution occurs in many forms but can generally be thought of as gaseous and particulate contaminants that are present in the earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**.

Air pollution is typically separated into two categories: outdoor air pollution and indoor air pollution. **Outdoor air pollution** involves exposures that take place outside of the built environment. Examples include fine particles produced by the burning of coal, noxious gases such as sulfur dioxide, nitrogen oxides and carbon monoxide; ground-level ozone and tobacco smoke. **Indoor air pollution** involves exposures to particulates, carbon oxides, and other pollutants carried by indoor air or dust. Examples include household products and chemicals, out-gassing of building materials, allergens (cockroach and mouse dropping, mold, pollen), and tobacco smoke.

This video summarizes the causes, consequences, and solutions to air pollution.



Sources of Air Pollution

A **stationary source** of air pollution refers to an emission source that does not move, also known as a point source. Stationary sources include factories, power plants, and dry cleaners. The term **area source** is used to describe many small sources of air pollution located together whose individual emissions may be below thresholds of concern, but whose collective emissions can be significant. Residential wood burners are a good example of a small source, but when combined with many other small sources, they can contribute to local and regional air pollution levels. Area sources can also be thought of as non-point sources, such as construction of housing developments, dry lake beds, and landfills.

A **mobile source** of air pollution refers to a source that is capable of moving under its own power. In general, mobile sources imply "on-road" transportation, which includes vehicles such as cars, sport utility vehicles, and buses. In addition, there is also a "non-road" or "off-road" category that includes gas-powered lawn tools and mowers, farm and construction equipment, recreational vehicles, boats, planes, and trains.

Agricultural sources arise from operations that raise animals and grow crops, which can generate emissions of gases and particulate matter. For example, animals confined to a barn or restricted area produce large amounts of manure. Manure emits various gases, particularly ammonia into the air. This ammonia can be emitted from the animal houses, manure storage areas, or from the land after the manure is applied. In crop production, the misapplication of fertilizers, herbicides, and pesticides can potentially result in aerial drift of these materials and harm may be caused.

Unlike the above mentioned sources of air pollution, air pollution caused by **natural sources** is not caused by people or their activities. An erupting volcano emits particulate matter and gases, forest and prairie fires can emit large quantities of pollutants (figure 11.2.3.a), dust storms can create large amounts of particulate matter, and plants and trees naturally emit volatile organic

compounds which can form aerosols that can cause a natural blue haze. Wild animals in their natural habitat are also considered natural sources of “pollution”.



Figure 11.2.3.a**:** Smoke from the Camp fire in November of 2018 covers much of Northern California and extends over the Pacific Ocean. Image by NASA Earth Observatory/Lauren Dauphin (public domain).

Criteria Air Pollutants

The Environmental Protection Agency has identified six common air pollutants called **criteria air pollutants**. They are particulate matter, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. These pollutants can harm health and the environment, and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. The U.S. Environmental Protection Agency (EPA) regulates them by developing criteria based on considerations of human and environmental health.

1. **Ground-level ozone** is not emitted directly into the air, but is created by chemical reactions between nitrogen oxides (NO_X) and the gaseous oxygen (O_2) in the atmosphere react in the presence of sunlight. It also forms when nitrogen oxides and volatile organic compounds (VOCs) react. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO_X and VOCs. Breathing ozone can trigger a variety of health problems, particularly for children, the elderly, and people of all ages who have lung diseases such as asthma. Ground level ozone can also have harmful effects on sensitive vegetation and ecosystems. (Ground-level ozone should not be confused with the ozone layer, which is high in the atmosphere and protects Earth from ultraviolet light; ground-level ozone provides no such protection).
2. **Particulate matter**, also known as particle pollution, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. Examples of human-generated particulate matter are from combustion (such as burning wood or coal) and mining (which releases dust). Wildfires or wind erosion are natural sources of particulate matter. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Furthermore, particles that are 2.5 micrometers in diameter or smaller can pass from the lungs into the bloodstream, through which they are transported to various organs and cause serious health effects.
3. **Carbon monoxide** (CO) is a colorless, odorless gas emitted from combustion processes. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from vehicles. However, volcanic eruptions and wildfires also release carbon monoxide. Carbon monoxide can cause harmful health effects by reducing oxygen delivery to the body’s organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.
4. **Nitrogen oxides** (NO_X) are a group of highly reactive gasses, which includes nitrogen monoxide (NO) and nitrogen dioxide (NO_2). EPA’s National Ambient Air Quality Standard uses NO_2 as the indicator for the larger group of nitrogen oxides. Nitrogen oxides forms quickly from emissions from cars, trucks and buses, power plants, and off-road equipment. Additionally, nitrogen oxides are released naturally by certain bacteria. In addition to contributing to the formation of ground-level ozone, and fine

particle pollution, nitrogen oxides react in the atmosphere to form nitric acid (HNO_3) and nitrous acid (HNO_2), which are components of Acid Deposition. Nitrogen oxides is linked with a number of adverse effects on the respiratory system.

5. **Sulfur dioxide** (SO_2) is mainly released from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment. Volcanoes are a natural source of SO_2. Sulfur dioxide is linked with a number of adverse effects on the respiratory system. It reacts in the atmosphere to form sulfuric acid (H_2SO_4), a component of Acid Deposition.
6. **Lead** is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in on-road motor vehicles (such as cars and trucks) and industrial sources. As a result of regulatory efforts in the U.S. to remove lead from on-road motor vehicle gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent between 1980 and 1999. Today, the highest levels of lead in air are usually found near lead smelters. The major sources of lead emissions to the air today are ore and metals processing and piston-engine aircraft operating on leaded aviation gasoline. Volcanoes and erosion are natural sources of lead.

Addressing Air Pollution

A combination of regulatory, economic, and technological strategies can reduce air pollution. The 1970 **Clean Air Act** is a key federal regulation that has successfully reduced emissions of air pollutants such as lead and sulfur dioxide. The Environmental Protection Agency sets an air quality standard for large emitters of criteria air pollutants, which is the maximum allowable amount of the pollutant that can be released. Each state then develops a plan to comply with these standards. Note that hundreds of air pollutants beyond the six criteria air pollutants are regulated under the Clean Air Act.

Economic incentives make it financially beneficial for individuals, institutions, or companies to use technologies or otherwise take action that limits air pollution. For examples, **green taxes** increase the cost of an environmentally harmful action. For example, Canada levies a green tax on fuel-inefficient vehicles. **Subsidies**, on the other hand reduce the cost of environmentally beneficial choices. For example, the federal solar tax credit in the United States allows homeowners to claim a percentage of the cost of installing solar panels when their filing taxes This amount would thus reduce taxes owed or be issued as a tax refund. (Increased usage of solar electricity ultimately reduces the need for coal and natural gas power plants, which generate air pollution.)

Tradable permits (**cap-and trade**) is another economic incentive. First, the total allowable amount of emissions for an entity (such as a state or country) is set. Next, emission credits are distributed to potential polluters. Industries that reduce emissions can sell their credits, while those with high emissions may be required. For example, large emitters of greenhouse gases in California must by carbon pollution permits. The purchase of these permits funds the California Climate Credit, which Californians receive as a reduction to their April and October electricity bills.

Finally, a variety of technologies reduce air pollution. For example, air filters and proper ventilation are essential for limiting indoor air pollution. Advances in public transportation (and policies that promote them), and energy-efficient vehicles further reduce air pollution. Electric vehicles also reduce air pollution (figure 11.2.3.*b*), particularly if the the electricity that supplies them comes from a clean, renewable source, such as solar panels. **Catalytic converters** make emissions from standard vehicles less harmful by facilitating chemical reactions. For example, they catalyze reactions that convert nitrogen oxides (NO_X) to nitrogen gas (N_2) and carbon monoxide (CO) to carbon dioxide (CO_2). (While carbon dioxide is a greenhouse gas, it is not directly poisonous as carbon monoxide is.)

Other technologies limit emissions from industry. For example, **smokestack scrubbers** remove some pollutants from power plant emissions before they are released and have reduced sulfur dioxide emissions from burning coal. **Electrostatic precipitators** negatively charge pollutants and remove charged pollutants with a positive electrode (figure 11.2.3.*c*). While electrostatic precipitators were originally developed for industry, smaller versions can be used as air purifiers in homes or businesses.



Figure 11.2.3.*b*: Mass transportation, especially those that use clean energy, reduces air pollution. Image by Mtattrain (CC-BY-SA).

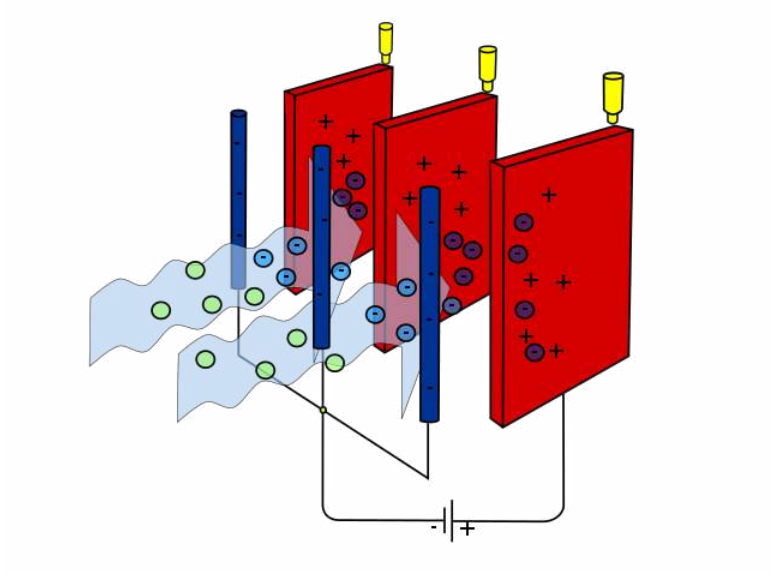


Figure 11.2.3.*c*: An electrostatic precipitator. Blue arrows represent the flow of air past metal rods, which negatively charge the pollutants. These are then drawn to positive electrodes (red, flat metal plates), removing the pollutants form the air. Image by Evan Mason (CC-BY-SA).

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Air Pollution

11.2.3.1: Acid Deposition

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11.2.3.1: Acid Deposition

Acid deposition is a term referring to a mixture of wet and dry deposition (deposited material) from the atmosphere containing higher than normal amounts of nitric and sulfuric acids. The precursors, or chemical forerunners, of acid deposition formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion (figure 11.2.3.1.*a*). Acid deposition occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles.

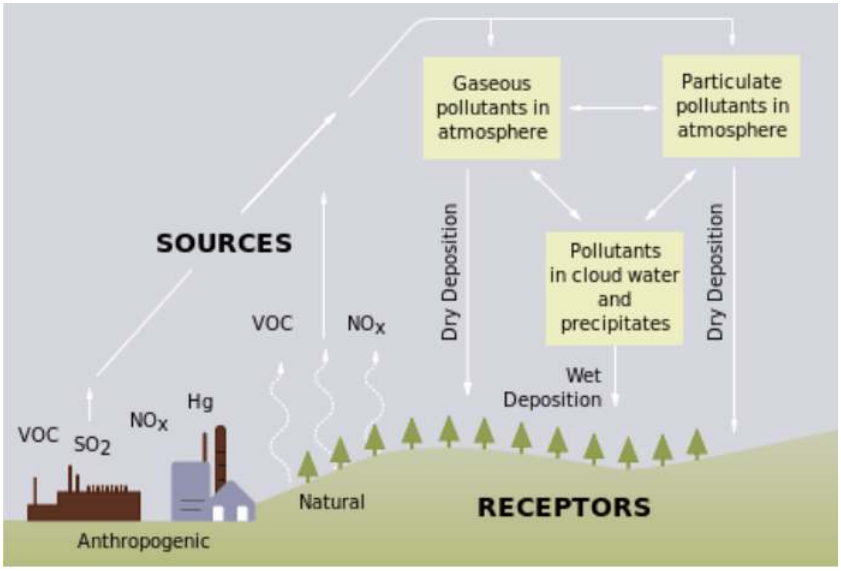


Figure 11.2.3.1.*a*: This diagram shows both anthropogenic and natural sources of acid deposition. Volatile organic compounds (VOCs), sulfur dioxide (SO_2), nitrogen oxides (NO_X), and mercury (Hg) are released, but only SO_2 and NO_X react to form acids. Three categories of pollutants interact with each other. These are gaseous pollutants in the atmosphere, particulate pollutants in the atmosphere, and pollutants in cloud water and precipitates. The former two categories form dry deposition, and the latter forms wet deposition. Acid deposition (both dry and wet deposition) reaches natural areas, which could be terrestrial (as pictured) or aquatic.

Acid deposition is measured using a scale called “pH.” The lower a substance’s pH, the more acidic it is. Pure water has a pH of 7.0. However, normal rain is slightly acidic because carbon dioxide (CO_2) dissolves into it forming weak carbonic acid, giving the resulting mixture a pH of approximately 5.6 at typical atmospheric concentrations of CO_2. The average pH of precipitation in the United States in 1980 was 4.6, but it has been gradually increasing due to reductions in sulfur dioxide and nitrogen oxide emissions (figure 11.2.3.1.*b*).

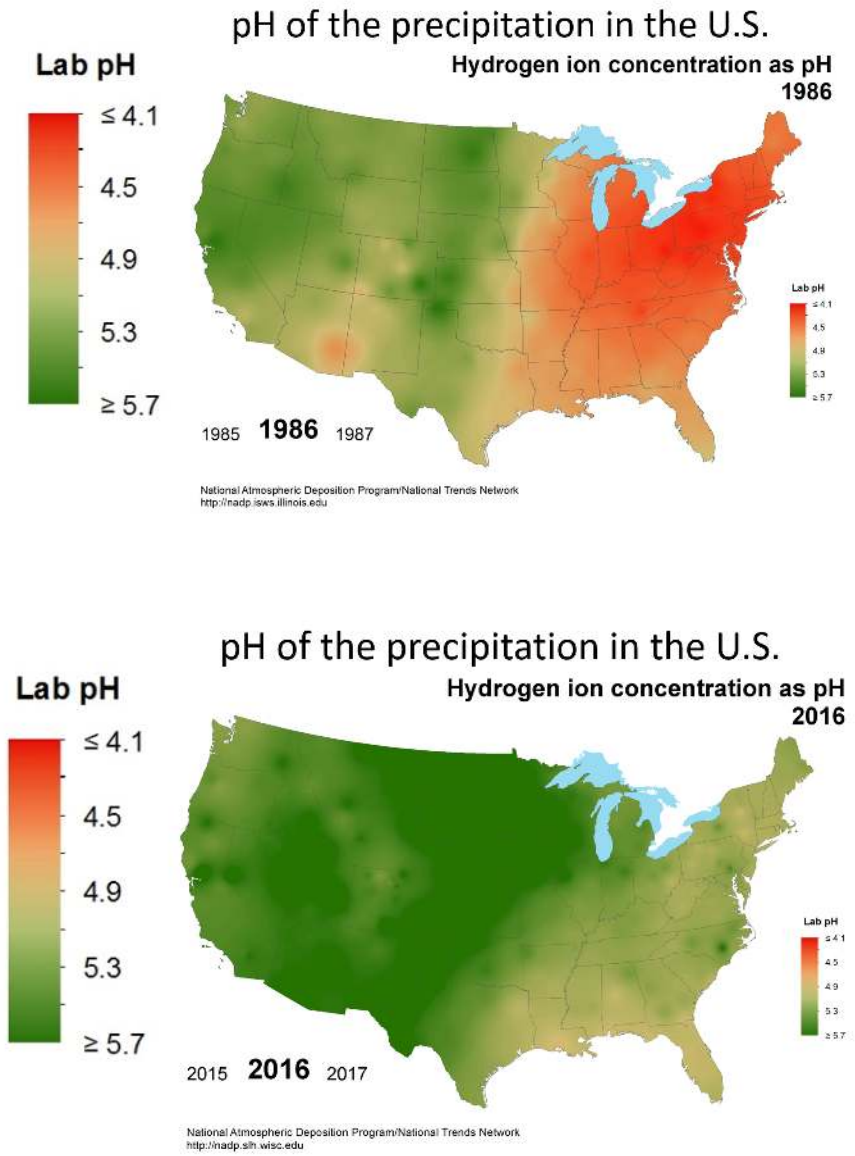


Figure 11.2.3.1.*b*: pH measures how acidic or basic a solution is, which depends on the concentration of hydrogen ions. Precipitation is normally slightly acidic, with a pH of around 5.6. (Anything below pH = 7 is considered acidic.) pH of precipitation was even more acidic in much of the East Coast of the U.S. in 1986 (acid deposition) with parts of Michigan, Ohio, Pennsylvania, and New York state reaching a pH of less than or equal to 4.1. The pH of the western United States in 1986 was closer to 5.0. Due to efforts to reduce air pollution, the pH of precipitation has moved closer to normal. By 2016, the pH of the eastern United States had increased to around 4.9, and the pH of the western United States had mostly returned to normal, with many regions having a pH of greater than or equal to 5.7. Images by National Atmospheric Deposition Program (public domain).

Effects of Acid Deposition

Acid deposition causes **acidification** of lakes and streams and contributes to the damage of trees at high elevations (for example, red spruce trees above 2,000 feet) and many sensitive forest soils. In addition, acid deposition accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. Prior to falling to the earth, sulfur dioxide (SO_2) and nitrogen oxide (NO_x) gases and their particulate matter derivatives—sulfates and nitrates—contribute to visibility degradation and harm public health.

The **ecological** effects of acid deposition are most clearly seen in the aquatic, or water, environments, such as streams, lakes, and marshes. Most lakes and streams have a pH between 6 and 8, although some lakes are naturally acidic even without the effects of

acid deposition. Acid deposition primarily affects sensitive bodies of water, which are located in watersheds whose soils have a limited ability to neutralize acidic compounds (called “buffering capacity”). Lakes and streams become acidic (i.e., the pH value goes down) when the water itself and its surrounding soil cannot buffer the acid deposition enough to neutralize it. In areas where buffering capacity is low, acid deposition releases aluminum from soils into lakes and streams; aluminum is highly toxic to many species of aquatic organisms. Acid deposition causes slower growth, injury, or death of **forests**. Of course, acid deposition is not the only cause of such conditions. Other factors contribute to the overall stress of these areas, including air pollutants, insects, disease, drought, or very cold weather. In most cases, in fact, the impacts of acid deposition on trees are due to the combined effects of acid deposition and these other environmental stressors.

Acid deposition contributes to the corrosion of **metals** (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones), and cars (figure 11.2.3.1.*c*).



Figure 11.2.3.1.*c*: A gargoyle that has been damaged by acid deposition.

Sulfates and nitrates that form in the atmosphere from sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions contribute to **visibility impairment,** meaning we cannot see as far or as clearly through the air. The pollutants that cause acid deposition—sulfur dioxide (SO_2) and nitrogen oxides (NO_x)—damage **human health**. These gases interact in the atmosphere to form fine sulfate and nitrate particles that can be transported long distances by winds and inhaled deep into people’s lungs. Fine particles can also penetrate indoors. Many scientific studies have identified a relationship between elevated levels of fine particles and increased illness and premature death from heart and lung disorders, such as asthma and bronchitis.

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11.2.4: Section Review

Summary

After completing this chapter you should be able to...

- Distinguish between point source and nonpoint source water pollution.
- Name and describe common water pollutants, including chemical, biological, and physical pollutants.
- Explain the mechanism of eutrophication.
- Summarize the current state of wastewater treatment globally.
- Describe the process of wastewater treatment, including pretreatment, primary treatment, secondary treatment, tertiary treatment, and disinfection and discharge.
- Summarize strategies for reducing water pollution.
- Identify sources of air pollution.
- List common air pollutants.
- Explain how CFCs caused ozone depletion, and global efforts to address this issue.
- Describe the causes and consequences of acid deposition.

Water pollution may arise from a single origin (**point source pollution**), or it may arise from multiple dispersed sources throughout the **watershed** (**nonpoint source pollution**). Water pollutants may be **chemical**, **biological**, or **physical**. **Oxygen-demanding waste** increases **biological oxygen demand** and causes **hypoxia**, depriving aquatic organisms of oxygen. This results from **eutrophication**, in which excess nutrients cause **algal blooms**.

Pathogens are the most deadly form of water pollution. They cause waterborne diseases, killing 485,000 people every year. Resolution of the global water pollution crisis requires multiple approaches to improve the quality of fresh water. The best strategy for addressing this problem is proper **wastewater treatment**. Strategies to reduce water pollution in general include the **Clean Water Act**, **remediation**, and **watershed management**.

Air pollution can be thought of as gaseous and particulate contaminants that are present in the Earth's atmosphere. Chemicals discharged into the air that have a direct impact on the environment are called **primary pollutants**. These primary pollutants sometimes react with other chemicals in the air to produce **secondary pollutants**. The commonly found air pollutants, known as **criteria air pollutants**, are particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead. These pollutants can harm health and the environment and cause property damage.

The ozone depletion process begins when **chlorofluorocarbons** (CFCs) and other **ozone-depleting substances** (ODS) are emitted into the atmosphere. Reductions in stratospheric ozone levels lead to higher levels of harmful ultraviolet radiation, particularly UVB, reaching the Earth's surface. The sun's output of UVB does not change; rather, less ozone means less protection, and hence more UVB reaches the Earth. The **Montreal Protocol** is an international effort to phase out CFCs, and has been successful in limiting ozone depletion.

Acid deposition occurs when certain air pollutants react with atmosphere to produce nitric and sulfuric acids. It can reach Earth as various forms of precipitation or as dry particles that later react to form acid. The precursors of acid deposition result from both natural sources, such as volcanoes and decaying vegetation, and **anthropogenic** (human) sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NOx) resulting from fossil fuel combustion. Acid deposition causes acidification of lakes and streams, contributes to the damage of trees and many sensitive forest soils. In addition, acid deposition accelerates the decay of building materials and paints, contributes to the corrosion of metals and damages human health. However, the severity of acid deposition has declined due ot regulations and technologies that limit air pollution.

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11.2.5: Solid Waste Management

Section Hook

Flushable wipes, are flushable right? No. Over and over, plumbers and waste water treatment workers state that they do not degrade fast enough and clogs drains and sewers across the globe. Not all flushable wipes are created equal, and some are better than others. Unfortunately, there are no legal requirements these products are required to passed to be called flushable, and the only guiding body is the integrity of the company manufacturing the wipes. If you want advice about your body you go to your doctor. If you want advice about your pipes, talk to your plumber. They will tell you that the only things that should go down your toilet are the 3 P's, pee, poo, and (toilet) paper.



Figure 11.2.5.*a*: Wipe isle at the store. Image by 維基小霸王 in Wikimedia Commons (CC-BY-SA4.0)

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11.2.5.1: Waste Generation

In natural systems, there is no such thing as waste. Everything flows in a natural cycle of use and reuse. Living organisms consume materials and eventually return them to the environment, usually in a different form, for reuse. **Solid waste** (or trash) is a human concept. It refers to a variety of discarded materials, not liquid or gas, that are deemed useless or worthless (figure 11.2.5.1.a). Humans modify natural substances, making them more difficult to breakdown, or store matter under conditions that slow its degradation. However, what is worthless to one person may be of value to someone else, and solid wastes can be considered misplaced resources. Learning effective ways to reduce the amount of wastes produced and to recycle valuable resources contained in the wastes is important if humans wish to maintain a livable and sustainable environment.



Figure 11.2.5.1.a: Trash is a uniquely human concept. Image by Piqsels (public domain).

Types of Waste

There are many subcategories of waste (figure 11.2.5.1.b). **Biodegradable** waste can be broken down by microbes whereas **nondegradable** waste does not readily break down. **Hazardous waste** is trash that presents a health risk. Specifically, hazardous wastes are defined as materials which are toxic, **carcinogenic** (cause cancer), **mutagenic** (cause DNA mutations), **teratogenic** (cause birth defects), highly flammable, corrosive, or explosive. Examples include batteries, fluorescent lights, various cleaners, and **e-waste**, which arises from discarded electronics. Precious metals can be extracted and recycled from hazardous waste, but it must be done safely.



Figure 11.2.5.1.b: Plastic cutlery is nondegradable, but these spoons and forks and made of wood, a biodegradable material. Image by BRRT/Pixabay (Pixabay license).

Solid Waste Sources and Composition

Agriculture and industry generate most of the waste globally followed by mining (figure 11.2.5.1.c). Together, these generate **non-municipal solid waste**. Some common items that are classified as non-municipal waste are: construction materials (roofing shingles, electrical fixtures, bricks); waste-water sludge; incinerator residues; ash; scrubber sludge; oil/gas/mining waste; railroad ties, and pesticide containers. The remaining waste, **municipal solid waste** (MSW), is made up of discarded solid materials from

residences, businesses, and city buildings. Globally, waste generated from industry generated was nearly 18 times that of MSW, and waste generated from agriculture was more than 4.5 times that of MSW.

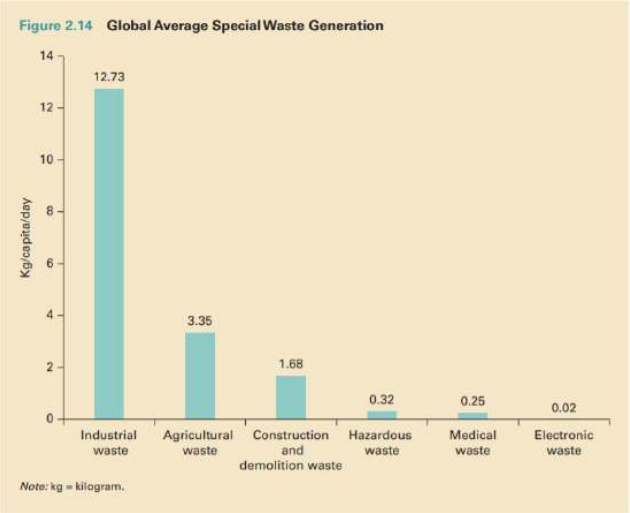


Figure 11.2.5.1.*c*: Global average special waste generation showing selected categories of waste in kilograms (kg) per person (capita) per day. 1 kg = 2.2 lbs. In order of greatest to least waste generation is industrial waste (12.73 kg/capita/day), agricultural waste (3.35), construction and demolition waste (1.68), hazardous waste (0.32), medical waste (0.25), and electronic waste (0.02). Image from What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050 (CC-BY)

The world generates 2.21 billion tons of municipal solid waste annually. Municipal solid waste makes up 3-9% of all waste in the U.S., and 292.4 million tons were generated in U.S. in 2018 (4.9 lbs per person per day). This contrasts with average values in Sub-Saharan Africa (1.01 lbs per person per day), South Asia (1.15 lbs per person per day), and East Asia and the Pacific (1.23 lbs per person per day). Daily waste generation per person in high income countries is projected to increase by 19 percent by 2050, compared to low- and middle-income countries where it is anticipated to increase by approximately 40 percent or more.

Municipal solid waste consists of materials from plastics to food scraps. The most common waste product is paper (about 23% of the total; figure 11.2.5.1.*d*). Other common components are yard waste (green waste), plastics, metals, wood, glass and food waste. The composition of the municipal wastes can vary from region to region and from season to season.

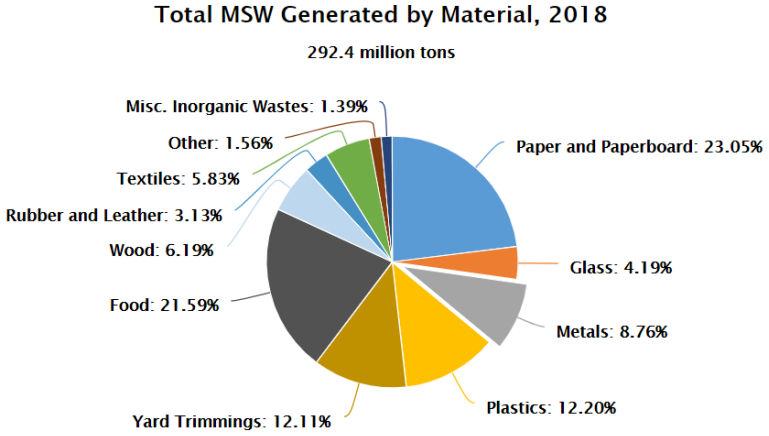


Figure 11.2.5.1.*d*: Composition of municipal solid waste (MSW) in the U.S. in 2018 before recycling. Paper and paperboard comprise 23.05% followed by food (21.59%), plastics (12.20%), yard trimmings (12.11%), metals (8.76%), wood (6.19%), textiles (5.83%), glass (4.19%), rubber and leather (3.13%), other (1.56%), and miscellaneous inorganic waste (1.39%). Image from EPA (public domain).

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- Solid Waste form *AP Environmental Science* by University of California College Prep (CC-BY). Download for free at CNX.
- Kaza, Silpa; Yao, Lisa C.; Bhada-Tata, Perinaz; Van Woerden, Frank. 2018. What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050. Urban Development;. Washington, DC: World Bank. © World Bank. (CC-BY)

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11.2.5.2: Waste Disposal

There are three primary methods for waste disposal: open dumps, sanitary landfills, and incineration. Sanitary landfills and incineration prevent reuse, recycling, and proper decomposition. While open dumps promote decomposition better than other methods of waste disposal and allow discarded materials to be salvaged or recycled, they promote disease spread and cause water pollution. They are thus illegal in many countries.

Open Dumps

Open dumps involve simply piling up trash in a designated area and is thus the easiest method of waste disposal (figure 11.2.5.2.a). Open dumps can support populations of organisms that house and transmit disease (reservoirs and vectors, respectively). Additionally, contaminants from the trash mix with rain water forming **leachate**, which infiltrates into the ground or runs off. This liquid leachate may contain toxic chemicals such as dioxin (a persistent organic pollutant), mercury, and pesticides.



Figure 11.2.5.2.a: An open dump in Vietnam. Image by Julien Belli (CC-BY).

Sanitary Landfills

After recycling, composting, and incineration, the remaining 50% of municipal solid waste (MSW) in the U.S. was discarded in **sanitary landfills** (figure 11.2.5.2.b). Trash is sealed from the top and the bottom to reduce contamination of surroundings (figure 11.2.5.2.c). Rainwater that percolates through a sanitary landfill is collected in the bottom liner, and this bottom layer thus prevents contamination of groundwater. The groundwater near the landfill is closely monitored for signs of contamination from the leachate. Layers of soil on top prevent disease spread. Each day after garbage is dumped in the landfill, it is covered with clay or plastic to prevent redistribution by animals or the wind.



Figure 11.2.5.2.b: A sanitary landfill in 1972. Image by Bill Shrout/EPA (public domain).

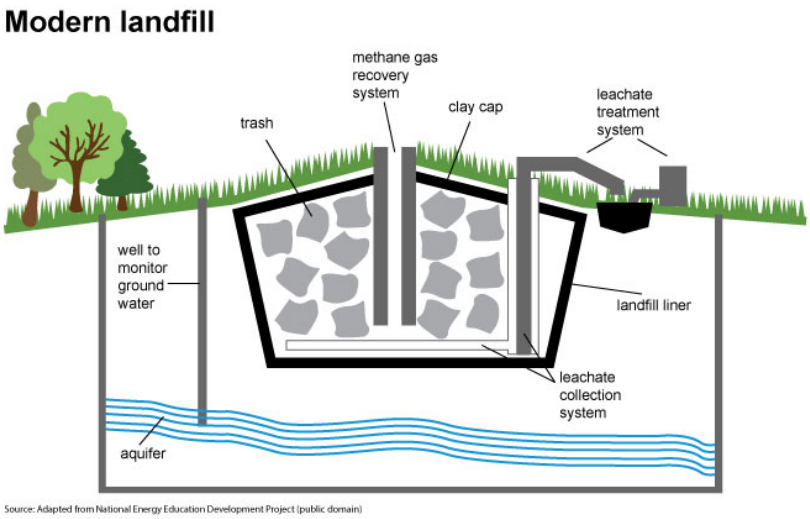


Figure 11.2.5.2.*c*: A sanitary landfill. Trash is compacted and stored underground. A landfill liner prevents leachate from draining into the aquifer and contaminating groundwater, which is monitored using a well. Additionally, leachate is collected and treated (leachate treatment system). A clay cap prevents animals or wind from accessing the trash. A methane gas recovery system captures the potent greenhouse gas, which can be used as a biofuel. Image by EPA/National Energy Education Development Project (public domain).

Several practices can reduce the environmental impact of sanitary landfills. Compacting in landfills reduces water and oxygen levels, slowing decomposition and promoting methane release. In the U.S., the Clear Air Act requires that landfills of a certain size collect landfill gas (biogas), which can be used as a biofuel for heating or electricity generation. Other gases such as ammonia and hydrogen sulfide may also be released by the landfill, contributing to air pollution. These gases are also monitored and, if necessary, collected for disposal. To address the often dry condition of wastes within landfills, the concept of bioreactor landfills has emerged. These recirculate leachate and/or inject other liquids to increase moisture and promote decomposition (and therefore increasing the rate of biogas production). Upon closure, many landfills undergo "land recycling" and can be redeveloped as golf courses, recreational parks, and other beneficial uses.

With respect to waste mitigation options, landfilling is quickly evolving into a less desirable or feasible option. Landfill capacity in the United States has been declining for several reasons. Older existing landfills are increasingly reaching their authorized capacity. Additionally, stricter environmental regulations have made establishing new landfills increasingly difficult. Finally, public opposition delays or, in many cases, prevents the approval of new landfills or expansion of existing facilities.

Incineration

Incineration is simply burning trash. This has several advantages: it reduces volume and can be used to generate electricity (**waste-to-energy**). In fact, the sheer volume of the waste is reduced by about 85%. Incineration is costly, however, and it pollutes air and water. Air pollutants released by incineration include particulates, sulfur dioxide, nitrogen oxides, methane, heavy metals (such as lead and mercury), and dioxins. The byproduct of incineration, ash, is often toxic. Depending on its composition, ash might require special disposal; other types of ash can be repurposed.

An incinerator processes trash and burns it in a **combustion chamber** (figure 11.2.5.2.$d-e$). The heat boils water, and the resultant steam is used to generate electricity. The smoke (called flue gases) goes through a **pollution-removal** before it is released, but it still contains some pollutants. The U.S. incinerated 11.8% of MSW in 2018.



Figure 11.2.5.2.d: Wheelabrator Technologies' Waste-to-Energy plant in Saugus, Massachusetts has been in service since 1975. Image and caption (modified) from Fletcher6 (CC-BY).

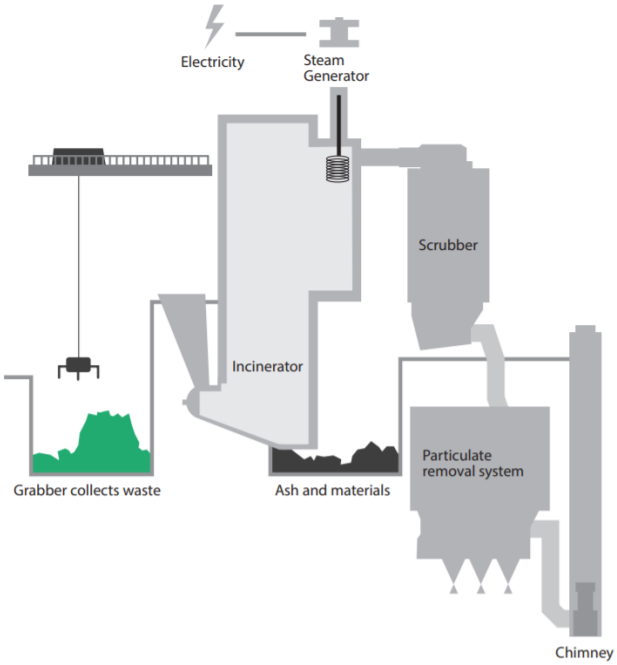


Figure 11.2.5.2.e: A schematic diagram of a waste incineration facility (waste-to energy system). A grabber collects the waste and transfers it into the incinerator. Heat from combusting the trash is used to produce steam and generate electricity. Emissions (flue gases) pass through a scrubber and particulate removal system to limit pollution before the gases are released through a chimney. Ash remains after incineration. Image by Kaza, Silpa; Bhada-Tata, Perinaz. 2018. Decision Maker's Guides for Solid Waste Management Technologies. Urban Development Series Knowledge Papers;. World Bank, Washington, DC. © World Bank. (CC-BY)

There are two kinds of waste-to-energy systems: mass burn incinerators and refuse-derived incinerators. In **mass burn incinerators** all of the solid waste is incinerated. The heat from the incineration process is used to produce steam. This steam is used to drive electric power generators. Acid gases from the burning are removed by chemical scrubbers. Any particulates (small particles that remain suspended in the air) in the combustion gases are removed by **electrostatic precipitators**, which charge particulates and remove them with electrodes. The cleaned gases are then released into the atmosphere through a tall stack. The ashes from the combustion are sent to a landfill for disposal.

It is best if only combustible items (paper, wood products, and plastics) are burned. In a **refuse-derived incinerator**, non-combustible materials are separated from the waste. Items such as glass and metals may be recycled. The combustible wastes are

then formed into fuel pellets which can be burned in standard steam boilers. This system has the advantage of removing potentially harmful materials from waste before it is burned. It also provides for some recycling of materials.

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- Biomass explained: Landfill gas and biogas. 2020. EIA. Accessed 01-18-2021 (public domain).

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11.2.5.3: Solid Waste and Marine Life

Ocean dumping has also been a popular way for coastal communities to dispose of their solid wastes. In this method, large barges carry waste out to sea and dump it into the ocean (figure 11.2.5.3.a). That practice is now banned in the United States due to the pollution problems it created. However, much trash escapes to the ocean through littering and illegal dumping. Additionally, wind carries trash off of overfilled containers, landfills, or open dumps (where they are still used).



Figure 11.2.5.3.a: Left: A garbage barge leaves Manhattan. Right: Marine debris at the beach. Left image and caption by EPA (public domain), and right image and caption by NOAA (public domain).

Garbage patches form from waste that escapes to the ocean. Plastic breaks down into smaller pieces when exposed to sunlight and ample oxygen. These pieces of plastic are trapped in calm parts of the ocean that are surrounded by strong, circular currents (figure 11.2.5.3.b). Garbage patches may not be visible from the surface of the ocean, and the plastic pieces may be up to 20 meters deep.

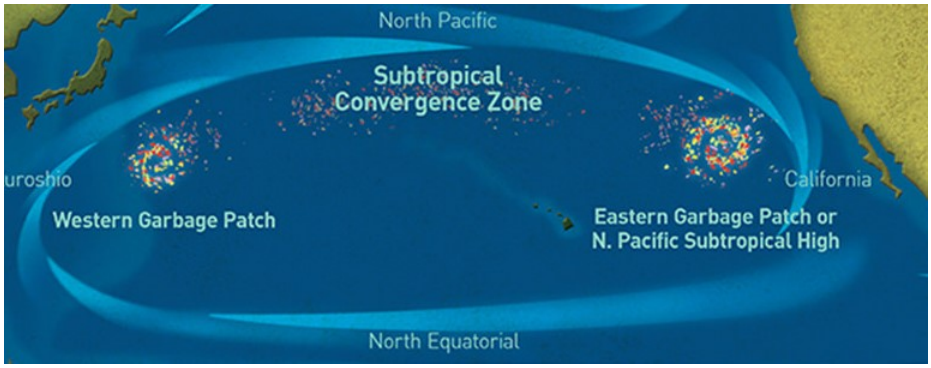


Figure 11.2.5.3.b: Locations of the largest garbage patches in the Pacific Ocean. The Western Garbage Patch is closer to Japan, and the Eastern Garbage Patch is closer to California. The Subtropical Convergence Zone is in the middle to the north. Ocean currents including the Kuroshio Current (left), North Pacific Current (top), California Current (right), and North Equatorial Current (bottom) are labeled. Image by Boyan Slat (public domain).

Plastic and other trash harms marine life in several ways. Old fishing nets and plastic six-pack rings trap wildlife. Additionally, organisms that ingest plastic risk choking. Ingested plastic may cut internal organs, limit space available for food, and carry toxins (figure 11.2.5.3.c).



Figure 11.2.5.3.c: Much of this dead albatross's digestive system was filled with plastic waste. Image by Forest and Kim Starr (CC-BY).

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11.2.5.4: Data Dive- Plastic in World Oceans

Overview

Our World in Data (OWID) is a scientific online publication that focuses on using research and data to help tackle global concerns such as poverty, disease, hunger, climate change, war, and inequitable treatment of our world's most vulnerable and unstable communities. Their website is particularly known for publishing a variety of graphs, some even interactive, to present the research that helps explain causes and consequences of global concerns to the public. One example graph, seen below, illustrates the pathway by which plastic pollution enters the world's oceans:

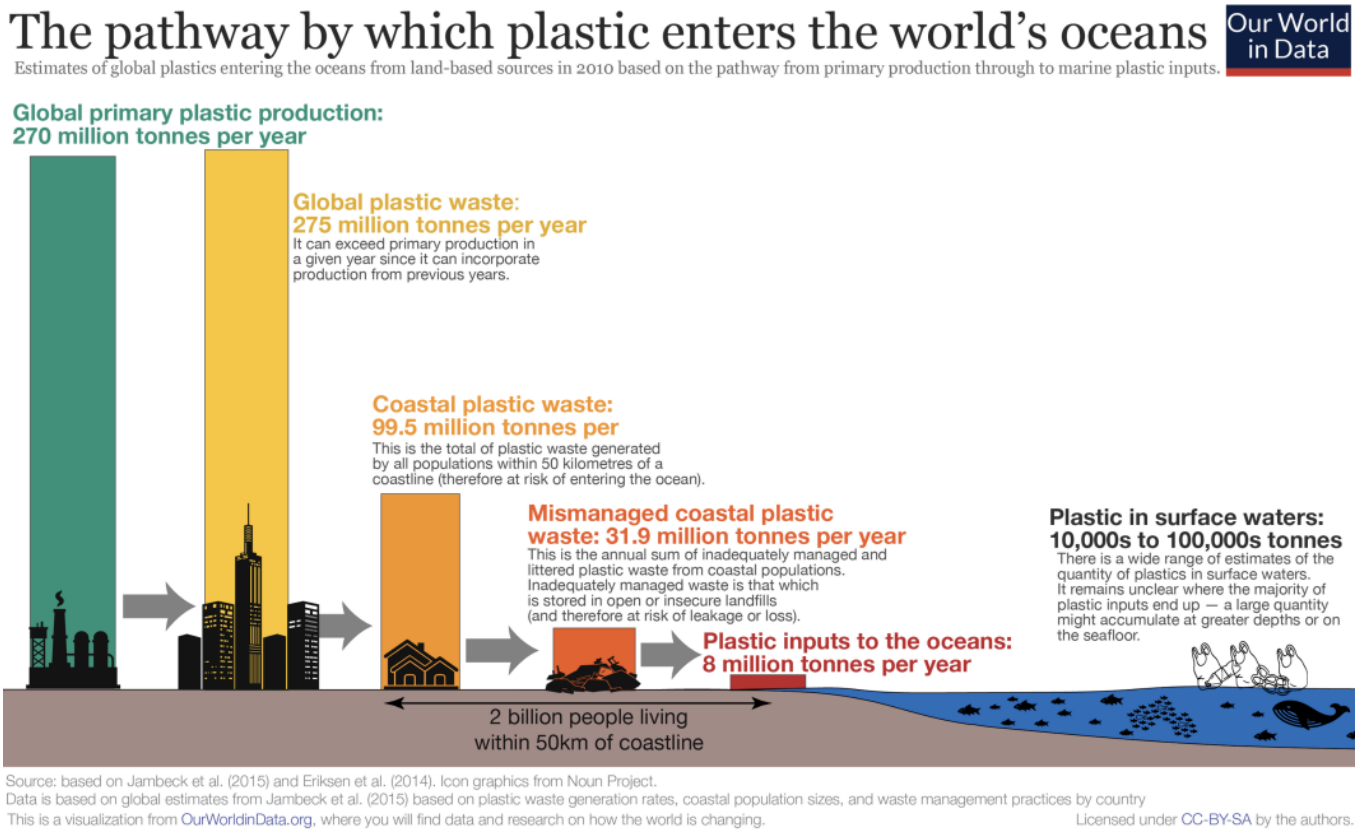


Figure 11.2.5.4.a: Plastic pathway into the ocean by million tonnes per year. Graph by Our World in Data (CC-BY-SA).

Questions

1. Reflect on how this bar graph is different than a standard bar graph. What do you like or not like about it?
2. What is this graph is illustrating about plastic waste?
3. Note that the global plastic waste is higher than the global plastic production. What does that tell you about the amount of plastic not yet classified as "waste"?
4. Provide a brief reflection for how these results make you feel and what they make you think about?
5. How can the results of this graph be used to inform future policies about plastic waste?

Raw Data From Above Graph(s)

Table 11.2.5.4.a**:** Raw data for plastic pathway into the ocean by million tonnes per year. Graph by Our World in Data (CC-BY-SA).

Waste Category	Tonnes Per Year
Global primary waste production	270 million
Global plastic waste	275 million
Coastal plastic waste	99.5 million
Mismanaged coastal plastic waste	31.9 million
Plastic inputs to the oceans	8 million
Plastic in surface waters	10,000s to 100,000s

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11.2.5.5: Waste Reduction

The **waste management hierarchy** lists processes to address waste in order of preference with the goals of limiting waste, minimizing environmental impact, and maximizing additional benefits (such as electricity generation or production of recycled goods). It is symbolized as an upside triangle, meaning that the largest volume of waste should be handled using the first process (most preferred), and the smallest volume should be handled using the last process (least preferred). These processes in order of preference are reduction, recycling, energy recovery (such as incineration), treatment, and disposal (figure 11.2.5.5.a). Individuals can exercise the first two processes by applying the four R's (see below). Unfortunately, the U.S. and the world overall, handles a large volume of waste using the least preferred method (disposal). As previously mentioned, about half of municipal solid waste (MSW) goes to a sanitary landfill for disposal. In contrast, only 23.5% of municipal solid waste (MSW) was recovered and recycled and another 8.5% was composted in 2018. Waste stream percentages also vary widely by region. As an example, San Francisco, California recycles or composts 80% of its waste material, whereas Houston, Texas recycles or composts only 19%.

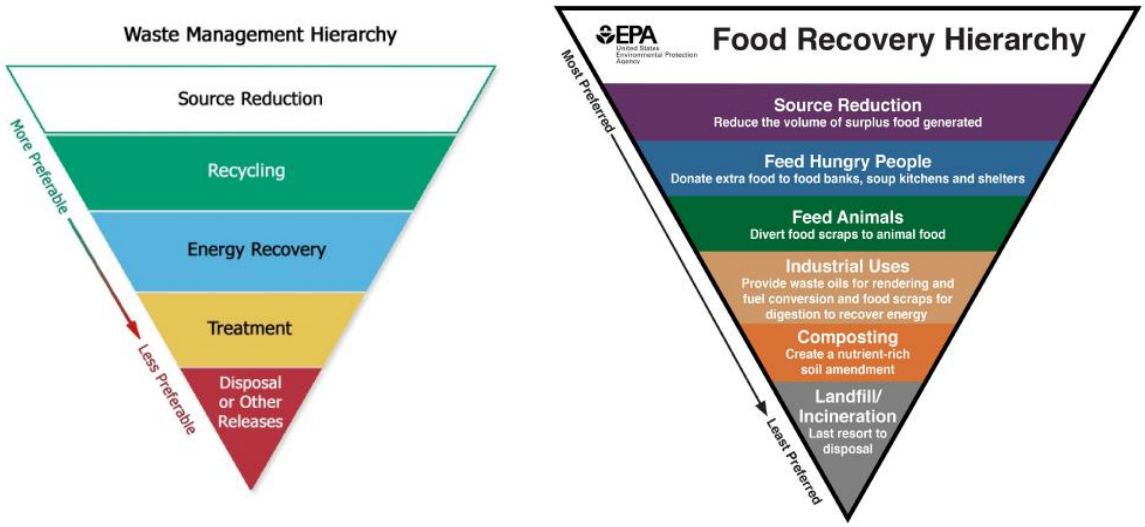


Figure 11.2.5.5.a**:** Left: The waste management hierarchy lists processes for handling waste from most to least preferable. They are source reduction, recycling, energy recovery, treatment, and disposal or other releases. Right: The food recovery hierarchy is a waste management hierarchy specific to food waste. It begins with source reduction (reduce the volume of surplus food generated). Next is feed hungry people (donate extra food to food banks, soup kitchens, and shelters. Third is feed animals (divert food scraps to animal food. Fourth is industrial uses (provide waste oils for rendering and fuel conversion and food scraps for digestion to recover energy. Fifth is composting (create a nutrient-rich soil amendment). The remaining waste goes to landfill or incineration as a last resort to disposal. Images by EPA (public domain).

Source reduction (waste minimization) refers to the strategies that minimize the amount of generated waste and/or reduce the toxicity of the resultant waste when designing or manufacturing products or services. Waste can be reduced by reusing materials, using less hazardous substitute materials, or by modifying components of design and processing. Source reduction in manufacturing not only saves resources, but it also reduces costs for the manufacturer and indirectly for the consumer. For example, minimal packaging reduces material use, increases distribution efficiency, and reduces fuel consumption and resulting air emissions. Similarly, building materials can be designed to reduce the overall mass of material needed for a given structure.

Recycling refers to recovery and reprocessing of useful materials. Numerous examples of successful recycling and reuse efforts are encountered every day. Many construction materials can be reused, including concrete, asphalt materials, masonry, and reinforcing steel. "Green" plant-based wastes are often recovered and immediately reused for mulch or fertilizer applications. Many industries also recover various byproducts for reuse. In some cases, the recycled materials are used as input materials and are heavily processed into end products. Common examples include the use of scrap paper for new paper manufacturing, or the processing of old aluminum cans into new aluminum products. In other cases, reclaimed materials undergo little or no processing prior to their

reuse. Some common examples include the use of tree waste as wood chips, or the use of brick and other fixtures into new structural construction. In any case, the success of recycling depends on effective collection and processing of recyclables, markets for reuse, and public acceptance and promotion of recycled products and applications utilizing recycled materials.

The Four R's

The **four R's** (refuse, reduce, reuse, and recycle) are strategies that allow individuals to limit the volume and negative impacts of the waste they generate. They resemble the waste management hierarchy, but focus at the individual scale rather than the scale of a company or waste management system. They are listed in order of most to least environmentally beneficial, and they are all better alternatives than discarding trash into the landfill. Recycling is last because it requires energy to reprocess waste.

To **refuse** is to decline products or processes that harm the environment if you do not need them. Choosing products without packaging is an example of refusing. To **reduce** is to choose products or processes with lower **ecological footprint** (the area of land required to produce them). Examples include products with limited packaging or durable items rather than flimsy or disposable ones. **Reuse** refers to using a product multiple times or finding an alternative use for it. For example, one could share, borrow, or rent items. A plastic yogurt or pudding container could be repurposed for storage or gardening. As noted above, **recycling** means to return used items to be reprocessed (figure 11.2.5.5.*b*). Commonly recycled materials include cardboard, glass, cans, and certain plastics.



Figure 11.2.5.5.*b***:** Recycling, or returning materials to be reprocessed, is the last of the four R's. If items cannot be refused, reduced, or reused, recycling is a better alternative than discarding into the landfill. Image by Intel Free Press (CC-BY).

Resin identification codes are the triangular symbols on recyclable plastics that indicate their composition (figure 11.2.5.5.*c*). A variety of materials make up plastics, and they are not all recycled the same way. Furthermore, your local recycling service may recycle some types of plastics but not others. Plastics with codes 1 and 2 are commonly recycled. For the codes, check with your local recycling service. Local businesses may house collection bins for plastics that are not commonly recycled. For example, grocery stores commonly have receptacles for recycling plastic bags, which fall under code 4.

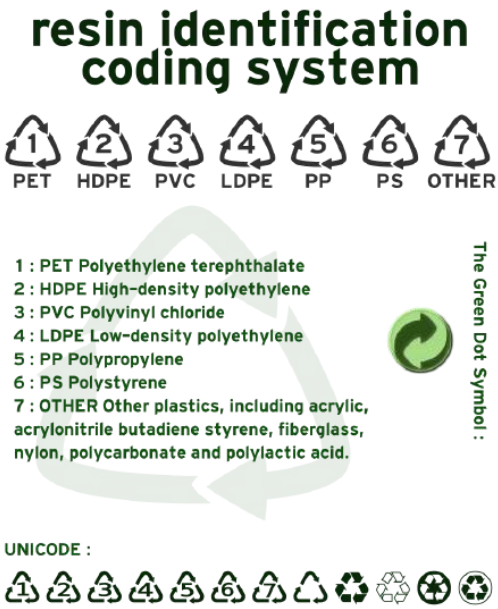


Figure 11.2.5.5.*c*): The resin identification coding system explains the chemical composition of various plastics. Some are commonly recycled, and others are not. The text in the image is, "1: PET Polyethylene terephthalate, 2: HDPE High-density polyethylene, 3: PVC Polyvinyl chloride, 4: LDPE Low-density polyethylene, 5: PP Polypropylene, 6: PS Polystyrene, 7: OTHER Other plastics, including acrylic, acrylonitrille butadiene styrene, fiberglass, nylon, polycarbonate and polylactic acid. Image by Filtre/OpenClipart Library (public domain).

Composting

Compost is organic material that can be added to soil to help plants grow (figure 11.2.5.5.*d*). Food scraps and yard waste together currently make up more than 30% of what we throw away and could be composted instead. Making compost keeps these materials out of landfills where they take up space and release methane, a potent greenhouse gas that contributes to climate change. Furthermore, compost enriches soil, helping retain moisture and suppress plant diseases and pests. It reduces the need for chemical fertilizers and encourages the production of beneficial bacteria and fungi. Composting can be done at an industrial scale, such as with yard waste collected from homes in a city. It can also be done at home.



Figure 11.2.5.5.*d*): Compost is a nutrient-rich substance formed from decomposition of yard and food waste that enriches garden soil. Image by EPA (public domain).

All composting requires three basic ingredients: browns, greens, and water. "Browns" are materials such as dead leaves, branches, and twigs. "Greens" are materials such as grass clippings, vegetable waste, fruit scraps, and coffee grounds. The brown materials provide carbon for your compost, the green materials provide nitrogen, and the water provides moisture to help break down the organic matter. A compost pile should have an equal amount of browns to greens. Layers of these organic materials with different particle sizes should be alternated.

Backyard Composting

Backyard composting requires a compost bin or pile to be placed in dry, shady spot near a water source (figure 11.2.5.5.e). Brown and green materials are added as they are collected, and larger pieces are chopped or shredded before they are added to the pile. Dry materials are moistened as they are added. Once the compost pile is established, grass clippings and green waste are mixed into the pile when added. When fruit and vegetable wastes are added, they are buried under 10 inches of compost material. Some homeowners cover the top of the compost with a tarp to keep it moist. When the material at the bottom is dark and rich in color, the compost is ready to use. This usually takes anywhere between two months to two years.



Figure 11.2.5.5.e): This compost bin contains food scraps and yard waste. Image by Ben_Kerckx/Pixabay (Pixabay license)

Indoor Composting

For those who do not have the space for an outdoor compost pile, materials can be composted indoors using a special type of bin, which can be purchased at a local hardware store, gardening supplies store, or made at home. Care must be taken to properly manage the compost pile and keep track of what is added such that it does not attract pests or rodents or smell bad. The compost should be ready in two to five weeks.

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- Composting at Home. Environmental Protection Agency. Accessed 01-18-2021 (public domain).

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11.2.5.6: Data Dive- "Flushable" Wipes

Overview

Ryerson University published a 2019 report titled, Defining “Flushability” for Sewer Use. This publication had the objective of making the public think twice about what you flush down the toilet in order to save money and the environment. In this experiment they tested 101 single use products, some labeled (and some not labeled) flushable. Some of the results of this can be seen in the graph below:

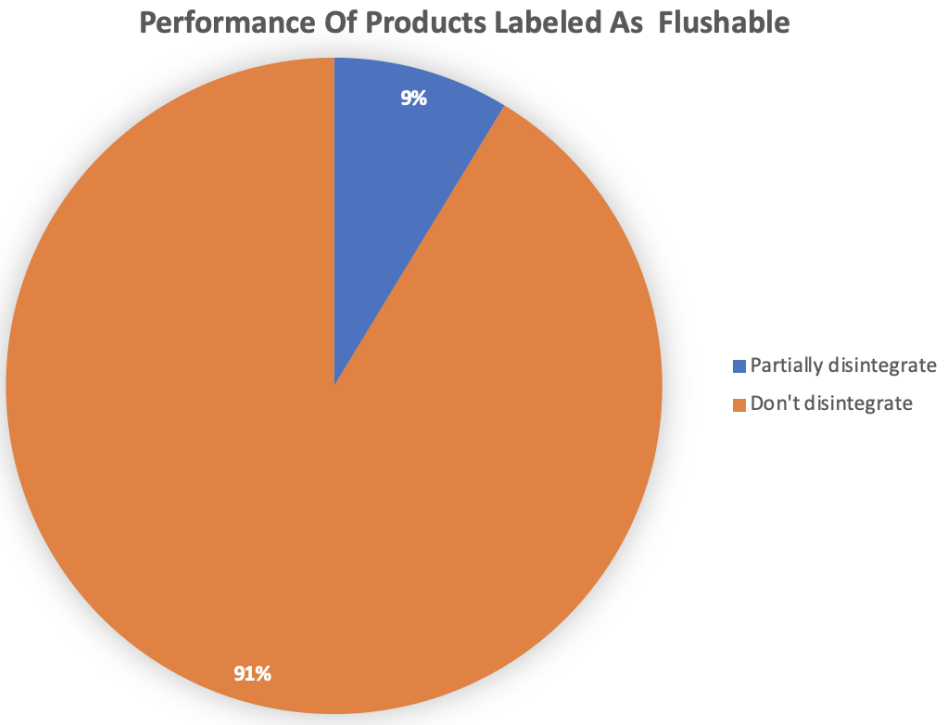


Figure \(\PageIndex{a}\): Percent of flushable wipes that could pass as flushable. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Khan A, Orr B, Jocksimovie D 2019 Flushability Report.

Questions

1. What type of data is this (qualitative or quantitative)?
2. What question(s) are the authors trying to answer with this graph?
3. What result is this graph illustrating relative to products labeled as “flushable?”
4. Provide a brief reflection for how these results make you feel and what they make you think about?
5. Do you think there should be a policy put in place that places restrictions on what the word “flushable” means? Why?

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11.2.5.7: Review

Summary

After completing this chapter you should be able to...

- Distinguish between biodegradable and nondegradable waste.
- Provide examples of hazardous waste.
- List the major waste generating processes globally.
- Compare the volume of waste generated per person per day in the U.S. with other countries around the world.
- Define municipal solid waste and describe its composition in the U.S.
- Compare open dumps, sanitary landfills, and incineration, outlining the advantages and disadvantages of each approach.
- Explain how trash enters the ocean and how it harms marine life.
- Explain the waste management hierarchy.
- List the four R's and provide examples of each.
- Explain the benefits and process of composting.

Solid waste refers to a variety of discarded materials that are deemed useless and discarded by humans. Waste may be easily broken down (**biodegradable**) or **nondegradable**. **Hazardous waste** is harmful to human health. Examples include batteries, cleaners, and **e-waste**. Agriculture, industry, and mining generate most of the world's waste. **Municipal solid waste** (MSW) is discarded from residences, businesses, and city buildings, and the U.S. generates more MSW per person per day than most countries around the world.

Three strategies for disposing of waste are open dumps, sanitary landfills, and incinerators. **Open dumps** cause disease spread, air pollution, and water pollution, and are thus illegal in the U.S. About half of the MSW in the U.S. goes to **sanitary landfills**, which compact trash and seal it to prevent pollution. **Incinerators** burn trash, which reduces its volume while generating energy.

Ocean dumping and escape of trash from overfilled bins and open dumps has contaminated the ocean with many plastics. These break into small pieces and form **garbage patches**. Plastic in the ocean can trap, poison, or otherwise harm marine life.

The **waste management hierarchy** diagrams the priorities of waste reduction. Source reduction and recycling are key to limiting waste and mitigating its environmental impacts. However, a large volume of trash goes to disposal, the least preferred method for handling waste. Individuals can limit their own waste by employing the **four R's**: **refuse**, **reduce**, **reuse**, and **recycle**. **Composting** at home also reduces food and yard waste.

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11.3: Impacts of Industrial Agriculture

Also known as conventional agriculture, **industrial agriculture** is a method of farming that involves use of synthetic fertilizer, synthetic pesticides, and machinery. Industrial agriculture is dependent on large investments in mechanized equipment powered mostly by fossil fuels. In the case of livestock, most production comes from systems where animals are highly concentrated and confined.

Synthetic Pesticides

Pests are organisms that occur where they are not wanted or that cause damage to crops, humans or other animals (figure 11.3.a). Thus, the term "pest" is a highly subjective term. A **pesticide** is a term for any substance intended for preventing, destroying, repelling, or mitigating any pest. Though often misunderstood to refer only to insecticides, the term pesticide also applies to **herbicides** (weed killers), fungicides, and various other substances used to control pests. Chemical pesticides can be effective, fast acting, adaptable to all crops and situations. When first applied, pesticides can result in impressive production gains of crops. However, despite these initial gains, excessive use of pesticides can be ecologically unsound (see Disadvantages of Industrial Agriculture). By their very nature, most pesticides create some risk of harm—pesticides can cause harm to humans, animals, and/or the environment because they are designed to kill or otherwise adversely affect living things. At the same time, pesticides are useful to society because they can kill potential disease-causing organisms and control insects, weeds, worms, and fungi.



Figure 11.3.a: The cotton boll weevil is considered a major pest because of the damage it does to cotton plants. Image by ARS USDA (public domain).

Monoculture Farming

Industrial agriculture employs **monoculture** farming, which involves growing only one species of crop in a large area (figure 11.3.b). The plants in a monoculture are evenly spaced and have the same planting, irrigation, fertilizer, harvesting, etc. requirements, and this uniformity results in efficient use of farming machinery. Often, the crop is a **high yield variety** (high yielding variety; HYV), which is produced through selectively breeding individual plants with desirable characteristics. Compared to traditional crops, HYVs can produce more per unit area of land. Monoculture farming compromises genetic and species diversity in agriculture, however, promoting the spread of pests and risking that all the plants for hundreds of acres could be susceptible to the same disease (see Genetic Diversity).



Figure 11.3.*b*: Monocultures like this potato farm (left) and cotton farm (right) make it easier to use farming equipment; however, this reduces genetic diversity and consumes fossil fuels. Left image by NightThree (CC-BY) and right image by Kimberly Vardeman (CC-BY).

Advantages of Industrial Agriculture

Industrial agriculture has delivered tremendous gains in productivity and efficiency. Food production worldwide has overall risen since the 1940s (figure 11.3.*c*); the World Bank estimates that between 70 percent and 90 percent of the recent increases in food production are the result of industrial agriculture rather than greater acreage under cultivation (figure 11.3.*d*). United States consumers have come to expect abundant and inexpensive food. Additionally, the use of synthetic pesticides ensures that produce is relatively free of blemishes (figure 11.3.*e*).

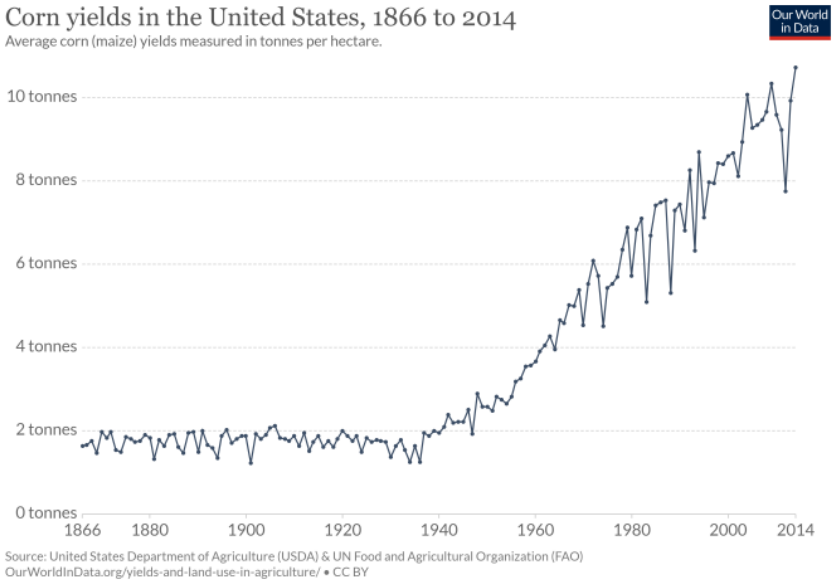


Figure 11.3.*c*: Corn yields in metric tons (tonnes; 1000 kilograms) per hectare over time. While yields have fluctuated from year to year, they have overall increased since the 1940s. This improving agricultural efficiency is partly due to industrial agricultural practices. Image by Hannah Ritchie and Max Roser/Our World in Data (CC-BY).

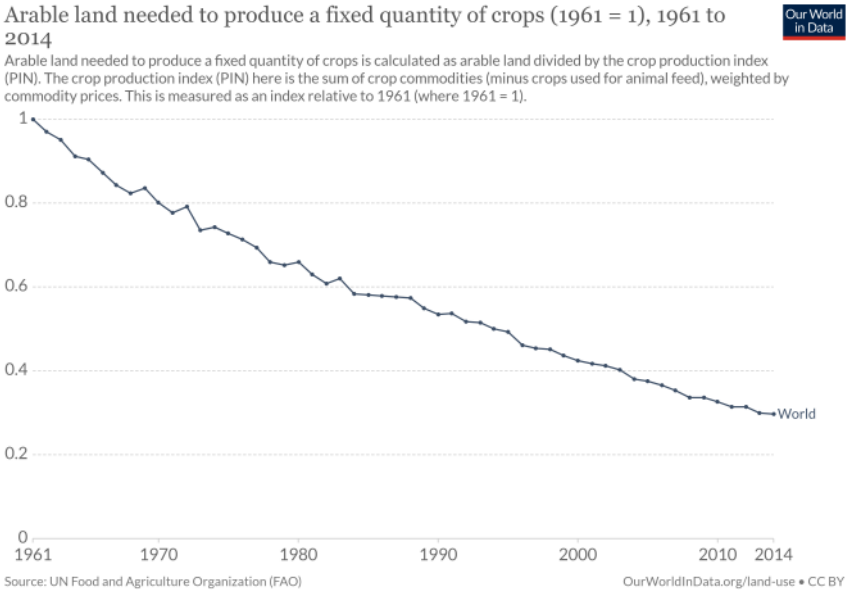


Figure 11.3.*d***:** The arable (farmable) land required to produce a fixed amount of a crop has decreased over time due to improved agricultural efficiency. Image by Hannah Ritchie and Max Roser/Our World in Data (CC-BY).



Figure 11.3.*e*: Many of us carefully inspect produce at the grocery store and select those without blemishes. This visually appealing produce results from synthetic pesticides use. Image by Amanda Mills (public domain).

Industrial agriculture expands where crops can be cultivated. Applying synthetic fertilizers to poor soils can make them fertile. Additionally, irrigation systems promote high agricultural productivity in regions and during seasons that would otherwise only support the most drought-tolerant species. For example, about 25% of the food consumed in the United States is produced in California's Central Valley, which receives little rain in the summer months (figure 11.3.*f*).

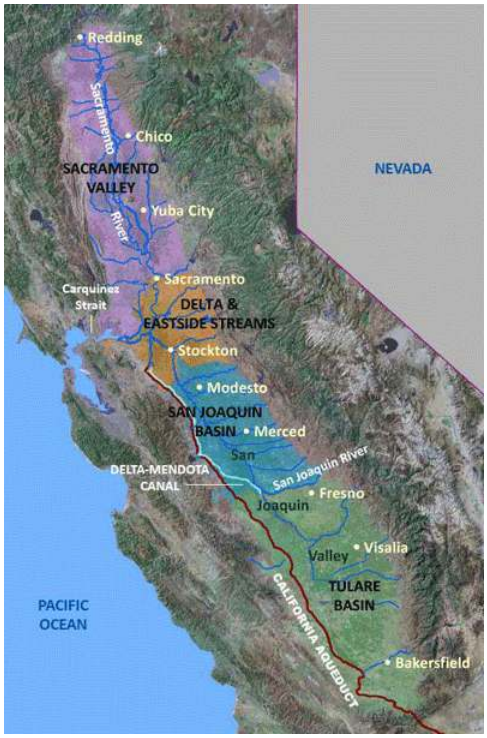


Figure 11.3.*f*: The four regions of California's Central Valley from north to south are the Sacramento Valley, Delta and Eastside Streams, San Joaquin Basin, and Tulare Basin. Image by USGS (public domain).

Disadvantages of Industrial Agriculture

Economically, the U.S. agricultural sector includes a history of increasingly large federal expenditures. Also observed is a widening disparity among the income of farmers and the escalating concentration of **agribusiness**—industries involved with manufacture,

processing, and distribution of farm products—into fewer and fewer hands. Market competition is limited and farmers have little control over prices of their goods, and they continue to receive a smaller and smaller portion of consumer dollars spent on agricultural products.

Economic pressures have led to a tremendous loss to the number of farms, particularly small farms, and farmers during the past few decades. More than 155,000 farms were lost from 1987 to 1997. Economically, it is very difficult for potential farmers to enter the business today because of the high cost of doing business. Farming equipment is expensive, and the industrial agricultural system favors large corporate farms, which can more easily invest in this equipment. While this equipment promotes efficiency, it also reduces the number of jobs in agriculture (figure 11.3.*g*).

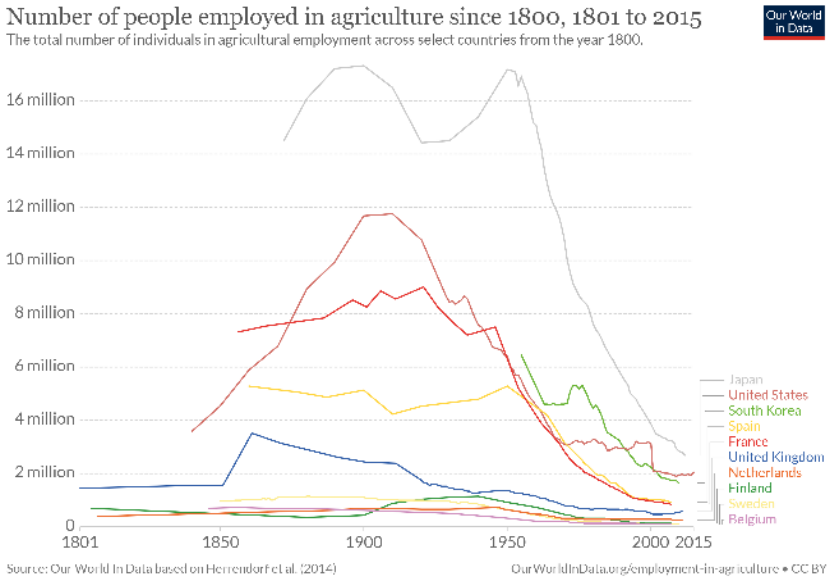


Figure 11.3.*g*: The number of people working in agriculture in selected countries over time (from 1801-2015). Generally, the number of agricultural workers has declined as farming practices increased in efficiency and as farming machinery completed tasks that were once manual. This is both an advantage because people are free to pursue other careers and a disadvantage because of the reduction in jobs. In Japan, the number of agricultural workers peaked above 16 million around 1900 and again around 1960. In the United States, it peaked to nearly 12 million around 1900. France followed a similar pattern, peaking around 1925 at approximately 9 million workers. There were over 6 million agricultural workers in South Korea in 1950, and this has overall declined (although there was a spike around 1980). In Spain the number of workers was over 5 million in 1950 and has since decreased. In the United Kingdom, the number of agricultural workers peaked around 1960 at about 3.5 million. The other countries shown (Netherlands, Finland, Sweden, and Belgium) have consistently had under 1 million agricultural workers. Image by Max Roser/Our World in Data (CC-BY).

The mechanical farming equipment required for industrial agriculture relies on fossil fuels. Burning fossil fuels releases air pollution, including greenhouse gases, which cause climate change. Additionally, the synthetic fertilizers and pesticides used in industrial agriculture are produced from fossil fuels. Furthermore, agriculture areas rarely contain as much biomass (organic matter that comprises living things) as biodiverse, intact ecosystems. Biomass is an important carbon sink because its organic molecules store carbon that could otherwise be in the atmosphere as carbon dioxide or methane, both greenhouse gases. Soils with a substantial organic component are also carbon sinks. Industrial agricultural practices that deplete these soils (see below) contribute to climate change, but alternative practices can promote this benefit of healthy soils (see Sustainable Agriculture).

While synthetic fertilizers provide crops with the necessary nutrients for high productivity, excess nutrients from fertilizers can enter bodies of water through runoff. This can lead to a bloom of algae or photosynthetic bacteria in lakes, rivers, and bays in a process called **eutrophication**. These photosynthetic microorganisms sometimes produce toxins that kill aquatic animals and can even harm the humans who consume these animals. Furthermore, they block aquatic plants from accessing light. Eventual decomposition of algal blooms requires oxygen, which results in **hypoxia** (low levels of dissolved oxygen), further harming aquatic species. Additionally, industrial agriculture pollutes water with pesticides and sediments. Pesticides are not only widespread in surface waters, but pesticides from every chemical class have been detected in groundwater.

Industrial agricultural practices often deplete soil quality. For example, wind and water erosion of exposed topsoil removes particles and nutrients from the soil (which also contributes to eutrophication and sediment pollution). Tilling (mixing the soil) and overgrazing of livestock exacerbates erosion. When livestock remove too much vegetation from an area, plant roots no longer anchor the soil in place, and erosion ensues. Farming equipment compacts the soil. This limits infiltration of water into the soil (decreases soil permeability), makes it more difficult for roots to penetrate the soil, and hinders gas exchange in roots. In extreme cases, soil has eroded and lost its ability to retain water that once arable (farmable) land becomes a desert-like (**desertification**; see Soil Degradation; figure 11.3.h).



Figure 11.3.h: Overgrazing depleted the soil in the Rukwa Plains of southwestern Tanzania. Image by Lichinga (CC-BY-SA).

Irrigation can lead to **salinization** (increased salinity). While the water itself eventually evaporates, is transpired, or drains from the soil, the minerals dissolved in the water may remain in the soil. Over time, these minerals can accumulate to levels that are toxic for most plants. As discussed in Water Usage, irrigation for agriculture accounts for 69% of global water usage. Withdrawal of sufficient water for irrigation contributes to water shortages and diverts water from ecosystems (see Aqueducts).

Repeated pesticide application exerts selective pressure on insects, fungi, and other crop pests to evolve pesticide resistance. By chance, some individuals in a pest population may carry gene versions that confer pesticide resistance. When these populations are exposed to pesticides, individuals with these gene versions are the most likely to survive and reproduce. They then pass these genes to their offspring, and pesticide resistance becomes more and more common in the population over time (figure 11.3.i). At this point, pesticides may need to be applied at greater concentrations or more frequently to achieve the same effect. If pesticide that was initially used is no longer effective at all, the farmer would be forced to find a different pesticide. Over 400 insects and mite pests and more than 70 fungal pathogens have become resistant to one or more pesticides.

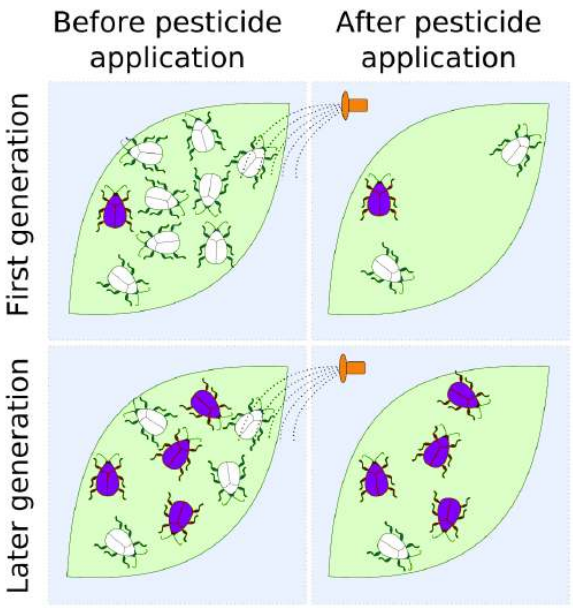


Figure 11.3.*i*: Pesticide application can exert selection for the evolution of pesticide resistance. In this hypothetical example, the purple beetle has a gene version that makes it resistant to pesticides (upper left). Pesticides are applied, killing most of the susceptible individuals (white beetles; upper right). In a later generation, purple, resistant beetles are more common because they had a better chance of surviving and reproducing (lower left). Upon another pesticide application, an even greater proportion of the population is resistant. Image modified from Delldot (CC-BY-SA).

The human health and environmental costs of pesticide use have been unevenly distributed. Despite the fact that the lion's share of chemical pesticides are applied in developed countries, 99 percent of all pesticide poisoning cases occur in developing countries where regulatory, health and education systems are weakest. Many farmers in developing countries overuse pesticides and do not take proper safety precautions because they do not understand the risks and fear smaller harvests. Making matters worse, developing countries seldom have strong regulatory systems for dangerous chemicals; pesticides banned or restricted in industrialized countries are used widely in developing countries. Farmers' perceptions of appropriate pesticide use vary by setting and culture. Prolonged exposure to pesticides has been associated with several chronic and acute health effects like non-Hodgkin's lymphoma, leukemia, as well as cardiopulmonary disorders, neurological and hematological symptoms, and skin diseases.

Pesticides have also placed stresses on pollinators and other beneficial insect species. They can lead to the destruction of natural enemies, which would regulate pest populations in an intact ecosystem. For example, once apple growers began controlling pests with the pesticide dichlorodiphenyltrichloroethane (DDT), which has since been banned, they quickly found their orchards being attacked by scale insects and mites. The reason: DDT had killed off their natural enemies. More generally, pollution from industrial agriculture along with habitat loss due to converting healthy ecosystems into agricultural fields is a major threat to biodiversity. As mentioned previously, monoculture farming limits biodiversity in crops.

With respect to animal agriculture, keeping livestock are kept in close quarters increases the risk of disease spread among them. For these reason, food animals are commonly given antibiotics, either preventatively or to treat existing infections. As discussed in the Infectious Diseases section, the overuse of antibiotics (whether in humans or farm animals) increases selection for the evolution of antibiotic-resistant strains of bacteria or other disease-causing organisms. Infections by antibiotic-resistant strains are more difficult to treat.

As with many industrial practices, potential health hazards are often tied to farming practices. Under research and investigation currently is the sub-therapeutic use of antibiotics in animal production, and pesticide and nitrate contamination of water and food. Farm worker health is also a consideration in all farming practices.

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11.4: Overharvesting

People have always hunted, collected, trapped, or otherwise harvested the food and other natural resources they need to survive. When human populations were small, at least relative to the abundance of their resources, and collection methods were relatively unsophisticated, people could sustainably harvest and hunt wildlife in their local environments. However, as human populations have increased, and roads have provided access to previously remote areas, our impact on the environment has escalated. At the same time, our methods of harvesting have become dramatically more efficient. Guns are now used instead of blowpipes, spears, or arrows, while networks of wire snares indiscriminately catch animals of all types, even young and pregnant females. Populations of species that mature and reproduce rapidly can often recover quickly after harvests and can thus be exploited sustainably; however, species that are slow-maturing and slow-reproducing cannot sustain current harvest levels. Consequently, many species are threatened due to **overharvesting** (overexploitation), the unsustainable collection of natural resources (Maxwell et al., 2016). Overharvesting may take on many forms, including hunting, fishing, logging, and gathering of plants and animals for medicine, captive collections, subsistence, commerce, or recreation purposes (Figure 11.3.1).

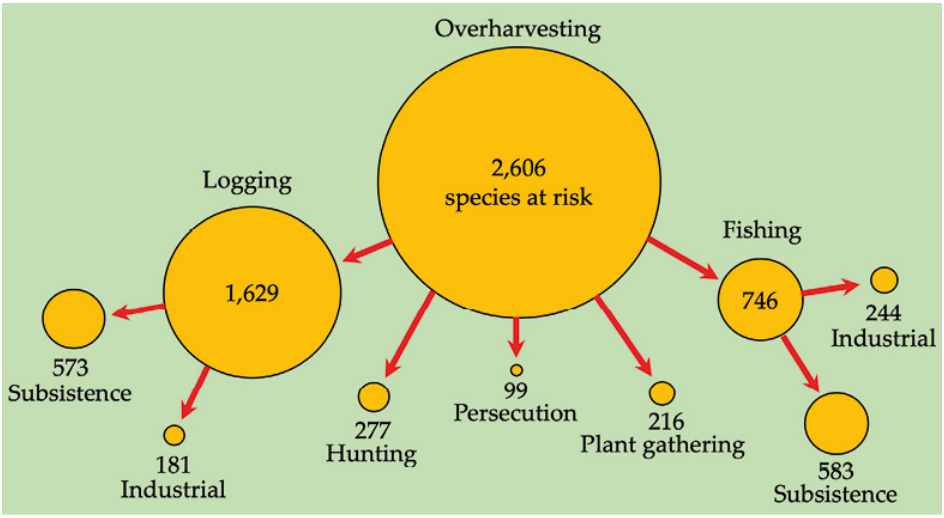


Figure 11.3.1 Overharvesting in Sub-Saharan Africa at scale: Over 60% of species that are threatened by overharvesting are also threatened (directly and indirectly) by logging. Nearly 30% of all species are threatened by fishing, and 10% by hunting and trapping. Source: IUCN, 2019, CC BY 4.0.

Terrestrial Animals

Terrestrial animals may be overexploited as sources of food, garments, jewelry, medicine, or pets. For example, the poaching of elephants for their valuable ivory and rhinos for their horns, which are used in traditional medicine, is a major threat to these species. There are also concerns about the effect of the pet trade on some terrestrial species such as turtles, amphibians, birds, plants, and even the orangutans. Harvesting of pangolins for their scales and meat, and as curiosities, has led to a drastic decline in population size (figure 11.3.2).



Figure 11.3.2: Pangolins are threatened by overexploitation. This work by David Brossard is licensed under CC-BY.

The Bushmeat Crisis

Bushmeat—wild sources of protein obtained on land by hunting and collecting birds, mammals, snails, and caterpillars—provides much of the protein in people's diets in many parts of the world. These hunting practices, particularly in equatorial Africa and parts of Asia, are believed to threaten several species with extinction. Traditionally, bush meat in Africa was hunted to feed families directly. However, recent commercialization of the practice now has bush meat available in grocery stores, which has increased harvest rates to the level of unsustainability. Additionally, human population growth has increased the need for protein foods that are not being met from agriculture. Species threatened by the bush meat trade are mostly mammals including many monkeys and the great apes living in the Congo basin. For example, more than 9,000 primates are killed annually for a single market in Côte d'Ivoire (Covey and McGraw, 2014); people from Central Africa harvest an astonishing 5.3 million tons of mammalian bushmeat annually (Fa et al., 2002). Usually seen as a conservation challenge in Africa's tropical forests, the **bushmeat crisis** also impacts savannah regions (reviewed in Lindsey et al., 2013)where bushmeat hunters, numbering between 1,500 and 2,000, remove over 600,000 kg of herbivore biomass from Botswana's Okavango Delta each year, despite the region's protected status and importance for ecotourism sectors (Rogan et al., 2017).

Very few animal populations can withstand such high extraction rates. Consequently, regions dependent on bushmeat have already seen substantially wildlife declines (Lindsey et al., 2013). At current exploitation rates, supplies are expected to decrease by an additional 80% within the next 50 years (Fa et al., 2003). Unless more sustainable, alternative sources of protein are found, people dependent upon bushmeat will see increased malnutrition and compromised livelihoods as bushmeat species are pushed to extinction. When that happens, families relying on bushmeat will face even worse food insecurity than that which is driving the current bushmeat crisis.

Exacerbating the risk of food insecurity, people in the affected regions will also suffer from compromised ecosystem services as populations of predators, seed dispersers, and pollinators are reduced (Rosin and Poulsen, 2016). For example, reduced mammal populations have been linked to reduced abundance of fruits and other useful plant products available for human consumption (Vanthomme et al., 2010). Some areas are already suffering from "empty forest syndrome"—a condition where a forest appears to be green and healthy, but is practically devoid of animals, and in which ecological processes have been irreversibly altered such that the forest's species composition will change over subsequent decades (Nasi et al., 2011; Benítez-López et al., 2019). The bushmeat crisis is thus a major concern to people concerned about biodiversity and/or human well-being.

The impact of traditional medicine

As the human population has increased, so has the demand for traditional medicine. Today, harvesting for traditional medicine is putting unsustainable pressure on species exploited for this purpose (Williams et al., 2014). One prominent example is vultures: the demand of vulture body parts, believed to bestow clairvoyant abilities, is driving massive vulture population declines across Africa. The growth in traditional medicine markets in East Asian countries such as China, Thailand, Cambodia, and Vietnam exacerbates these problems. For example, as tigers (*Panthera tigris*, EN) and rhinoceros have become scarce in Asia, Asian traditional healers are increasingly targeting African predators and rhinoceros to satisfy their market demands. Another group of species threatened by the Asian traditional medicine trade is sea horses (*Hippocampus* spp.). Due to population declines from overharvesting, sea horse exports from Kenya and Tanzania to East Asia have halved over recent years; yet, more than 600 kg of dried sea horses (over 254,000 individuals) continue to be exported annually (McPherson and Vincent, 2004). Exploitation for Asian traditional medicine markets has already pushed the western black rhinoceros (*Diceros bicornis longipes*, EX) to extinction. In a similarly perilous position is the northern white rhinoceros (*Ceratotherium simum cottoni*, CR); with only two non-reproductive females left in the world, this species is now considered **committed to extinction**. A group of species sought after by both African and Asian traditional medicine markets is pangolins, thought to be the most heavily poached animals on Earth. For example, between 2012 and 2016, more than 20 tons of African pangolin scales (involving up to 30,000 animals) were seized during law enforcement operations across the region (Andersen, 2016). The problem is also getting worse: authorities intercepted 13 tons of scales in Singapore in 2019, all from a single shipment believed to travel from Nigeria to Vietnam (Geddie, 2019). With such a large active operational scale, it comes as no surprise that all four African pangolin species are now threatened with extinction (IUCN, 2019).

The impact of live animal trade

Millions of non-domesticated animals are sold as pets around the world each year (Table 11.3.1). Given that many of these pets were originally collected in the wild, it is no surprise that the most popular species tend to be at a high risk of extinction (Bush et al., 2014). These huge numbers are magnified by the extra millions of animals needed to compensate for deaths during collection and shipping. Collection of wild animals for pets and other purposes has a massive impact of biodiversity around the world.

Coral reefs are extremely diverse marine ecosystems that face peril from several processes. Reefs are home to 1/3 of the world's marine fish species—about 4,000 species—despite making up only one percent of marine habitat. Most home marine aquaria house coral reef species that are wild-caught organisms—not cultured organisms. 82 of the 291 species of African freshwater fish known to occur in the pet trade are considered threatened with extinction (UNEP-WCMC, 2008).

Among the most popular groups of wildlife traded are Africa's parrots (Figure 11.3.3). For example, 32,000 wild-sourced African grey parrots (**Psittacus erithacus**, EN) were imported into the European Union in 2005 (UNEP-WCMC, 2007). Combined with habitat loss, the wild bird trade has already caused extirpations of this species in some areas of West Africa (Annorbah et al., 2015). While it is true that collecting wild animals for the pet trade sustains many people's livelihoods, research on harvesting of ornamental fish has shown that this practice is not sustainable in the long term (Brummet et al., 2010). It is therefore critical to find ways to make these practices more sustainable, for the sake of the pet collectors and biodiversity.

Table 11.3.1 Examples of groups targeted in global wildlife trade, and their levels of exploitation.

Group	Number traded each year	Notes
Orchids	250 million	Mainly cultivated, but about 10% sourced from the wild. Illegal trade—and mislabeling to avoid regulation—a major problem.
Succulent plants	35 million	Mainly cultivated, but about 15% sourced from the wild. Illegal trade remains a major problem.
Corals	13 million	Collected using destructive methods; used for aquarium decor and jewelry.
Reptiles	7.2 million	Mainly sourced from the wild for zoos and pet trade, but increasingly from farms. Does not include large skin trade.
Birds	2.3 million	Mostly perching birds destined for zoos and pet trade. Also includes legal and illegal trade of parrots.
Ornamental fish	2 million	Most originate from wild reefs, caught by illegal methods that damage the surrounding coral reef and other wildlife.
Primates	148,000	Used for biomedical research, while many also destined for pets, circuses, zoos, and private collections.

Sources: http://cites-dashboards.unep-wcmc.org, data presented as live specimens exported from 2011–2015. Data generally do not include illegal traded specimens, which are usually not reported to CITES.



Figure 11.3.3 Wild-caught African grey parrots crammed into a travel crate before export to Asia. Researchers estimate that over 60% of smuggled parrots die from stress, dehydration, and smothering during transit (Mcgowan, 2008). Because of trade-driven population declines, CITES banned all international trade in this species in October 2016. Photograph by Lwiro Primates, CC BY 4.0.

Overfishing

Pressure on biodiversity in aquatic environments is also increasing as people continue to harvest fish, sea turtles, dolphins, shellfish, and manatees for meat at increasing rates. For about one billion people, aquatic resources provide their main source of animal protein. Modernized fishing methods play a major role in the decline of biodiversity (Figure 11.3.4). Also, in the marine environment, motorized fleets and enormous factory ships can now spend months at sea where they catch fish to sell at local and global markets (Ramos and Grémillet, 2013; Pauly et al., 2014). Some estimates suggest that wild-caught seafood could be virtually absent by 2050 if current exploitation levels persist (Worm et al., 2006).

Many fishing boats are docked with a snowy mountain in the background.

Figure 11.3.4: Fishing boats at marine fishers. Alaskan waters have been fished by people for thousands of years, but they are under pressure from modern fishing technologies and large-scale extraction. Source: National Oceanic and Atmospheric Administration

For many aquatic organisms, the indirect impacts of modern commercial fishing methods outweigh direct exploitation (Figure 11.3.5). One example is **ghost fishing**, which causes thousands of animals to die each year after becoming entangled in dumped, abandoned, and lost fishing gear. Similarly, approximately 25% of fish harvests are considered **bycatch**—animals that are accidentally caught, injured, or killed during fishing operations. Recent declines in skates, rays, turtles, sharks, dolphins, and seabirds have all been linked to incidental deaths as bycatch (Cox et al., 2007; Carruthers et al., 2009).

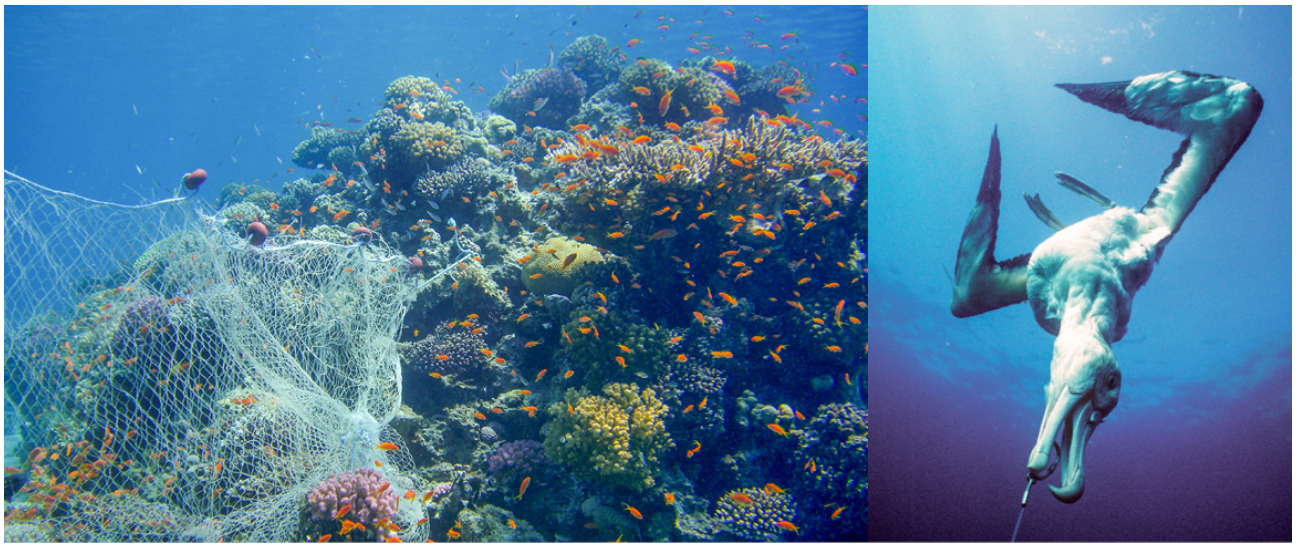


Figure 11.3.5 (Top) Discarded fishing gear, such as this ghost net, poses an entanglement hazard to marine wildlife. Photograph by Tim Sheerman-Chase, https://www.flickr.com/photos/tim_uk/2692835363, CC BY 2.0. (Bottom) A wandering albatross (*Diomedea exulans*, VU) that was a victim of bycatch, the accidental catching of non-target species during fishing operations. Photograph by Graham Robertson, CC BY 4.0.

Figure 11.3.6 illustrates the extent of overfishing in the U.S. Despite considerable effort, few fisheries are managed sustainability. For example, the western Atlantic cod fishery was a hugely productive fishery for 400 years, but the introduction of modern fishing vessels in the 1980s and the pressure on the fishery led to it becoming unsustainable. Bluefin tuna are in danger of extinction. The once-abundant Mediterranean swordfish fishery have been depleted to commercial and biological exhaustion.

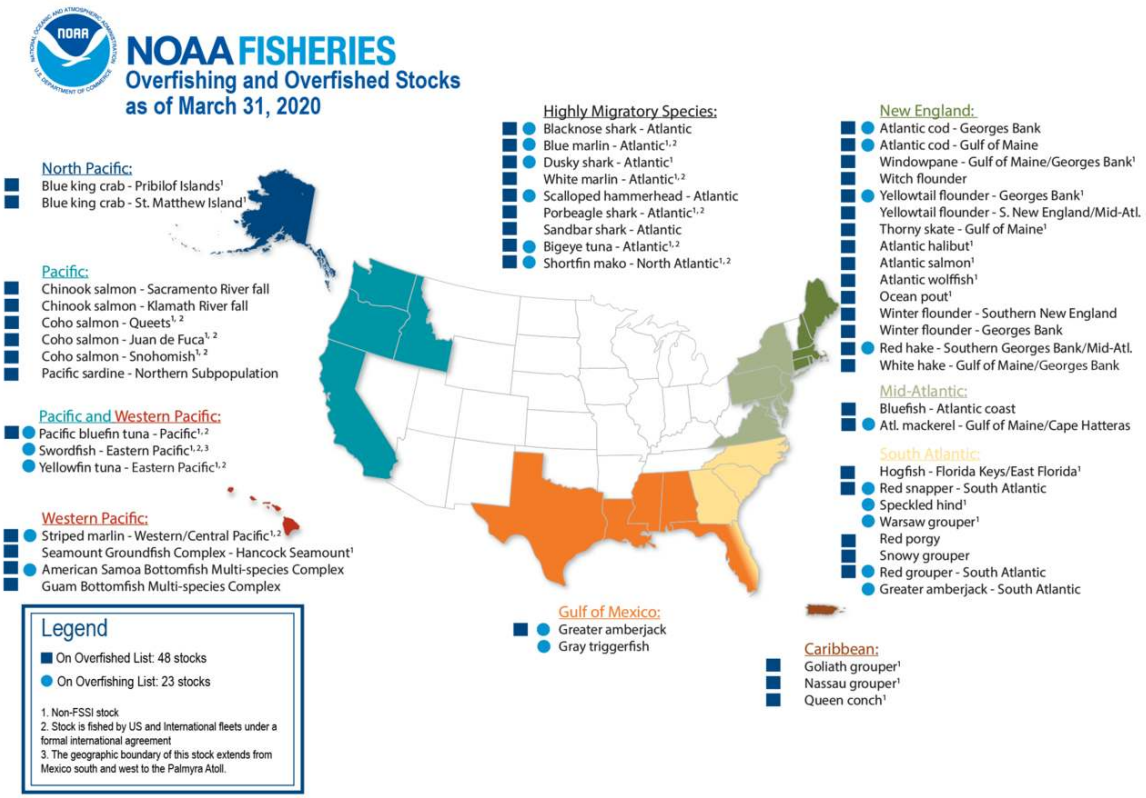


Figure 11.3.6: Map of overfishing and overfished stocks in the U.S. by region. Stocks on the overfishing list are being harvested too quickly, and those on the overfished list have population sizes that are too low. For example, stocks of Chinook salmon, Coho

salmon, and Pacific sardines are overfished in the Pacific. Some species, including stocks of Pacific bluefin tuna and Atlantic cod, are on both the overfishing and overfished lists. Image by NOAA (public domain).

Most fisheries are managed as a common resource, available to anyone willing to fish, even when the fishing territory lies within a country's territorial waters. Common resources are subject to an economic pressure known as the **tragedy of the commons**, in which fishers have little motivation to exercise restraint in harvesting a fishery when they do not own the fishery. This results on overexploitation. In a few fisheries, the biological growth of the resource is less than the potential growth of the profits made from fishing if that time and money were invested elsewhere. In these cases—whales are an example—economic forces will drive toward fishing the population to extinction.

Overfishing can result in a radical restructuring of the marine ecosystem in which a dominant species is so overexploited that it no longer serves its ecological function. For example, overfishing a tertiary consumer could causes populations of secondary consumers to increase. Secondary consumers would then feed on primary consumes (like zooplankton), decreasing their population size. With fewer zooplankton, populations of primary producers (**phytoplankton**, or photosynthetic microorganisms) would be unregulated (see Food Chains). The collapse of fisheries has dramatic and long-lasting effects on local human populations that work in the fishery. In addition, the loss of an inexpensive protein source to populations that cannot afford to replace it will increase the cost of living and limit societies in other ways. In general, the fish taken from fisheries have shifted to smaller species, and the larger species are overfished. The ultimate outcome could clearly be the loss of aquatic systems as food sources.

Overharvesting of plant products

Some plant and fungal species are also overexploited, particularly if they are slow-growing. While legal and illegal timber and firewood extraction is a major source of deforestation throughout parts of the world, it is also an important extinction driver. In fact, logging and other forms of wood harvesting have already contributed to the extinction of at least six plant species in Sub-Saharan Africa, with an additional 116 species considered *Critically Endangered* in part due to these threats (IUCN, 2019). Other plant species face extinction due to exploitation for medicines, spices, fragrances, and ornaments. For example, White's ginger (*Mondia whitei*)—reputed to have aphrodisiac and antidepressant properties—has been harvested to extirpation in parts of central Kenya and South Africa (Aremu et al., 2011). Similarly, harvesting rates of African blackwood (*Dalbergia melanoxylon*, NT)—popular for making musical instruments and fine furniture—are currently unsustainable because the tree is slow-growing, has low germination rates, and extractions are seldom offset with planting of new seeds or seedlings (Amri et al., 2009). In addition, stocks of wild ginseng, which is valued for its health benefits, are dwindling. Peyote cactus, which causes hallucinations and is used in sacred ceremonies, is also declining. Yarsagumba, dead moth larvae that were infected by fungal parasites (caterpillar fungus, *Ophiocordyceps sinensis*), is overexploited because it is highly valued in traditional medicine and used as an aphrodisiac (figure 11.3.7).



Figure 11.3.7: Yarsagumba is a combination of moth larvae and the fungus that infected and killed it. Image by Punya (CC-BY-SA).

Challenges in managing overharvesting

One of the biggest challenges in combating overharvesting is the non-enforcement and/or outright absence of legal controls to protect exploited species. But even where strong regulatory frameworks exist, the sheer scale of the problem poses practical challenges for effective enforcement, as billions of dollars flow among participants in illegal wildlife trade, which include local people trying to make a living, professional poachers, corrupt government officials, unethical dealers, and wealthy buyers who are not concerned about how the wildlife products they use were obtained. The illegal wildlife trade has hit Africa's megafauna particularly hard. For example, even though there has been an international ban on the ivory trade since 1989, thousands of African elephants continue to be illegally killed on an annual basis (Box 11.3.1). Similarly, despite a ban on rhinoceros horn trade since 1977, an increasing number of rhinoceros succumb to poaching every year (Figure 11.3.8). Worse yet, the illegal wildlife trade shares many characteristics and practices with the illegal trade in drugs and weapons; in some cases, the same syndicates run these various criminal enterprises (Christy and Stirton, 2015). Apprehending these criminal networks is generally very dangerous, requiring vast resources.

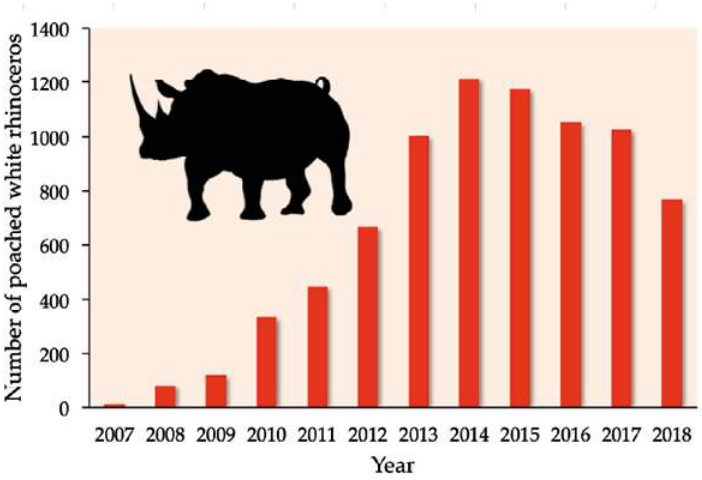


Figure 11.3.8 More than 7,200 rhinoceros were illegally killed in South Africa between 2007 and 2017. Fortunately, illegal killings have declined in recent years, thanks to massive anti-poaching campaigns and increased law enforcement efforts. Source: SADEA,

CC BY 4.0.

Box 11.3.1 Conserving Elephants in the Anthropocene

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As our increasingly human-dominated planet enters a new geological era, will there still be room for Earth's largest land mammals? Or will there be, as happened to mammoths, sabre-toothed cats, and giant sloths during the Pleistocene, another hominid-induced extinction of large mammals? Our new human-dominated era has become known as the Anthropocene (Waters et al., 2015), and the animals are, of course, Africa's elephants.

Elephants encapsulate the dilemmas of conserving large charismatic mammals. They are dominant ecosystem engineers that, depending on their densities, can facilitate or adversely impact species diversity and ecosystem processes. They are also economically important to ecotourism industries and revered by many; ivory ornaments and carvings have been valued highly by many cultures past and present. But elephants are also regarded as dangerous pests by expanding small-scale farming communities, responsible for destroying crops and killing people. While retaliatory killings and habitat loss (primarily through agricultural expansion) certainly contribute to the endangerment of elephants, poaching to supply Asian markets is the primary cause behind massive population reductions we are currently witnessing (Wittemyer et al., 2014).

Africa's elephants have, in the past, been greatly exploited, first for their meat and later also for their ivory. In 1887, about 1,000 tonnes of ivory were being exported from Africa (Spinage, 1973) and, by 1900, elephant populations in many African countries had all but collapsed. In Southern Africa, for example, it was feared that they might soon go extinct. However, with effective protection, elephant populations increased twentyfold, to more than 200,000, south of the Zambezi River by the 1970s. Elsewhere, elephant numbers also recovered, and, in the mid-1970s, the continental elephant population was estimated to be more than 1 million. But a rapid escalation of the illegal killing of elephants for ivory and meat soon followed, accompanied by a steep rise in the price of ivory. In response, African elephants were placed on CITES Appendix II in 1976 to control the international trade in ivory. Elephants in some Southern African countries were well protected, so numbers continued to grow. However, elsewhere poaching and illegal trade in ivory continued and, in 1989, the African elephant was placed on CITES Appendix I, which banned all international trade in elephants and elephant products. The result was a decline in the price of ivory, and recovery of many populations.

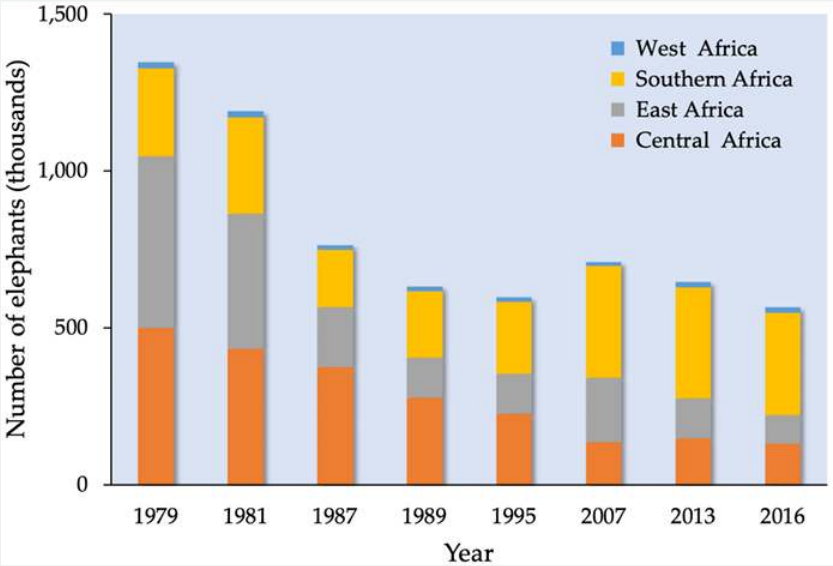


Figure 11.3.9 Estimated number of elephants in West, Central, East and Southern Africa between 1979 and 2016. Source: http://africanelephantdatabase.org, CC BY 4.0.

Conservationists, and the world at large, traditionally regarded the African elephant as a single species. Recent morphometric and genetic evidence has revealed that forest and savannah elephants represent two distinct species, with forest elephants (*Loxodonta cyclotis*) occupying the West and Central African forests, and the larger savannah elephants (*Loxodonta africana*) being widespread in non-forested regions of Sub-Saharan Africa (Roca et al., 2015). The distinction has important implications for their conservation, as each of these elephant species now viewed on its own is even more sensitive to population declines (CBD, 2015).

Since about 2006, poaching of elephants again began to escalate, in part a response to an increase in the price of ivory, poorly funded wildlife agencies, and corruption (Hauenstein et al., 2019). The scale of these killings is extraordinary. For example, an estimated 30,000 elephants were killed in 2013 alone. Forest elephants declined by about 60% (Maisel et al., 2013). While population trends for savannah elephants vary across the region, they too face increased poaching pressure (Chase et al., 2016). Due to these large-scale killings, combined with the impact of habitat loss from agricultural expansion, West Africa's elephants are today confined to small isolated protected areas with a total population of about 17,000 (Maisel et al., 2013). Elephant population trends in East Africa vary: numbers are increasing in Uganda and Kenya, but Tanzania has lost some 60,000 elephants in the last few years. In Southern Africa, Botswana has the largest elephant population, estimated in 2014 to number at least 130,000. Neighboring Zimbabwe has a population of 83,000 elephants, much the same number as it had in 2001. However, two of Zimbabwe's four regional populations declined significantly between 2006 and 2014 with a loss of at least 20,000 elephants (Figure 11.3.9).



Figure 11.3.10 Savannah elephants at a waterhole in Hwange National Park. Hwange, Zimbabwe's flagship protected area, has been a hotspot of poacher activity in recent years. By lacing waterholes and salt licks with cyanide during the dry season, poachers killed over 100 elephants here in 2013 (Cruise, 2017); several elephant poisoning events have occurred since then. Photograph by D.H.M. Cumming, CC BY 4.0.

Global and national efforts to curb elephant poaching are currently focused on improving law enforcement on the ground, intercepting ivory shipments to Asia, closing ivory markets in Africa and Asia, and leading campaigns to reduce demand for ivory in major consuming countries in Asia, particularly in China. Importantly, while these initiatives are relieving poaching pressure on African elephant populations, they fail to address core issues relating to the interactions between people and elephants in the rural areas of Africa. A high proportion of elephant ranges lie outside protected areas where they overlap with people. Relieving continued pressures on elephants, outside as well as inside protected areas, would only happen if people who are harmed by elephants derive enough benefits from elephants and other wildlife to outweigh the direct and indirect costs of sharing land with them. Community-based natural resource management (CBNRM) projects, such as those in Namibia show that this can be achieved. Establishing secure and sustainable funding streams through payments for ecosystem services, or payments for co-existing with large dangerous mammals such as elephants, could extend these promising initiatives even further.

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11.5: Persecution

Persecution involves the indiscriminate abuse or killing of a group of animals, generally used as a strategy to prevent property damage (e.g. crop-raiding elephants) and livestock depredation (e.g. lions endangering cattle). Some animals are also persecuted because of the real or perceived dangers they pose to humans; this includes the indiscriminate killing of sharks, snakes, and spiders to avoid bites, and culling of bats to prevent spread of **zoonotic diseases** (Schneeberger and Voigt, 2016). Lastly, local folklore also contributes to persecution: animals, such as moles, chameleons, and owls are sometimes indiscriminately killed because of cultural beliefs that they bring bad luck.

> While killing a (potential or perceived) problem animal may bring a certain instant gratification, it is a short-term solution that often causes more harm than good.

While killing a (potential or perceived) problem animal may bring a certain instant gratification, it is a short-term solution that often causes more harm than good. Culling bats, for example, may in fact increase the prevalence of the same zoonotic diseases people are trying to control (Schneeberger and Voigt, 2016). Persecution also leads to the loss of ecosystem services, as it often targets ecosystem engineers and keystone species. Retaliatory poisoning is particularly harmful for all the other useful organisms that may be killed in the process. One study in Namibia estimated that about 100 non-target animals are killed for every target animal, putting harmless species also at risk (Brown, 2006). Among the most vulnerable to such poisoning are vultures, which may be accidentally poisoned by bait set out for problem predators, or directly targeted for traditional medicine and to hide poaching activities. In June 2019, 537 vultures (comprising five different Endangered and Critically Endangered species) were killed in Botswana after scavenging from three poisoned elephant carcass (de Greef, 2019). This mass poisoning event was particularly devastating because it was during the vulture breeding season, so many vulture chicks likely also died from starvation if not from eating tainted meat brought back to the nest by their parents.

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11.6: Invasive Species and GMOs

An **exotic species** is a species that occurs beyond its native range, most often because humans have moved it, whether intentionally or not. Most exotic species do not establish viable populations in the new areas to which they have been moved because the new environments may not meet their needs, because native species may outcompete them or otherwise displace them, or because there may not be a sufficient number of individuals to become established. However, a small number of exotic species go on to become **invasive species**—exotic species that rapidly spread and increase in abundance at the expense of native species and ecosystems. While there is no definitive list of qualities that predict which exotic species can become invasive, many invasive species have the following in common: (1) they begin to reproduce at an early age; (2) they can reproduce rapidly; (3) they lack sufficient predators in their introduced range; (4) they disperse easily; (5) and they are generalist species, able to survive in a variety of ecosystems.

Spread of invasive species

As stated above, invasive species spread and invade new areas because human activities move them there. Some of the most prominent means by which human activities facilitate the spread of invasive species include:

- *Agriculture*: Large industries exist to grow agricultural plants for crop production, ornamental plants for gardens, grasses for pastures, and livestock for food. Many of these organisms later escape from cultivation and captivity and go on to invade and harm local ecosystems. Other species spread when industry workers accidentally harvest the seeds of weedy plants along with commercial seeds, and then sow those seeds in new localities, while microbes, parasitic organisms, and insects may be transported with plant leaves and roots, in potting soil, or even attached to transported animals.
- *Accidental transport*: Many invasive species spread to new areas because people transported them unintentionally. Domestic rats (*Rattus* spp.) and mice (*Mus* spp.) are classic examples: they have spread around the world as stowaways aboard ships. A great number of invasive plants that currently occur in South Africa's Cape Floristic Province arrived by accident by clinging onto the luggage and hiking gear of tourists (Anderson et al., 2015).
- *Biological control:* Environmental and agricultural organizations sometimes use biological control to manage the spread of, and harm caused by, invasive species. While this approach can be very effective, in rare cases the biocontrol agent can become invasive and harm native species, rather than its intended target. For example, domestic cats that were introduced to Marion Island off Africa's south coast feasted on native seabirds—in some cases, even causing seabird extirpations—instead of the rats and mice they were meant to control (Bloomer and Bester, 1992). For this reason, very careful research is necessary to test the appropriateness of a biocontrol agent before being released.
- *Deliberate introductions:* Soon after their arrival, colonists released hundreds of European birds and mammals into countries like South Africa and Kenya to make the African countryside feel more familiar. Other species, especially fish (e.g. trout, bass, and carp), were released to provide food and recreational opportunities. Many of these species have subsequently become so successful that they harm native species.
- *Captive escapees*: Many invasive species were originally kept as pets or ornamental plants but have escaped from captivity to establish feral populations that harm local wildlife. Some of the most problematic aquatic invasive species are common pets that people dumped in streams, lakes, or storm drains because they could not care for them anymore. Finding these escapees before they establish should thus be a priority.

Impact of invasive species

Invasive species have many negative consequences for native biodiversity: they displace native species through competition, alter the structure and composition of natural communities, and sometimes also hybridize with native species. These impacts may also translate to financial losses, as invasive species compromise ecosystem services (Figure 11.6.1), damage infrastructure, and spread infectious diseases. Natural communities are at particular risk in cases where invasive species change ecosystem structure and functioning so much that native species can no longer survive.



Figure 11.6.1 The tickberry (*Lantana camara*) may be pretty, but it is a serious invasive species across Africa. Where it invades, it reduces the productivity of natural ecosystems and agricultural lands by forming dense thickets that outcompete native plants. This plant is also toxic to animals, including livestock and pets. Photograph by Alves Gaspar, https://en.Wikipedia.org/wiki/File:LantanaFlowerLeaves-3.jpg, CC BY-SA 3.0.

Genetically modified organisms

A topic of conflict among conservation biologists is the increased popularity of **genetically modified organisms (GMO)**. A GMO is an organism whose genetic material has been altered to provide useful or improved products and services. To do this, scientists typically use genome editing technologies to transfer genes from a "source" organism into the DNA of the target organism. For example, scientists can transfer a bacterial gene that produces an insect toxin into a crop, such as maize, to obtain a GMO that can resist insect herbivory. Farmers using this GMO maize would then be able to increase production and reduce pesticide use (Gewin, 2003). While GMOs are usually associated with the development of pest-resistant and drought-resistant crops, uses are highly varied. For example, in Senegal, GMO technologies are used to produce tilapia that are better adapted to local ecosystems (Eknath et al., 2007). GMO technologies are being used to develop new and cheaper medicines (Concha et al., 2017), and to combat important diseases: trials in Burkina Faso shows that fungi genetically engineered to produce spider toxins caused a 99% collapse in malaria-carrying Anopheles mosquito populations within 45 days (Lovett et al., 2019). GMOs can even be used for conservation purposes, like developing new methods to combat invasive species (Esvelt et al., 2014), creating more effective bioenergy sources (Beer et al., 2009), and making vulnerable species more **resistant** to climate change (Piaggio et al., 2017). Some scientists even hope to combat plastic pollution by creating a genetically modified bacterium able to consume plastic waste (Austin et al., 2018).

The use of GMOs is not a new phenomenon. Selective breeding, hybridization, and other forms of artificial selection—techniques that have been used for much of human history—all result in different forms of genetically modified crops and animal species. This history of genetic modification is common to nearly all crop species. For example, cabbage, broccoli, Brussel sprouts, cauliflower, and kale were all developed from a single species of wild mustard plant (Figure 11.6.2). Wild nightshade was the source of tomatoes, eggplant, tobacco, and potatoes, the latter developed by humans 7,000 – 10,000 years ago in South America. However, technological advances in genetic engineering have enabled scientists to transfer genes from and between different taxa that have not previously been used in selective breeding programs (i.e. viruses, bacteria, insects, fungi, and shellfish). GMO technologies that transfer genetic material between wholly disparate taxa has led to concern about the unknown and unintended consequences of such "crossovers". Some people are also concerned that GMOs that escape from captivity or cultivation (e.g. Gilbert, 2010) could hybridize with closely-related wild species, endangering native wildlife while resulting in new, aggressive weeds and virulent diseases. Additionally, the use of GMO crops could potentially harm non-crop species (e.g. insects, birds, and soil organisms) that live in, on, or near the GMO crops. Concerns have also been raised about the potential effects to people eating GMO foods, leading some governments to regulate GMO research and commercial applications differently than traditional agriculture. However, after decades of research, it appears that GMO food is safe to eat (Blancke, 2015).



Figure 11.6.2: *Brassica oleracea* is a plant in the mustard family and is known as wild cabbage. From it were developed many familiar crops, such as cauliflower, broccoli, Brussel sprouts, and of course, cabbage. Image by Kulac (CC-BY-SA).

Clearly, GMOs offer a wide range of opportunities which could directly and indirectly benefit biodiversity conservation. However, the benefits of GMOs must be examined and weighed against the potential risks on a case by case basis. It is probably wise to proceed cautiously, to study GMOs thoroughly, and to monitor their impacts on ecosystems and human health in the areas where they are used. These investigations could involve workshops where experts come together to perform **environmental impact assessments (EIA)**. The potential but unknown impacts of GMOs can also be mitigated by limiting the ability of these organisms to spread or reproduce (Muir and Howard, 2004).

Examples of Genetically Modified Crops

Many genetically modified crops have been approved in the U.S. and produce our foods. The first genetically modified organism approved by the U.S. Food and Drug Administration (FDA) in 1994 was **Flavr Savr™ tomatoes**, which have a longer shelf life (delayed rotting) because a gene responsible for breaking down cells in inhibited. Flavr Savr tomatoes are genetically modified (because their DNA has been altered) but not trasgenic (because they do not contain genes from another species). The Flavr Savr tomato did not successfully stay in the market because of problems maintaining and shipping the crop. **Golden rice** produces β-carotene, a precursor to vitamin A (figure 11.6.3; β-carotene is also in high concentrations in carrots, sweet potatoes, and cantaloupe, giving them their orange color.) **Roundup Ready®** corn, cotton, and soybeans are resistant to this common herbicide, making it easier to uniformly spray it in a field to kill the weeds without harming the crops (figure 11.6.4).



Figure 11.6.3: Golden rice has an orange-yellow color because it contains up to 35 µg β-carotene (a precursor to vitamin A) per gram of rice, which could prevent millions of cases of blindness worldwide. Image by International Rice Research Institute (CC-BY).



Figure 11.6.4: Roundup is a common herbicide. Roundup Ready® plants are genetically modified to resist roundup, meaning the herbicide does not kill them. This allows farmers to uniformly spray Roundup, killing weeds without harming the crops. Image by Mike Mozart (CC-BY).

Crops have also been engineered to produce insecticides. *Bacillus thuringiensis* (Bt) is a bacterium that produces protein crystals that are toxic to many insect species that feed on plants. Insects that have eaten Bt toxin stop feeding on the plants within a few hours. After the toxin is activated in the intestines of the insects, death occurs within a couple of days. The gene to produce **Bt toxin** has been added to many crops including corn (figure 11.6.5), potatoes, and cotton, providing plants with defense against insects.

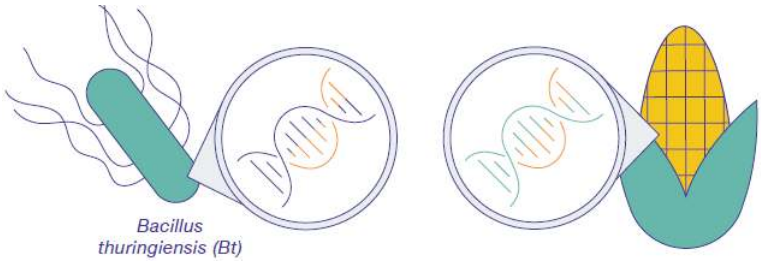


Figure 11.6.5: Genetic engineering to produce Bt corn. The gene from *Bacillus thuringiensis* that produces Bt toxin is removed and inserted into the corn plant. The Bt corn now produces the insecticide (Bt toxin) and can defend itself against pests. Image by FDA (public domain).

Genetically modified foods are widespread in the United States. For example, 94% of soy crops were genetically modified for herbicide resistance in 2020. Likewise, 8% of cotton and 10% of corn crops were modified for herbicide resistance in addition to the 83% of cotton and 79% of corn crops that were genetically modified in multiple ways.

Genetically modified animals have recently entered the market as well. **AquaAdvantage® salmon** are modified to grow more rapidly and were approved in November of 2015. However, as of March 2021, they have still not been sold due to legal challenges. In 2020, the FDA approved **GalSafe™ pigs** for medicine and food production. These pigs lack a molecule on the outside of their cells that cause allergies in some people.

Disadvantages of Genetically Modified Crops

Social Concerns

Intellectual property rights are one of the important factors in the current debate on genetically modified crops. Genetically modified crops can be patented by agribusinesses, which can lead to them controlling and potentially exploiting agricultural markets. Some accuse companies, such as Monsanto, of allegedly controlling seed production and pricing, much to the detriment of farmers (figure 11.6.6).



Figure 11.6.6: Protesters in Washington D.C. oppose genetically modified organisms and Monsanto specifically. Image cropped from Sarah Stierch (CC-BY).

Environmental Concerns

Genetically modified crops present several environmental concerns. Monoculture farming already reduces biodiversity, and cultivating genetically modified crops, for which individual plants are quite similar genetically, exacerbates this. The use of Roundup Ready® crops naturally encourages widespread herbicide use, which could unintentionally kill nearby native plants. This

practice would also increase herbicide residues on produce. While Bt crops are beneficial in the sense that they do not require external insecticide application, but Bt toxin is spread in their pollen. An early study found that Bt corn pollen may be harmful to monarch caterpillars (figure 11.6.7), but only at concentrations that are seldom reached in nature. Follow-up studies found that most of Bt corn grown did not harm monarchs; however, the one strain of Bt corn did was consequently removed from the market.



Figure 11.6.7: An early study suggested that pollen containing Bt toxin can harm beneficial and native insects, like this monarch caterpillar. However, without Bt crops, farmers are more likely to spray insecticides, circulating more harmful chemicals than pollen from Bt crops does. Image by Judy Gallagher (CC-BY).

Through interbreeding, or hybridization, genetically modified crops might share their transgenes with wild relatives. This could affect the genetics of those wild relatives and have unforeseen consequences on their populations and could even have implications for the larger ecosystem. For example, if a gene engineered to confer herbicide resistance were to pass from a genetically modified crop to a wild relative, it might transform the wild species into a **super weed** – a species that could not be controlled by herbicide. Its rampant growth could then displace other wild species and the wildlife that depends on it, thus inflecting ecological harm.

Not only could escaped genes alter weedy species, but they could also enter populations of native species. This could make some native species better competitors than they were previously, disrupting ecosystem dynamics. (They could potentially outcompete other native species with which they would otherwise coexist.)

While there is evidence of genetic transfer between genetically modified crops and wild relatives, there is not yet evidence of ecological harm from that transfer. Clearly, continued monitoring, especially for newly-developed crops, is warranted.

The escape of genetically modified animals has potential to disrupt ecosystems as well. For example, if AquaAdvantage salmon were to escape into natural ecosystem, as farmed fish often do, they could outcompete native salmon, including endangered species. Their genetic modification, which facilitates rapid growth, could result in a competitive advantage.

Are Genetically Modified Crops the Solution We Need?

Significant resources, both financial and intellectual, have been allocated to answering the question: are genetically modified crops safe for human consumption? After many hundreds of scientific studies, the answer is yes. But a significant question still remains: are they necessary? Certainly, such as in instances like Hawaii's papaya, which were threatened with eradication due to an aggressive disease, genetic engineering was a quick and effective solution that would have been extremely difficult, if not impossible, to solve using traditional breeding practices.

However, in many cases, the early promises of genetically engineered crops – that they would improve nutritional quality of foods, confer disease resistance, and provide unparalleled advances in crop yields – have largely failed to come to fruition. NASEM's GE Crop Report states that while genetically modified crops have resulted in the reduction of agricultural loss from pests, reduced pesticide use, and reduced rates of injury from insecticides for farm workers, they have not increased the rate at which crop yields are advancing when compared to non-GE crops. Additionally, while there are some notable exceptions like golden rice or virus-resistant papayas, very few genetically engineered crops have been produced to increase nutritional capacity or to prevent plant disease that can devastate a farmer's income and reduce food security. The vast majority of genetically modified crops are

developed for only two purposes: to introduce herbicide resistance or pest resistance. Genetically modified crops are concentrated in developed countries, and their availability in developing countries, where they are perhaps most needed, is limited (figure 11.6.8).

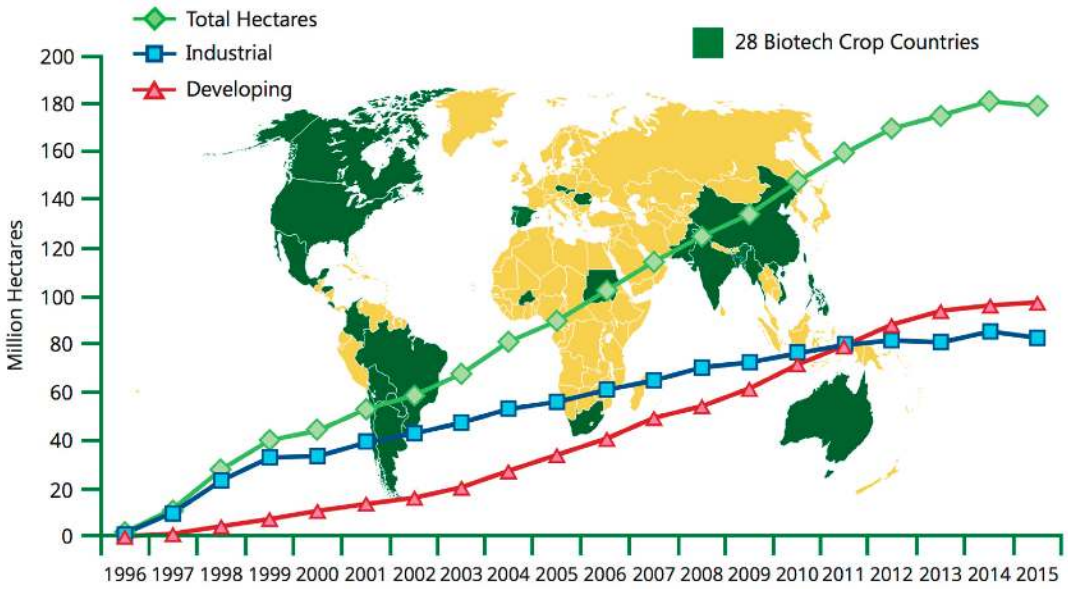


Figure 11.6.8: Global area of genetically modified crops in millions of hectares 1996–2015. Overall, the hectares of genetically modified crops has increased, and in 2011, developing countries surpassed industrial countries. By 2015, out of the 28 countries that grew biotech crops, 20 were developing, and only eight were developed countries. Latin American, African, and Asian farmers together grew 97.1 million hectares (54%) of the global 179.7 million biotech hectares, whereas industrial countries only planted 83 million hectares or 46%. Image and caption (modified) from Taheri, F., Azadi, H., & D'Haese, M. (2017). A World without Hunger: Organic or GM Crops? *Sustainability*, *9*(4), 580. doi:10.3390/su9040580. (CC-BY)

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11.6.1: Overview of Invasive Species

Invasive species are non-native organisms that, when introduced to an area out of its native range, disrupt the community they invade. **Non-native** (exotic) refers to species occurring outside of their historic distribution. Invasive species have been intentionally or unintentionally introduced by humans into an ecosystem in which they did not evolve. Human transportation of people and goods, including the intentional transport of organisms for trade, has dramatically increased the introduction of species into new ecosystems. These new introductions are sometimes at distances that are well beyond the capacity of the species to ever travel itself and outside the range of the species' natural predators. Invasive species can cause ecological and economic damage. They threaten other species through competition for resources, predation, or disease.

In the United States, invasive species like the purple loosestrife (*Lythrum salicaria*) and the zebra mussel (*Dreissena polymorpha*) have drastically altered the ecosystems they invaded. Some well-known invasive animals include the emerald ash borer (*Agrilus planipennis*) and the European starling (*Sturnus vulgaris*; figure 11.6.1.*a*). Whether enjoying a forest hike, taking a summer boat trip, or simply walking down an urban street, you have likely encountered an invasive species.

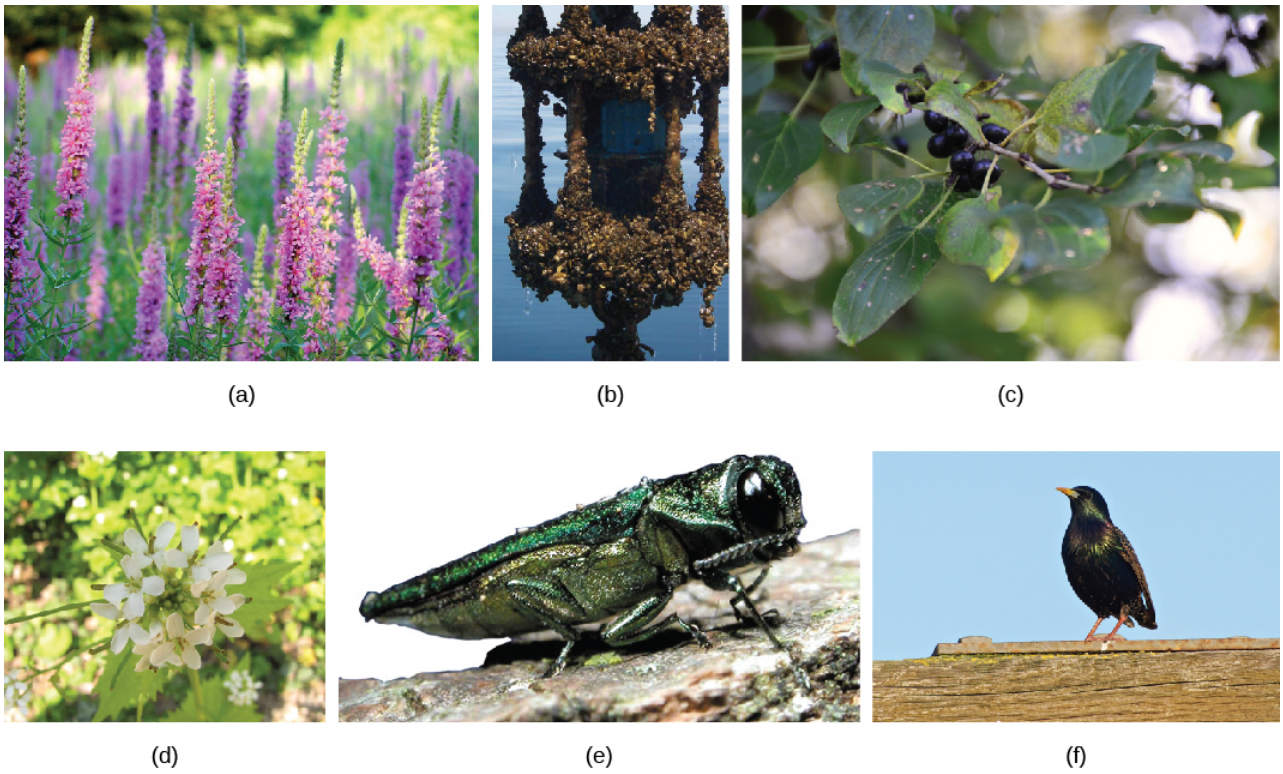


Figure 11.6.1.*a*: In the United States, invasive species like (a) purple loosestrife (*Lythrum salicaria*) and the (b) zebra mussel (*Dreissena polymorpha*) threaten certain aquatic ecosystems. Some forests are threatened by the spread of (c) common buckthorn (*Rhamnus cathartica*), (d) garlic mustard (*Alliaria petiolata*), and (e) the emerald ash borer (*Agrilus planipennis*). The (f) European starling (*Sturnus vulgaris*) may compete with native bird species for nest holes. (credit a: modification of work by Liz West; credit b: modification of work by M. McCormick, NOAA; credit c: modification of work by E. Dronkert; credit d: modification of work by Dan Davison; credit e: modification of work by USDA; credit f: modification of work by Don DeBold)

Asian Carp

One of the many recent proliferations of an invasive species concerns the Asian carp in the United States. Asian carp were introduced to the United States in the 1970s by fisheries (commercial catfish ponds) and by sewage treatment facilities that used the fish's excellent filter feeding abilities to clean their ponds of excess plankton. Some of the fish escaped, and by the 1980s they had colonized many waterways of the Mississippi River basin, including the Illinois and Missouri Rivers.

Voracious feeders and rapid reproducers, Asian carp may outcompete native species for food and could lead to their extinction. One species, the grass carp, feeds on phytoplankton and aquatic plants. It competes with **native** species (those that historically occurred in the area and are adapted to the local ecosystem) for these resources and alters habitats for other fish by removing aquatic plants.

In some parts of the Illinois River, Asian carp constitute 95 percent of the community's biomass. Although edible, the fish is bony and not desired in the United States.

The Great Lakes and their prized salmon and lake trout fisheries are being threatened by Asian carp. The carp are not yet present in the Great Lakes, and attempts are being made to prevent its access to the lakes through the Chicago Ship and Sanitary Canal, which is the only connection between the Mississippi River and Great Lakes basins. To prevent the Asian carp from leaving the canal, a series of electric barriers have been used to discourage their migration; however, the threat is significant enough that several states and Canada have sued to have the Chicago channel permanently cut off from Lake Michigan. Local and national politicians have weighed in on how to solve the problem. In general, governments have been ineffective in preventing or slowing the introduction of invasive species.

Effect on Endemic Species

Lakes and islands are particularly vulnerable to extinction threats from introduced species. In Lake Victoria, the intentional introduction of the Nile perch was largely responsible for the extinction of about 200 species of cichlids (see Patterns of Biodiversity). The accidental introduction of the brown tree snake via aircraft (figure 11.6.1.*b*) from the Solomon Islands to Guam in 1950 has led to the extinction of three species of birds and three to five species of reptiles endemic to the island. Several other species are still threatened. The brown tree snake is adept at exploiting human transportation as a means to migrate; one was even found on an aircraft arriving in Corpus Christi, Texas. Constant vigilance on the part of airport, military, and commercial aircraft personnel is required to prevent the snake from moving from Guam to other islands in the Pacific, especially Hawaii. Islands do not make up a large area of land on the globe, but they do contain a disproportionate number of endemic species because of their isolation from mainland ancestors.

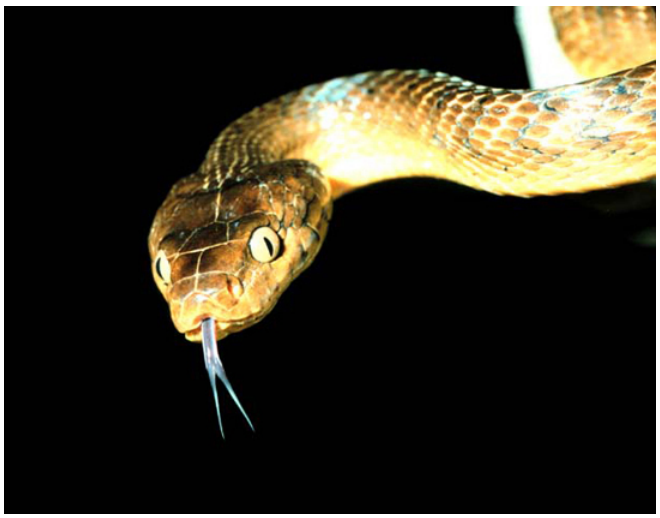


Figure 11.6.1.*b*: The brown tree snake, *Boiga irregularis*, is an exotic species that has caused numerous extinctions on the island of Guam since its accidental introduction in 1950. (credit: NPS)

Introduction by Ballast Water

Many introductions of aquatic species, both marine and freshwater, have occurred when ships have dumped ballast water taken on at a port of origin into waters at a destination port. Water from the port of origin is pumped into tanks on a ship empty of cargo to increase stability. The water is drawn from the ocean or estuary of the port and typically contains living organisms such as plant parts, microorganisms, eggs, larvae, or aquatic animals. The water is then pumped out before the ship takes on cargo at the destination port, which may be on a different continent. The zebra mussel was introduced to the Great Lakes from Europe prior to 1988 in ballast water. The zebra mussels in the Great Lakes have created millions of dollars in clean-up costs to maintain water intakes and other facilities. The mussels have also altered the ecology of the lakes dramatically. They threaten native mollusk populations, but have also benefited some species, such as smallmouth bass. The mussels are filter feeders and have dramatically improved water clarity, which in turn has allowed aquatic plants to grow along shorelines, providing shelter for young fish where it did not exist before. The European green crab, *Carcinus maenas*, was introduced to San Francisco Bay in the late 1990s, likely in

ship ballast water, and has spread north along the coast to Washington. The crabs have been found to dramatically reduce the abundance of native clams and crabs with resulting increases in the prey species of those native crabs.

Invasive Species as Diseases

Invading exotic species can also be disease organisms. It now appears that the global decline in amphibian species recognized in the 1990s is, in some part, caused by the fungus *Batrachochytrium dendrobatidis* (Bd), which causes the disease chytridiomycosis (figure 11.6.1.*c*). There is evidence that the fungus is native to Africa and may have been spread throughout the world by transport of a commonly used laboratory and pet species: the African clawed frog, *Xenopus laevis*. It may well be that biologists themselves are responsible for spreading this disease worldwide. The North American bullfrog, *Rana catesbeiana*, which has also been widely introduced as a food animal but which easily escapes captivity, survives most infections of *B. dendrobatidis* and can act as a disease **reservoir** by storing the infectious fungus.



Figure 11.6.1.*c*: This Limosa harlequin frog (*Atelopus limosus*), an endangered species from Panama, died from a fungal disease called chytridiomycosis. The red lesions are symptomatic of the disease. (credit: Brian Gratwicke)

Early evidence suggests that another fungal pathogen, *Geomyces destructans*, introduced from Europe is responsible for white-nose syndrome, which infects cave-hibernating bats in eastern North America and has spread from a point of origin in western New York State (figure 11.6.1.*d*). The disease has decimated bat populations and threatens extinction of species already listed as endangered: the Indiana bat, *Myotis sodalis*, and potentially the Virginia big-eared bat, *Corynorhinus townsendii virginianus*. How the fungus was introduced is unknown, but one logical presumption would be that recreational cavers unintentionally brought the fungus on clothes or equipment from Europe.



Figure 11.6.1.*d*: This little brown bat in Greeley Mine, Vermont, March 26, 2009, was found to have white-nose syndrome. (credit: modification of work by Marvin Moriarty, USFWS).

Biological Control of Invasive Species

One reason why invasive species proliferate dramatically outside of their native range is due to **release from predators**. This means that parasites, predators, or herbivores that usually regulate their populations are not present, allowing them to outcompete or overpredate native species, which are still regulated. Based on this principle, organisms that regulate the invasive species populations have been introduced to the newly colonized areas in some cases. The release of organisms (or viruses) to limit population size is called **biological control**. As described in the examples below, biological control of invasive species has had varying success, exacerbating the problem in some cases and solving it in others.

Prickly-pear Cactus (*Opuntia*)

Introduced into Australia, this cactus soon spread over millions of hectares of range land driving out forage plants. In 1924, the cactus moth, *Cactoblastis cactorum*, was introduced (from Argentina) into Australia. The caterpillars of the moth are voracious feeders on prickly-pear cactus, and within a few years, the caterpillars had reclaimed the range land without harming a single native species. However, its introduction into the Caribbean in 1957 did not produce such happy results. By 1989, the cactus moth had reached Florida, and now threatens five species of native cacti there.

Purple Loosestrife

The leaf beetle (*Galerucella calmariensis*) has been introduced to suppress purple loosestrife, a noxious weed (figure 11.6.1.*e*). A combination of four biological controls, including the leaf beetle were released in Minnesota since 1992. While it has not eradicated populations of this invasive species, biological control largely removed leaves from 20% of the purple loosestrive populations where it was released, which could reduce competition for native species. The biological controls established populations in most locations where they were released and even spread to new patches of purple loosestrife.



Figure 11.6.1.*e*: Young larvae of the leaf-beetle feed in and on the developing buds of plants, often destroying them. This may stunt plant growth and delay or prevent flowering. Adults (shown) and older larvae feed on leaves and cause severe defoliation. Leaf-beetles can be used to as a biocontrol for invasive plants such as purple loosestrife.

Klamath Weed

In 1946 two species of *Chrysolina* beetles were introduced into California to control the Klamath weed (St. Johnswort) that was ruining millions of acres of range land in California and the Pacific Northwest. Before their release, the beetles were carefully tested to make certain that they would not turn to valuable plants once they had eaten all the Klamath weed they could find. The beetles succeeded beautifully, restoring about 99% of the endangered range land and earning them a commemorative plaque at the Agricultural Center Building in Eureka, California.

European Rabbit

In 1859, the European rabbit was introduced into Australia for sport. With no important predator there, it multiplied explosively (figure 11.6.1.*f*). The raising of sheep (another imported species) suffered badly as the rabbits competed with them for forage.

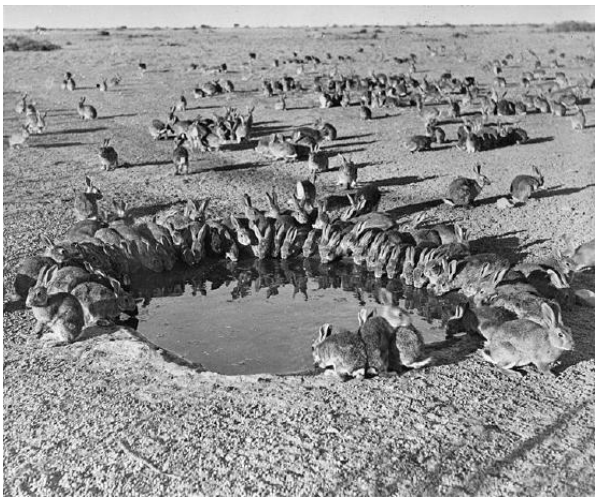


Figure 11.6.1.*f*: These rabbits in Australia removed all forage plants, which ordinarily supply them with water as well as food. They thus had to drink from a pool. Image by National Archives of Australia (public domain).

In 1950, the **myxoma virus** was brought from Brazil and released. The epidemic that followed killed off millions of rabbits (more than 99% of the population). Green grass returned, and sheep raising once again became profitable. Rabbit populations gradually increased, however, because the rabbits evolved to be more resistant to the virus, and the myxoma virus evolved to cause less damage. (Parasites, like viruses, benefit from multiplying inside the host and spreading to other individuals. If they kill their hosts too soon, they typically limit opportunities to multiply and spread.) More recently, the rabbit hemorrhagic disease virus has been used as biological control.

Strategies for Effective Biological Control

To summarize the lessons learned from biological control successes and failures, only candidates that have a very narrow target preference (eat only a sharply-limited range of hosts) should be chosen. Each candidate should be carefully tested to be sure that once it has cleaned up the intended target, it does not turn to desirable species. Biological controls must not be used against native species. Finally, introduction of non-native species into the environment should be avoided because they could themselves be invasive.

Attributions

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11.7: Parasites and Diseases

Parasites and diseases have always been an important natural factor in regulating the ecology of wildlife, especially in wild populations that have become unsustainably large. Today, however, human activities are facilitating increased spread and transmission of parasites and other pathogens, sometimes even creating conditions for epidemics to develop (Figure 11.7.1). Consequently, parasites and diseases have become a major threat to wildlife, including those already suffering under low population sizes and densities.

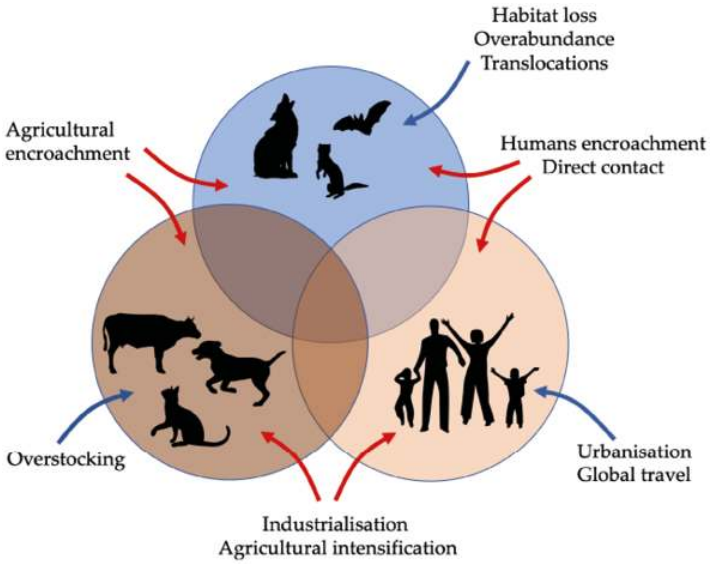


Figure 11.7.1 Habitat loss and encroachment of human activities into natural areas increase the rates of transmission of infectious diseases such as influenza, rabies, canine distemper virus, and Ebola between wildlife, domestic animals, and human. This figure illustrates the infection and transmission routes of rabies. Blue arrows represent factors that leads to higher infection rates, while red allows represent factors that contribute to the spread of the disease among the three vulnerable groups. After Daszak et al., 2000, CC BY 4.0.

One way in which humans elevate the impact of parasites and diseases on wildlife is by exposing native species to harmful organisms that they have never previously encountered, and thus have no evolved coping mechanisms. For example, population declines and extirpations of about 200 frog species across the world (Tarrant et al., 2013; Hirschfeld et al., 2016), is due, in part, to a disease caused by the chytrid fungus (*Batrachochytrium dendrobatidis*). This disease, known as chytridiomycosis (Figure 11.7.2), affects a frog's ability to absorb water and electrolytes through the skin (Alroy, 2015). It likely originated in the Korean Peninsula (O'Hanlon et al., 2018), and spread across the world through trade with African clawed frogs (*Xenopus laevis*, LC) (Weldon et al., 2004). As of yet, there is no cure for this disease, and it continues to be seen as one of the biggest threats currently facing the world's amphibians.



Figure 11.7.2 Biologists swabbing an olive striped frog (*Phlyctimantis leonardi*, LC) in Gabon to screen for the chytrid fungus. Frogs from Cameroon has tested positive (Baláž et al., 2012) which suggests the species might be at risk; however, thus far no ill effects have been observed. Photograph by Brian Gratwicke, https://www.flickr.com/photos/briangratwicke/4395505435, CC BY 2.0.

Disease transmissions can also occur when humans and their pets or livestock interact with wildlife (Cumming and Cumming, 2015). For example, during the early 1990s about 25% of lions in Tanzania's Serengeti National Park were killed by canine distemper virus which they contracted from domestic dogs living near the park (Kissui and Packer, 2004). But even chytridiomycosis (discussed above) can become an **anthroponotic disease**, transferred from frog to frog by a careless biologist that handles a healthy frog after a sick one without taking precautions against transmission. Some diseases (e.g. Ebola; flu; and tuberculosis) can be anthroponotic and **zoonotic** (transferred from animals to humans). While the impact of Ebola on humans in Africa is well-known, it is worth noting that gorillas suffer 90% mortality when exposed to Ebola, compared to 50% mortality in humans. In fact, it was an Ebola outbreak in 2004 that caused the western lowland gorilla (Gorilla gorilla gorilla, CR) to be classified as highly threatened by the IUCN (Genton et al., 2012).

Humans also indirectly facilitate the transmission and spread of parasites and pathogens. While there are some exceptions (notably social insects), transmission and infection rates are typically low for wildlife living in large, complex ecosystems because they have space to move away from disease-carrying droppings, saliva, old skin, and other sources of infection. However, these natural buffers against pathogens and parasites are removed when humans confine those organisms to small areas (such as small fenced reserves) or keep them in crowded conditions. In addition to forcing those organisms to remain in close contact with potential sources of infection, crowded conditions lead to deterioration of habitat quality and food availability. Both these factors increase the organisms' stress levels and reduce their body conditions which, in turn, lowers their resistance to parasites and diseases (reviewed in Gottdenker et al., 2014).

Parasites and diseases also threaten captive wildlife populations, including those kept at zoos and other **ex situ conservation** facilities. Because of the proximity in which different species are kept, captive conditions may allow for easier spread of diseases. An added complication with captive populations is that some individuals may function as disease reservoirs. These individuals generally appear healthy because they are fairly resistant to the disease they carry, yet they are able to infect other susceptible individuals. Disease reservoirs frequently limit opportunities for translocation of captive populations, even when dealing with threatened species. For example, well-meaning people often bring raggedy-looking yet healthy penguins in moult to rehabilitation centres, hoping the penguins will be released once "better". Yet, those animals might never be released back in the wild to avoid the risk of transmitting diseases to wild penguin populations (Brossy et al., 1999).

The impacts of diseases are bound to become more important in the future of conservation biology, especially as growing human populations and increased competition for space increase the need for single-species management and ex situ conservation. Disease management should therefore always be taken very seriously, and appropriate steps taken to avoid disease transmissions.

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11.8: Data Dive- Threats to Biodiversity

Overview

Starting in 1998, the World Wildlife Federation (WWF) began publishing the Living Planet Report. This report analyzes the health of the plant relative to the impact humanity has on it, and is updated every two years. This report continually urges humanity, especially world leaders, to work together to build a more sustainable, resilient, and healthy future for people and nature. In the 2018 update, there was an overview of the major threats to biodiversity for several animal families of concern. See the graph of their results below:

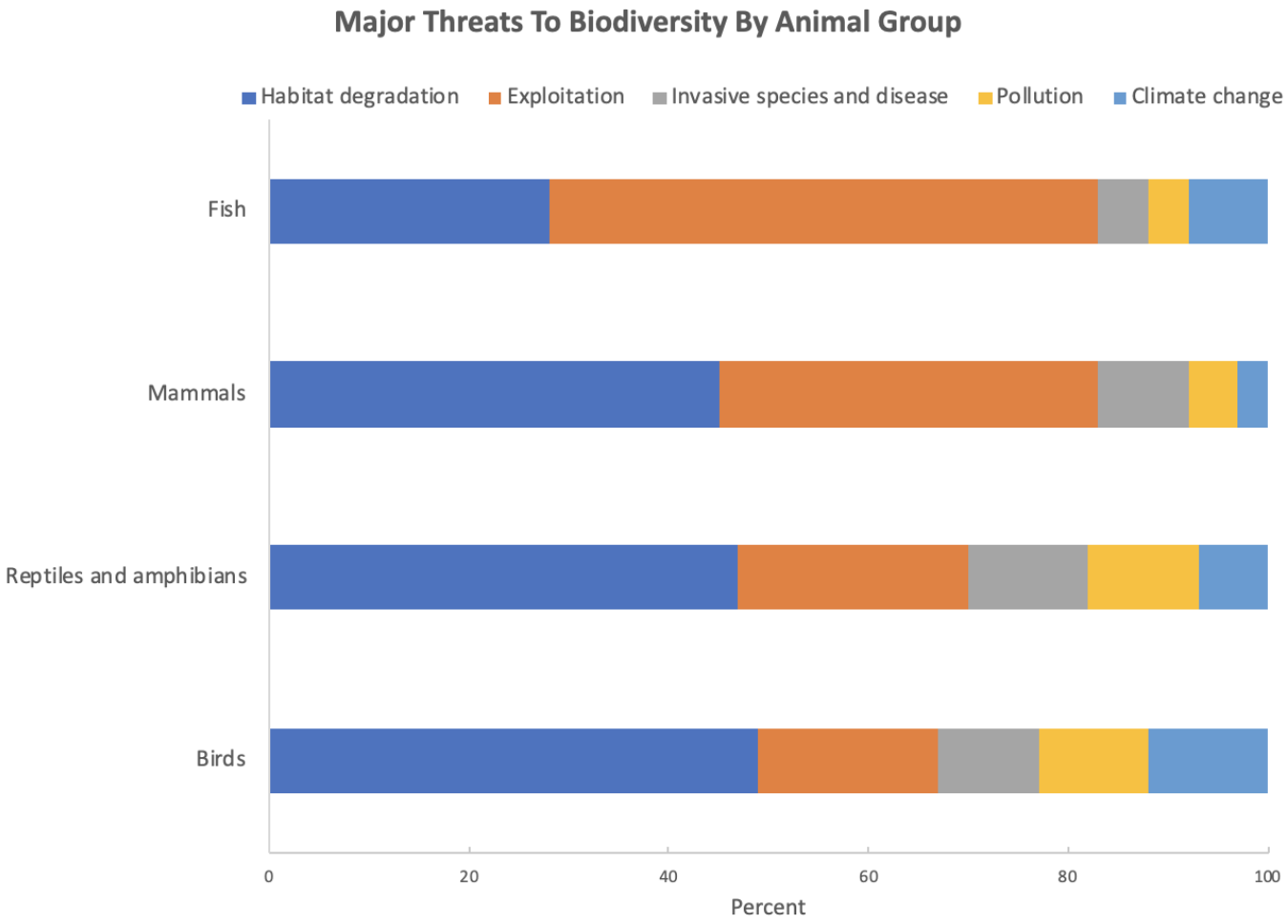


Figure 11.8.*a*: Percent of biodiversity threats to various animal groups. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Living Planet Report 2018 Aiming Higher.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What animal category above is most affected by habitat destruction? What about exploitation?
3. What category above has the largest impact (on average) on all species?
4. What is different for the fish data patterns compared to the other animal categories? Why?
5. How can the results of this graph to inform future conservation efforts?
6. Based on what you have learned in the chapter, list two other categories of life that you think should be added to the graph. Provide at least one reason for each as to why you think it should be added.

Raw Data From Above Graph(s)

Table 11.8.*a***:** Raw data for percent of biodiversity threats to various animal groups. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Living Planet Report 2018 Aiming Higher.

Animal Group	Habitat Degradation	Exploitation	Invasive Species And Disease	Pollution	Climate Change
Birds	49	18	10	11	12
Reptiles/Amphibians	47	23	12	11	7
Mammals	45	38	9	5	3
Fish	28	55	5	4	8

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11.9: Summary

1. Many threats to biodiversity do not lead to immediate and/or direct mortality, but instead have sublethal impacts that compromise organisms' fitness over time. Responses to these silent, insidious, and easily-overlooked threats are often delayed, especially when the negative effects are felt only years after exposure.
2. Environmental pollution leaves ecosystems uninhabitable for native wildlife, and cause sickness and death in wildlife and people. Common causes of pollution include pesticides, heavy metals, plastic, fossil fuels, fertilisers, light, heat, and noise, leading to pollution of water, groundwater, air, and soil.
3. Overharvesting is becoming an increasingly damaging threat to biodiversity because people have better access to previously unexploited areas and are adopting increasingly efficient methods for harvesting wildlife products. Persecution, which has its roots in human-wildlife conflict, is becoming an important threat because a growing human population is increasingly encroaching on the shrinking remaining natural habitats.
4. Invasive species outcompete local species and change the structure and composition of their native ecosystems. Human activity is responsible for these invasions, by accidentally or deliberately moving wildlife to new regions of the world. Some invasive species require a great amount of effort and resources to manage.
5. Disease transmission and spread increase when wildlife is confined to small areas and/or crowded conditions. Diseases may also be transmitted between wildlife, domesticated species, and even humans. Managing for diseases is also important in zoos and other ex situ facilities, because diseases spreading from one individual to another can prevent those individuals from being released into the wild.

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11.10: Topics for Discussion

1. Which forms of environmental pollution are most prominent in the region where you live? Which natural ecosystems are impacted most severely by this pollution? How are humans affected? What do you think can be done to reduce or even eliminate this pollution?
2. Consider all the fishing, hunting, trapping, collecting, logging, and other wildlife harvesting activities in your region. Which activities are well managed, and which are not? Why is it so difficult to regulate these activities, when so many people know that overharvesting would eventually harm local economies, their families, and their livelihoods? What measures do you think can be put in place to control overharvesting in your region, or at least reduce its impact?
3. Briefly describe what biological control is, and what its benefits are. What are the risks involved in biological control? How can these risks be predicted and avoided?
4. Can you name a few diseases that can be transmitted from people to wildlife, and from wildlife to people? Which species are involved in each of these diseases? How does the transmission of each of these diseases impact the conservation management of species involved?

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CHAPTER OVERVIEW

12: Extinction

12.1: Introduction to Extinction
12.2: History of Extinction
12.3: Rates of Extinction
12.4: What is Extinction?
12.5: Which Species are at Risk of Extinction?
12.6: Characteristics of Threatened Species
12.7: Problems of Small Populations
12.8: Is De-extinction a Solution?
12.9: Summary
12.10: Topics for Discussion
12.12: Bibliography

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12.1: Introduction to Extinction



Extinctions are seldom attributable to only one threat; rather, multiple stressors may act synergistically to drive the demise of a species. Pictured here is a Hewitt's ghost frog (*Heleophryne hewetti*, EN), which is globally restricted to an area of 140 km2 in the Cape Floristic Region. It is threatened by alien vegetation, overly frequent fires, erosion, siltation, and construction of roads and reservoirs, all of which deteriorate its clear, fast-flowing stream habitat. Photograph by Werner Conradie, CC BY 4.0.

Species have evolved and disappeared since the very first species (thought to be microorganisms living in hydrothermal vents) made an appearance on Earth. Some species outcompeted others for access to limiting resources; some were driven to extinction by dangerous pathogens; some just found it hard to survive in constantly evolving ecosystems. While many extinction events have been rather limited in scope and, hence, caused only one or a few extinctions at a time, there have been instances where perturbations were so impactful that they drove very large numbers of species to extinction over a short period of time. There have been five such past **mass extinction events**—periods marked by the sudden and dramatic loss of a large percentage of species (Figure 12.1.1). But these mass extinctions have also been followed by periods that favored increased rates of speciation, during which new species evolved to fill the niches left empty by the extinctions.

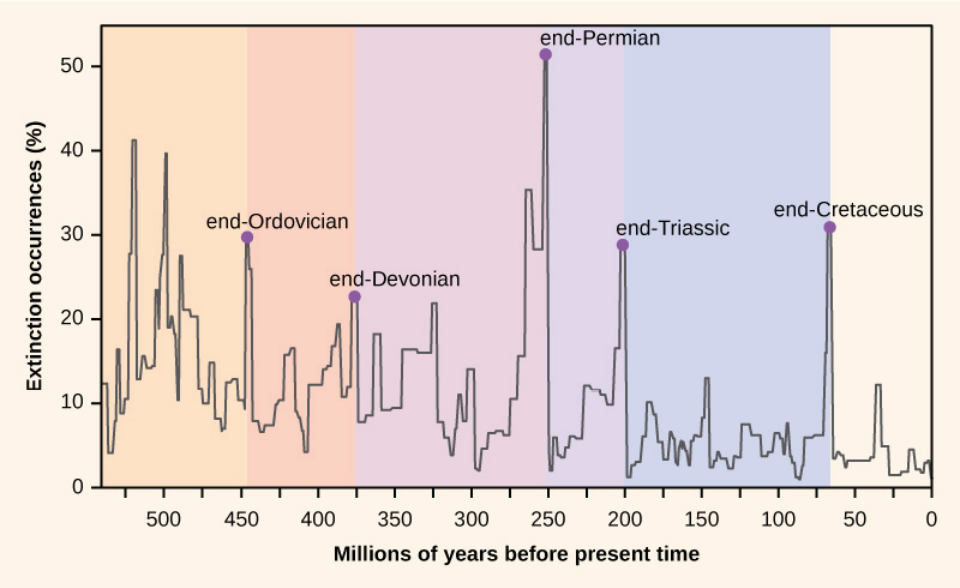


Figure 12.1.1 There have been five past mass extinction events—periods when natural events changed Earth's environment so dramatically that between 60–95% of species were wiped away forever—over Earth's geological history. So far, the most dramatic extinction event occurred at the end of the Permian period, about 250 million years ago, and thought to be the result of widespread volcanic activity and climate change. The most recent mass extinction, at the end of the Cretaceous period about 65 million years ago and thought to be the result of a massive asteroid impact, saw the disappearance of non-avian dinosaurs. Source: OpenStax, 2019, CC BY 4.0.

Nature's ability to balance extinctions with speciation was greatly disturbed around 300,000 years ago, when *Homo sapiens* made their appearance on Earth. Since then, humans have gradually increased their dominance on the natural world, leading to large-scale restructuring and destruction of biological communities. Human modifications of Earth's climatic, biological, and geochemical environments accelerated greatly during the rise of agriculture (12,000–15,000 years ago) and again during the **Industrial Revolution** (1760–1840), when fossil fuel usage and urbanization became the norm. Now, many scientists recognize today's new and distinct human-dominated **geological epoch**, the Anthropocene (Waters et al., 2015). One notable feature of the Anthropocene is that species extinctions are increasing at such rapid rates that many conservation biologists now recognize that we are also witnessing the beginnings of Earth's **sixth extinction episode** (Barnosky et al., 2011; Ceballos et al., 2017). However, unlike previously, this extinction episode is caused by human activities rather than natural events.

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12.2: History of Extinction

Speciation and Extinction

The number of species on the planet, or in any geographical area, is the result of an equilibrium of two evolutionary processes that are ongoing: speciation and extinction. **Speciation** occurs when new species evolve, and **extinction** is the global loss of a species. When speciation rates begin to outstrip extinction rates, the number of species will increase; likewise, the number of species will decrease when extinction rates begin to overtake speciation rates. Throughout Earth's history, these two processes have fluctuated —sometimes leading to dramatic changes in the number of species on Earth as reflected in the fossil record (Table 12.2.a).

Mass Extinctions

Paleontologists have identified five events in geological history of sudden and dramatic losses in biodiversity, with more than half of all extant species disappearing from the fossil record. **Extant** species are those that are surviving (not extinct) at a point in time. These five events are called mass extinctions. There are many lesser, yet still dramatic, extinction events, but the five mass extinctions have attracted the most research. An argument can be made that the five mass extinctions are only the five most extreme events in a continuous series of large extinction events that have occurred since 542 million years ago.

The fossil record of the mass extinctions was the basis for defining periods of geological history, so they typically occur at the transition point between geological periods. The transition in fossils from one period to another reflects the dramatic loss of species and the gradual origin of new species. These transitions can be seen in the rock layers. Table 12.2.a provides the names and dates of the five mass extinctions.

In most cases, the hypothesized causes are still controversial; however, the causes of the most recent event, the end-Cretaceous extinction, are best understood (table 12.2.a). It was during this extinction event that the dinosaurs, the dominant vertebrate group for millions of years, disappeared from the planet (with the exception of a theropod clade that gave rise to birds). Indeed, every land animal that weighed more then 25 kg (55 lbs) became extinct. The cause of this extinction is now understood to be the result of a cataclysmic impact of a large meteorite, or asteroid, off the coast of what is now the Yucatán Peninsula. Biodiversity recovery times after mass extinctions vary, but have been up to 30 million years.

Table 12.2.a**:** Summary of the five mass extinctions, including the name, dates, percent of biodiversity lost, and hypothesized causes.

Geological Period	Mass Extinction Name	Time (millions of years ago)	Loss in Biodiversity	Hypothesized Cause(s)
Ordovician–Silurian	end-Ordovician O–S	450–440	85% of marine species	Global cooling and then warming, gamma-ray burst from supernova removed ozone layer
Late Devonian	end-Devonian	375–360	79-87% of all species	Unknown
Permian–Triassic	end-Permian	251	96% of marine species and 70% of terrestrial (land) species	Volcanic activity, decrease on dissolved oxygen in the oceans
Triassic–Jurassic	end-Triassic	205	76% of all species	Climate change, asteroid impact, volcanic eruptions
Cretaceous–Paleogene	end-Cretaceous K–Pg (K–T)	65.5	50% of animals and plants	Asteroid impact

The Pleistocene Extinction is one of the lesser extinctions, and a recent one. It is well known that the North American, and to some degree Eurasian **megafauna**, or large animals, disappeared toward the end of the last glaciation (cooling) period. The extinction appears to have happened in a relatively restricted time period of 10,000–12,000 years ago. In North America, the losses were quite dramatic and included the woolly mammoths (last dated about 4,000 years ago in an isolated population), mastodon, giant beavers,

giant ground sloths, saber-toothed cats, and the North American camel, just to name a few. The possibility that the rapid extinction of these large animals was caused by overhunting, a type of overexploitation, was first suggested in the 1900s. Research into this hypothesis continues today. It seems likely that overhunting caused many pre-written history extinctions in many regions of the world.

The Sixth Mass Extinction

The sixth, or Holocene, mass extinction appears to have begun earlier than previously believed and has mostly to do with the activities of *Homo sapiens*. Since the beginning of the Holocene period, there are numerous recent extinctions of individual species that are recorded in human writings. Most of these are coincident with the expansion of the European colonies since the 1500s.

One of the earlier and popularly known examples is the dodo bird. The dodo bird lived in the forests of Mauritius, an island in the Indian Ocean. The dodo bird became extinct around 1662 (figure 12.2.*b*). It was hunted for its meat by sailors and was easy prey because the dodo, which did not evolve with humans, would approach people without fear. Introduced pigs, rats, and dogs brought to the island by European ships also killed dodo young and eggs.



Figure 12.2.*b*: The dodo bird was hunted to extinction around 1662. (credit: Ed Uthman, taken in Natural History Museum, London, England)

Steller's sea cow became extinct in 1768; it was related to the manatee and probably once lived along the northwest coast of North America. Steller's sea cow was first discovered by Europeans in 1741 and was hunted for meat and oil. The last sea cow was killed in 1768. That amounts to 27 years between the sea cow's first contact with Europeans and extinction of the species.

In 1914, the last living passenger pigeon died in a zoo in Cincinnati, Ohio. This species had once darkened the skies of North America during its migrations, but it was hunted and suffered from habitat loss through the clearing of forests for farmland. In 1918, the last living Carolina parakeet died in captivity. This species was once common in the eastern United States, but it suffered from habitat loss. The species was also hunted because it ate orchard fruit when its native foods were destroyed to make way for farmland. The Japanese sea lion, which inhabited a broad area around Japan and the coast of Korea, became extinct in the 1950s due to fishermen. The Caribbean monk seal was distributed throughout the Caribbean Sea but was driven to extinction via hunting by 1952.

As described in the next section, the current high rates of extinction will cause a large and rapid decline in the biodiversity of the planet. According to a 2019 United Nations report, 1 million species are at risk of extinction. Considering there are estimated to be 8-11 million species total (see The Number of Species on Earth), that means up to 12.5% of species could go extinct, and many of them within our lifetimes.

Estimates of Present-Time Extinction Rates

The **background extinction rate** is estimated to be about 1 extinction per million species each year (E/MSY). For example, if there are 8-11 million species in existence, then we would expect 8-11 of those species to become extinct in a year.

Estimates of extinction rates are hampered by the fact that most extinctions are probably happening without observation. One contemporary extinction-rate estimate uses the extinctions in the written record since the year 1500. For birds alone, this method yields an estimate of 26 E/MSY, almost three times the background rate. However, this value may be underestimated for three reasons. First, many existing species would not have been described until much later in the time period and so their loss would have gone unnoticed. Second, we know the number is higher than the written record suggests because now extinct species are being described from skeletal remains that were never mentioned in written history. And third, some species are probably already extinct even though conservationists are reluctant to name them as such. Taking these factors into account raises the estimated extinction rate to nearer 100 E/MSY. The predicted rate by the end of the century is 1500 E/MSY.

A second approach to estimating present-time extinction rates is to correlate species loss with habitat loss, and it is based on measuring forest-area loss and understanding species–area relationships. The species-area relationship is the rate at which new species are seen when the area surveyed is increased (figure 12.2.*c*). Likewise, if the habitat area is reduced, the number of species seen will also decline. This kind of relationship is also seen in the relationship between an island's area and the number of species present on the island: as one increases, so does the other, though not in a straight line. Estimates of extinction rates based on habitat loss and species–area relationships have suggested that with about 90 percent of habitat loss an expected 50 percent of species would become extinct. Species–area estimates have led to estimates of present-day species extinction rates of about 1000 E/MSY and higher.

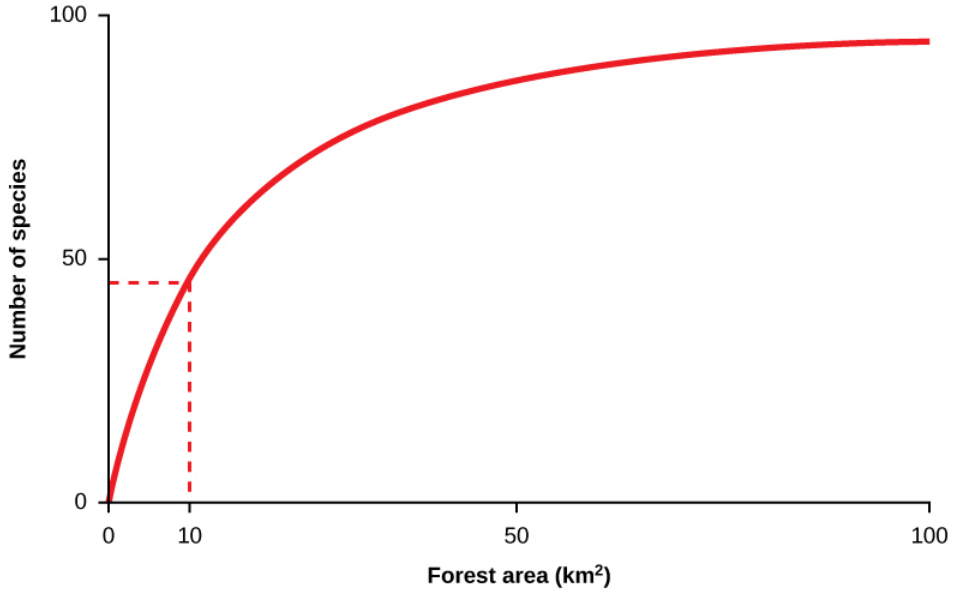


Figure 12.2.*c*: A typical species-area curve shows the cumulative number of species found as more and more area is sampled. The curve has also been interpreted to show the effect on species numbers of destroying habitat; a reduction in habitat of 90 percent from 100 km^2 to 10 km^2 reduces the number of species supported by about 50 percent.

Many extinctions will affect species that biologists have not yet discovered. Most of these "invisible" species that will become extinct currently live in tropical rainforests (figure 12.2.*d*). These rainforests are the most diverse ecosystems on the planet and are being destroyed rapidly by deforestation to provide timber and space for agriculture.



Figure 12.2.*d*: This tropical lowland rainforest in Madagascar is an example of a high biodiversity habitat. This particular location is protected within a national forest, yet only 10 percent of the original coastal lowland forest remains, and research suggests half the original biodiversity has been lost. (credit: Frank Vassen)

Extirpation

The elimination of species at a local level–known as **extirpation** – also poses threats to the integrity and sustainability of ecosystems. Widespread extirpation can obviously lead to extinction, but absence of species, even at a local scale, can affect ecosystem function. For example, by the mid-1920s wolves had been extirpated from Yellowstone National Park, although they continued to thrive elsewhere. When wolves were reintroduced to the park in the mid-1990s, they regulated elk populations, benefiting the vegetation and plant communities (see Ecosystem Restoration). What mattered for ecosystem function in Yellowstone was whether wolves were present there, not just whether the species survived somewhere.

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UN Report: Nature's Dangerous Decline 'Unprecedented'; Species Extinction Rates 'Accelerating'. 2019. United Nations. Accessed 2020-08-01.

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12.3: Rates of Extinction

If extinction and speciation are natural processes, an obvious question follows: “Why should we care about the loss of biodiversity?” The answer concerns not individual species extinctions as much as the *increasing rate* of these extinctions (Figure 12.3.1 and 12.3.2). While a species can be wiped off Earth over a relatively short period of time, speciation typically occurs slowly as the genetic makeup of a population shifts over thousands of years. Unfortunately, we are currently losing species 1,000 times faster than **natural background extinction rates** (for mammals estimated to be 1.8 extinctions per 10,000 species per 100 years, Barnosky et al., 2011), and future rates may be 10,000 times higher that background rates (de Vos et al., 2015). Because over 99% of current species extinctions have been linked to human activity rather than natural processes (Pimm et al., 2014), observations on past extinctions and subsequent speciation may not apply to the present. Moreover, unlike before, humans now share the planet with the species we are wiping out. These losses mean that we are also losing the benefits we gain from nature at unprecedented rates.

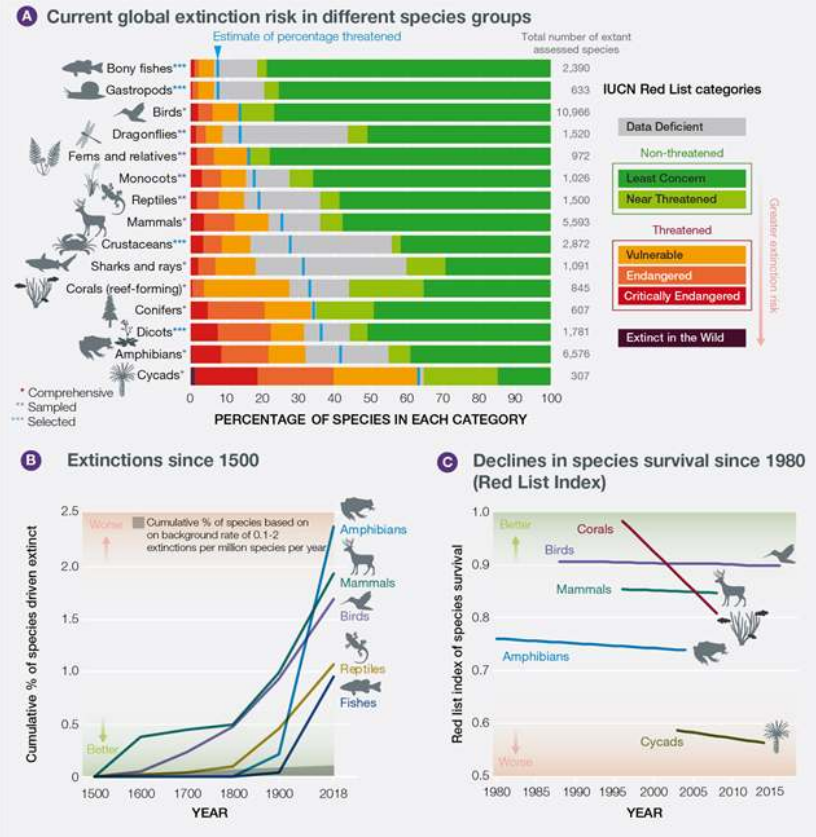


Figure 12.3.1: Global rates of extinction and risk of extinction has increased dramatically. A. Percentage of species threatened with extinction according to assessments by the IUCN Red List. B. Extictions for vertebrate groups since 1500. C. Red List Index for different groups assessed by the IUCN. A value of 1 is equivalent to all species classified as least concern and a value of 0 is equal to all species in the group extinct. (IPBES Global Assessment report 2019, data from IUCN Red List)

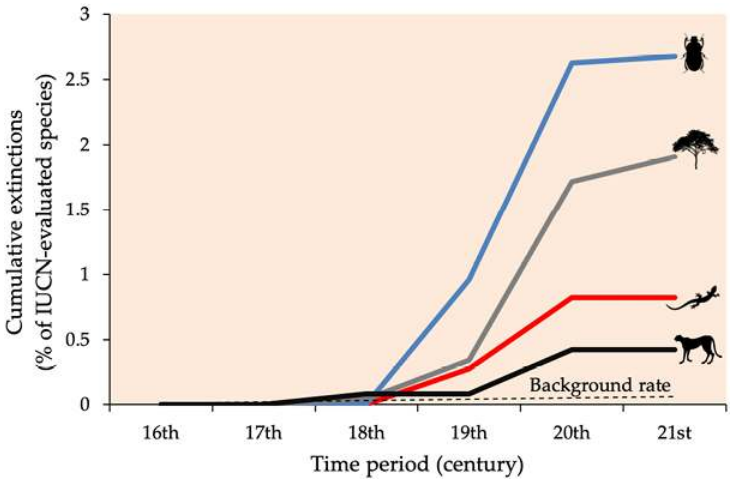


Figure 12.3.2 Percentage of Sub-Saharan Africa invertebrates, plants, reptiles, and mammals that have gone Extinct, Extinct in the Wild, and likely Extinct since the year 1500. Dashed line represents the natural rate of extinctions expected without human influences. After Ceballos et al., 2015, CC BY 4.0.

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12.4: What is Extinction?

The term “extinct” has several nuances in conservation biology, and its meaning can vary somewhat depending on the context:

Over ninety-nine percent of recent extinctions have been caused by human activities.

- A species is **globally extinct** when no individuals of that species remains alive anywhere in the world. The bluebuck (*Hippotragus leucophaeus*, EX) has been globally Extinct since the last individual was shot around 1800 (Kerley et al., 2009).
- Four (possibly seven) species of cycad (*Encephalartos* spp.)—ancient seed plants that were dominant in the age of the dinosaurs—are currently considered **extinct in the wild**; in other words, they exist only in cultivation; in captivity; or another human-managed situation (IUCN, 2019).
- A species is **locally extinct**, also called extirpated, when it is extinct in a part of its historic range but can still be found elsewhere in the world. Cheetahs (*Acinonyx jubatus*, VU) once roamed throughout much of Africa, but are now extirpated in over 90% of their historical range (Durant et al., 2017).
- A species is **ecologically extinct** (also called **functionally extinct**) if it persists at such low numbers that its role in an ecosystem is negligible. Africa’s vultures are ecologically extinct over much of their range and thus unable to remove diseased carcasses from the environment, posing both an ecological and socio-economic hazard.

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12.5: Which Species are at Risk of Extinction?

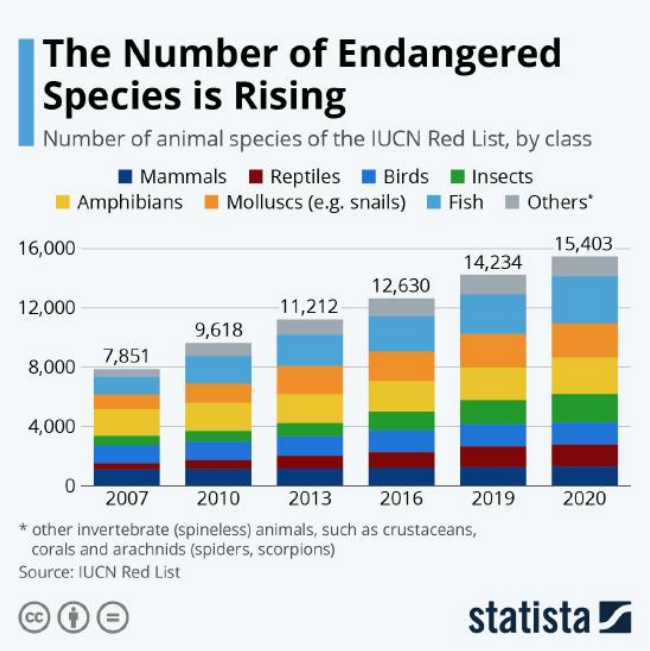


Figure 12.5.1: Number of animal species in select classes classified as endangered by the IUCN Red List between 2007 and 2020. (Statista, Data from IUCN Red List, CC_BY)

The number of species at risk of extinction continues to rise (Figure 12.5.1). An important task for conservation biologists is to identify and prioritize those species in greatest danger of extinction. Accomplishing this task requires biologists to collect and review all the information we have on each species. To facilitate this major undertaking, the IUCN has formalized the evaluation and reporting of threatened species assessments using an internationally accepted standard of conservation categories to reflect a taxon's risk of extinction. These nine categories (Figure 12.5.2), known as Red List Assessments (IUCN, 2017), are:

- *Extinct (EX)*. These species are no longer known to exist.
- *Extinct in the Wild (EW)*. These species exist only in cultivation, in captivity, or other human-managed situations.
- *Critically Endangered (CR)*. These species have an extremely high risk of going extinct in the wild.
- *Endangered (EN)*. These species have a very high risk of extinction in the wild.
- *Vulnerable (VU)*. These species have a moderately high risk of extinction in the wild.
- *Near Threatened (NT)*. These species are close to qualifying for a threatened category but are not currently considered threatened.
- *Data Deficient (DD)*. Inadequate information exists to determine the risk of extinction for these species.
- *Least Concern (LC)*. These species are not considered Near Threatened or threatened. (Widespread and abundant species are included in this category.)
- *Not Evaluated (NE)*. Species that have not yet been evaluated.

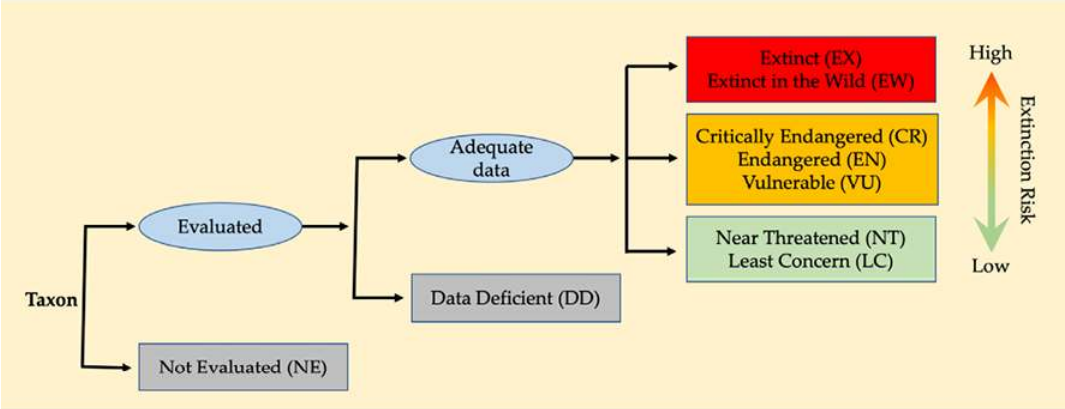


Figure 12.5.2 Flow diagram illustrating the structure of the IUCN categories of conservation status. An evaluated species can be considered at lower risk of extinction, at high risk of extinction (i.e. threatened), or extinct. A species for which not enough data are available for evaluation is considered Data Deficient (DD). After IUCN, 2017, CC BY 4.0.

These categories, and the **Red List Criteria** used to classify each species (Table 12.5.1), are broadly based on population viability analysis, and consider population size, population trends, and habitat availability. Species that are *Extinct in the Wild*, *Critically Endangered*, *Endangered*, and *Vulnerable* categories are officially considered "threatened with extinction". The advantage of this system is that it provides a standard protocol by which decisions can be reviewed and evaluated according to widely accepted yet flexible criteria. Consequently, species, subspecies, varieties, populations, and subpopulations can be assessed on a global or regional level, all under a unified set of standards. The resultant threat status assessment forms the basis of Red Data Books and Red Lists: detailed lists of threatened wildlife by group and/or by region compiled by the IUCN and its affiliate organizations. All global (and many regional) Red List assessments are freely available at http://www.iucnredlist.org, with feedback links provided from which anyone can alert the IUCN if they find errors or have suggestions for improvements.

Table 12.5.1 The IUCN's Red List criteria for evaluating a taxon's threat status. A species that meet any one of criteria A–E could be classified as Critically Endangered.

Red List criteria A–E	Summary criteria used to evaluate a taxon as Critically Endangered
A. Population size declining	The population size has declined by 90% (or more) over last 10 years or 3 generations (whichever is longer).
B. Geographical range declining	The species is restricted to < 100 km2 and it occurs at a single location and its distribution range is observed/expected to decline.
C. Small and declining populations	There are less than 250 mature individuals left and population has declined by 25% (or more) over last 3 years or 1 generation (whichever is longer).
D. Small populations	There are less than 50 mature individuals left.
E. Population viability analysis	There is a 50% (or greater) chance of extinction within 10 years or 3 generations.

a Additional criteria for Critically Endangered, as well as criteria for Endangered and Vulnerable listings can be found at http://www.iucnredlist.org.

A decline in geographic range is a predictor of vulnerability to extinction. A 2020 study published in Nature Communications determined that species of birds, amphibians and mammals have lost approximately 18% of their natural, historic range size and may lose up to 21% by 2100 (Beyer and Manica 2020). Figure 12.5.3 depicts the relationship between declining range size and habitat loss due to urban and agricultural land conversion.

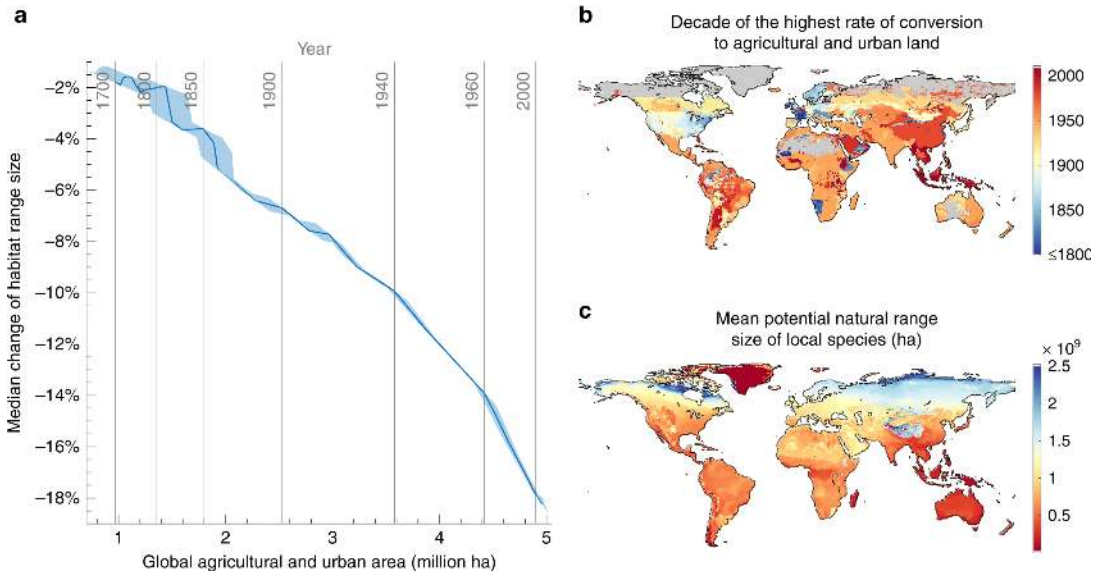


Figure 12.5.3: **a** Across-species median range loss against the cumulative global agricultural and urban area. Uncertainty bands are based on the uncertainty of the land-use reconstruction. **b** Local time of the highest rate of conversion to agricultural and urban land up until 2010. **c** Mean potential natural range size of species locally present for the natural biome distribution in 1850 and no anthropogenic land use. (From Beyer, R.M., Manica, A. Historical and projected future range sizes of the world's mammals, birds, and amphibians. *Nat Commun* **11,** 5633 (2020). https://doi.org/10.1038/s41467-020-19455-9, CC-BY-4.0)

Course-filter assessments

To fill Red List species assessment gaps, conservation biologists are increasingly relying on broader metrics, or **coarse-filter assessments**, to identify groups of species that are threatened with extinction. One such method, which reduces the need to evaluate every individual species, is to identify ecosystems that are threatened. This premise rests on the assumption that any threatened ecosystem will contain many threatened species. Hence, protecting and restoring threatened ecosystems will simultaneously allow many populations living in those ecosystems to recover. To facilitate this type of coarse-filter assessment, the IUCN recently established a Red List of Ecosystems (RLE, http://iucnrle.org). The RLE assesses ecosystem status against five criteria: (1) distribution declines, (2) distribution restrictions, (3) environmental degradation, (4) disruption of ecological processes and interactions, and (5) quantitative estimates for risk of ecosystem collapse (Keith et al., 2013). While the ecosystem assessment protocol was only recently developed its holistic strategy promises a more comprehensive accounting of local biodiversity which could be more informative than an accumulation of single species assessments.

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12.6: Characteristics of Threatened Species

While a great number of factors may make a species vulnerable to extinction, conservation biologists have observed that species most vulnerable to extinction generally fall under one of six main groups:

- *Species with small populations*: Some species have very small populations, consisting of just a few individuals. Such small populations are highly vulnerable to random variations in demography or environmental conditions, and to the loss of genetic diversity—all factors that increase the risk of extinction. Species whose population sizes naturally fluctuate between large and small populations also fall in this category, as they are at an increased risk of extinction during the small population phases of those fluctuations.
- *Species with declining populations*: Trends in population sizes tend to persist, so populations that are declining in abundance face a high risk of extinction (Caughley, 1994) unless conservation managers identify and address the causes of decline.
- *Species with restricted distribution ranges:* Some species, such as those that are restricted to oceanic islands; mountains peaks; or isolated lakes, can be found only in a limited geographic range. A major disturbance, such as a cyclone/hurricane or drought, could easily affect that entire species' range, potentially driving the species to extinction.
- *Species with only one or a few populations*: A sufficiently large disturbance—such as a wildfire, storm, or disease outbreak—can wipe out a single population of a species. For a species with only one population, that means its extinction, while the loss of even a single population leaves species with only a few populations more vulnerable to the next disturbance. Species in this category (few populations) overlap with those in the previous category (restricted distribution ranges) because species with few populations tend to have restricted ranges.
- *Species that are exploited by people*: Overharvesting can easily reduce a population to the point of extinction. Even if overharvesting is stopped just before the point of extinction, it may still have reduced a population to a size where it becomes susceptible to one or more of the three additional pressures faced by small populations.
- *Species with critical symbiotic relationships*: Species that are members of obligate symbiotic relationships (where one species cannot survive without another) will go extinct if its host disappears. For instance, larvae of the rhinoceros stomach botfly (Gyrostigma rhinocerontis) mature in the stomach lining of African rhinoceros, and no other species (Barraclough, 2006). Thus, if the host species (the rhinoceros) were to go extinct, so would the botfly, Africa's largest fly species. This phenomenon in which one species' extinction leads to the extinction of other is called a coextinction (Koh et al., 2004), while a series of linked coextinctions is called an extinction cascade.

The following characteristics are also linked with extinction, although the links are not as strong as is the case with the previous six categories:

- *Animal species with large body sizes*: Large animals generally require large ranges and more food, have lower rates of reproduction, and have smaller population sizes relative to smaller animals. Often, they are harvested by humans for material benefits. Consequently, within groups of related species, the largest are generally also the most vulnerable to extinction—that is, a larger species of carnivore, ungulate, or whale is more likely to go extinct than a smaller carnivore, ungulate, or whale.
- *Species that require a large home range*: Individuals or social groups of some species must forage over wide areas to fulfill their needs. When portions of their range are being degraded or fragmented, the remaining area will eventually be too small to support a viable population.
- *Species that are poor dispersers*: Moving to more suitable habitat is a common survival response following altered environmental conditions. But species with poor dispersal abilities may be doomed to extinction if they are unable to move to more suitable areas elsewhere.
- *Seasonal migrants*: A migratory species depends on intact ecosystems at two or more locations to complete its life cycle. If those ecosystems, either at stop-over sites along migration routes and/or at migratory endpoints, are damaged, the species may be at risk of extinction.
- *Species with low genetic diversity*: Because genetic diversity enables species to adapt to changing environmental conditions, species with low genetic diversity are more vulnerable to extinction because they have less ability to adapt to new diseases, new predators, or recent changes in their ecosystems.
- *Species that evolved in stable ecosystems*: Species that evolved in relatively stable environments (e.g. tropical ecosystems) are often threatened with extinction because under stabile conditions, a species is unlikely to retain the ability to adapt to

environmental changes such as altered microclimates.

- *Species with specialized requirements*: Specialist species are often threatened with extinction because they are unable to adapt to altered ecosystems.
- *Group-living species*: A range of factors leaves group-living species at risk of extinction. For example, a herd of ungulates, a flock of birds at their night-time roost, or a school of fish can be harvested in its entirely by people using highly effective techniques. Even if some individuals remain, the harvesting may still leave the population below a critical threshold needed for effective foraging, mating, or territorial defence. This link between population size/density and individual fitness is termed the **Allee effect.**
- *Species that have had no prior contact with people*: Species that encounter people for the first time are **ecologically naïve**—they lack avoidance strategies that promote survival during these encounters. Ecologically naïve species thus have a higher chance of extinction than species that have already survived human contact.
- *Species closely related to species that recently went extinct*: Groups of closely-related taxa, where some members are threatened or already extinct, often share characteristics that elevate their threat of extinction. Groups of related taxa that include many threatened species include apes, cranes, sea turtles, and cycads.
- *Species that live on islands*: Island species generally exhibit many of the characteristics mentioned above. In addition, the mere fact that an island is surrounded by ocean means that species that are unable to swim or fly have nowhere to go when they need to escape a threat.

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12.7: Problems of Small Populations

While some small populations have persisted against the odds, sufficiently large populations are generally needed to prevent eventual extinction (Halley et al., 2016). Small populations—which include species that have always had small populations and previously large populations that have been reduced to a few individuals—face three additional inherent and unavoidable pressures. These three additional pressures are: (1) loss of genetic diversity; (2) demographic stochasticity; and (3) environmental stochasticity and natural catastrophes. We will now examine how each of these pressures can lead a small population to eventual extinction. Much of this discussion is based on a ground-breaking manuscript by New Zealand ecologist Graeme Caughley, which discusses at length the threats faced by small and declining wildlife populations (Caughley, 1994).

Loss of genetic diversity

Species with high genetic diversity are generally more able to adapt to and reproduce under new conditions such as those brought by environmental changes. These adaptations can occur at both individual and population levels. For example, under climate change, some genes may allow some populations to adapt their ranges faster or better tolerate warmer and wetter environments, while **phenotypic plasticity**—the ability of one gene to express itself differently under different conditions—may allow certain individuals to better adapt to a changing environment. One species that displays remarkable phenotypic plasticity is the crystalline iceplant (*Mesembryanthemum crystallinum*); by regulating its photosynthetic pathways, an individual plant can adjust its water needs based on the amount of salt and moisture available in the environment (Tallman et al., 1997). Such flexibility may explain why this species, native to southwestern Africa, North Africa, and Europe, has been a successful invader in environments as diverse as those in South America, North America, and Australia.

While populations with many individuals usually also have high levels of genetic diversity, small populations regularly suffer from low levels of genetic diversity. This low genetic diversity not only leaves those populations unable to adapt to changing conditions, but also makes them more susceptible to a variety of deleterious genetic effects (Caughley, 1994). Each of these effects leads to even greater loss of fitness and genetic diversity, hence even larger population declines, and eventually extinction. In the next sections, we discuss further why these deleterious genetic effects are so harmful to small populations.

Genetic drift

In wildlife populations, there are always some alleles that are relatively common, and others that are relatively rare. The relative abundance of any of these alleles may however change from one generation to another purely by chance. While common alleles generally tend to stay common, rare alleles have a high chance of being randomly lost in subsequent generations. Consider how each parent only passes on half of their genetic code to each offspring; this means that the ability of a rare allele to persist is dependent on how many individuals carry it, which individuals produce offspring, and how many offspring those individuals produce. Another important factor is population size (Figure 12.7.1): in any small population, only a limited number of individuals can carry any single allele, so the smaller the population, the higher the likelihood that alleles are lost to the next generation. This loss of alleles is called **genetic drift**.

Genetic Variation Worksheet

Small and isolated populations are expected to experience significant losses of genetic variation over time. To illustrate this point, consider an isolated heterozygous population that is not subjected to mutation. The proportion of original heterozygosity (H) that remains after one generation can be estimated using the formula (Wright 1931):

$$H = 1 - 1/[2N_e]$$

where (N_e) is effective population size. A population with $N_e = 2$ (two breeding individuals) would thus retain 75% of its original heterozygosity after one generation:

$$H = 1 - 1/4 = 1.00 - 0.25 = 0.75$$

But without a source for new genetic material, this population's heterozygosity will continue to decrease. After t generations (H_t):

$$H_t = H^t$$

The heterozygosity remaining in our population with two breeding individuals would thus be 56% after two generations (0.75 x 0.75), 24% after five generations, and 6% after ten generations. In contrast, a population with one hundred breeding individuals would retain 99.5% of its original heterozygosity after one generation, 98% after five generations, 95% after ten generations.

The migration of only a few individuals each generation or so can be enough to counter genetic drift in small populations. Mutation can theoretically also help, but natural mutation rates—estimated to be between 1 in 10,000 and 1 in 1,000,000 per gene per generation—are too rare to have an impact.

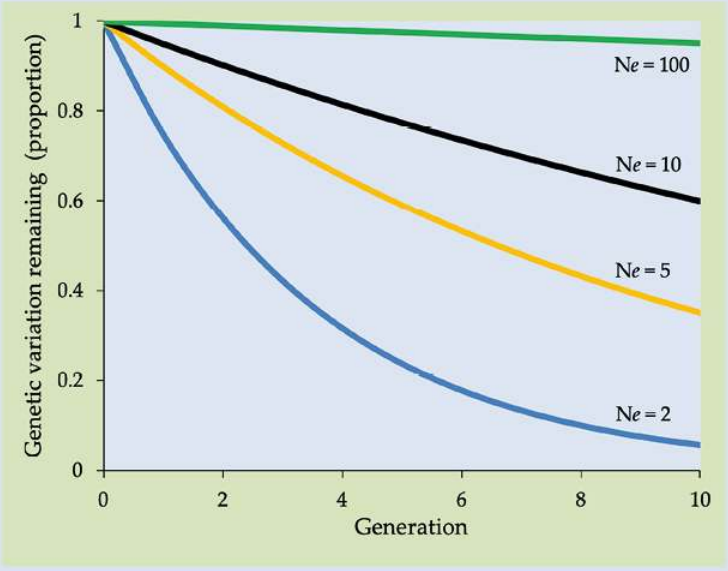


Figure 12.7.1 The amount of genetic diversity that is randomly lost over time due to genetic drift is highly dependent on a population's effective population size (Ne). A theoretical population with Ne = 2 may lose approximately 95% of its genetic diversity over 10 generations, while a population with Ne = 100 may lose only 5%. After Meffe and Carroll, 1997, CC BY 4.0.

While genetic drift equates to a loss of genetic diversity, there are some cases where populations show no obvious ill effects. Such may have been the case for female elephants in South Africa's Addo Elephant National Park (Figure 12.7.2). Hunting once nearly killed off this entire population; by the time they were adequately protected in 1931, only 11 animals remained, eight of which were female. Of those eight females, at least four were tuskless, while only two, maybe three, females carried both tusks. Over the next decades, Addo's female elephants have shown increasing degrees of tusklessness; by 2002, only 2% of females had tusks (by comparison, 96–98% of elephant females are normally expected to develop tusks, Maron, 2018). One can therefore postulate that

the allele responsible for the tusk development in female elephants became rare, and that the progressive loss of tusked females is a sign of genetic drift (Whitehouse, 2002). While Addo's female elephants do not show any known limitations from being tuskless, the loss of alleles can also be devastating to the population suffering from genetic drift if, for example, the lost allele(s) coded for traits that would have allowed a species to adapt to a changing environmental condition.



Figure 12.7.2: Elephants in Addo National Park, South Africa. Most of the female elephants do not have tusks due to genetic drift. (Photo by NJR ZA, CC-BY-SA-3.0 via Wikimedia Commons)

It is important to note that genetic drift is distinct from natural selection. That is, genetic drift involves random changes in the frequency of alleles, whereas natural selection involves changes in traits in response to sexual selection or specific environmental conditions. For example, reduced tusk size in some heavily-hunted elephants in Africa (e.g. Chiyo et al., 2015) is a selective pressure in response to hunting that favor large tusks—this is distinct from Addo's female elephants that have lost their tusks even in the absence of selective hunting pressure.

> Mating among closely related individuals, which occurs in small populations, often results in lower reproductive success and weaker offspring.

Inbreeding depression

In large populations, a variety of instinctive mechanisms are in place to promote **heterosis**, which occur when offspring have a level of genetic variation that improves their individual evolutionary fitness. Some species are predisposed to disperse from their place of birth to prevent sibling–sibling or parent–offspring mating, while others are restrained from mating with close relatives through sensory cues such as individual odors. Many plants have morphological and physiological traits that facilitate cross-pollination and reduce self-pollination.

However, in small populations with few unrelated mates, the urge to breed might be stronger than the mechanisms that promote heterosis. Under these conditions, rather than forgoing reproduction, breeding among closely-related individuals (or **inbreeding**) can occur. This breeding among close relatives might result in **inbreeding depression**, which can occur when closely-related parents give their offspring two copies of a deleterious allele. Individuals suffering from inbreeding depression typically have fewer offspring or have offspring that are weak or fail to reproduce. Genetic studies have shown how birth defects in several small populations can be attributed to inbreeding depression (Xue et al., 2015). Inbreeding depression has also been identified as the reason why some small populations are more susceptible to diseases (Trinkel et al., 2011). Inbreeding depression can result in a vicious cycle for declining population sizes, where such declines can lead to even more inbreeding depression, and eventually extinction.

Outbreeding depression

Large populations have many ecological, behavioral, and physiological mechanisms that prevent hybridization, the production of offspring among genetically distant taxa, whether they be individuals of different species, or individuals of the same species but with different adaptations (the latter being intraspecific hybridization). As with inbreeding depression, these mechanisms may fail in small populations, leading to **outbreeding depression** (Frankham et al., 2011). Because offspring that result from outbreeding depression have traits that are intermediate to their parents, they may not be adapted to either of the parents' ecosystems. For example, one study found that plants suffering from outbreeding depression have weakened defenses against herbivory (Leimu and Fischer, 2010). Outbreeding depression may also lead to a breakdown in physiological and biochemical compatibility between would-be parents—hybrid sterility is a well-known consequence of this breakdown. Consequently, species and populations suffering from outbreeding depression often show similar symptoms to inbreeding depression, including lower fitness, weakness, and high rates of mortality.

The opposite of outbreeding depression is hybrid vigor. Under these conditions, the hybrid offspring can be quite strong in an evolutionary sense; they may even outcompete their parent species.

Population bottlenecks

In some taxa, such as butterflies, annual plants, and amphibians, population size varies dramatically from generation to generation. During some years, populations can be so large that they appear to face little risk of extinction. However, abundant years can be misleading when followed by successive years of low abundance. Generally, in a population that undergoes extreme size fluctuations, the population size required to ensure continued persistence (i.e., the **minimum viable population (MVP)**) is in effect much nearer the lowest than the highest number of individuals in any given year. However, during years with low abundance, a phenomenon known as a **population bottleneck** may occur—that is, the small population size may lead to the loss of rare alleles from one generation to the next (Figure 12.7.3). Population bottlenecks may lead to more inbreeding depression which, in turn, reduces reproductive success (Heber and Briskie, 2010) and increases vulnerability to diseases (Dalton et al., 2016).

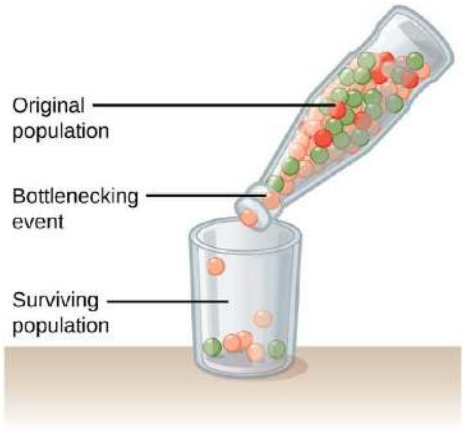


Figure 12.7.3: The post bottleneck population will have less genetic diversity due to lost alleles. (Copyright; author via source)

New populations founded by only a few individuals are vulnerable to a special type of population bottleneck, the **founder effect**. The founding individuals of a new population by definition start off with low genetic diversity, much less than the original population that the founders left behind. This low genetic diversity puts the new population at risk of further genetic diversity declines, which have lasting effects through time. This situation can occur naturally when only a small number of individuals disperse to establish a new population or when founder individuals come from a small population that already suffered from low genetic diversity. Being mindful of these concerns is especially important for translocation or captive breeding projects. For example, to prevent extinction of the world's smallest gazelle, the Speke's gazelle (*Gazella spekei*, EN), a captive population of this species, almost entirely restricted to Somalia, was established in the USA. The founder population for this captive breeding project consisted of only one male and three females, leading to severe levels of inbreeding depression and high mortality rates in offspring (Kalinowski et al., 2000). Understanding the importance of managing for genetic diversity can help avoid these and other challenges that can threaten the success of translocation projects.

Demographic stochasticity

Demographic stochasticity (also known as demographic variation) refers to random variations in a population's demographic traits (e.g. sex ratios, birth rates, death rates), the cumulative effect of variation in individual organisms' fitness. In any natural population, some individuals will produce fewer offspring than average, while others will produce more than average; some individuals will produce no offspring at all. Similarly, some individuals die younger than average, while others live longer than average. For populations that are sufficiently large, average birth and death rates provide relatively stable descriptions of key aspects of that population's demography. However, when a population's size decreases to below a certain threshold, variations in fitness of a small number of individuals can have a large impact on the overall populations' demographic parameters, causing population size and other characters to fluctuate up or down unpredictably (Schleuning and Matthies, 2009). Consider, for example, an isolated population of crocodiles with only a few females. As with many other reptiles, offspring sex ratios of crocodiles are determined by the environmental temperature during incubation (Hutton 1987). If, by chance, the population experiences two years of high temperatures, which favor male offspring, and the few females die by chance, the all-male population may be doomed for extinction unless some female crocodiles immigrate from elsewhere.

> The social systems of group-living animals can easily be disrupted when their population size or density falls below a critical level.

Environmental stochasticity and catastrophes

Environmental stochasticity, the unpredictable variation in environmental conditions, can cause dramatic population size fluctuations over time, and hence, substantially increase the risk of extinction. Consider, for example, how the development rate of many insects is strongly temperature-dependent (e.g. Rebaudo and Rabhi, 2018). In an average or warm year, young insects that hatch on time and feed well may result in ecologically fit adults that produce many young, whereas unusually cold years might reduce hatching success and larval activity, which could also reduce adult fitness (Gibert et al., 2001). So, highly unfavorable conditions in any one year can cause dramatic population declines, or even push a species to extinction if conditions persist over successive years across its range.

The increased risk of extinction from environmental stochasticity also applies to natural catastrophes that can occur at unpredictable intervals (e.g. droughts, storms, earthquakes, and fires). Range-restricted species are particularly vulnerable to this kind of threat.

Environmental stochasticity tends to increase the probability of extinction more than does demographic stochasticity. As discussed, this is especially true for small populations and range-restricted species.

The extinction vortex

As populations decline in size, they become increasingly vulnerable to the combined impacts from the loss of genetic diversity, inbreeding depression, Allee effects, environmental stochasticity, and demographic stochasticity. All these factors tend to lower reproduction, increase mortality rates, and reduce population size even more, in turn driving populations to extinction at increasingly faster rates over time (Fagan and Holmes, 2006). Conservationists sometimes compare this phenomenon to a vortex, spiralling inward, moving faster (or declining faster in the case of a population) as it gets closer to the center. At the centre of this **extinction vortex** (Gilpin and Soulé, 1986) is oblivion—the extinction of the species (Figure 12.7.4).

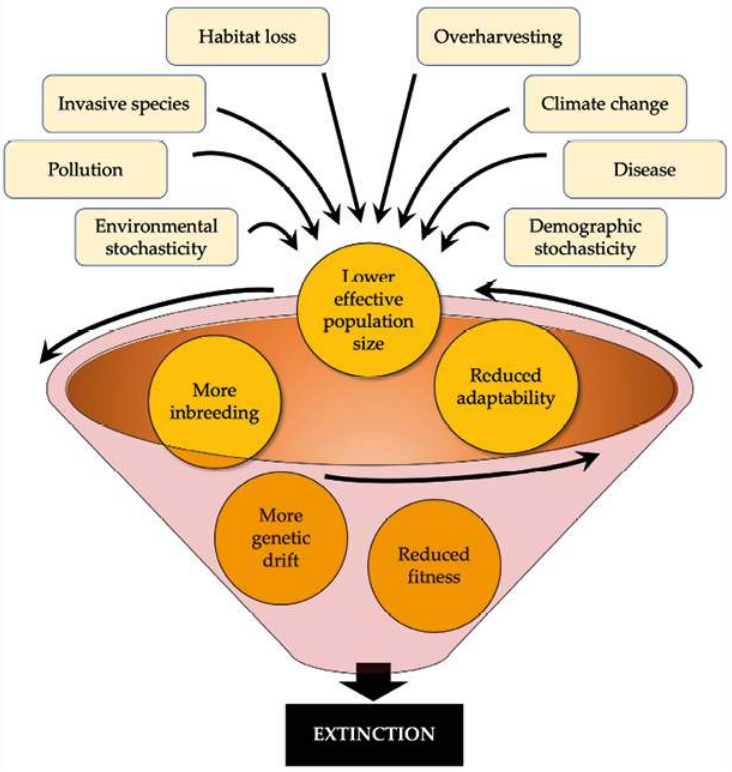


Figure 12.7.4 The extinction vortex describes a process whereby the factors that affect small populations can drive its size progressively downward towards extinction. CC BY 4.0.

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12.8: Is De-extinction a Solution?

One of the more interesting conservation debates to have emerged in recent years involve efforts to reverse extinction. This field, known as **de-extinction** or resurrection biology aims to revive extinct species, and eventually to reintroduce viable populations to their original locations (Seddon, 2017). One possible method, called “breeding back”, aims to produce individuals genetically similar to an extinct species by selective breeding of extant species that carry genetic material of their extinct relatives. This is the main method currently being used to revive the aurochs (*Bos primigenius*, EX), the ancestor of today’s domestic cattle (Stokstad, 2015). Other “breeding back” projects place less emphasis on genetics and more on morphology, by selectively breeding individuals with certain traits to produce individuals that visually appear similar to the extinct species.



Figure 12.8.1 Not extinct anymore? A selective breeding program in South Africa has raised several plain’s zebras that closely resemble the extinct quagga. The progress from one generation to the next can be seen in this photo, with the adults showing reduced striping, and the foal showing brown hues. Photograph by The Quagga Project, CC BY 4.0.

The second popular method used for de-extinction is **cloning.** This involves the transfer of viable genetic material from an extinct species to the eggs (or embryo) of a closely related surrogate mother, who will hopefully give birth to an individual of the extinct species. Cloning has been used in selective breeding of livestock for many years, and plans are also currently underway to use cloning to prevent the extinction of highly threatened species such as the northern white rhinoceros. Despite the promise that cloning offers for reviving extant and recently extinct species, cloning species that went extinct many years ago has been more challenging. So far, attempts to clone Spain’s Pyrenean ibex (*Capra pyrenaica pyrenaica*, EX) and Australia’s gastric-brooding frog (*Rheobatrachus silus*, EX) have produced individuals that lived for only a few minutes (Ogden, 2014).

Despite the progress made, de-extinction is one of the most controversial and polarizing debates to emerge among conservation biologists in recent years. Proponents of de-extinction hope that the early work described above paves the way for the resurrection of extinct species once the threats that drove them to extinction have been managed. Many resurrection biologists have even started establishing banks where genetic material of threatened species is **cryopreserved** for future use. They also hope that their work will inspire more people to be interested in science in general and especially in conservation. Protected areas with extinct species may even draw tourists that can fund conservation projects, while reintroductions of once-extinct species can revive lost ecosystem services.

Bringing a species back from extinction is, however, highly controversial for several reasons. First, there is the argument that the limited funds available for conservation are better spent on species currently facing extinction rather than on projects with possibly insurmountable technical challenges. Others argue that there is no point in spending millions of dollars to bring back an extinct species if we cannot even solve the extinctions drivers that caused the demise of the extinct species in the first place. Conservationists also wonder how the issues facing small populations will be managed, especially early in the process. Many believe that these small compromised populations will simply occupy valuable space in zoos and protected areas that can be better used for protecting extant species. There are also major misgivings about whether the resurrected species will fill the same ecosystem function as before since they may behave differently; in fact, some worry that unpredictable behaviors may introduce new harmful threats to ecosystems. Many conservationists are also worried that the public’s concern for species currently threatened may fade if there is a perception that we can simply revive the species after the last individual died. Lastly, ethical questions are frequently raised about humans essentially trying to “play God” with these “vanity projects”, and the possibility that

this entire field will undermine one of the most important foundations of conservation biology—that we need to act now because extinction is forever. Clearly there are some advantages, but also disadvantages, to de-extinction. Most importantly, much research still needs to happen for this to be a viable idea.

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12.9: Summary

1. The rates of species extinction are currently 1,000 times greater than natural background levels; this may soon increase to 10,000 times. Over 99% of modern extinctions can be attributed to human activity. These extinctions are leading to the rapid loss of ecosystem services.
2. The IUCN has developed quantitative criteria that assign species to nine conservation categories based on their risk of extinction. Species that are Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), and Vulnerable (VU) are officially considered “threatened with extinction”. The five other categories are Extinct (EX), Near Threatened (NT), Least Concern (LC), Data Deficient (DD), and Not Evaluated (NE).
3. Species with the following characteristics are particularly vulnerable to extinction: species with small populations, species with declining populations, species with restricted distribution ranges, species with one or only a few small populations, species that are exploited by people, and species with critical symbiotic relationships.
4. Small populations are at high risk of extinction because they are vulnerable to several deleterious genetic factors, as well as demographic and environmental stochasticity. Such populations often require intensive management to prevent them from becoming a victim of an extinction vortex.
5. De-extinction as a scientific field aims to revive extinct species using methods such as selective breeding and cloning. But this practice is controversial, and not practical with current technology.

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12.10: Topics for Discussion

1. Why should you, or anyone else, be concerned if a species becomes extirpated (also known as locally extinct)? How does this concern compare to when a species becomes globally extinct?
2. Use the IUCN Red List (http://www.iucnredlist.org) to identify one species in your country that is currently threatened with extinction. How might this species be affected by the various challenges facing small populations? Consider genetic, physiological, behavioral, and ecological factors, as appropriate.
3. Think of an imaginary animal that was recently discovered. Imagine this animal is also threatened with extinction. Name three characteristics that make your imaginary animal vulnerable to its threats. Now discuss some steps that can be implemented to ensure that your animal will continue to survive.
4. A herd of 80 rhinoceros have been moved from South Africa to Australia to “save the species” because “there is no safe place in Africa for rhinos today” (see Hayward et al., 2017). What do you think of this plan? Do you think the project will be successful? What are the main opportunities and challenges? Once you’re done answering the question read Lundgren et al. (2017) and decide if you still feel the same.

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CHAPTER OVERVIEW

13: Applied Population Biology

13.1: Introduction to Applied Population Biology
13.2: Monitoring Population Size
13.3: Estimating Extinction Risk
13.4: Data Dive- Island Fox Populations
13.5: Topics for Discussion
13.7: Bibliography
13.8: Summary

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13.1: Introduction to Applied Population Biology



Staff from the Frankfurt Zoological Society (FZS) conducting an aerial survey over Selous Game Reserve, Tanzania. Photograph by Daniel Rosengren, https://commons.wikimedia.org/wiki/File:FZS_plane_conducting_an_aerial_survey_in_Selous_Game_Reserve,_Tanzania.jpg, CC BY 4.0.

Even without human influences, the size of any wildlife population may be stable, increasing, decreasing, or even fluctuating. These population changes, combined with occasional natural perturbations, can and have driven some species and populations to extinction. Such natural extinction events generally occur at local scales, and are interspersed by long periods of little change, so that overall ecosystem stability is not compromised. Moreover, as explained by the intermediate disturbance hypothesis (e.g. Bongers et al., 2009), localized disturbances and subsequent local extinctions play an important role in maintaining regional biodiversity, as they increase opportunities for a greater variety of species to live in an area (Figure 13.1), at least until succession drives them out again. Some species that colonize the empty niches left by extinctions or extirpations may even evolve to become new species over time.



Figure 13.1 A treefall gap allowing sunshine to penetrate the canopy in the sacred Bubi Forest on Bioko Island, Equatorial Guinea. Treefall gaps and other localised natural disturbances benefit regional biodiversity because they provide opportunities for a greater

variety of species to eke out an existence. Responses do vary, however, from ecosystem to ecosystems: while fire disturbance maintains most grassland and savannah ecosystems, it has an overall negative impact on tropical forests. Photograph by Luke L. Powell/Biodiversity Initiative, CC BY 4.0.

Human-driven disturbances often occur at larger scales and more frequently than natural perturbations. Consider, for example, the large amount of natural forests that are converted to agricultural land every year, or climate change impacts that are affecting every ecosystem on Earth. Because these disturbances are so widespread and occur with such regularity, they are causing a wholesale destabilization of the natural environment. Many species and populations are unable to cope with these fast and vast changes and are consequently undergoing sharp declines. The human-driven extinctions that follow are leaving compromised ecosystems more vulnerable to invasions by widespread generalist species and exotic species. What remains is an environment dominated by only a few species unable to offer many of the ecosystem services we depend upon. To prevent further harm, we need to identify the most vulnerable species and ecosystems and develop strategies that can slow or even reverse current extinction rates. But how can we identify the species most likely to go extinctions soon, and how can we determine which actions should be taken to save them? The field of population biology, defined as the study of population dynamics over time and space, provides us the tools to answer many of these questions.

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13.2: Monitoring Population Size

The primary aim of population monitoring is to detect changes in the environment, population size, and species distribution over time. Such monitoring efforts frequently focus on a particular area or a population of concern, but it can also target more common but sensitive species, such as butterflies and macroinvertebrates, which can function as indicator species to assess ecosystem condition. The great number of methods (which are all types of surveys) used to monitor populations usually fall into one of three different categories: biodiversity inventories, population censuses, and demographic studies.

Biodiversity inventories

A biodiversity inventory is an attempt to document which species are present in some defined locality. Such an effort can focus on one specific taxa (e.g. a bird survey) or several taxa, on a small area (e.g. a city park) or large area (e.g. a large national park), over a short period of time (e.g. a few hours) or long period of time (e.g. several years). There are many methods to compile a biodiversity inventory, ranging from uncomplicated to highly organized, performed by a single person or a large team of experts. Some of the most popular methods for biodiversity inventories include site visits by professional naturalists and questionnaires distributed among local people. To tap into the knowledge and eagerness of amateur naturalists, conservation biologists are also increasingly compiling biodiversity inventories using citizen science surveys. Rapid biodiversity assessments (RAP) are sometimes used to compile an inventory under tight deadlines to answer urgent questions and inform urgent decisions. A bioblitz is a special type of biodiversity inventory during which experts on a range of taxa come together to record all the living species within a designated area over a brief period (usually over 24 hours).

While biodiversity inventories seldom offer the kinds of detailed data required to predict likelihood of a species' persistence, they have several uses in conservation. First, a biodiversity inventory can be a comparatively inexpensive and straightforward method to broadly monitor an area's species and populations. Biodiversity inventories conducted over a wide area can also help determine the distribution of a species, while a comparison with follow-up inventories can highlight distribution changes (which often correspond to population changes).

Population censuses

A population **census** (also called a count) uses a repeatable sampling protocol to estimate the abundance or density of a population or species which, in turn, can tell us whether a population is doing well or not. When a species is easy to detect, relatively sedentary, and the sampling area is small, a comprehensive census of all individuals may be possible. However, comprehensive censuses are generally very difficult, if not impossible, to conduct when implemented on large or highly mobile populations, or over large areas. In these cases, it may be better to restrict the census to a more manageable subsection of the population, by dividing the area of interest into sampling units, and randomly censusing only some of the units. Population estimates that capture only a fraction of the overall population can then serve as an index for broader trends, or it can be used to estimate the total population size through **extrapolation**, if the researcher knows which fraction of the population or area was counted.

Some popular methods for censusing subsections of wildlife populations are, sampling plots, distance sampling, and mark-recapture surveys. Sampling plots are popular in studies focusing on plants and invertebrates, allowing biologists to systematically count each individual observed in a small area. A **quadrat** is a square structure that is randomly located on the ground and used to count the number of individuals that lie within its boundaries. To obtain an accurate count using this method, the square must be placed at random locations within the habitat enough times to produce an accurate estimate. (Figure 13.2.1). Birds and mammals are often censused using distance sampling, during which all observed individuals on predetermined transects or from points are tallied. The number of individuals observed in the count area can then be extrapolated to obtain population size (or density) estimates for individual (or multiple) species observed across the entire area of interest. Aerial censuses are often used to conduct distance sampling transects over large and open areas, while point counts and walked line-transects are more popular for small areas or closed-canopy ecosystems (White and Edward, 2000).

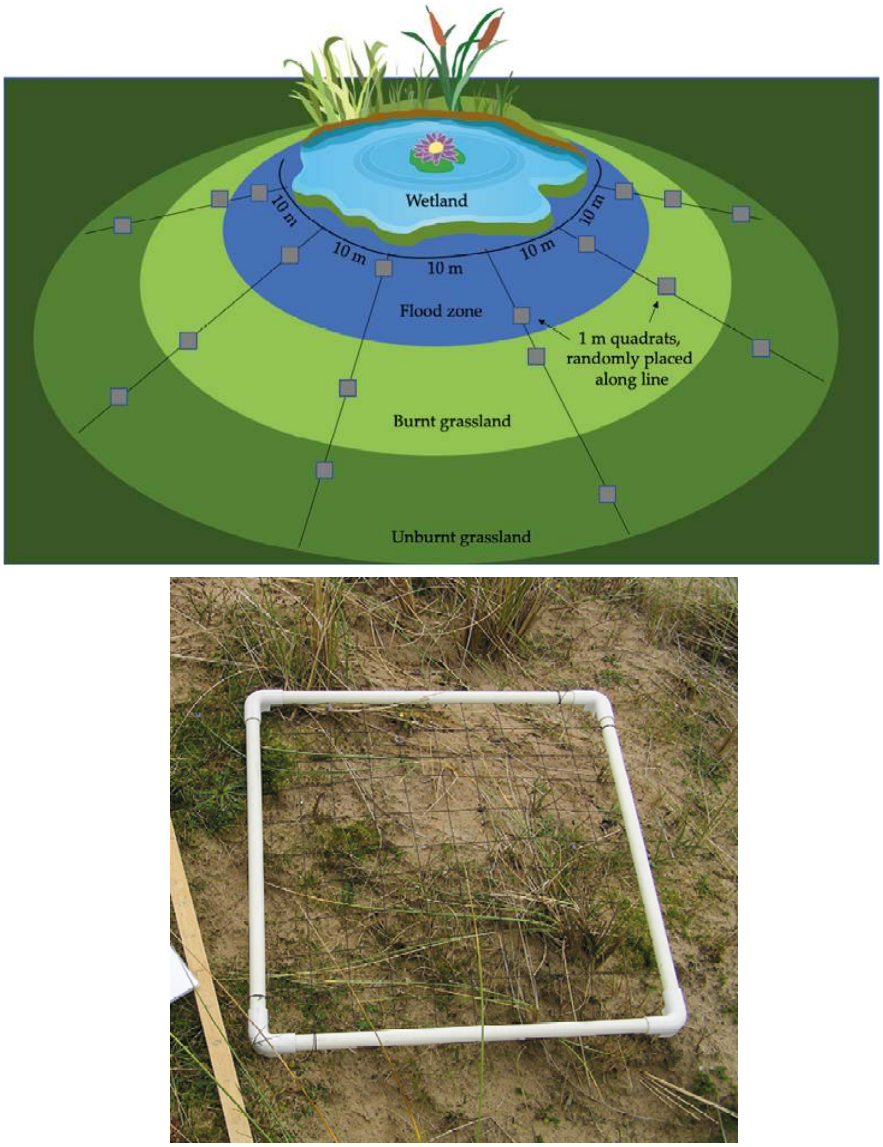


Figure 13.2.1: (Top) A schematic of a systematic sampling protocol using quadrat frames. Dividing a large area into smaller sampling units makes the survey task much more feasible. The survey can be performed in the field, or photos such as these can be taken for analysis once back at the office. CC BY 4.0. (Bottom) A quadrat frame divided into 10x10 cm squares, set out to monitor the species richness and abundance of plants in a grassland recovering from a fire. Photograph by Yohan Euan, https://commons.wikimedia.org/wiki/file:quadrat_sample.jpg, CC BY-SA 3.0.

Box 13.2 Sea Turtle Conservation along Africa's Atlantic Coast

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Virtually all the characteristics of sea turtles' life histories make them difficult to study and conserve. They are long-lived, slow growing, migratory, and almost entirely ocean-dwelling. Although they return to their natal beaches to reproduce, these are usually thousands of kilometers from their developmental and adult foraging grounds. In addition, sea turtle habitat often

overlaps with areas of high human use such as developed coastlines and intensive fisheries. Describing population ranges and assessing interaction with human threats is thus critical to their survival.

Over recent decades, we have learnt much about sea turtles along the coastline of Africa (Figure 13.2.1) thanks to extensive research efforts. For instance, we know that these coasts host globally important populations of green turtles (*Chelonia mydas*, EN) in Mauritania, Guinea Bissau, Equatorial Guinea and Republic of the Congo; loggerheads (*Caretta caretta*, VU) on Cabo Verde; hawksbills (*Eretmochelys imbricata*, CR), on São Tomé and Principe; leatherbacks (*Dermochelys coriacea*, VU) in Equatorial Guinea and Gabon; and olive ridleys (*Lepidochelys olivacea*, VU) in Gabon and Angola.



Figure 13.2.2 (Top) One of thousands of leatherback sea turtle females nesting in Gabon every year. Photograph by M.J. Witt, CC BY 4.0. (Bottom) An olive ridley turtle hatchling makes its way to sea on a northern Angolan beach where the local community ensures its protection. Photograph by A. Formia, CC BY 4.0.

One of Africa's most remarkable sea turtle populations is Gabon's leatherback rookery, the biggest in the world with as many as 15,000 to 41,000 nesting females (Witt et al., 2009). Gabon also hosts the largest olive ridley rookery in the Atlantic (Metcalfe et al., 2015), and foraging grounds for green and hawksbill turtles. Until the late 1990s, virtually nothing was known about these populations, other than the fact that eggs and adults were frequently collected for human consumption. Since then, a multi-pronged approach has been adopted to describe and protect Gabon's sea turtles. Intensive coastal monitoring has allowed scientists to assess spatio-temporal trends in nesting frequency and abundance, and levels of nest-site fidelity and reproductive success. Using techniques, such as satellite telemetry, flipper tagging, oceanic modelling, and dispersal simulations, and genetic and isotopic analyses, researchers have been able to map sea turtle behavior at sea, in Gabon's coastal waters, and during post-nesting migrations to foraging grounds off South America and South Africa (i.e. Formia et al., 2006, Maxwell et al., 2011, Witt et al., 2011, Pikesley et al., 2018).

Building upon this knowledge, measures have been established to quantify and reduce the impact of threats to Gabon's sea turtles. In 2002, the Gabonese government created a system of national parks and protected areas encompassing approximately 80% of Gabon's sea turtle nests; in 2017, a new network of 20 marine protected areas (MPA) was officially created, covering 26% of Gabon's territorial waters (Parker, 2017). Laws enacted in 2011 prohibit all hunting, capture, and commercialisation of sea turtles. Trained observers on-board industrial fishing vessels quantify sea turtle bycatch from bottom trawling and tuna seiners and reduce mortality by treating and releasing captured turtles. In addition, the Gabonese government now requires that all shrimp trawlers use turtle excluder devices (TED), aluminium grids sewn into the nets allowing sea turtles and other large bycatch to escape, while conserving shrimp catch; similar devices are being developed for fish trawlers. Ongoing efforts are shifting traditional turtle hunting and other destructive practices toward more sustainable fisheries. Turtle-watching ecotourism also represents a growing potential to increase awareness and incentivize conservation efforts.

Nevertheless, African sea turtle conservation remains a formidable challenge. Although the economic context is changing rapidly, impoverished coastal villagers in many countries continue to collect turtles and eggs for local consumption or market sale, and many wealthier urbanites continue to consider them delicacies. These problems are often compounded by corruption, political instability, inadequate law enforcement, and development priorities focused on destructive exploitation. With funding

deficits, combating these challenges sometimes seems like a losing battle, but public attitudes are slowly shifting. Even in remote beach villages, the idea that a turtle alive is worth more than dead is no longer such a bizarre concept.

Mark-recapture surveys, mark-resight surveys, and sight-resight surveys are popular for species that are easy to catch, trap, or individually recognized. In this case, captured (and thus counted) individuals would be marked for future identification, after which the total population in an area is estimated by accounting for the proportion of marked and unmarked individuals seen on subsequent visits. The marking of animals can be done with a variety of procedures, including using highly visible tags, paint approved for animal use, or unique marks on the animal itself. This method involves marking captured animals in and releasing them back into the environment to mix with the rest of the population. Later, a new sample is captured and scientists determine how many of the marked animals are in the new sample. This method assumes that the larger the population, the lower the percentage of marked organisms that will be recaptured since they will have mixed with more unmarked individuals. For example, if 80 field mice are captured, marked, and released into the forest, then a second trapping 100 field mice are captured and 20 of them are marked, the population size (N) can be determined using the equation in the worksheet below (Figure 13.2.3)

Using our example, the equation would be:

$$\frac{(80 \times 100)}{20} = 400$$

These results give us an estimate of 400 total individuals in the original population. The true number usually will be a bit different from this because of chance errors and possible bias caused by the sampling methods.

Demographic studies

Demographic studies monitor individuals of different ages and sizes over time (Figure 13.2.3) to obtain a more comprehensive dataset than would be produced by population censuses. Most demographic studies use the same methods that what would be used for a population census; however, in addition to counting and marking, individuals would also be aged, measured for size and body condition, and sexed, when possible. The best demographic studies involve collecting these data from the same individuals over time, which is easiest when working with sedentary species (e.g. plants), populations in an enclosed space (e.g. in a small fenced reserve), animals that are fairly resident and/or habituated to human presence, or individuals carrying biologging devices (Kays et al., 2015). This may not always be possible, in which case biologists may obtain data from different individuals during each field session, to serve as an index for larger population trends.

Mark-recapture survey worksheet

Mark–recapture survey, basic formula (Caughley 1977):

$$N = \frac{M \times n}{m}$$

where
N = Population size;
M = Number of individuals marked (first visit);
n = Number of individuals seen (second visit);
m = Number of marked individuals seen (second visit).

Assume 21 individuals were marked with ear tags on the first visit. With 13 marked individuals recaptured out of a total of 30 individuals (both marked and unmarked) captured on a second visit, the estimated population size is:

$$N = \frac{21 \times 30}{13} = 48 \text{ individuals}$$



Figure 13.2.3 A biologist gathering biometric data from a juvenile central African slender-snouted crocodile (Mecistops leptorhynchus, CR) in the DRC. The crocodile will be tagged with a permanent marker before release so it can be recognized when caught again. Accompanying the photo is an example of mark-recapture survey worksheet to estimate population size. Photograph by Terese Hart, CC BY 4.0.

The data obtained from demographic studies are often used in combination with mathematical modeling to guide and refine conservation strategies. For example, researchers frequently compare the age structure (i.e. the percentage of juveniles, reproductively active adults, and older post-reproductive-age adults) of a declining population to that of a stable population to identify causes of decline, and the population parameters that are most sensitive to disturbances. This information can then be used to predict population sizes at different points in the future, and how those populations may respond to different management scenarios. The aim of many demographic studies is to predict, and identify strategies to reduce, extinction risk.

Recent progress in collecting survey data

> Camera traps, hair snares, and fecal samples all provide non-invasive sampling techniques to obtain baseline data needed for conservation assessments.

Collecting genetic material on elusive and rarely-seen animals with **non-invasive techniques** such as hair snares and fecal sampling are also becoming increasingly popular means of collecting survey data. These non-invasive techniques reduce the need

for researchers to be in the field, thereby reducing both the researchers' exposure to dangerous conditions and disturbances to the populations they are trying to monitor.

Camera traps represent another non-invasive survey technique whose popularity has greatly increased in recent years. These special cameras, often placed at supplemental food or next to wildlife paths, are activated automatically when an animal passes into the area covered by the camera's motion sensors (Figure 13.2.4). This photographic record of movement can then be used to obtain biodiversity inventories, population size estimations, or even to compile demographic datasets (Steenweg et al., 2017).



Figure 13.2.4 (Left) A nature conservation student sets a camera trap in northern South Africa to monitor leopard (*Panthera pardus*, VU) and brown hyena (*Parahyaena brunnea*, NT) populations on a privately protected area. Photograph by Kelly Marnewick, CC BY 4.0. (Right) Congo peafowl (Afropavo congensis, VU)—a highly elusive species—investigating a camera trap in the DRC. Photograph by Lukuru Foundation, CC BY 4.0.

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13.3: Estimating Extinction Risk

Biologists often use the positive relationship between population size and likelihood of persistence to predict the probability that a population may go extinct at some point in the future. One of the most popular tools for making such predictions is **population viability analysis (PVA)**. A PVA can be thought of as a type of extinction risk assessment; it uses demographic data and mathematical methods to predict at what point in the future a population or species is likely to perish. In addition, by considering a species' resource requirements and the availability of limiting resources, biologists can use the results of a PVA to identify a species' most vulnerable life stages, and to estimate how management techniques may influence population size and extinction risk. In this way, PVAs can guide conservation decisions by highlighting the need to, for example, modify harvesting regulations, perform translocations, or provide and protect a greater amount of suitable habitat. Even the IUCN's Red List Criteria uses PVA as a criterion to help prioritize conservation targets: populations with low extinction risk may not require immediate attention, while those approaching extinction thresholds will gain higher priority.

Probability of extinction

> Population viability analysis (PVA) uses demographic data and mathematical methods to predict if a population or species is likely to persist or perish.

The main purpose of a PVA is to estimate the viability (or time to extinction) of a species or population from observed population sizes and growth rates. Consider a population with 100 individuals that loses 50% of its individuals each year. A simple model will suggest that this population will lose 50 individuals the first year, 25 individuals the second year, and so on, until no individuals are left in the seventh year. The probability of extinction for this population is thus 100%, and the time to extinction is seven years. But how do we deal with the more realistic complex variations in population sizes we see in nature?

A more realistic PVA begins by constructing a mathematical model representing the population of interest using data obtained from a demographic study, which may include the current age (or size) structure of the population, average birth rates, and average survival rates of each age class. This dataset would be organized in a format suitable for PVA modeling using a database package, and then analyzed using the methods of matrix algebra. Because results from this initial model have only one outcome—a population that is either stable or growing/declining at a fixed rate—it is called a **deterministic model**. Typically, deterministic models are then tailored to include a variety of independent environmental parameters, such as food availability, storm frequency, or invasive competitors. Variability can also be added into the model by allowing some or all the model elements (e.g. survival rate or habitat availability) to vary within their observed ranges of values. Catastrophic events, such as a fire that kills a large proportion of the population, can also be programed to occur at random points in time. Hundreds or even thousands of simulations of this complex model can then be run to determine changes in population size over time, the probability of population extinction within a certain period, and the median time to extinction. Because of the variability built into this more complex model, each iteration's output will vary from the next; for that reason, it is called a **stochastic model**. The choice of models and the parameters included depend on the goals of the analysis and the management options under consideration.

Minimum viable population

When a PVA shows that a population has a relatively high risk of extinction, a logical next step would be to determine what could be done to prevent the extinction from happening. In general, protecting larger populations reduces extinction probability (Figure 13.3.1). To understand exactly how large is large enough, a PVA can also be used to estimate a **minimum viable population (MVP)**. As the name implies, an MVP is the smallest number of individuals necessary for a population to have a chance of long-term persistence, despite the potential effects of demographic, environmental, and genetic stochasticity, and natural catastrophes faced by small populations. This is well illustrated in the influential paper by Shaffer (1981), who compared setting MVP targets to planning for floods; engineers cannot rely on the average annual rainfall when designing flood control systems near rivers and wetlands. Instead, they must design systems that can also handle extreme rainfall and flooding events. These extreme events may occur rarely, perhaps once every 50 years, but they will likely occur during the lifetime of a flood control system. Similarly, to maximize the long-term protection of a threatened species, we must take actions that protect them in both average and extreme years characterized by catastrophic events such as cyclones/hurricanes, forest fires, and disease epidemics (Anderson et al., 2017).

This is especially true considering future climate change scenarios, where every year may be uncharacteristically harsh, in effect a 50-year event.

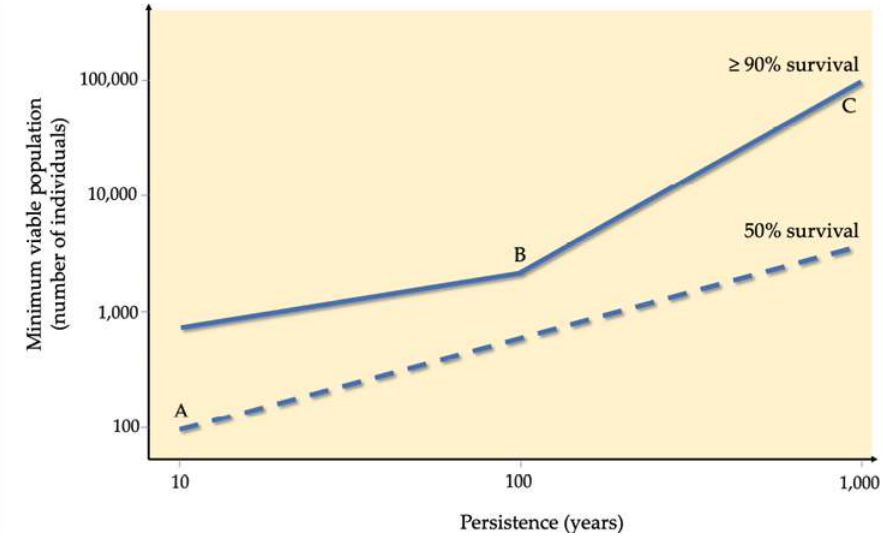


Figure 13.3.1 A graph (both axes on log scales) derived from a meta-analysis including 1,198 species showing how a larger minimum viable population (MVP) size translates to a higher likelihood of persistence over time. (A) If the goal is for 50% chance of persistence after 10 years, 100 individuals are required; (B) If the goal is for 90% chance of persistence after 100 years, 3,000 individuals are required; (C) If the goal is for 90% chance of persistence after 1,000 years, 100,000 individuals are required. After Traill et al., 2010, CC BY 4.0.

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13.4: Data Dive- Island Fox Populations

Overview

The Island Fox Conservation Working Group and Friends of the Island Fox nonprofit organization work hard to continually fund research and conservation projects to ensure the continued survival of the island fox. In addition, they also have educational outreach programs about the island fox as an endangered species to get public support. Every June the Island Fox Conservation Working Group meets to go over updates and plan for the future. In the 2019 meeting they discussed population trends across the six island fox subspecies and determine what those populations mean for the subspecies trajectory moving into the future. The results of this meeting can be seen in the graph and table below:

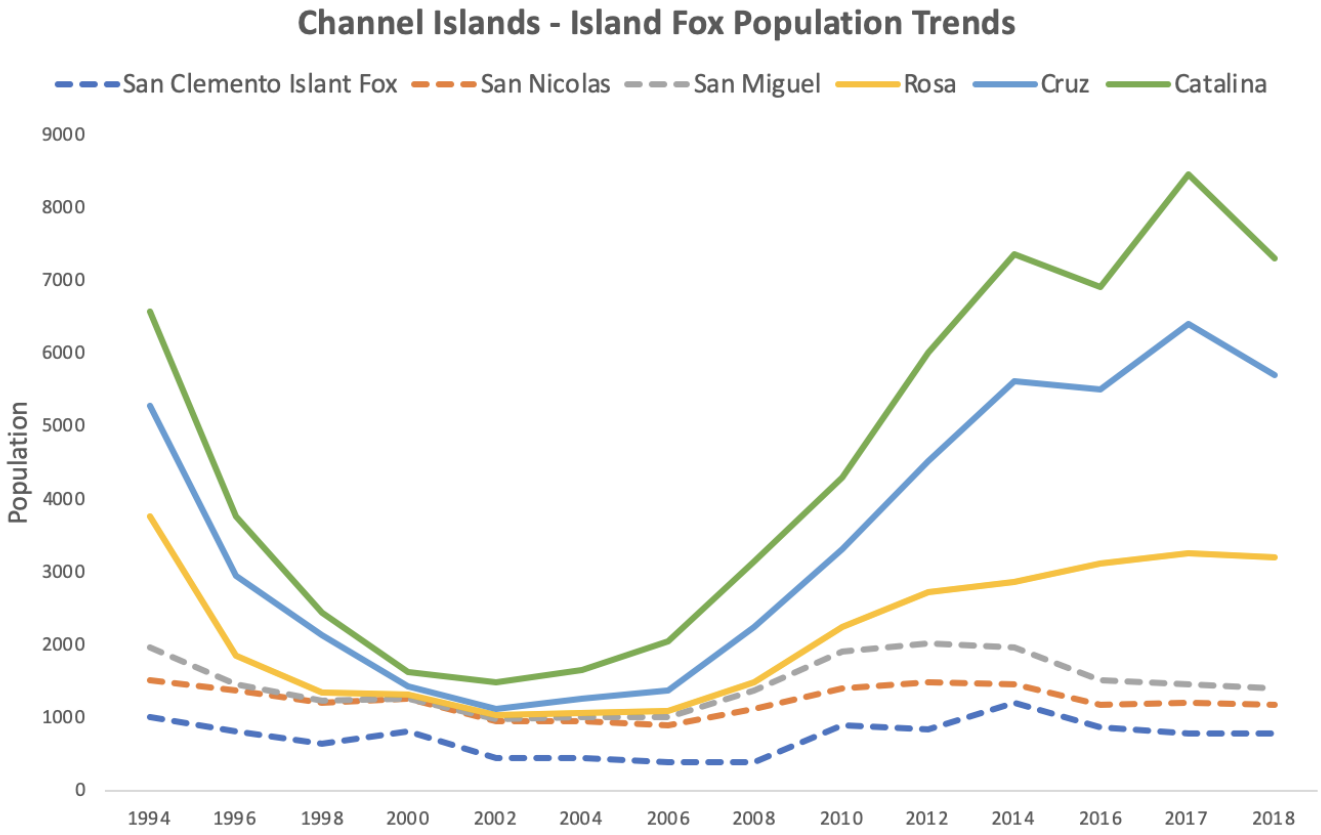


Figure 13.4.*a*: Population trends for subspecies of island fox (solid lines = large island subspecies, dashed lines = small island subspecies). Graph by Rachel Schleiger (CC-BY-NC) modified from data in 2019 Island Fox Status Update.

Table 13.4.*a***:** The 2019 designated statuses for the subspecies of island fox based on fox population and island size. Graph by Rachel Schleiger (CC-BY-NC) modified from data in 2019 Island Fox Status Update.

Island	Island Size	Fox Population	Status
San Miguel	Small	171	Concerned
San Nicolas	Small	400	Improved
Santa Rosa	Large	1862	Stable
Santa Cruz	Large	2462	Stable
Santa Catalina	Large	1571	Stable
San Clemento	Small	778	Stable

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph and table?
3. Which subspecies of island fox do you think is the most stable? Why?
4. Which year(s) were bad (meaning population estimates were very low) for most of the island fox subspecies?
5. As noted in the graph, populations are estimated for each subspecies annually. Why do you think an annual estimation was chosen in the conservation plan instead of a longer time interval?

Raw Data From Above Graph(s)

Table 13.4.*b***:** Raw data for population trends for subspecies of island fox (solid lines = large island subspecies, dashed lines = small island subspecies). Graph by Rachel Schleiger (CC-BY-NC) modified from data in 2019 Island Fox Status Update.

Year	San Clemento	San Nicolas	San Miguel	Santa Rosa	Santa Cruz	Santa Catalina
1994	1000	520	450	1800	1500	1300
1996	810	550	100	400	1100	800
1998	650	550	40	100	800	300
2000	800	450	20	50	100	200
2002	450	500	25	60	90	350
2004	450	500	50	70	200	375
2006	400	506	100	80	300	650
2008	400	725	260	100	750	900
2010	900	500	500	350	1050	1000
2012	850	640	525	700	1800	1500
2014	1200	263	510	900	2750	1750
2016	860	329	329	1600	2400	1400
2017	775	255	255	1800	3150	2050
2018	790	400	200	1800	2500	1600

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13.5: Topics for Discussion

1. Read the manuscript by Pfab and Witkowski, (2000), which is a PVA study that is relatively easy to understand. Can you identify some strengths and weaknesses of this PVA? Which assumptions did this study make? What parameters were used? Are there any other model parameters you think could have been useful?
2. For this exercise, you are going to construct a simple PVA for a threatened frog species on a sheet of paper. This frog formerly occupied an expansive lowland forest, which over time was disturbed and degraded. A recent survey was able to find only ten frogs (five males and five females), all in one small, isolated forest patch that can accommodate up to 20 frogs. In the spring, males and females form mating pairs; each pair typically produce zero, one, two, three, or four, offspring that survive to breeding age the following year (to create this demographic dataset, flip four coins for each mated pair; the number of heads is the number of offspring). The sex of the offspring is assigned at random (flip a coin for each young animal, with heads for males and tails for females. Individuals not mated because of uneven sex ratios do not breed. After the breeding season, all the adult frogs die. (A) Run five different population simulations for five generations each, and chart population size over time. What percentage of populations would go extinct within the 10 generations? (B) Perform a sensitivity analysis by making the frogs' living conditions more severe. For example, lower the number of frogs found during the survey to six, or impose 50% mortality on offspring every year due to introduced rats. (C) Perform another sensitivity analysis by making the frogs' living conditions more accommodating. For example, examine the impact of supplying extra food to the frogs, which would allow more offspring to be produced each year. Examine the results of all your different models to determine which factor is most important to address to ensure the frog species does not go extinct.

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13.8: Summary

1. Protecting a threatened species requires a firm grasp of its population biology. Long-term monitoring using biodiversity inventories, population censuses, and demographic studies can reveal temporal changes in population size and distribution and help to distinguish short-term fluctuations from long-term decline.
2. Biologists are increasingly relying on innovative methods to track wildlife populations and demographics. Among the most popular are market surveys, hair snares and faecal sampling, while photos taken by tourists and camera traps have also been used to obtain population-level data.
3. Population viability analysis (PVA) uses demographic, genetic, and environmental data to predict changes in population sizes and extinction risk over time. Sensitivity analysis can be used to guide conservation action by estimating how different management actions will affect a population's extinction probability.
4. Minimum viable population estimates can be used to determine how many individuals are needed to reduce the threat of extinction, while maximum sustainable harvest estimates can be used to set harvest limits on species threatened by overharvesting.
5. Many surveys are poorly designed, leading to biased data, poor survey precision, and misleading results, which hamper our ability to halt biodiversity losses. To overcome these challenges, surveys should be representative, sufficiently large, and conducted repeatedly over time.

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CHAPTER OVERVIEW

14: Conserving Ecosystems

14.1: Introduction to Conserving Ecosystems
14.2: Measures of Biodiversity Loss
14.3: Ecosystem Monitoring
14.4: Maintaining Complex and Adaptive Ecosystems
14.5: Restoring Damaged Ecosystems
14.6: Ecosystem Restoration
14.7: Combatting Climate Change Through Ecosystem Conservation
14.8: Summary
14.9: Topics for Discussion
14.11: Bibliography

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14.1: Introduction to Conserving Ecosystems



Rising 500 m above the Sahelian plains of Mali, the sandstone cliffs of the Bandiagara Escarpment are home to the Dogon people, whose unique homes are carved into the cliff's walls. The Escarpment is a World Heritage Site, known for its outstanding cultural and natural value. However, both nature and humans are suffering from environmental degradation due to climate change and unsustainable land use. Photograph by Timm Guenther, https://commons.wikimedia.org/wiki/File:Les_Falaises_de_Bandiagara.jpg, CC BY-SA 3.0.

Habitat loss (and its associated degradation) is currently the most important threat facing the world's biodiversity today. When an ecosystem is destroyed or degraded, its ability to sustain wildlife is compromised, and the individuals that depend on that ecosystem for survival either need to adapt or move elsewhere, or they will die. Conversely, preventing ecosystem degradation and destruction is one of the single most important actions we can take to protect biodiversity. In the process, we also improve our own well-being, given that natural ecosystems are our first line of defence against natural disasters, and provide us with food, clean water, and other ecosystem services.

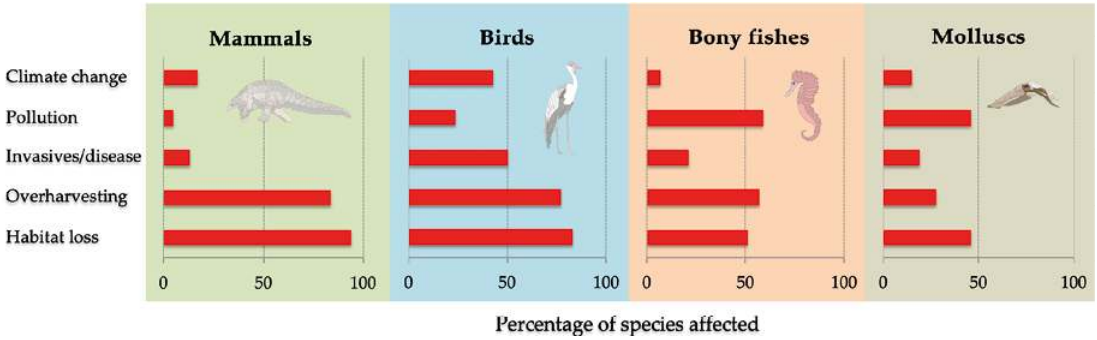


Figure 14.1 Habitat loss and degradation, much of which are driven by agriculture, are the most important threats, followed by overharvesting, invasive species and disease, and pollution. Groups of species often face similar threats: mammals and birds are more likely to be threatened by habitat loss, while fish and molluscs are more likely to be threatened by pollution. Percentages add up to more than 100% because many species face multiple threats. The influence of climate change is under-estimated because its impact on most species still need to be assessed. Source: IUCN, 2019, CC BY 4.0.

Broadly speaking, ecosystem conservation involves three different activities: (1) monitoring ecosystems, (2) maintaining ecosystems, and (3) restoring damaged ecosystems. While many books have been written on each of these three activities, the broad overview this chapter provides will hopefully enable readers to gain a basic understanding of the tools and methods used in ecosystem conservation.

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14.2: Measures of Biodiversity Loss

The Red List

The **International Union for the Conservation of Nature (IUCN)** coordinates efforts to catalog and preserve biodiversity worldwide. One way scientists gauge trends in biodiversity is by monitoring the fate of individual species. Since 1964, the IUCN has compiled information in the Red List of Threatened Species, which includes plants, animals, fungi, and selected brown algae species. Updates to the Red List are released every four years.

Species can be classified into nine Red List categories based on their extinction risk. Firstly, there are species that are already **extinct** and those that are **extinct in the wild**, meaning that the remaining individuals are only found in captivity. Species at risk of extinction are called **threatened**. Species that are at risk of becoming threatened are called **near threatened**. The Emperor Penguin (*Aptenodytes forsteri*) is an example a near threatened species, mainly due to habitat loss and climate change (figure 14.2.a). Those with little risk of extinction are designated **least concern**. Note that only a fraction of the 8-11 million species on Earth are identified (see The Number of Species on Earth). For many of the species that are identified, data still needs to be gathered before they can be assigned to a Red List category (**data deficient**). Less than 10% of the approximately 1.5 million identified species have been assessed for the Red List at all. Species that have not been assessed are deemed **not evaluated**.



Figure 14.2.a: The Emperor Penguin is an example of near threatened species. Image by Christopher Michel (CC-BY).

There are three categories of threatened species: **vulnerable, endangered,** and **critically endangered**. Of these, critically endangered species have the greatest risk while vulnerable species are at the least risk out of the threatened categories. The African elephant (*Loxodonta africana*) is listed vulnerable species due to poaching and habitat loss (figure 14.2.b). Interestingly, the forest subspecies (*L. africana cylotis*) is at much greater risk than the savanna subspecies (*L. africana africana*), but the Red List category is assigned at the species level in this case. The blue whale (*Balaenoptera musculus*) is endangered due to pollution, climate change, and poaching (figure 14.2.c). Fortunately, blue whale population size is increasing. Several species of pitcher plants, which trap insects as a source of nitrogen, are critically endangered due to overexploitation and habitat loss (figure 14.2.d).



Figure 14.2.*b*: The African forest elephant (*Loxodonta africana cylotis*) is at greater risk of extinction than the savanna subspecies. When both subspecies are grouped together, African elephants are considered vulnerable. Image by Peter H. Wrege (CC-BY-SA).



Figure 14.2.*c*: The blue whale (*Balaenoptera musculus*) is categorized as endangered according to the IUCN Red List. Image by Mike Baird (CC-BY).



Figure 14.2.*d*: *Nepenthes aristolochioides* is a critically endangered pitcher plant. Image by Alfindra Primaldhi (CC-BY).

Extinct and Threatened Animals

Scientists know much more about the state of **vertebrates**—especially mammals, birds, and amphibians—than they do about other forms of animal life. Of 6,594 described mammal species, 96 species have become extinct during the last 500 years (Mammal Diversity Database). According to the Red List, approximately 26% of mammal species worldwide are known to be threatened. A smaller percentage (about 14%) of the world's 10,721 identified bird species (Birds of the World) are threatened (figure 14.2.*e*).



Figure 14.2.*e*: North American passenger pigeons lived in enormous flocks and were once the most numerous birds on earth. Market hunting on a massive scale and habitat destruction combined to extinguish them as a species in the early twentieth century. Image by James St. John (CC-BY).

Among the well-studied vertebrates, amphibians are faring especially poorly. Of the more than 6,000 known species of amphibians, 35 have become extinct worldwide since 1500 (figure 14.2.*f*), and two others are extinct in the wild (Red List). Overall, 41% of the world's amphibian species are known to be threatened (Red List). Only small proportions of the world's species of reptiles and fish have been evaluated for purposes of the Red List. Among those, 34% of selected reptiles and 8% of selected bony fishes are threatened (Red List).



Figure 14.2.*f*: The extinct golden toad of Monteverde, Costa Rica, was last seen in 1989. Its extinction is attributed to fungal infection combined with especially hot, dry weather. Source: U.S. Fish and Wildlife Service via Wikimedia Commons

Invertebrates comprise the vast majority of animals, an estimated 97% of animal species. They include everything from insects and arachnids, to mollusks, crustaceans, corals, and more. Few of these groups have been assessed in a comprehensive way, but assessments within some groups call attention to disturbing, large-scale trends. For example, 33% of the world's reef-building corals are already considered threatened (Red List), and many more of them are experiencing rates of decline that move them toward threatened status (figure 14.2.*g*). The demise of reef-building corals has magnified ecological impacts, since so much other marine life depends on them.

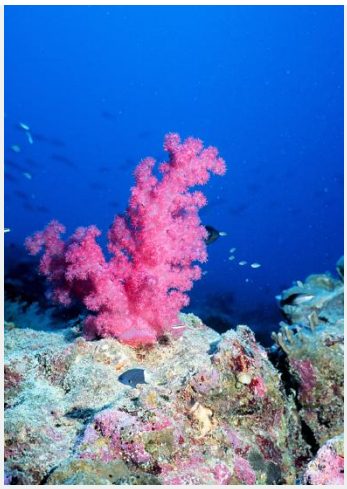


Figure 14.2.*g*: Reef-formal corals, such this pink soft coral, are at high risk of extinction. Source: Linda Wade via National Oceanic & Atmospheric Administration (NOAA)

Ecosystem Loss and Alteration

Another way of gauging biodiversity involves assessment on the scale of ecosystems. The causes of wholesale losses of ecosystems are much the same as those driving extinction or endangerment of species, with habitat destruction and fragmentation being the primary agent. Worldwide, for example, the conversion of land to agriculture and cultivation have led to significant losses in grassland ecosystems. In North America, nearly 70% of the tallgrass prairie ecosystem (which once covered 142 million acres) has been converted to agriculture, and losses from other causes, such as urban development, have brought the total to about 90%. Current estimates indicate that agricultural activity and cultivation systems now cover nearly 25% of the Earth's surface

According to the United Nations Millennium Ecosystem Assessment, by the beginning of the 21st century, 15 of the world's 24 ecosystems, from rainforests to aquifers to fisheries, were rated in serious decline. For example, tropical rainforests, which are the habitats for nearly half of the world's plant and animal species, covered about 4 billion acres in past centuries, but only 2.5 billion acres remain and nearly 1% is being lost annually. Losses have been especially severe in the tropics of Africa and Southeast Asia. Current estimates indicate that about 50% of the world's wetland habitat has been lost. (Note that wetlands are a broad collection of many different ecosytem types.) The former extent of wetland habitats worldwide (fresh, brackish and salt) is difficult to determine but certainly exceeded a billion acres.

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14.3: Ecosystem Monitoring

A complex and adaptive ecosystem in which all the chemical, physical, and biological components, functions, and processes are intact and functioning normally is considered a **healthy ecosystem** (but see Cumming and Cumming (2015), for a discussion on this value-based term). In contrast, disturbing any of an ecosystem's components, functions, and/or processes will, by definition, alter them to some degree (Table 14.3.1). In many cases, ecosystems that have been exposed to certain forms and levels of disturbances remain healthy because there is redundancy in the roles performed by different ecosystem components. This ability of an ecosystem to withstand certain forms and levels of disturbances is referred to as ecosystem stability. Ecosystem stability could be the result of one or both of two qualities: resistance and resilience. **Resistance** is the ability of an ecosystem to retain the same characteristic communities and natural cycles throughout and after a disturbance event, while **resilience** is the ability of an ecosystem to rapidly recover or adapt after a disturbance event. For example, if the number of native aquatic insect species decline after non-native fishes are introduced to previously fish-free ponds, the pond's ecosystem has low resistance. But if the native insect community recovers rapidly after the non-native fishes were removed, the ecosystem is resilient.

Table 14.3.1 Three ways how humans have changed the natural world.

Natural function	Changes attributed to human activities
Land surface	As much as half of the world's ice-free land surface has been transformed to cater to people's need for natural resources. Much of these changes are driven by agricultural activities.
Nitrogen cycle	Human activities release massive amounts of nitrogen into natural ecosystems on a daily basis. Much of this occurs through the use of nitrogen fertilisers, burning fossil fuels, and cultivating nitrogen-fixing crops.
Atmospheric carbon cycle	Scientists estimate that humans would have doubled levels of carbon dioxide in the Earth's atmosphere by the middle of this century. This is primarily the result of fossil fuel use and deforestation.
Wildlife populations	Human activities are currently causing a sixth mass extinction.
Pollutants	Pollution from human activities have become so omnipresent that it is hard to escape its impacts. Microplastics have been found in drinking water and the food we eat.

Sources: MEA, 2005; Kulkarni et al., 2008; http://www.livingplanetindex.org

Many forms of ecosystem disturbances are easy to observe. Consequently, monitoring these visible forms of disturbances—such as the outright destruction of a forest or plastic pollution on a beach—focuses less on detection and more on developing systematic survey protocols that can provide information on whether a disturbance is spreading and increasing in intensity, or whether conservation action is successful in containing the threat. However, some disturbances are subtler, unobtrusive, and thus difficult to detect; examples include pesticide drift and agricultural runoff. Adopting a "wait and see" approach to detecting these invisible forms of disturbances can be particularly damaging, since that approach generally ends at a point where the harm will either be impossible to reverse or will require significantly more resources and time than would have been the case if the problem was addressed earlier. In this way, there are many similarities between monitoring ecosystem health and human health—some ailments are easier to diagnose than others, but we avoid the worst-case scenarios by screening regularly for diseases and treating the threatening ones promptly.



Figure 14.3.1 Biologists sampling benthic invertebrates from Lake Ontario, which straddles the New York/ Canada boundary, as part of a Cooperative Science and Monitoring Initiative project . (Photo By NYS DEC, via Flickr, CC-BY-NC-ND-2.0).

Perhaps the most popular method conservation biologists use to monitor ecosystem health is known as **biomonitoring**. By monitoring the abundance and/or fitness of sensitive species (Box 14.3), biologists can sometimes detect ecosystem degradation before it becomes apparent to the human eye or escalates to a point where it starts impacting human lives (Bornman and Bouwman, 2012). Monitoring environmental indicators such as macroinvertebrates (Figure 14.3.1) is particularly popular when examining the ecological condition of aquatic ecosystems; mayflies, caddisflies, and stoneflies—specialists of undisturbed streams—are often replaced by flies and midges in polluted and disturbed environments. Sometimes however, when plants or animals are not easily monitored, certain aspects of those species can still be monitored. One example is monitoring total plant biomass as a proxy for soil nutrients or intensity of herbivory. Another option is to perform a bioassay, during which a sensitive organism (typically water fleas or plankton) is released into a potentially contaminated environment to see if death or declining health occurs.

Box 14.3 Using Insects to Monitor Environmental Health

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Insects are important to nearly every terrestrial food web in the world and serve a multitude of different purposes: some insects are responsible for pollination of plants while others are scavengers that clean up dead plant and animal material. In some cases, our understanding of an insect species' ecological role can make it suitable as an indicator of environmental health. Biomonitoring looks at the presence and abundance of organisms within their natural communities to assess the impact of environmental disturbances; this knowledge can then be used to guide ecosystem management. An indicator taxon is one whose impact can be specifically and precisely measured; its abundance serves as a measure of the overall health of an ecosystem. Understanding how the presence and abundance of indicator species, and the relative abundance of tolerant and intolerant species, reflects the relative health of an environment can allow for rapid surveys of impaired ecosystems to assess trends as well as to track changes following remediation and restoration efforts.

Over the past few years, biomonitoring with insects as indicator taxa has become increasingly popular in Ghana. Butterflies are especially popular because they show varying relative sensitivities to environmental change; the abundance of certain butterfly species can for example be used to study the impact of habitat loss, fragmentation, and climate change (Kyerematen et al., 2018). The presence and abundance of butterflies more characteristic of open and disturbed ecosystems (Figure 14.3.2) can, for example, be used as an indicator of forest degradation.



Figure 14.3.2 Because the green-banded swallowtail (*Papilio nireus*) prefers open woodlands, researchers in Ghana are using their abundances in forests as a measure of habitat degradation. Photograph by Celesta von Chamier, CC BY 4.0.

Aquatic insects, particularly benthic macroinvertebrates, are also useful bioindicators. Freshwater resources, such as lakes and rivers, provide water for drinking and washing to local people, and a home for economically important taxa, such as fish and shellfish. Protecting these water sources is therefore important for safeguarding people's health and livelihoods. The presence, absence, and diversity of certain benthic macroinvertebrates, even at the order level, can provide valuable information about whether a waterbody is being degraded or not (Kyerematen et al., 2014; Nnoli et al., 2019). A recent study showed that dragonfly and damselfly diversities and populations along the coastal Densu River in Ghana vary widely depending on the physical condition of the river and surrounding area (Acquah-Lamptey et al., 2013).

With their high diversity and varying tolerances for ecosystem conditions, insects are extraordinarily suited as ecological indicators in environmental monitoring. Each insect species is also part of a wider biological community with important ecological roles. If lost, not only will an abundance of other life be affected, such a loss may also hint at a looming crisis facing people living in those compromised ecosystems.

At times, conservation biologists may need to measure the physical environment to assess environmental health. This approach is particularly common when tracking pollution, for example by monitoring for changes in **biochemical indicators**. For example, measuring total phosphorus, nitrogen, and dissolved oxygen load in streams and other surface water can help scientists track eutrophication. Measuring these and other biochemical indicators is usually accomplished directly via chemical analysis of environmental samples, such as soil and water. Sometimes however, biochemicals indicators are tracked indirectly via biological samples obtained from plants and animals. Because they bio-accumulate heavy metals and other pollutants, filter feeders such as clams and mussels (e.g. Bodin et al., 2013) are particularly useful in this regard as they can be used to detect very low concentrations of harmful chemicals in the environment.

Monitoring ecosystems with geospatial analysis

A persistent challenge facing biologists who monitor ecosystems—and other aspects of biodiversity—is achieving consistency across space and time. Consider a survey of a sensitive bird community to track ecosystem change; not only will different observers have varying levels of experience, but they will almost certainly see different birds during an early morning census compared to one later in the afternoon due to differences in biology and behavior between species. These factors introduce error into monitoring data, which in turn can mask the effect a biologist tries to measure (Buckland and Johnston, 2017). Laboratory scientists' control for these **confounding factors** by making multiple measurements under strictly controlled conditions. But for conservation biologists working outside in the wind and rain, repeated observations under similar conditions can be near impossible.

Geospatial analysis offers a variety of tools that allow biologists to overcome some of these traditional field monitoring challenges. These tools use **geographic information systems (GIS)** computer software packages to store, display, and manipulate a wide variety of data representing the natural environment, biodiversity, and human land-use patterns as they relate to one another on Earth's surface. GIS thereby allows biologists to easily visualize and analyze spatial relationships between mapped data, which

may include aspects such as vegetation types, climate, soils, topography, geology, water availability, species distributions, existing protected areas, human settlements, and human resource use (Figure 14.3.3). Understanding such relationships helps conservation biologists to prioritize their actions, for example by identifying areas where data are lacking, where an environmental change requires further investigation, or where gaps in regional protected areas network exist.

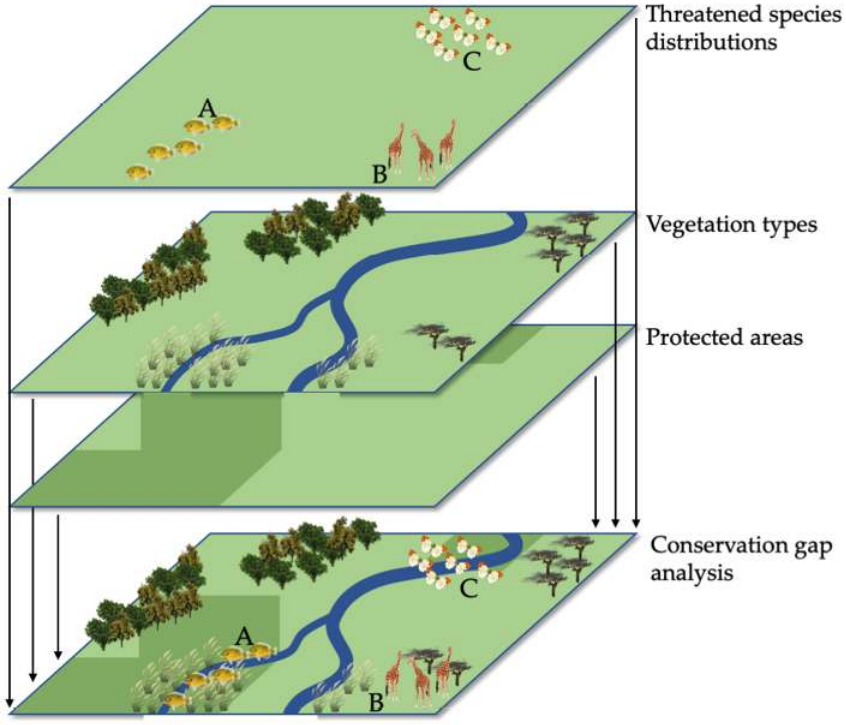


Figure 14.3.3 Distribution maps for three threatened species are overlaid onto maps of protected areas and vegetation types to identify potential conservation gaps. This GIS analysis shows that Species A is well protected, Species B is protected to some extent, and Species C is not protected at all. Species C would thus be considered a high conservation priority. After Scott et al., 1991, CC BY 4.0.

Remote sensing is a special branch of geospatial analysis directed at obtaining ecosystem data without making physical contact (i.e. boots on the ground) with the observation site. Before the turn of the 20th century, the most popular form of remote sensing was aerial photography from airplanes. These aerial photographs facilitated geographers' ability to draw maps of landscape features, including human infrastructure and natural vegetation patterns. Remote sensing opportunities greatly expanded from 1960 onward, with the launch of the National Aeronautical Space Administration's (NASA) first **Earth observation satellites**, to take photographs of Earth from space for weather forecasting. Subsequent satellite programs expanded their scope to also collect additional data of Earth's surface and atmosphere. While much of this data would have been useful to conservation, early satellite data products were very expensive and thus largely out of reach of the larger conservation community. This all changed in 2008 when NASA started distributing their Earth observation products for free to the public, heralding an era in which remote sensing became a standard tool in the conservation field.

Today, hundreds of Earth observation satellites circle the planet, offering near real-time access to unbiased and consistent environmental datasets of nearly all terrestrial surfaces, oceanic surfaces and floor depths, and the atmosphere, all from the comfort of a computer connected to the internet (Wilson et al., 2013). Scientists use these products in ecosystem monitoring efforts, including monitoring water quality (Dube et al. 2015), forest loss (Laporte et al., 2007) (Figure 14.3.4), coral reef health (McClanahan et al., 2011), desertification (Symeonakis et al., 2004), and fire regimes (Archbald et al., 2010). Linking the information obtained by Earth observation satellites to biological information collected on the ground has proved invaluable in monitoring species' threat statuses (Di Marco et al., 2014), ecosystem connectivity (Wegmann et al., 2014), and habitat suitability (Torres et al., 2010), as well as understanding how biodiversity responds to environmental changes.



Figure 14.3.4: NASA's Landsat images of the Nile Delta from 1984 (left) to 2021 (right). Egypt is losing agricultural land in the Nile Delta due to urban development at an alarming rate. Only 4% of Egypt's land is suitable for agriculture and is being converted as the population in Egypt has grown to 100 million, of which 95% live in the Nile Delta. (Image courtesy of NASA)

The popularity and utility of these products have preceded and facilitated the expansion of other remote sensing applications in ecosystem monitoring. Among the most popular are radar products (Figure 14.3.5), which have become the standard method for obtaining elevation and other terrain data (NASA, 2009, 2013), as well as estimates of carbon stocks (Carreiras et al., 2012). Advances have also been made in using hyper-spectral imagery to monitor soil properties (Mashimbye et al., 2012) and even individual trees (Naidoo et al., 2012). LiDAR has enabled biologists to map three-dimensional vegetation, which can be used to explain animal movements (Loarie et al., 2013; Davies et al., 2016) and measure carbon stocks and forest loss (Burton et al., 2017).

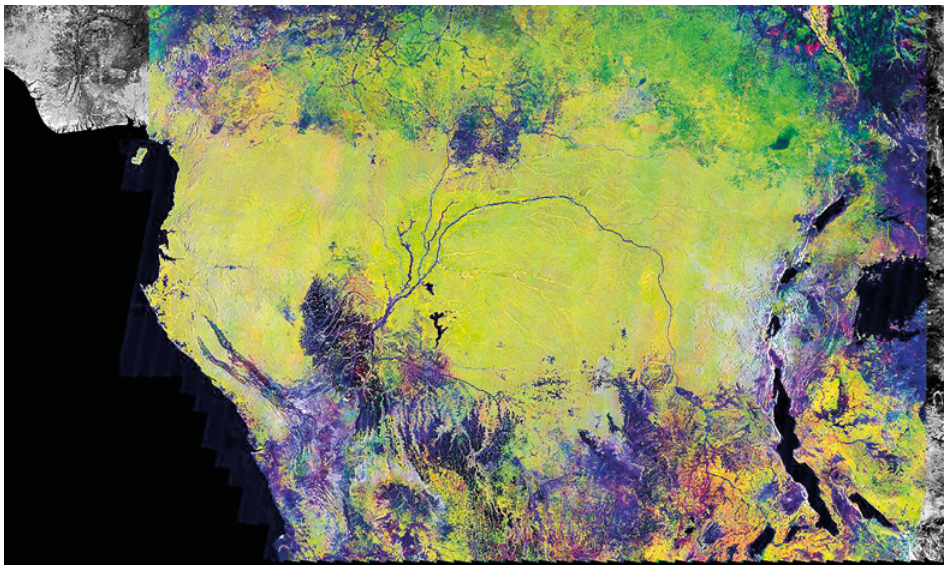


Figure 10.3.5 A radar composite of equatorial Africa obtained in 1996 by Japan's Earth Resources Satellite. The area shown covers about 7.4 million km2. Due to the filters applied to the image, yellow represents flooded forests, palm plantations, and urban areas; green represents forest, and black represents surface water. Savannahs may be black, blue, purple, or green, depending on the ecoregion type. Displays such as these allow researchers to map ecosystems, and ecosystem loss at a much larger scale than if only field observations were used. Image courtesy of NASA, https://images.nasa.gov/details-PIA01348.html, CC0.

Despite the opportunities presented by remote sensing, it is critical to remember that it is not a substitute for traditional field monitoring methods. Most importantly, remote sensing applications cannot be considered reliable without verification using field data (see Burton et al., 2017). Most remote sensing products are also relatively new, which does not allow for enough opportunities to compare across time. In the absence of historical remotely sensed data, geospatial analysts usually choose the best **reference site** currently available; this may expose those analysts to **shifting baseline syndrome**, because the chosen reference site may be vastly different from earlier states the scientists are actually interested in studying (Bunce et al., 2008; Papworth et al., 2009). Remote sensing is, therefore, not a cure-all for ecosystem monitoring challenges; it is simply a powerful tool to supplement traditional field-based monitoring.

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14.4: Maintaining Complex and Adaptive Ecosystems

Even when monitoring data show that an ecosystem is healthy, management is often required to maintain those desired conditions. That is because very few ecosystems are completely free of human influences. For example, rivers and streams carry pollutants far beyond the point of contamination and roads acting as firebreaks suppress natural fire regimes. Today, even the most isolated patches of habitats may not be completely protected from the influences of global processes such as climate change. To maintain complex and adaptive ecosystems, conservation biology is guided by four complementary management principles: (1) maintain ecosystem processes, (2) minimize external threats, (3) be adaptive, and (4) be minimally intrusive.

Maintaining critical ecosystem processes

Ecologists generally divide **ecosystem processes** into four disparate yet interdependent categories: water cycling, nutrient cycling (which include the carbon and nitrogen cycle), energy flow, and community dynamics. The linkages between these processes create feedback loops, where changes in one factor may be amplified elsewhere. Maintaining ecosystem processes is thus very important because small, seemingly small, changes can have major impacts on biological communities.

The water cycle

The water cycle refers to the distribution of water through an ecosystem, and includes the absorption and distribution of water vapor, rainwater, and surface water in lakes, rivers, and oceans. Since much of the water cycle happens out of sight and is generally associated with large-scale phenomena, such as weather patterns and anthropogenic climate change, land managers sometimes fail to recognize how local factors influence the water cycle. This is a grave mistake; many deadly ecological disasters (e.g. desertification, flooding, and landslides) can be attributed to disturbances to the water cycle at the local scale.

Outside of ensuring sustainable use of water resources, maintaining vegetation cover arguably plays the most important role in preserving the water cycle at local scales. Plants and their roots enable soil to store and release water, and make these water reserves available for soil organisms, which in turn aid in decomposition of dead plants and animals. In contrast, a loss of vegetation cover increases surface runoff, which leads to deteriorating soil conditions through nutrient **leaching** and erosion of fertile topsoil. An increasing number of studies have also shown how forest loss can change a region's climate by reducing rainfall which in turn exacerbates drought conditions (Lawrence and Vandecar, 2015). For example, forest clearing for agriculture has reduced rainfall by 50% over much of West Africa (Garcia-Carreras and Parker, 2011). Many forest restoration programs thus focus on reversing these losses.

When restoring degraded forests and other ecosystems to repair the water cycle and other ecosystem services, it is important to remember that complex ecosystems with locally-adapted plants are generally the most effective in maintaining the water cycle and other ecosystem services (Burton et al., 2017).

The nutrient cycle

The nutrient cycle involves the cycling of essential nutrients such as carbon, nitrogen, sulphur, and phosphorus through the ecosystem. Like the water cycle, natural vegetation cover plays an important role in maintaining the nutrient cycle. That is because plant roots slow water runoff which, in turn, help soil to retain nutrients dissolved in water. Plants also form a major component of above-ground and below-ground biomass. When dead plant biomass is decomposed along with animal waste products, nutrients previously absorbed through plant roots are released back into the soil and water, where they can once again be absorbed by living plants and other consumers.

Unfortunately, vegetation cover, decomposition, and fire dynamics (discussed below) alone cannot ensure a healthy nutrient cycle. Much land is nutrient impoverished because soil nutrients are lost quicker than they are replaced. One of the main causes is unsustainable agricultural practices (Sanchez, 2010), such as farming on sandy soils and in tropical forests. These areas are nutrient-poor, so crop yields are typically low. Because these areas are prone to leaching, a large proportion of synthetic fertilizers added to supplement impoverished soils leaches into groundwater or washes into nearby streams and lakes, threatening water supplies by causing harmful algae blooms and eutrophication. To compensate, the failing farmers may resort to even more unsustainable land conversions (Wallenfang et al., 2015). Careful management of the nutrient cycle is thus critical for both biodiversity conservation and socio-economic well-being, particularly given its importance to food security (Drechsel et al., 2001). To achieve this, there is an urgent need to adopt more sustainable land management practices.

Ecosystem processes are linked into multiple feedback loops, so changes in one factor are amplified elsewhere.

Energy flow

Energy flow—a crucial component of ecosystem productivity —refers to the capture and storage of solar energy by primary producers (photosynthetic plants, algae, and some bacteria), and the distribution of that energy to consumers, detritivores, and decomposers. Although solar energy can appear as an unlimited resource in many ecosystems, the energy available to consumers (i.e. herbivores and carnivores) is limited because only about 10% of the energy obtained at one trophic level is passed on to the next (Figure 14.4.1). Being at the top of the food chain, apex predators are in a particularly vulnerable position because seemingly small disruptions at lower trophic levels will have a cumulative impact on the energy available to them. Such disruptions may include reduced prey populations (e.g. overharvesting of herbivores) or foraging disruptions (e.g. a predator needing to walk further to find prey). Maintaining energy flow generally involves maintaining complex, species-rich ecosystems so that consumers have ample opportunities to fulfill their energy needs for finding prey, growth, reproduction, and other activities.

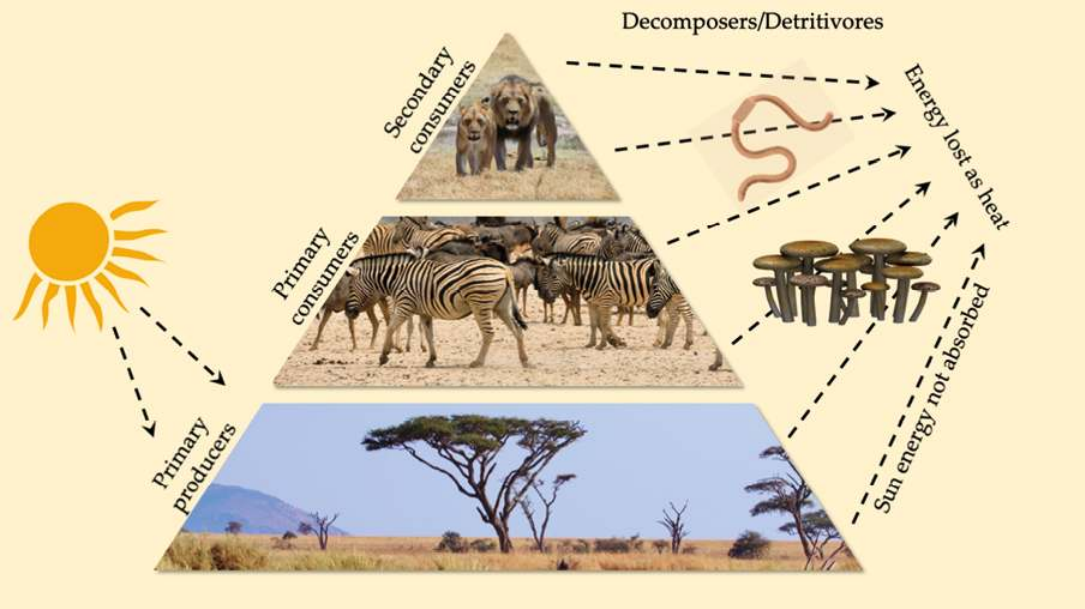


Figure 14.4.1 A food pyramid of a model savannah ecosystem, showing the various trophic levels and energy pathways. About 90% of energy is lost at each trophic level through respiration and animal waste excretion.CC BY 4.0.

Community dynamics

In ecosystem conservation, maintaining viable populations of different interacting species is as important as maintaining important ecosystem processes, such as ecosystem productivity and ecological succession. This focus often falls on maintaining populations that form part of important mutualistic relationships such as pollination and seed dispersal, predator-prey interactions, and even healthy levels of competitive and parasitic interactions (which allow more species to persist). Of interest is the preservation of keystone species and ecosystem engineers, which has an outsized effect on community dynamics. As illustrated in this, and other, chapters, disrupting community dynamics through pollution, overharvesting, or any other threat facing biodiversity, generally leads to impoverished natural communities. Impoverished communities may in turn provide opportunities for invasive species to colonize an area, further perpetuating biodiversity losses.

Fire Dynamics

Although fire is generally not considered one of the four fundamental ecosystem processes, it plays such an important role in biodiversity management, including maintaining the four fundamental ecosystem processes, that it deserves its own discussion. Burning existing vegetation releases carbon and other essential nutrients beneficial for plant growth into the environment. Similarly, fire also plays a critical role in the flow of energy, community dynamics, and overall maintenance of **fire-dependent ecosystems**, such as grasslands, savannahs, and Mediterranean communities. Suitably low intensity fires seldom kill living plants; rather, they encourage seed germination and seedling growth by reducing dead material that may crowd new growth, by exposing bare mineral soil (the substrate required for many seeds to germinate), and by releasing vital nutrients into the soil. This periodic

removal of dead material also prevents fuel load accumulation, thereby preventing future fires from becoming destructive. In contrast, without fire, fire-dependent ecosystems will slowly transform into unproductive scrublands suffocated by encroaching woody vegetation (Smit and Prins, 2015). Then, when wildfires do occur (e.g. through human negligence or lightning) the resultant accumulated fuel loads increase the intensity and heat of fires, creating very dangerous and difficult to control scenarios.

Obviously, given the potentially destructive force of fire, land managers who use fire as a management tool must consider many aspects before setting a **prescribed burn**, also known as a controlled burn (Figure 14.4.2). Foremost, to prevent a fire from becoming destructive to natural communities and nearby human developments, burning must be done in a well-planned manner with careful consideration given to the area's ecology, weather forecasts, and fire-readiness of the site (Goldammer and de Ronde, 2004; Kelly and Brotons, 2017).



Figure 14.4.2 A fire crew from the Kaibab National Forest in Arizona set and manage a prescribed fire. The fire is intended to mimic natural periodic fire and reduce fuels, keeping the forest ecosystem healthy. (Photo by David Hercher, US Forest Service, Southwestern Region, Kaibab National Forest, from Flickr CC BY 2.0).

Fire **management plans** that match natural fire regimes produce the best results for effective **ecosystem management**. Land managers accomplish this by ensuring that their burn plans mimic the local area's natural fire season, fire frequency, and flame intensity, while also accounting for management goals and local ecological factors such as rainfall and geology (see e.g. van Wilgen et al., 2010, 2014). The size of each burn area must also be considered. Best practices suggest not burning the entirety of a community at a time; rather, burning only portions of an area allows for more habitat heterogeneity, provides opportunities for non-burrowing animals to take refuge in unburned areas, and maximizes ecosystem diversity. However, because of the high density of houses in some ecosystems, the periodic fires needed for locally-adapted vegetation to persist are often extinguished because of the threat to human settlement (van Wilgen et al., 2012).

While fire plays an important role in many landscapes, it is important to note that overly frequent fires can be a threat even to fire-dependent communities. For example, habitat degradation resulting from too many fires in quick succession can leave a natural community vulnerable to invasions by harmful species (Masocha et al., 2011). Overly frequent fires can also prevent seedling recruitment by directly killing vulnerable young plants, and by depleting the seed bank because seedlings do not have sufficient time to mature and set seed.

Fire-sensitive ecosystems (e.g. tropical forests, high mountains, and peat bogs) must also be managed carefully to avoid fire disturbance, which can lead to habitat loss and edge effects. One way to accomplish this is to educate farmers living adjacent to fire-sensitive ecosystems on how to safely manage their land with fire. Careful fire management, led by good science, is bound to become increasingly important in the future, given that wildfires are expected to become more frequent and more intense under climate change (Pricope and Binford, 2012).

Minimizing external threats

Human activity cannot and does not need to be eliminated from nature; in fact, the structure and diversity of many of today's natural landscapes—and to which today's wildlife are adapted to—are in part the result of past human activities (e.g. Garcin et al., 2018). Today, there are over 7 billion people on Earth, so our impacts are more pervasive than for the majority of history. There is,

thus, an urgent need to utilize natural resources in such a way that future generations will also benefit from the ecosystem services that previous generations have left us. This requires a concerted effort from every sector in human society to minimize those threats we impose on the ecosystems around us. This includes preventing pollution, large-scale human disturbances, overharvesting, and habitat destruction.

Major strides have been made in recent years towards achieving these goals. Governments are updating laws to safeguard the environment, industries are refining recycling and waste disposal methods, new techniques are being developed to remove pollutants from the environment, and individual citizens are becoming more aware of their individually small but collectively significant impacts on the environment. We should be proud of the progress being made and continue to strive for improvements. But one external threat that requires greater attention and understanding is invasive species.

Controlling invasive species

Invasive species degrade and destroy natural ecosystems by outcompeting native species, disturbing ecosystem processes, and altering the physical environment. Limiting these harmful impacts can be particularly challenging since exotic species that establish themselves in a new area can build up such large numbers, become so widely dispersed, and be so thoroughly integrated into ecosystems (i.e. naturalized) that eradicating them entirely would be extraordinarily difficult and expensive, or as in the case of tickberry (*Lantana camara*) perhaps even impossible (Bhagwat et al., 2012). This is not only a problem facing conservation biology, but also agriculture, where invasive species often spread from one farm to another, forestry, where invasive species are spread between saw mills and along logging routes, and fisheries, where native resources are outcompeted, sometimes up-ending an entire local industry. The impact of invasive species on farming communities is particularly severe—they lose tens of billions of dollars each year while trying to combat deteriorating grazing lands, reduced crop yields, and escalating pest control expenses.

Because invasive species are often very hard to eradicate once established, the foremost step in avoiding invasive species' harmful impacts is to avoid opportunities for new invasions. This requires raising awareness across all levels of society about the dangers posed by invasive species, both to the natural world and to agricultural and natural resources systems. There is also a need for citizens, scientists, and industry to monitor for potential and known invasive species, and promptly implement intensive control efforts to stop establishment and spread. Florida citizens are asked to report sightings of the Burmese python, which is disrupting the Florida Everglade ecosystem (Figure 14.4.3) These pythons are thought to have originated as released or escaped pets but have now increased substantially in numbers. The **Global Register of Introduced and Invasive Species** (http://www.griis.org) is a free, online searchable source to facilitate these tasks, by providing information about the impact and control of invasive species. Governments can also partake in efforts to control invasive species. While most African countries screen agricultural imports for pests, countries, such as Australia and New Zealand, take this task particularly seriously, with trained officials screening each visitor (and returning residents) and package for hitchhiking species before they cross those countries' borders. Lastly, it would require increased dialogue between conservation biologists and land managers to make a careful and thorough assessment prior to the deliberate introduction of a new species, even if thought of as beneficial.



Figure 14.4.3: The Burmese python, *Python molurus bivittatus*, native to southeast Asia, has been introduced to the Florida Everglades where it has led to significant declines in animal populations on which it preys including wood storks, Key Largo woodrats and bobcats. The pythons also compete with native predators for habitat and food. (Photo by US Fish and Wildlife Service, via Wiki commons, CC-BY-2.0)

Despite best practices, not all invasions can be prevented, and for those that do occur, an early detection and rapid response strategy offers the best chance to limit harm. This usually involves raising awareness of potential invasive species to ensure biologists and other stakeholders will recognize a new invasion, efforts to screen for such species on a regular basis, and implementing direct attack approaches, such as using herbicides, pesticides, or mechanical control once detected. While addressing a new invasion as soon as possible, it is also important to consider and contain the risks each direct attack approach carries. For example, herbicides and pesticides carry a risk of killing non-target native species via pesticide drift, while mechanical control may cause disturbances such as trampling, undue soil disturbance, and even pollution.

Another method to manage established pests is biological control, also called biocontrol. Biocontrol typically relies on one or more natural enemies from an invasive species' original range to control the pest in its introduced range. One of the main benefits of biocontrol is that it ensures cost-effective, long-term, area-wide control of an invasive species, beyond the capabilities of chemical pesticides and mechanical control. Biocontrol also allows for opportunities to control invasive species that are hard to manage with chemical pesticides and mechanical control (at least without significant additional harm to the environment), such as submerged aquatic weeds (Coetzee et al., 2011). Third, biocontrol agents are highly host-specific, thereby eliminating the impact that chemical pesticides and mechanical control have on non-target organisms. Lastly, an effective biocontrol agent ideally eliminates the need for chemical pesticides and mechanical control, thereby reducing threats such as pesticide pollution and ecosystem degradation.

Biocontrol does have some drawbacks. Primary among them is the significant upfront investment required, as candidate species first need to be found, and then extensively tested for host specificity and potential interactions with native wildlife before being released. Biocontrol also requires careful monitoring after release to determine effectiveness as well as to carefully check for impacts on non-target native species. This monitoring needs to be conducted over the long term, because biocontrol agents typically require several years before they establish self-sufficient colonies in the wild and might only then show signs of unintended impacts. Because alternative methods for controlling invasive species can also kill biocontrol agents (causing conflicting results and wasted resources), additional coordination is required before applying biocontrol and alternative pest management strategies simultaneously in the same area. Lastly, there is no guarantee that a biocontrol agent will be effective.

While the most popular biocontrol agents generally involve insects, disease-causing pathogens can also be used for biocontrol. Feline panleukopenia virus (also known as feline distemper) was highly effective in managing a feral cat population that caused the extirpation of seabirds on Sub-Antarctic Marion Island; some birds are now even returning as breeders (Bester et al., 2002). In an effort to reduce the use of chemical pesticides on food crops, efforts are also currently underway to find fungal pathogens to control introduced pests impacting African crops, including pea leafminers (*Liriomyza huidobrensis*), originally from South America (Akutse et al., 2013), and banana weevils (*Cosmopolites sordidus*), originally from Southeast Asia (Akello et al., 2008).

Some of the most effective pest control programs use an integrated pest management (IPM) approach that relies on using multiple pest control methods described above either simultaneously or in succession (van Wyk and van Wilgen, 2002). Strategic planning to coordinate best practices can also help offset some of the costs of invasive species control (Rahlao et al., 2010) and ensure that important pest sources are not missed (van Wilgen et al., 2007). When considering the best method to control an invasive species, it may also help to consider how our own actions inadvertently encourage invasive species. For example, an over-reliance on synthetic fertilizer has been shown to cause eutrophication (Chislock et al., 2013) and encourage growth of aquatic invasive plants (Coetzee and Hill, 2012; Bownes et al., 2012).

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14.5: Restoring Damaged Ecosystems

Ecosystems are regularly disturbed by natural phenomena such as floods from cyclones/hurricanes, or wildfires started by lightning. Nevertheless, natural disturbances typically lead to succession and a return to ecological conditions that can sustain high levels of biodiversity. In contrast, ecosystems that humans have damaged or destroyed through activities such as unsustainable agriculture and deforestation, overgrazing, or pollution tend to lose their ability to rebound without human intervention.

Ecological restoration is the practice of restoring damaged ecosystems to a point where their ecosystem functions and species composition resemble their original or near-original state. **Restoration ecology**, in turn, is the scientific study of restoring damaged ecosystems, communities, and populations. Ecological restoration is often the best method for providing for the long-term use of degraded sites, whether considered from the perspectives of ecology, social benefit, or even economic benefit. Consequently, and unsurprisingly, this practice and the science originally developed in response to attempts to restore economically valuable ecosystem functions: creating wetlands to prevent flooding, reclaiming mining sites to prevent pollution and soil erosion, revegetating overgrazed rangelands to increase grass production, and planting trees on cleared areas to improve agroforestry.

Best practices in ecological restoration have undergone major advances in recent decades. In the past, restoration methods mostly aimed for quick economic benefit, which resulted in simplified ecosystems that either failed to establish or degraded after a short time. To avoid such costly mistakes, restoration plans of today increasingly aim for the permanent re-establishment of healthy ecosystems that could support sustainable industries such as ecotourism, wildlife management, carbon sequestration, and low-level grazing by livestock. Ecological restoration often also makes economic sense; a study from South Africa found that every US $1 invested in restoring ecosystem services would generate US $8.30 for the local economy (de Wit et al., 2008).

Ecological restoration approaches

There are four main approaches to ecological restoration (Figure 14.5.1):

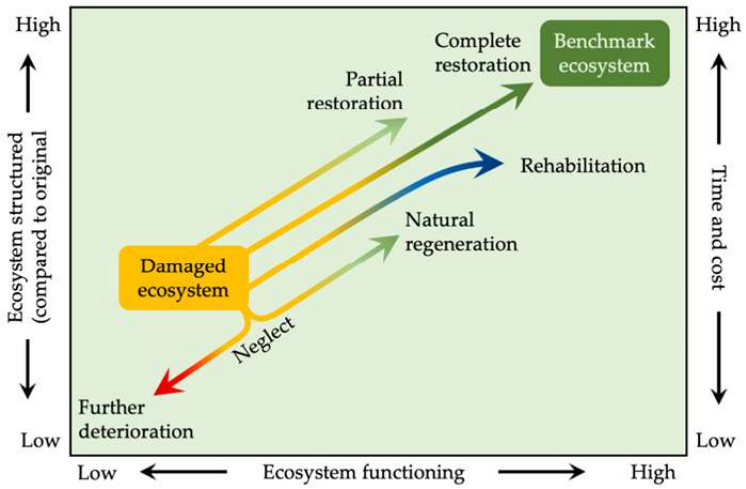


Figure 14.5.1 Several approaches can be followed when restoring an ecosystem, ranging from taking no action and letting the ecosystem regenerate naturally to completely restoring a degraded site. The best course of action will depend on a project's end goals and the resources available. After Bradshaw, 1990, CC BY 4.0.

- *Natural regeneration*. Degraded areas, such as abandoned fields or logged areas, are allowed to naturally reseed and return to grasslands or forests. Land managers often choose this approach when active restoration is too expensive, when earlier restoration attempts have failed, or when experience has shown that the ecosystem is resilient and can recover on its own (e.g. Crouzeilles et al., 2017).
- *Rehabilitation*. Land managers improve conditions of a degraded ecosystem by transitioning it to another, different ecosystem type. For example, land managers could rehabilitate a degraded forest by transitioning it to a tree plantation. Rehabilitation could involve replacing just a few species or many species.
- *Partial restoration*. Land managers restore some ecosystem functions and some of the species that were dominant or characteristic of the ecosystem. For example, as a part of a grassland restoration, land managers might initially replant a few key species that are hardy and contribute to ecosystem functioning; they could delay restoration of rare species until later phases.
- *Complete restoration*. Land managers restore an area to benchmark ecosystem structure, mix of species, and ecosystem functioning. Complete restoration usually requires an active program to modify the site, reintroduce native species, and eliminate or reduce the factors that were degrading the ecosystem.

Before a restoration project is initiated, and the type of approach is decided upon, land managers must consider how quickly the ecosystem can recover, resource needs and availability, the availability of locally adapted taxa, and the work that might be required to allow the restored

community to persist over the long term. Examples of specific considerations include how to prepare soils, how to handle translocated organisms, when and how much fertilizer and water to add, and how to prevent invasions by unwanted species (Galatowitsch and Richardson, 2005; Zabbey and Tanee, 2016). It is also important to remember that ecosystems generally fail to recover if the factor that caused them to become degraded in the first place is not removed or reduced. For instance, efforts to reverse desertification would require a reduction of grazing pressure and unsustainable agricultural practices.

Some conservation efforts center around a single species. Often this is a charismatic animal that elicits public interest, such tigers, sea otter, or the California Condor. The specific approach depends on specific threats based by the species of focus. A common strategy is to propagate rare plants and reintroduce them to locations where they were **extirpated** (went locally extinct). Protecting or restoring habitat is another component of the conservation of rare plant species.

Seemingly unimpressive species can still serve vital ecological roles, but they are often overlooked in conservation efforts. In fact, a 2007 study by Colléony and colleagues found that people more often donated to conservation efforts for species that were more similar to humans rather than choosing those that were at greatest risk of extinction. Broad approaches such as establishing protected areas and ecosystem restoration benefit charismatic and non-charismatic species alike. Additionally, broad approaches protect unidentified and species that have not been assessed.

To measure restoration success, biologists often aim to restore degraded areas to conditions (ecosystem functions or species composition) comparable to a chosen benchmark or **reference site**. Reference sites provide practical targets for restoration and can be used to quantitatively assess of the success of a restoration project. Comparing restoration progress against a reference site also allows land managers to intervene or adjust their methods if restoration goals are not being met. This approach, in which land managers monitor conditions and adjust their protocols as and when needed, is known as **adaptive restoration**.

Major restoration targets

Many human-altered ecosystems have proven to be good candidates for ecological restoration. These include tropical rainforests, wetlands, rangelands, and coral reefs.

Tropical forests: Tropical forests cover less than 10% of Earth's land surface; yet, they contain more than half of all terrestrial species (Cortlett and Primack, 2011). When these forests are lost, we lose substantial biodiversity and ecosystem services. For this reason, tropical forest restoration initiatives have received much attention in recent years. Towards the end of this chapter we will discuss a major global effort focussed on restoring degraded tropical forests, known as REDD+.

Wetlands: Because of the recognized importance of wetlands in providing flood control and other ecosystem services, damaged wetlands are frequently targeted in restoration efforts. Wetlands are defined by their hydrology; therefore, wetland restoration projects often the focus on restoring a site's original hydrology. Wetland restoration can also occur through activities like dam removals or replacing exotic vegetation that deplete groundwater with native vegetation to promote groundwater retention (Sirami et al., 2013). Importantly, true wetland restorations are notoriously difficult to accomplish. It can be relatively easy to replant a wetland to look as it previously looked, but to restore the foundational hydrology often requires sophisticated engineering. In many cases, partial wetland rehabilitation is the best that can be achieved.

Mangrove swamps (Figure 14.5.2) provide nursery grounds for many economically important fisheries, protect coastal communities against powerful storms, and prevent saltwater from intruding into freshwater systems (van Bochove et al., 2014). They are also among the world's most important carbon sinks, storing four times more carbon per hectare than other types of tropical forests (Donato et al., 2011). Yet, over 35% of the world's mangrove swamps have already been degraded by agriculture, urban expansion, pollution, and commercial shellfish farming (MEA, 2005; Giri et al., 2011). To regain these lost services, several communities are now restoring their mangroves, while also adopting more sustainable practices to reduce damage to these important habitats (Feka et al., 2009). Mangrove (as any other) restoration projects do need to be planned carefully to ensure success. For example, it is important to choose ecologically-appropriate species to plant, rather than the fastest growing species that promises quick (but not necessarily optimal) results. Another concern is that mangroves are often exploited, restored, and managed as forests, while the primary determinants of their function and structure—hydrology, soils, and nutrients—are neglected (Lewis, 2005; Gopal, 2013). Recent work showed that natural regeneration of mangrove swamps may produce more diverse, resilient, and productive ecosystems compared to planting efforts (Wetlands International, 2016). These issues will need to be addressed to ensure the long-term sustainability of mangrove restoration efforts.



14.5.2 (Left) Classic air-breathing roots of a mangrove tree in Senegal. Photograph by Ji-Elle, https://commons.wikimedia.org/wiki/File:Carabane-Mangrove.JPG, CC0. (collecting oysters among mangroves in Senegal's Saloum Delta. Photograph by Julien mmons.wikimedia.org/wiki/File:Cueilleuse_traditionnelle_d%27Hu%C3%AEtres_de_mangrove,_Sine_Saloum,_femme_du_village_de_Soucouta,_S%C3%A9n%C3%A A 4.0.

Seasonal drylands: Through extensive land mismanagement (primarily overgrazing and unsustainable agriculture), a large portion of seasonal drylands are undergoing desertification, the conversion of once-productive land to desolate man-made deserts—large dry unproductive dust bowls with no vegetation. The degradation of these lands has crippled agriculture, obliterated natural biological communities, and displaced millions of people. While many drylands seem to regenerate naturally when pressures associated with land mismanagement are removed at an early stage, extended periods of mismanagement hamper recovery by leading to a loss of natural seed banks, nutrients, and microsites that allow for seedling establishment.

Coral Reefs: Coral reefs are one of the world's most important marine ecosystems, both ecologically and economically. They provide food to local communities, support ecotourism industries, and protect coasts by reducing wave energy by as much as 97% (Ferrario et al., 2014). Yet, coral reefs are also one of the most threatened marine ecosystems, impacted heavily by overharvesting, pollution, sedimentation, and climate change. Nevertheless, restoring coral reefs is well worth it; a meta-analysis found that it is nearly 20 times cheaper to restore coral reefs than to construct artificial systems for coastal protection (Ferrario et al., 2014). As such, several initiatives are now in progress to restore coral reefs, ranging from transplanting corals and boosting sea urchin populations for seaweed control to creating artificial reefs that can act as substrate for coral settlements (Lindahl, 2003; Edwards and Gomez, 2007).

The future of ecological restoration

Research in restoration ecology has grown rapidly in recent years. Many reviews (e.g. Suding, 2011) and books (e.g. Falk et al., 2016) have recently been published on the topic. The Society for Ecological Restoration (SER) was established in 1988 to support the field, and two scientific journals (Restoration Ecology and Ecological Restoration) publish hundreds of papers each year on the topic, in addition to the papers published in other ecological and conservation journals. The growth in research provides scientists and land managers more studies and evidence to inform planning and improvement of restoration projects.

A recent development in the field involves **biodiversity offsets** (ten Kate et al., 2004; MacFarlane et al., 2016). A system generally used by developers, biodiversity offsets aim to achieve no net loss of biodiversity during economic development; some projects even aim for a net overall biodiversity gain. Developers accomplish this by compensating for the ecosystem damage (or loss of threatened species populations, Kormos et al., [2014]) that may be incurred during a development project. This compensation usually follows one or more of three main strategies: (1) reducing the extent of damage at the development site, (2) restoring or protecting natural communities at a different "receptor site" as compensation for what is being lost, and (3) enhancement of the remaining natural communities after development.

While biodiversity offsets (and other restoration initiatives in general) sound good in theory, it is important to remember that the most effective biodiversity conservation strategy remains protecting and managing intact ecosystems. Studies and practical experience have shown that ecological restoration efforts often fail to recreate key characteristics of their reference sites, including species composition or ecosystem functioning, even after years of effort and investment. It is also important to remember than some ecosystems regenerate very slowly—tropical forests require more than 100 years to develop (Bonnell et al., 2011)—so even effective restorations may take decades to provide the full range of benefits. In cases where biodiversity offsets are pursued, it is critical to ensure that these initiatives indeed offer true conservation gains by mitigating the various associated risks (Coralie et al., 2015; Gordon et al., 2015; Maron et al., 2016).

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14.6: Ecosystem Restoration

Ecosystem restoration is the process of bringing an area back to its natural state, before it was impacted through destructive human activities. It holds considerable promise as a mechanism for maintaining or restoring biodiversity and reinstating ecosystem services. It requires a broad interdisciplinary approach involving many different scientific fields of study (for example, biology, ecology, hydrology and geology). Reintroducing wolves, a top predator, to Yellowstone National Park in 1995 led to dramatic changes in the ecosystem that increased biodiversity. The wolves (figure 14.6.*a*) function to suppress elk and coyote populations and provide more abundant resources to the detritivores. Reducing elk populations has allowed revegetation of **riparian areas** (those along the banks of a stream or river), which has increased the diversity of species in that ecosystem. Reduction of coyote populations by wolves has increased the prey species previously suppressed by coyotes. In this ecosystem, the wolf is a **keystone species**, meaning a species that is instrumental in maintaining diversity within an ecosystem. Removing a keystone species from an ecological community causes a collapse in diversity. The results from the Yellowstone experiment suggest that restoring a keystone species effectively can have the effect of restoring biodiversity in the community. Ecologists have argued for the identification of keystone species where possible and for focusing protection efforts on these species. It makes sense to return the keystone species to the ecosystems where they have been removed.

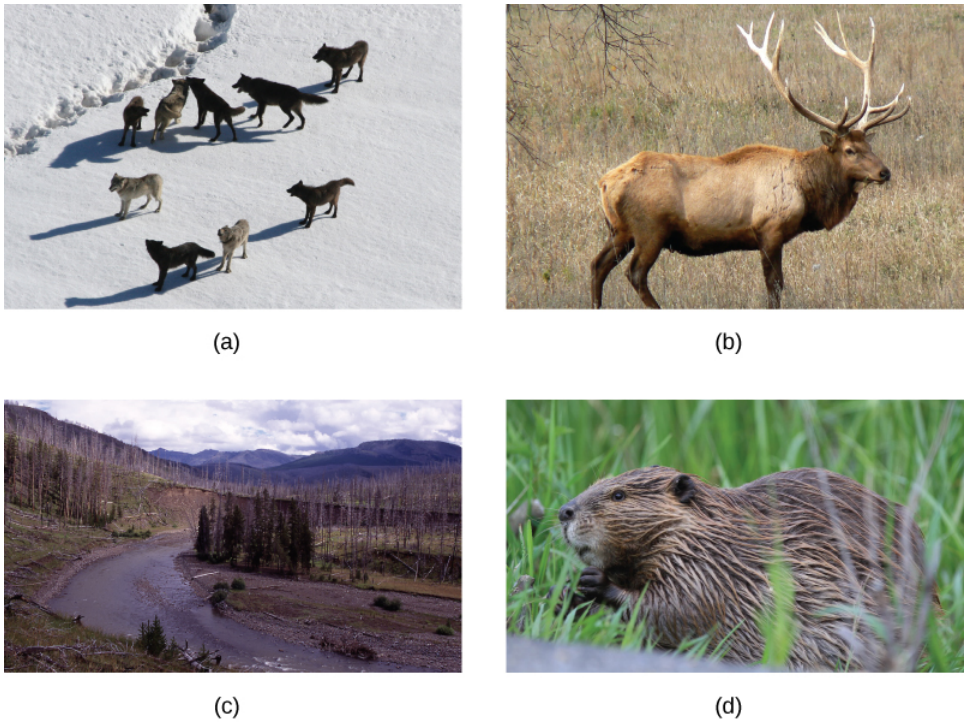


Figure 14.6.*a*: (a) The Gibbon wolf pack in Yellowstone National Park, March 1, 2007, represents a keystone species. The reintroduction of wolves into Yellowstone National Park in 1995 led to a change in the grazing behavior of (b) elk. To avoid predation, the elk no longer grazed exposed stream and riverbeds, such as (c) the Lamar Riverbed in Yellowstone. This allowed willow and cottonwood seedlings to grow. The seedlings decreased erosion and provided shading to the creek, which improved fish habitat. A new colony of (d) beaver may also have benefited from the habitat change. (credit a: modification of work by Doug Smith, NPS; credit c: modification of work by Jim Peaco, NPS; credit d: modification of work by "Shiny Things"/Flickr)

Other large-scale restoration experiments underway involve dam removal. In the United States, since the mid-1980s, many aging dams are being considered for removal rather than replacement because of shifting beliefs about the ecological value of free-flowing rivers. The measured benefits of dam removal include restoration of naturally fluctuating water levels (often the purpose of dams is to reduce variation in river flows), which leads to increased fish diversity and improved water quality (see Dams and Reservoirs for more about the impact of dams). In the Pacific Northwest of the United States, dam removal projects are expected to increase populations of salmon, which is considered a keystone species because it transports nutrients to inland ecosystems during its annual spawning migrations. In other regions, such as the Atlantic coast, dam removal has allowed the return of other spawning anadromous fish species (species that are born in fresh water, live most of their lives in salt water, and return to fresh water to spawn). Some of the largest dam removal projects have occurred recently, such as Elwha Dam on the Olympic Peninsula of

Washington State. The large-scale ecological experiments that these removal projects constitute will provide valuable data for other dam projects slated either for removal or construction.

Besides physical processes, socioeconomic factors must also be considered in a restoration project. Actions of humans have historically been important in shaping ecosystems, and are important in determining the success of restoration efforts. Because the cost to restore an individual site can involve millions of dollars, government support is a necessity.

Environmental Remediation

Danger to human health from both historic and modern pollution requires that cleanup measures be implemented. **Remediation** is aimed at neutralization, containment, and/or removal of the polluting chemicals. The goal is to prevent the spread of the pollution, or to reduce it to levels that will not appreciably risk human health. Many times, it is physically impossible or financially unfeasible to completely clear all contamination. Often, experts and the public disagree on how clean is clean enough.

Many communities are struggling to find the funds and technological expertise needed to clean up polluted areas. Some settings, such as brownfields, can be remediated fairly easily. **Brownfields** are abandoned industrial or commercial facilities or blighted urban areas that need to be cleansed of contamination before they can be redeveloped. Other areas, because of their size or the extreme toxicity of their contaminants, require very expensive, complex, and long-term remediation. Many of these have been designated as Superfund sites.

Superfund sites are areas with the most toxic contamination in the United States. The contamination may not only make the site itself too dangerous to inhabit, but often leaks toxic levels of pollutants into the surrounding soil, water, or air. An example of a Superfund site is Love Canal in Niagara Falls, New York (figure 14.6.*b*). The canal was a chemical waste dump for many years, then in the 1950's was covered with soil and sold to the city. Over time, many homes and a school were built over the former dump. In the 1970's, heavy rains raised the water table and carried contaminants back to the surface. Residents noticed foul smells, and gardens and trees turned black and died. Soon after, rates of birth defects, cancer, and other illnesses began to rise sharply. In 1977, the State of New York and the federal government began remediation work. Buildings were removed, and all residents were bought out and relocated, contaminated deposits and soils were excavated, and remaining soils and groundwater were treated and sealed off to prevent further spread of the contamination. Remediation activities have now been completed at this site.



Figure 14.6.*b*: Love Canal. Source: US Environmental Protection Agency

The type of pollution and the medium affected (air, water, or soil) determine remediation methods. Methods include incineration, absorption onto carbon, chemical methods, or bioremediation. **Bioremediation** is the use of plants, bacteria, or fungus to "digest" the contaminant to a non-toxic or less toxic form. All of these methods tend to be expensive and time-consuming.

Reclamation and Mitigation

Reclamation involves salvaging some features of a degraded habitat, but it may not restore the ecosystem fully (figure 14.6.*c*). For example, instead of abandoning a mined area once resources have been collected, it can be reclaimed by planting vegetation, reshaping the landscape, and redirecting water flow. However the reclaimed land still lacks many features of the original ecosystem, such as complex topography, vegetation that took tens or hundreds of years to grow, soil quality, and an intricate network of streams.

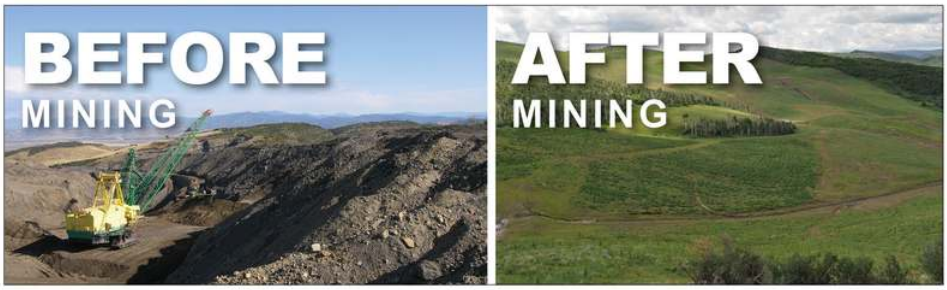


Figure 14.6.*c*: The Seneca Yoast coal once land has been cleared in preparation for mining (left) and after reclamation (right). Image by Peabody Energy, Inc. (CC-BY).

Sometimes, actions can be taken to avoid, reduce or compensate for the effects of environmental damage. Such **mitigation** efforts have been taken by the Army Corps of Engineers during construction projects. The native plants are removed from a site before construction begins and transplanted at a special holding site. After the construction project is completed, the native plants are replanted using those from the holding site. Another example of mitigation might involve the creation or enhancement of wetlands in one area, in order to compensate for permitted wetland losses in another area. Mitigation often goes hand-in-hand with restoration. Texaco, in conjunction with environmental groups and the United States Fish and Wildlife Service, restored 500 acres of agricultural lands in the lower Mississippi Delta to bottomland hardwoods. Texaco received environmental credits for the mitigating effects of the new woodlands on air quality.

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14.7: Combatting Climate Change Through Ecosystem Conservation

Complex natural ecosystems play an important role in mitigating the destructive effects of climate change. Prominently, living plants sequester greenhouse gases from the atmosphere (Zarin et al., 2015); in contrast, their loss due to habitat loss increases greenhouse gas emissions. Studies have also shown how ecosystems with high complexity (Betts et al. 2018) and species diversity (Mokany et al., 2014; Isbell et al., 2015) are better buffered against climate change. Lastly, by maintaining and restoring carbon-sequestering ecosystems, we also provide opportunities for climate-sensitive species to persist despite the threat of climate change pace.

One of the foremost initiatives aimed at combating climate change through ecosystem conservation and restoration is known as the **Reducing Emissions from Deforestation and Forest Degradation (REDD+**, http://www.un-redd.org) program. Set up by the UN, REDD+ provides financial incentives to local communities and landowners that make conservation of carbon-sequestering ecosystems worth more than destroying them. Funding for REDD+ is obtained through **carbon trading** programs, in which individuals and organizations looking to offset their emissions buy **carbon credits**. The funds obtained through REDD+ are then invested in initiatives that promote ecological restoration and reduce local dependence of intact ecosystems by creating alternative income streams such as sustainable crop, timber, honey, milk, and meat production.

The original aim of REDD+ was to safeguard primary old-growth forests, but the diversity of goals set out by REDD+ also include improving ecosystem connectivity, protecting threatened species, and preventing further loss and degradation of carbon-sequestering ecosystems other than forests.

Yet the future of these opportunities is not secure. Concerns exist regarding the effectiveness of REDD+ programs, much of which is based on problematic implementation, long-term funding security, lack of monitoring, and lack of concrete conservation goals (Phelps et al., 2011; Panfil and Harvey. 2015; Fletcher et al., 2016). For example, there are concerns that REDD+ programs can develop into a form of perverse subsidies, such as when native vegetation is cleared to establish plantations (Figure 14.7.1) with trees that have a high risk of becoming invasive (Lindenmayer et al., 2012). Similarly, there are concerns about the strong emphasis on forests, possibly at the expense of other important ecosystems and ecosystem services (Bond, 2016). Conservation biologists continue to be hopeful that REDD+, as with the range of approaches described in this chapter, will provide opportunities for land managers and scientists to successfully protect and restore biodiversity now and into the future.



Figure 14.7.1 The Reducing Emissions from Deforestation and Forest Degradation (REDD+) program aims to promote forest conservation by paying landowners to protect forests on their lands. However, there are concerns that some REDD+ funds have become a form of perverse subsidies, for example when native vegetation is cleared to establish plantations of invasive trees. To ensure program sustainability, it is important to strike a balance between meeting short-term development goals and ensuring the protection of a complex and adaptable biological landscape that can provide a variety of ecosystem services over the long term. Photographs by Johnny Wilson, CC BY 4.0.

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14.8: Summary

1. Ecosystem conservation and management involves three different activities: (1) monitoring ecosystem components, (2) maintaining healthy ecosystems, and (3) restoring damaged ecosystems.
2. An ecosystem in which all the chemical, physical, and biological components and processes are functioning normally is considered healthy. Ecosystems that remain healthy through disturbance are resistant, while ecosystems that rapidly recover after disturbance are resilient.
3. Ecosystems can be monitored using direct observation, environmental or biochemical indicators, and remote sensing analysis. It is important that any monitoring method be consistent and repeatable across space and time.
4. To maintain ecosystems that can support diverse ecological communities, conservationists are guided by three complementary management principles: (1) maintain critical ecosystem processes (water cycling, nutrient cycling, energy flow, community dynamics), (2) minimise external threats, and (3) be adaptive yet minimally intrusive.
5. Ecological restoration is the practice of restoring damaged ecosystems to an agreed-upon benchmark. This can be accomplished via rehabilitation, partial restoration, complete restoration, or taking no action. The strategy followed will depend on each project's goals and resource availability.

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14.9: Topics for Discussion

1. Read the articles by Bunce et al. (2008) and/or Papworth et al. (2009) about shifting baselines. Then think of a natural ecosystem in your region; it could even be an ecosystem in a protected area. How do you think that ecosystem looked 50 years ago? What about 100 years ago? And 1,000 years ago? At what time do you think the ecosystem was able to support the most diverse ecological community? What would you do to restore (or maintain) the ecosystem to this state? Would such a restoration project impact some species negatively? Is that a problem?
2. Consider all the aquatic communities in your region (ponds, marshes, streams, rivers, lakes, estuaries, coastal waters, etc.). Who is responsible for managing these ecosystems, and how do they balance the need for protecting biodiversity with the needs of society for natural resources? What additional conservation projects would you implement to help protect those ecosystems in the coming decades?
3. Imagine that the last population of a threatened bird species (which draws birdwatchers to the area) lives along a river nearby. This river also has numerous endemic species of fish, shellfish, and insects. A foreign company recently obtained permission to dam the river for hydropower generation. Beyond the impact of flooding, the dam will also cause various forms of pollution which will destroy the threatened birds' food source and nesting area. Upon writing about the challenge in the local newspaper, you receive US $1 million from an anonymous donor to save the bird. The company is willing to forego the development in exchange for the US $1 million. It will cost an additional $750,000 to implement an effective ecological restoration program that can reverse the threatened birds' population declines. Is it better to buy out the company and not devote additional resources to ecological restoration and researching the bird? Or would you rather spend the money on finding alternative ways to protect the bird and the other endemic species? Explain your answers.

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CHAPTER OVERVIEW

15: Preventing Extinctions

15.1: Introduction to Preventing Extinctions
15.2: Species-level Conservation
15.3: Studying Species and Populations
15.4: Saving Species Through Translocations
15.5: Managing and Facilitating Movement Dynamics
15.6: Managing Species Sensitive to Climate Change
15.7: Ex Situ Conservation Strategies
15.8: Thoughts on Neglected Taxa
15.9: Summary
15.10: Topics for Discussion
15.12: Bibliography

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15.1: Introduction to Preventing Extinctions



Tourists appreciating a southern right whale (*Eubalaena australis*, LC) from a whale charter boat operating from Hermanus, South Africa. Considered the "right" whale by 19th century whalers, the species was hunted to near extinction by the early 1900s, when only 300 individuals were left in the world (Reilly et al., 2013). Following the international ban on whale hunting, their populations have steadily recovered. Today it is considered safe from extinction, enabling towns such as Hermanus to base their thriving tourism industry on whale watching. Photograph by Southern Right Charters, CC BY 4.0.

There are many examples in this textbook illustrating how species have been saved from the brink of extinction. For some, the solution was simple: halt the threats that caused their populations to decline. In other cases, more drastic steps were required, like moving the last remaining individuals into captivity until the threats have been reversed. Many species that persist with low population sizes would likely not have survived without human intervention (Figure 15.1).

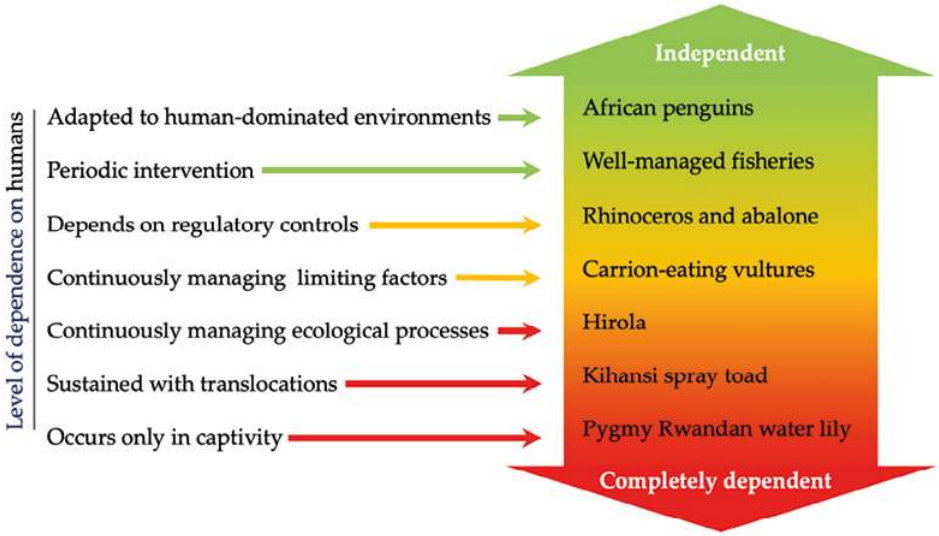


Figure 15.1 The continuum of species management approaches. Some threatened species exist under such low population sizes that they depend on active human intervention for recovery, while others can persist with minimal intervention. Each of the examples have been discussed elsewhere in the book. After Scott et al., 2005, CC BY 4.0.

In each of these success stories, the most important first steps involved determining the ecological needs of the species at risk and understanding the factors that made that species vulnerable to extinction. This chapter reviews some of the most important concepts for understanding and managing those needs and risks. The concepts reviewed in this chapter include methods to study species and

populations, actions that can be taken to increase population sizes, and strategies that can help maintain evolutionary processes such as genetic exchange. This chapter also considers how to manage for climate change and discuss the importance of ex situ conservation strategies.

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15.2: Species-level Conservation

Some conservation efforts center around a single species. Often this is a charismatic species that elicits public interest, such as tigers, sea otters, or the California Condor. The specific approach depends on the specific threats to the focus species. When California Condor population size plummeted, leaving only 23 individuals, they were relocated into a controlled environment and provided with optimal conditions for reproduction. This is called **captive breeding**. Individuals have since been **reintroduced** into the environment. One threat to the species was lead from bullets that were entering the food chain and ultimately poisoning the California Condor. Public education and providing lead-free bullets was thus another component of their conservation plan. By 2016, the population size increased to 446 individuals, with 276 of those living in the wild.

When disease puts species at risk, vaccination may be part of the conservation plan. For example, the black-footed ferret of the Great Plains is threatened by sylvatic plague as well as habitat loss. In response, peanut buttered-flavored oral vaccines were distributed over their habitats. Conservation efforts also focused on captive breeding and reintroduction. Once thought to be extinct, there are now several hundred black-footed ferrets in captivity and similar numbers in the wild (figure 15.2.*a*).

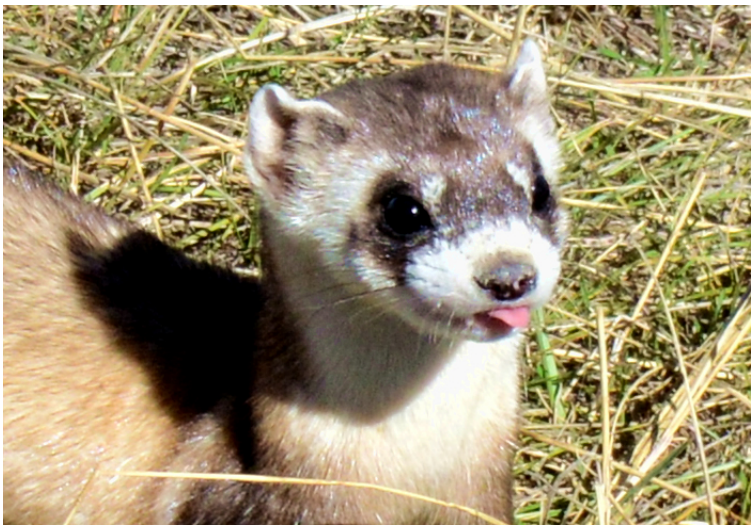


Figure 15.2.*a*: A black-footed ferret kit at the National Black-footed Ferret Conservation Center in Colorado. Image by Ryan Moehring/USFWS (CC-BY)

Protecting or restoring habitat is another component of species-level conservation. For example, the Northern Spotted Owl lives in old-growth forests. Protecting intact old-growth forests and restoring forest habitat is thus critical to their success. This is accompanied by removal of the Barred Owl, an invasive that competes with the Northern Spotted Owl. Similarly, removal of the invasive iceplant *Carpobrotus edulis* from California coasts, restores conditions for endangered dune vegetation (figure 15.2.*b*-d). In other cases, habitat restoration involves promoting populations of native species that support those at risk, such as promoting vegetation that provides food and shelter for waterfowl.



Figure 15.2.*b*: Vegetation at Martin Dunes in California. Iceplant is visible in the forefront. Photo by USFWS (public domain).



Figure 15.2.*c*: *Carpobrotus edulis* is an invasive iceplant that forms thick mats and outcompetes coastal vegetation. Image by Dr. Dwayne Meadows, NOAA/NMFS/OPR (public domain).



Figure 15.2.*d*: Removal of the iceplant restores habitat for endangered species, such as Menzies' wallflower. Image by Gordon Leppig & Andrea J. Pickart, FWS (public domain).

Seemingly unimpressive species can still serve vital ecological roles. For example, the delta smelt is an important food source for larger fish species. Additionally, it serves as an **indicator species** because the health of its populations reflect overall ecosystem health. While the delta smelt has been a focus of species-level conservation, non-charismatic species are often overlooked. In fact, a 2007 study by Colléony and colleagues found that people more often donated to conservation efforts for species that were more similar to humans rather than choosing those that were at greatest risk of extinction. Broad approaches such as establishing protected areas and ecosystem restoration benefit charismatic and non-charismatic species alike. Additionally, broad approaches protect unidentified and species that have not been assessed.

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Colleony, Agathe, Susan Clayton, Denis Couvet, Michel Saint Jalme, and Anne-Caroline Prevot. (2017). Human preferences for species conservation: Animal charisma trumps endangered status. *Biological Conservation*. 206. 263-269. DOI

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15.3: Studying Species and Populations

To save a species from extinction, it is vital to have a firm grasp on the species' distinctive characters, in other words its **natural history**. To obtain this natural history information, 10 important factors need to be considered:

> To save a species from extinction, it is vital to have a firm grasp on the species' distinctive characters, in other words its natural history.

- *Population biology*: How many individuals are there in the population? How many males, females, juveniles, breeding adults, and individuals past breeding age are there? What is the species' life expectancy? How have these aspects changed over time?
- *Habitat*: In what kind of environment can the species be found? How do these ecosystems change over time and space? Does the species have a complex life history that requires multiple habitats (e.g. frogs that live on land generally need water for breeding)? What factors are important to maintain suitable habitat?
- *Distribution*: Where in the world can the species of concern be found? At what rate is its distribution increasing/decreasing? What factors drive these increases/decreases?
- *Morphology*: What are the defining traits, or range of traits, of the species' appearance? How do the species' unique morphological characteristics help it survive? Are there closely-related species that appear similar (i.e. cryptic species) and with which it can be misidentified?
- *Limiting resources*: What types of resources does the species need to survive? Are any of these resources in short supply? Does the distribution of these important resources change over time and space?
- *Physiology*: Are there any special requirements the species' physical and biochemical processes need for it to grow, survive, and reproduce? What are the conditions under which meeting these requirements is especially hard?
- *Behavior*: How do individuals act or behave? Is the species sedentary, nomadic, or migratory? Do individuals group together, disperse at random throughout landscapes, or space themselves out at regular distances? How do these behaviors help it survive?
- *Genetics*: How much do genes vary within the species? How are the species' genetics linked to its morphology, physiology, and behavior? Are there local genetic adaptations? Is the genetic variation in key traits sufficient to allow the species to adapt to environmental changes? Are there any deleterious genetic concerns?
- *Biological interactions*: In what ways do individuals of the species interact with each other and with other species? Which of these interactions are critical for survival? Are there any competitors, predators, parasites, or diseases affecting the species?
- *Interactions with humans*: How sensitive is the species to human activity? Do humans use the species in any way? Is the species sustainably harvested? Is the species associated with human-wildlife conflict?

Understanding the natural history of a species directly informs conservation strategies. For example, if we know where a species occurs and what its habitat needs are, we are in a better position to prioritize which areas need to be protected or how ecosystems need to be restored. Similarly, if we know that an important food resource is missing, perhaps during a drought or due to human activities, conservationists could provide supplemental feeding until the limiting resource has recovered (Figure 15.3.1). Depending on the species in question, some factors play a more important role than others. For example, managing a disease outbreak may play a more important role in the conservation of a widespread migratory bird (that can spread diseases to other species), while managing for genetic diversity may play a more prominent role in the conservation of a small population of fishes restricted to only one lake. For many widespread species, different factors affect different subpopulations. In such cases each subpopulation might need to be managed as its own evolutionary significant unit (ESU; see e.g. Dubach et al., 2013) to retain unique local adaptations and genetic markers.



Figure 15.3.1 In some areas where diminishing food supplies threaten vulture populations, conservationists are supplementing their diets by placing carcasses at “vulture restaurants”. These vulture restaurants often depend on cooperation with local farmers who donate livestock that have died. Photograph by Hoedspruit Endangered Species Centre, CC BY 4.0.

Obtaining natural history data

Conservationists rely on several resources and techniques to obtain natural history information. Initial steps often involve reviewing published and unpublished literature to understand what is known (and not known) about a species. Literature reviews do have some drawbacks: they can take a long time, may uncover contradictory information, and may lack critical information relevant to a local area or specific population. For this reason, and especially when decisions need to be made under tight schedules, conservation biologists may need to speed up their initial species review by sourcing natural history information from subject matter experts who are familiar with the species or ecosystem of concern.

While literature reviews, expert opinions, and traditional ecological knowledge are important first steps to collect natural history information, the most reliable method remains fieldwork, where multiple individuals from the population of concern in the area of interest are observed repeatedly over time. Indeed, most of natural history information we have today was obtained during detailed notetaking by naturalists—biologists who dedicate much of their time to better understand the natural world—in the field.

Unfortunately, there are still major gaps in our understanding of the living world. Consequently, a very large number of threatened species, including better-known groups (e.g. reptiles, Tolley et al., 2016), lack the kinds of data necessary to ensure that we can give them the best chance of survival. Filling these gaps is also becoming harder since it is costly and sometimes logistically impossible (or dangerous) for naturalists to spend an extended period in the field. There is also a trade-off in the breadth and depth of data collection possible: the more area one covers, the less detailed the data; conversely, when one collects more detailed data, the scope of the study is reined in for logistical constraints. Further, there is also a limit to the number of organisms any one individual observer can study at any one time.

Species distribution modeling (SDM), also known as environmental niche modeling, is becoming increasingly popular for determining a species’ distribution and habitat needs. SDMs overlay species location data, obtained during field work, onto a selection of relevant environmental variables (e.g. forest cover, elevation, soil type) using GIS software, after which special modeling algorithms estimate the species’ ecological niche and distribution (Figure 15.3.2). This information enables conservation biologists to identify previously unknown habitat patches (which may represent undiscovered and unprotected populations) or empty habitats (which may be used in translocations). While distribution modeling offers very useful conservation tools, it is important to learn about the different techniques under the guidance of an expert to avoid making costly mistakes (McPherson et al., 2006; Pearson et al., 2006).

Species distribution modeling, also known as environmental niche modeling, is becoming increasingly popular for determining a species’ distribution and habitat needs.

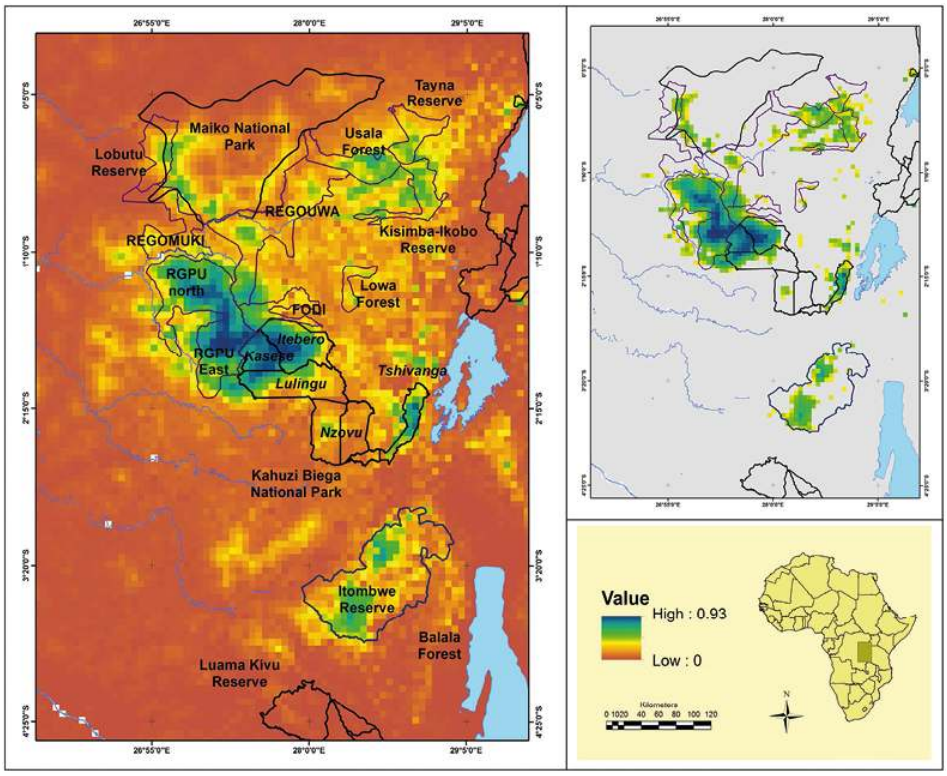


Figure 15.3.2 A species distribution model over the global range of the Grauer's gorilla. Purple and green areas indicate potentially suitable habitat while yellow and red areas indicate unsuitable habitat. The analysis highlighted that the gorilla is found in high-altitude forests far from deforestation activity. The map also shows which areas should be safeguarded to secure the species' survival. Source: Plumptre et al., 2016, CC BY 4.0.

Experimentation offers powerful methods to better understand competing theories and hypotheses, and to gain insight into how specific management actions may influence population dynamics. Experimentation is often associated with controlled environments such as laboratories; however, this is often impossible and sometimes even unethical to perform laboratory experiments on threatened species. Instead, conservation researchers may opt for natural experiments, which allows for the target species or population to be studied in its natural ecosystem.

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15.4: Saving Species Through Translocations

Because the probability of extinction increases rapidly for small populations, conservation biologists often invest considerable energy into increasing the size of small and declining populations. Often, these projects involve improving the extent and quality of suitable habitat or mitigating threats such as overharvesting. When appropriate, conservation biologists may sometimes resort to **translocations**—moving individuals from sites where they are threatened (e.g. unprotected lands or a paper park) or overabundant (e.g. a well-managed protected area or ex situ conservation facility) to sites where they can offer a larger contribution to conservation efforts.

> Understanding a species' ecological needs is critically important for translocations, because it influences the choice of release site and type of preparations needed.

Conservation biologists generally recognize four basic translocation approaches:

- **Restocking** (also called augmentation) occurs when wildlife managers increase the size and genetic diversity of existing populations, by releasing individuals that have been raised in captivity or that have been obtained from other wild populations.
- **Reintroduction** occurs when wildlife managers release individuals into areas where they occurred in the past but not at present. The areas must be ecologically suitable and the factors that caused the extirpation must have been reduced or eliminated for a reintroduction to be successful.
- **Introduction** involves creating new populations by moving individuals to suitable areas outside that species' historical range. Introductions are usually considered when reintroductions are impossible because the species' historical range has been degraded too severely or because persistent threats will lead to reintroduction failure.
- **Assisted colonization** (also called assisted migration) is a special class of introduction where biologists "assist" species with poor dispersal capabilities to adapt their ranges in response to environmental changes. It is anticipated that this strategy will become an important conservation tool in preventing extinctions where climate change outpaces the speed of natural migration.

Important considerations for translocations

Section 15.3 broadly discussed the importance of understanding the ecological and other natural history needs when protecting threatened species. Understanding a species' ecological needs is equally, if not more, important for translocations, because it influences the choice of release site and type of preparations needed (Figure 15.4.1). Complementing the 10 factors mentioned in Section 15.3, the next section briefly introduces some of the most important considerations during translocations.



Figure 15.4.1 A team of wildlife rehabilitators release a group of Cape vultures (*Gyps coprotheres*, EN) near a vulture restaurant in South Africa. Releasing the vultures near a supplemental food source greatly enhances their chances for survival after release. The vultures have wing tags to enable monitoring of each individual after release. Photograph by VulPro, CC BY 4.0.

Determining need and feasibility

Perhaps the most important factor to consider before starting a translocation is to determine whether it is necessary. Translocations carry risks, not only for the target population to be moved, but also the individuals left behind and for the recipient ecosystem. These risks expose translocation projects to a high risk of failure, particularly if preparations are inadequate and essential resources (e.g. funding, trained staff) are in short supply. Translocations also demand considerable resources—resources that can at times be better spent mitigating the threats the target population face. While these considerations may seem obvious, a recent review found that most translocations projects are initiated without proper cost-benefit analyses (Pérez et al., 2012). To improve translocation practices, conservationists seriously considering a translocation project are encouraged to review the 10 criteria outlined in Pérez et al. (2012), some of which also overlap with the considerations mentioned below.

Support from local stakeholders

It is also important to consider, at an early stage, how the public will view the translocation project. Some people may feel the resources used in a translocation are better invested elsewhere; others dislike translocations because they view it as a threat to their livelihood—this is especially true when carnivores are involved (Gusset et al., 2008). Because of these and other potential conflicts and emotions, it is crucial that translocation projects (like any conservation activity) obtain the support from local stakeholders at an early stage. It is helpful to be transparent from the outset and to explain the project's goals, as well as the benefits the local community may gain (e.g. attract more tourists, restore a degraded ecosystem service). Good public outreach also provides opportunities to address the public's concerns and misconceptions about the project and about biodiversity conservation in general.

Identifying suitable habitat

It goes without saying that the probability for success is greatly improved when the translocated individuals are released in good quality habitat. This is particularly true for species with poor dispersal capabilities, such as plants that reproduce through vegetative propagation: the plants could die in an environment that is too sunny, shady, wet, or dry. While this point may seem obvious, many translocations fail because individuals are released in inferior habitats (Armstrong and Seddon, 2007). One of the reasons for this potential habitat mismatch is because wildlife may perceive the environment differently than humans, so a site that may look good to the human eye may lack one or more overlooked limiting resource. **Refugee species**—species forced to live in suboptimal habitat due to threats present in their preferred habitat (e.g. Ali et al., 2017)—also present a challenge to biologists who may unwittingly view inferior habitat as optimal and base conservation decisions on essentially bad information. The same challenge presents itself at **ecological traps**—unsuitable environments that an organism mistakenly perceives as optimal habitat (e.g. Sherley et al., 2017). These are some of the most important reasons why biologists need to be cautions when using species distribution models (SDM) when identifying areas suitable for translocations. To mitigate costly translocation failures, it is advisable that releases start small, and have multiple phases, to assess how released individuals respond to their new environment. Conducting experimental and adaptive releases can also reduce uncertainty by evaluating different release scenarios (Menges et al., 2016).

> Species forced to live in suboptimal habitat due to threats present in their preferred habitat may lead biologists to unwittingly view inferior habitat as optimal.

It is also important to ensure that any habitat identified as suitable is free from threats such as pollution and invasive species that may lead to declining health or even death for released individuals.

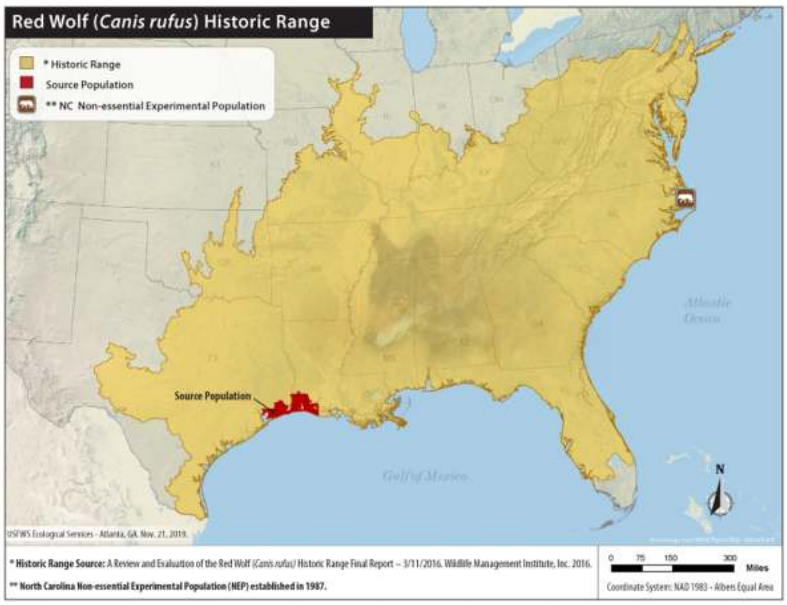






Figure 15.4.2 (Top Right) The Red Wolf, *Canis lupus*, was declared extinct in the wild in 1980 due to habitat destruction and predator control programs. Captive breeding programs, translocation, and monitoring have increased the population to 17-19 known wild individuals as of 2024 with 290 captive individuals. Photograph by USFWS, Public Domain. (Bottom) Wolf pup to be fostered into a wild litter. Photograph by USFWS, Public Domain. (Top Left) Historic range and source population map. Photograph by USFWS, Public Domain.

Considering genetics and behavior

Translocation projects also need to consider the genetic makeup, social organization, and behavior of a species that is being released. It is preferable to use individuals from the same genetic stock as individuals that already occur (or have occurred) in the release area to avoid outbreeding depression and to capture local adaptations. Such efforts simultaneously also contribute to conservation of genetic diversity, as opposed to the pollution thereof if individuals from different genetic stock are mixed.

Group-living species, particularly those vulnerable to Allee effects, need to be released in sufficient numbers so they can maintain their natural social organization and behavior. For species that need to be released in groups, it is preferable to release socially integrated animals rather than individuals unfamiliar with each other (Gusset et al., 2008). Releasing groups of animals does have

its own set of challenges. For example, social groups abruptly released from captivity may disperse explosively, possibly leading to project failure.

> The ultimate aim of most translocation projects is to establish populations that are self-sustaining, free from inbreeding, and interactive participants of their communities and ecosystems.

How many individuals to release

The ultimate aim of translocation projects is to establish **ecologically relevant** populations, meaning populations that are self-sustaining, free from inbreeding, and an interactive participant of its community and ecosystem. The probability of achieving this goal increases as more individuals are being released. Because translocation projects typically do not have an unlimited supply of individuals to release, wildlife managers often rely on quantitative models to estimate the minimum number of individuals that should be released and how many times releases should occur.

> The ability to establish new populations through translocations does not reduce the need to protect threatened species still in their natural habitats.

While releasing more individuals certainly improves the likelihood of establishing a self-sustaining population, it is also important to determine how many individuals the target community can sustain. In other words, the release area should contain enough suitable habitat to support the territories of all the released individuals. To determine how many individuals can be sustained, wildlife managers may calculate the release area's **carrying capacity**—an estimate of the maximum number of individuals an ecosystem can support. The carrying capacity concept has its roots in the livestock trade, where farmers wanted to maximize the number of animals on their land without risking overgrazing. While the concept has gained popularity in conservation biology in recent decades, calculating the carrying capacity for wildlife is very complex because of all the multi-faceted interactions that characterize healthy ecosystems. For example, the carrying capacity for a wild population can depend on factors such as food, water, shelter, soil nutrients, and sunlight availability, as well as more species-specific natural history factors such as habitat quality, home range, sex ratios (Tambling et al., 2014), and interactions with other species (Lindsey et al., 2011).

Preparing individuals for release

Translocation projects using individuals obtained from the wild are generally much more successful than those using captive-bred individuals, given that wild individuals are already adapted to a life where they must fend for themselves. Nevertheless, some projects may have to use captive-bred individuals, particularly when the target species is extinct in the wild, or when individuals were brought to an ex situ conservation facility because it is easier to breed them under human care in controlled conditions. In such cases, a great amount of effort may be required to prepare the captive-bred individuals for releases.

A major drawback when using captive-bred individuals is that they may have lost the important adaptations required for survival and successful reproduction in the wild. Pre-release training, which varies according to the species, can sometimes overcome this drawback. For predators, it may involve providing low risk prey, such as chickens and domestic rabbits in holding facilities until their hunting skills are better developed (Houser et al., 2011). For plants propagated indoors, it may involve hardening them off by placing them outside for increasingly longer periods to gradually introduce them to sun, wind, and temperature changes during the day. To help young birds disassociate humans from food, human trainers sometimes use puppets or wear costumes (Figure 15.4.3) during feeding time to mimic the appearance and behavior of wild individuals (Valutis and Marzluff, 1999). Another method, which may promote behavioral enrichment, involves **cross-fostering**, in which unrelated parents helps raise the offspring of a threatened species. However, cross-fostering using different species may lead to a new set of problems, like behavioral changes and hybridisation, if the young subsequently associate with the wrong species. A great amount of care and research are thus needed before such strategies are attempted.



Figure 15.4.3 Wattled cranes (*Grus carunculate*, VU) sometimes lay two eggs, but always abandon the second egg. Conservation biologists in South Africa are collecting the discarded eggs, which are then hatched in a captive breeding program. To avoid the captive chicks associating humans with food and safety after release, handlers use special crane costumes when interacting with the birds. Photograph by Daniel Dolpire, CC BY 4.0.

Whether using captive-bred or wild individuals for translocations, individuals may have to be fed, sheltered, trained, or otherwise cared for after release to give them time to become more familiar with their new surroundings. This approach, known as **soft release**, involves keeping the released individuals in pre-release holding facilities for a period; it may also include some form of assistance after release to increase opportunities for success. Soft releases also provide an opportunity to introduce captive-bred organisms to wild individuals of the same species that can act as "instructors" for survival in the new environment, or for unfamiliar individuals to bond into cohesive units (Gusset et al., 2006).

The alternative to soft release is a **hard release**—an abrupt release of individuals from captivity without assistance such as food supplementation. While hard releases are popular (because they are relatively easy to perform), it is a risky strategy that faces a high risk to failure (Brown et al., 2007; Wimberger et al., 2009). Hard releases can however be appropriate under the right conditions (Hayward et al., 2007b). For example, hard releases are often use in **head-starting** programs (Figure 15.4.4) for reptiles and amphibians (Scheele et al., 2014), where conservation biologists collect wild individuals and raise them past their most vulnerable life stages before releasing them again where they were collected.



Figure 15.4.4 Local children releasing leatherback sea turtles (Dermochelys coriacea, VU) as part of an environmental education project in Equatorial Guinea. Known as head-starting, conservationists would sometimes collect sea turtle eggs in the wild, hatched in captivity, and raise the offspring past their most vulnerable stage before releasing them back where they were found. Photograph by Katharine Clukey/TOMAGE-INDEFOR, CC BY 4.0.

Post-release monitoring

A translocation project does not end after the last individual was released. Rather, ongoing monitoring should be implemented to determine whether a translocation was successful, what degree of success was achieved, whether adaptive management is needed, whether additional releases should be conducted, or whether the project should be aborted. A well-designed monitoring plan can also highlight the consequences of translocation on the broader ecosystem, such as the impact that predators introduced to a new area may have on prey populations and competing species (Groom et al., 2017). Because some responses in translocated populations can be rather subtle and take many years to show or subside, post-release monitoring should ideally be a long-term endeavor.

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15.5: Managing and Facilitating Movement Dynamics

Some ecosystems are transient in nature—their character is temporary and will change because of disturbance and succession. Consequently, species that occupy those transient habitats are bound to be naturally extirpated at one time or another. Consider, for example, a small population of wildflowers occurring in a river's floodplain; at some stage, there is going to be a flood that will wash away those flowers. But the flooding also disperses seeds downstream, allowing for new wildflower populations to establish in suitable habitat elsewhere. These shifting populations linked by movements between them are better characterized as a **metapopulation** (a "population of populations") (Figure 15.5.1) consisting of several subpopulations. For some metapopulations, every subpopulation is transient: their distribution changes dramatically with each generation. Other metapopulations involve relatively permanent subpopulations with only a few individuals dispersing each generation. Some metapopulations consist of one or more source populations whose sizes are stable or increasing, and several sink populations whose sizes fluctuate depending on environmental conditions. Some sink subpopulations may undergo such dramatic fluctuations that they would be extirpated in unfavorable years were it not for population rescue by immigrants from source populations.

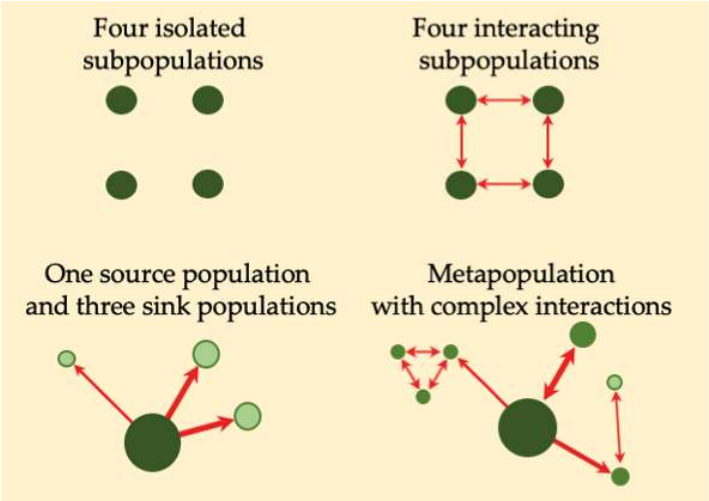


Figure 15.5.1 A range of metapopulation patterns is possible in nature. In this illustration, population size is represented by the size of the circle, while movement direction and intensity are indicated by the direction and thickness of the arrows. After White, 1996, CC BY 4.0.

Habitat fragmentation threatens metapopulation dynamics by reducing opportunities for dispersal across the landscape. When there is too little movement of individuals between habitat fragments, the dwindling subpopulations within those fragments are at risk of extirpation or even extinction. In contrast, well-connected subpopulations maintain themselves by colonizing empty niches, exchanging genetic material, and adapting to changing environments. Dispersal also maintains critical ecosystem processes, such as pollination and seed dispersal. Consequently, conservation biologists have invested significant resources in recent years to maintain and restore wildlife movements within fragmented ecosystems.

Connectivity in terrestrial ecosystems

Maintaining and restoring **ecosystem connectivity**—the ability of ecosystems to facilitate the dispersal of individuals between different areas—involves maintaining and restoring wildlife movements that are (at risk of being) impeded by human activities. The most popular method to maintain (or restore) connectivity in a fragmented landscape is to maintain (or restore) **habitat linkages**, also called wildlife corridors, habitat corridors, dispersal corridors, or movement corridors. All these terms refer to continuous tracts of suitable habitat with little to no dispersal barriers that connect otherwise isolated habitat patches and populations.

> Maintaining and restoring ecosystem connectivity is an important strategy for conserving wildlife whose movements are impeded by human activities.

Connectivity is important in every ecosystem on Earth. However, given the linear characteristic of **riparian zones** along rivers and stream—and hence a larger proportional impact of edge effects —we might consider connectivity in these spatially restricted systems to be particularly important (Figure 15.5.2). Protecting and restoring riparian zones as habitat linkages resonates with a variety of people because these areas provide a range of important ecosystem services, including flood control and water purification. Conservationists can tap into this energy by lobbying for laws that prohibit activities such as logging, housing, and industrial developments within a certain distance from a river or stream. By protecting ecosystem services associated with riparian zones, these laws simultaneously also maintain wildlife refuges (Monadjem and Reside, 2008), source populations (Vosse et al., 2008), and habitat linkages (Bentrup et al., 2012; McLennan and Plumptre, 2012). In contrast, inadequate protection of riparian ecosystems not only compromises connectivity, but also negatively affect species not overtly dependent on these buffer areas. For example, research from Southeast Asia has shown that losing riparian ecosystems in an otherwise palm oil dominated landscape reduced stream quality, which in turn reduced local fish diversity by up to 36% (Giam et al., 2015). In contrast, protecting riparian zones were found to increase palm oil yields (Horton et al., 2018). With so many riparian areas currently being degraded and destroyed, there is an urgent need for stronger riparian protection laws, and for more effective enforcement of those laws.



Figure 15.5.2 Protecting riparian zones such as this one along the Turkwel River in northern Kenya is an effective strategy for maintaining connectivity and securing a range of ecosystem services. Photograph by Bernard Dupont, https://www.flickr.com/photos/berniedup/17966234205, CC BY-SA 2.0.

At times, when it is impractical to establish or restore continuous habitat linkages, biologists may opt to protect and restore **stepping stone habitats** (Figure 15.5.3). As the name implies, stepping stone habitats are a special type of habitat linkage that facilitate dispersal along a patchwork of isolated habitat patches within a matrix of unsuitable or inhospitable habitat. Stepping stones thereby divide long dispersal events through a long stretch of inhospitable terrain up into shorter, and thus more manageable, sections. Stepping stone habitats are particularly important for migratory species that rest and refuel at stop-over sites between the end-points of their migratory route (Runge et al., 2015)—each stop-over site can be viewed as a stepping stone habitat. Prominent examples of stepping stone habitats that deserve protection include sacred forests which can act as stop-over sites for migratory forest birds; wetlands and estuaries, which can act as stop-over sites by migratory waterbirds; and small forest reserves, which can act as stepping stones between a network of other protected areas (Riggio and Caro, 2017).

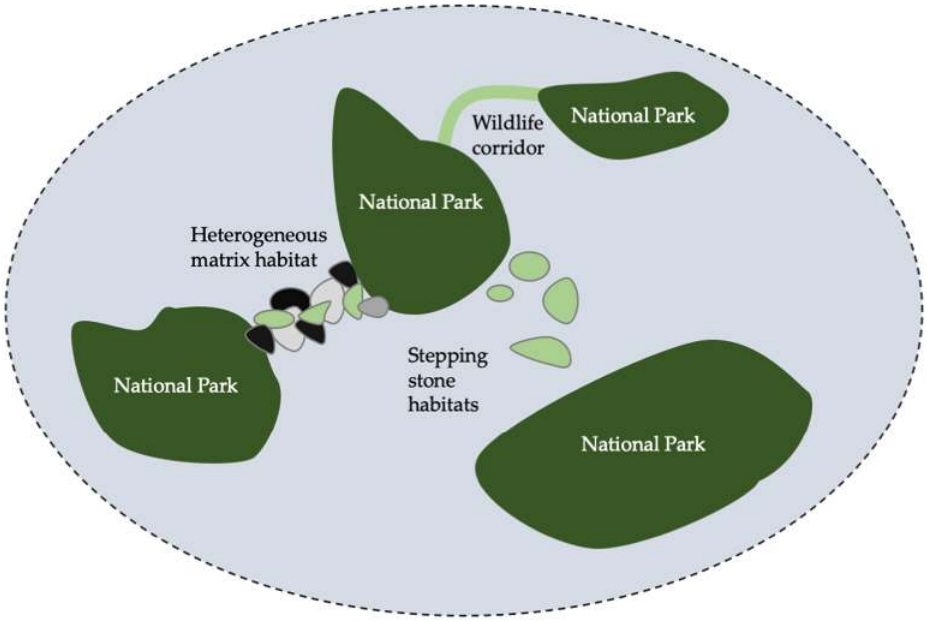


Figure 15.5.3 Methods to reconnect fragmented metapopulations (or maintain connectivity) can take many forms. The three main strategies are to maintain or restore wildlife corridors (e.g. to link two isolated forest patches), maintain or restore stepping stone habitats (e.g. a patchwork of wetlands or sacred forests), or facilitating movement through the matrix with sustainable land use tenures (e.g. removing fences). After Bennett, 2004, CC BY 4.0.

Box 15.5.1

Sandhill Cranes (*Antigone canadensis*) are a mainly migratory bird species that nest in marshes and bogs and rely on wetlands and open fields for stopover points during migration. Wetlands, agricultural fields, and river valleys serve as stepping stones on the migratory route from winter grounds in Mexico, central California, and the southern US, to breeding grounds in northern North America and Siberia. Although as of 2021, none of the migratory Sandhill Crane populations are declining, their future depends on suitable breeding and wintering habitat and fields and wetlands along migration routes. Wetland loss and land conversion for development are of concern. Local non-migratory subspecies in Cuba and Mississippi are endangered due to habitat loss. (audubon.org)



Male Sandhill Cranes. Photo by Eric Afyouni, WikiCommons, CC-BY-3.0

Connectivity in freshwater ecosystems

Dams have always played an important role in hydropower generation and securing a year-round supply of water for farms, industries, and cities. Unfortunately, recent evidence suggests that reservoirs may create more problems than they solve. Of concern is their contribution to greenhouse gases (Deemer et al., 2016), as well as their role in blocking dispersal of aquatic organisms. To counter these negative impacts, governments across the world are decommissioning and removing dams and other types of artificial water impoundments. For instance, over the past 30 years more than 1,174 dams were removed in the USA; the 72 dams removed in 2016 alone restored more than 3,000 km of streams (Thomas-Blate, 2016). Similar efforts are also underway in Europe (http://www.ecrr.org), where river restoration efforts have been initiated at over 1,100 locations across 31 countries. Unfortunately, not only are efforts to restore freshwater connectivity lagging across Africa; in many cases, even more rivers are currently being dammed (Winemiller et al., 2016).

> While dams play an important role in hydropower generation and securing a year-round supply of water, recent evidence suggests that they create many environmental problems, including blocking species dispersal.

Connectivity in marine ecosystems

Ecosystem connectivity is also important in marine ecosystems. Many marine organisms, including economically important species, breed and feed in different areas at different times of the year, and use established dispersal routes to move between those areas. It is thus important to protect these dispersal routes so we can maintain these marine ecosystems and ecosystem services.

> Maintaining movement dynamics in marine seascapes involves protecting and restoring marine corridors, estuarine linkages, and coastal habitat linkages.

There are three main strategies to maintain and restore movement dynamics of marine seascapes. First, marine corridors—zones used by whales and other marine species to move between feeding and breeding grounds—should be protected. Marine biologists in several countries successfully reduced collisions between whales and ocean-faring vessels with minor adjustments to shipping lanes that previously crossed marine corridors (Silber et al., 2012). Second, estuarine linkages should be protected, and restored where needed.

Management considerations in connectivity conservation

While intuitively appealing, there are a few potential drawbacks to connectivity that conservation planners should consider when planning to establish new habitat linkages (reviewed in Haddad et al., 2014). Prominently, connecting historically isolated populations may lead to outbreeding depression, for example when populations with different local adaptations are connected. Habitat linkages may also act as bottlenecks that expose dispersing animals to greater risks of predation and enable pests and diseases to spread easier. Care must be taken to ensure that wildlife do indeed perceive the landscape “connected”; a habitat linkage that may look good to the human eye may in fact be perceived as inhospitable habitat to wildlife (Newmark, 2008). A recent study from the Americas has shown that the habitat quality of a single stepping stone habitat can determine whether a migration is successful or not (Gómez et al., 2017).

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15.6: Managing Species Sensitive to Climate Change

Earth's temperature is well on its way to exceed the 2°C increase cap set by global authorities in 2016. Many species that need to adapt to these changes are unable to do so, either because of their limited dispersal capabilities or because of human-induced habitat fragmentation. Others that can disperse may risk decoupling of important symbiotic relationships, as the species involved may not disperse at the same speed, or the same distance. While slowing habitat loss could slow the overall impacts of climate change, preventing the extinction of many climate-sensitive species will require a range of pro-active conservation management strategies that allow species to adapt at their own pace as and when needed.

One of the most important strategies for protecting climate-sensitive species is to identify and protect their likely future habitats. This task of predicting where suitable habitats may be found in future is generally accomplished by identifying and projecting a species' climatic niche (or bioclimatic envelope) using species distribution models (SDM, Pearson and Dawson, 2003). Previously, it was described how SDM use location data overlaid onto environmental variables to estimate a species' environmental niche, and how this information can then be used to predict where else a species may occur in a landscape. A similar strategy is followed when predicting a species' future climate-adapted range. Here, location data are overlaid onto present-day climate variables (e.g. average temperature and rainfall) to define the species' climatic niche; these niche limits are then projected onto the landscape of interest using future climate scenarios. Much effort has also been made in recent years to incorporate aspects, such as physiology (Kearney and Porter, 2009) and biological interactions (e.g. Araújo and Luoto, 2007), in predicting future ranges.

Once future ranges have been identified, the next task is to recognize and protect/restore critical dispersal pathways. While a general strategy of increasing ecosystem-wide connectivity will certainty also benefit climate-sensitive species, conservationists could specifically target climate adaption, by maintaining and restoring **climate corridors**—dispersal pathways between the current and future ranges (Mawdsley et al., 2009). Several efforts (e.g. Williams et al., 2005; Phillips et al., 2008; Ayebare et al., 2013) are currently underway to establish and protect species-specific and community-specific climate corridors, as predicted using advanced distribution modeling techniques. These and other studies have shown that likely climate corridors often include north–south river valleys, ridges, and coastlines to facilitate poleward distribution shifts, while habitat linkages that cross gradients of elevation, rainfall, and soil types will help climate adaptation across more complex landscapes.

Assisted colonization is an alternative conservation strategy to save species with dispersal limitations and specialized interactions. Also called assisted migration, assisted colonization involves the pro-active translocation of climate-sensitive species from their present ranges to their future ranges. Sometimes, even species able to self-disperse may require assisted colonization. For example, African penguins (Spheniscus demersus, EN) are currently undergoing population declines because of climate change-induced shifts in fish populations on which they depend for food (Sherley et al., 2017). To re-establish this important biological interaction, conservationists are currently using assisted colonization to establish two new penguin colonies further east from existing colonies (Birdlife South Africa, 2019), in an area where fish populations have remained healthy (Figure 15.6.1).



Figure 15.6.1 BirdLife South Africa, in partnership with CapeNature, are introducing rehabilitated African penguins to two new sites several hundred kilometers east of existing colonies. The hope is that the translocated penguins will establishing colonies that is buffered from the negative effects of climate change and fluctuating fish populations. Here members of the public are witnessing the first releases. Photograph by Michael Bridgeford, CC BY 4.0.

As with any translocation project, introducing climate-sensitive species to new areas carries significant risks, including decoupling them from critical limiting resources and symbiotic relationships. It is thus imperative to start small, by translocating only a few well-monitored individuals. If monitoring shows that the initial releases were successful, one can then plan for further releases over time. Because this strategy is still new, it is also important to disseminate your experiences to the broader conservation community, for example by presenting results at conferences or in scientific journals.

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15.7: Ex Situ Conservation Strategies

The best strategy for protecting biodiversity over the long term is to protect existing wild populations in their natural ecosystems. This strategy, known as on-site, or **in situ conservation**, not only protect entire ecological communities—including thousands of species and their interactions—but also natural processes and ecosystem services. However, if the last populations of a threatened species are too small to remain viable, if they continue to decline despite conservation efforts, or if their threats do not subside, then in situ conservation may prove ineffective. In such cases, sometimes the only option left to prevent an imminent extinction is to capture those last remaining individuals and transfer them to a facility where they can be cared for under artificial, human-controlled conditions. This strategy is known as off-site, or **ex situ conservation**, and may involve individuals that were collected in the wild, orphaned, confiscated, or displaced and have nowhere else to go. Thanks to ex situ efforts, many plants and animals that are extinct in the wild continue to survive in zoos, aquaria, and botanical gardens.

Ex situ and in situ conservation are complementary strategies (Figure 15.7.1; see also Conde et al., 2011). For example, many ex situ conservation programs aim to raise enough healthy individuals to support translocation projects when appropriate habitats are available.

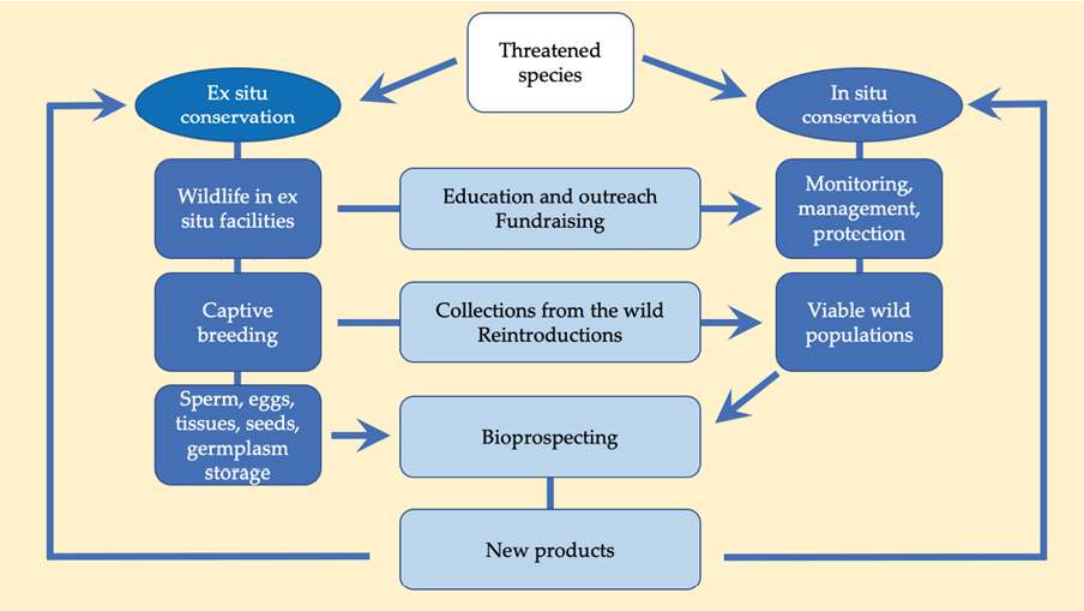


Figure 15.7.1 There are several ways in which in situ (on site) and ex situ (off-site) conservation can complement each other. No species conforms exactly to this idealized model, but nearly all species present some of these elements. After Maxted, 2001, CC BY 4.0.

Safeguarding a well-represented sample of the world's biodiversity play only a small role in ex situ conservation efforts. Maintaining self-sustaining wildlife populations under human care not only reduce the need to collect individuals for research from the wild; it also allows researchers to study aspects such as physiology, genetics, and demographics of threatened species (Conde et al., 2019) using methods that might not be possible without animals in captivity. These studies can then provide knowledge and experience to help protect both ex situ and in situ populations. For example, the establishment of the Demographic Species Knowledge Index (Conde et al., 2019), summarize demographic data obtained from ex situ conservation facilities, play a crucial role in filling gaps in datasets for population viability analyses. Ex situ facilities also play a critical role in captive breeding, head-starting, public outreach, education, and fundraising for in situ conservation. Many ex situ facilities have also become directly involved—and sometimes even taking leading roles—in field conservation efforts (Wilson et al., 2019). Lastly, many ex situ facilities directly connect conservation to social and economic progress through off-site education, employment, and implementation of a range of different community development activities (Ferrie et al., 2013).

Recent efforts to increase knowledge transfer among ex situ facilities has greatly enhanced their contribution to overall conservation efforts. Facilitated by organizations such as the IUCN's Conservation Planning Specialist Group (CPSG), ex situ facilities now regularly share information on best practices for care and handling of species in human care, including aspects such as nutritional requirements, optimal housing conditions, and veterinary techniques to anesthetize, immobilize, and reduce stress for

animals when they are being moved or during medical treatments (see http://www.cpsg.org). Much of this information is stored in a central database called the Zoological Information Management System (ZIMS). Maintained by Species360, ZIMS keeps track of animal **husbandry**, medical, and breeding information on over 6.8 million animals belonging to more than 21,000 species for over 1,000 member institutions in 90 countries. Ex situ facilities that maintain these records and comply with operations standards in animal welfare, conservation, education, and research can also apply to become an accredited institution with the World Association of Zoos and Aquariums (WAZA).

Types of ex situ facilities

Many types of facilities help to preserve ex situ populations. Here we describe some of the most common, including zoos and aquaria for animals, and botanical gardens and seed banks for plants.

Zoos around the world currently contribute to the conservation of nearly 7,000 species of terrestrial vertebrates (mammals, birds, reptiles, and amphibians) by caring for more than 500,000 individual animals. They do not do this alone; they often work with government agencies, universities, and a variety of other organizations who use zoo animals for research, education, and other conservation activities. While zoos traditionally focused on displaying charismatic animals that draw visitors, many zoos are now also investing in the conservation of small threatened vertebrates, as well as invertebrates, such as butterflies, beetles, dragonflies, spiders, and molluscs (many of which are also cheaper to maintain).

Aquaria are the aquatic version of zoos, specialized in caring, displaying, and conserving marine and freshwater biodiversity, such as fishes, corals, molluscs, and crustaceans (Figure 15.7.2). Most organisms currently in aquaria have been obtained from the wild, but conservationists are constantly refining techniques to breed more species in captivity to limit wild collecting. Recent and dramatic increases in aquaculture, which currently accounts for roughly a third of fish and shellfish production globally, have made ex situ conservation of aquatic species even more important. The hope is that these ex situ populations will help maintain genetic stocks and act as insurances against disease outbreaks introduced by domestic fish, molluscs, and crustaceans.

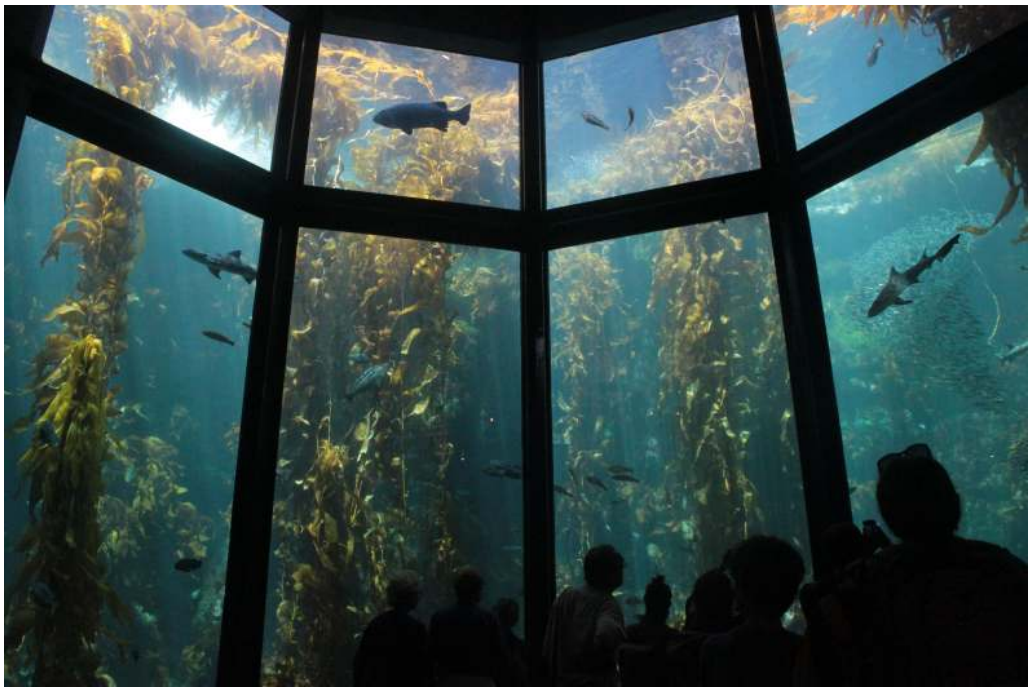


Figure 15.7.2 Aquaria provide opportunities to observe species such as those in this Kelp Forest exhibit at the Monterey Bay Aquarium, which many people would not have experienced otherwise. Photograph by Cam Vilay, via Wikimedia Commons, CC BY 2.0.

Botanical gardens (and **arboretums**, which specialize on trees and other woody plants) are dedicated to the collection, cultivation and educational curation of living plant species (Figure 15.7.3). Botanical gardens across the world house more than 6 million living plants, representing over 80,000 species—approximately 25% of the world's vascular flora (Wyse Jackson, 2001). The world's oldest and largest botanical garden—the Royal Botanic Gardens in London, UK—maintains over 28,000 plant taxa, nearly

10% of plant taxa in the world. Like zoos and aquaria, botanical gardens play a critical role in conservation efforts through public outreach and education.



Figure 15.7.3: The Berlin Botanical Garden. Image by Paul VanDerWerf (CC-BY).

A few botanical gardens and research institutes have developed collections of seeds, known as **seed banks**, which take advantage of the fact that seeds of most plants can survive for long periods when stored in cold, dry conditions. The seeds deposited in seed banks may be obtained from the wild, or from cultivated specimens. When gathering material from the wild, botanists generally target populations from across a species' geographical and habitat ranges so their collections can capture as much of each species' genetic diversity as possible. In this way, seed banks play a crucial role not only in conservation of plant species richness, but also genetic diversity. Seed banks may even be the only means some plant species are protected. Because many seeds of each species are usually collected, seed banks also provide a convenient opportunity for translocation projects. That is because safeguarded seed collections can be used to propagate not just large numbers of seedlings but, in some cases, custom-developed genetic mixtures to maximize local adaptations. The world's largest and most diverse seed bank is the Millennium Seed Bank, UK. At the end of 2018, the Millennium Seed Bank cataloged over 2.25 billion seeds from over 39,000 species; its billionth seed, from an African bamboo, was deposited in April 2007.

> Seed banks contribute to conservation of genetic diversity of plants by collecting material across target species' geographical and habitat ranges.

Challenges facing ex situ facilities

While the contribution of ex situ conservation facilities to overall biodiversity conservation strategies is significant (Conde et al., 2011), there are some drawbacks that need to be considered. For example, due to the limited number of individuals that can be maintained under human care, especially for larger animals, there is an increased risk that captive populations may suffer from threats facing small populations, such as inbreeding depression and demographic stochasticity. There is also a concern that ex situ conservation can contribute to hybridization concerns, for example if different cryptic species are accidentally managed as a single species. To avoid these threats, many ex-situ facilities manage their captive populations jointly as a single interbreeding metapopulation. They do this through studbooks which track the origin, pedigree, and demographic history of each individual in participating facilities. By maintaining and referring to these studbooks, ex situ conservation facilities can make informed decisions regarding transfer and breeding recommendations.

> Ex-situ facilities often manage captive populations as a single metapopulation using studbooks to track the origin and demographic history of breeding individuals.

Funding also remains an obstacle, given that ex situ facilities typically require large, long-term, funding commitments, in comparison to many in situ conservation activities. One consequence of funding limitations is that ex situ facilities mostly focus on showy or charismatic species that attract visitors, so small and less charismatic species are not always afforded equal protection (Brooks et al., 2009). Many ex situ facilities are also more inclined to house non-threatened species that are easier and less costly to care for, rather than threatened species with specialized needs (Table 15.7.1). For example, despite the fear of looming mass amphibian extinctions due to a disease caused by the chytrid fungus (*Batrachochytrium dendrobatidis*) (Alroy, 2015), 75% of ex situ amphibian collections consist of non-threatened species, with only 6.2% of all threatened amphibians afforded ex situ protection (Dawson et al., 2016). Neglecting threatened species in ex situ conservation efforts also creates a feedback loop, by maintaining a limited understanding on how to care for the species most in need.

Table 15.7.1 Number and percentages of terrestrial vertebrate species from Sub-Saharan Africa currently maintained in the world's ex situ facilities. Values in parenthesis represent percentage of all species, threatened species, and CITES-listed species for each taxon class, respectively.

	Mammals	Birds	Reptiles	Amphibians	Total
Worldwide	659 (55%)	1,470 (65%)	197 (27%)	44 (5%)	2,370 (47%)
Africa	110 (9%)	234 (10%)	34 (4%)	6 (1%)	384 (8%)
Asia	136 (11%)	327 (14%)	22 (3%)	2 (0%)	487 (10%)
Oceania	37 (3%)	61 (3%)	6 (1%)	1 (0%)	105 (2%)
Europe	191 (12%)	465 (20%)	73 (10%)	19 (2%)	748 (15%)
North America	145 (12%)	311 (14%)	53 (7%)	14 (2%)	523 (10%)
South America	40 (3%)	72 (3%)	197 (27%)	44 (5%)	353 (7%)
Threatened species	45 (23%)	42 (20%)	22 (21%)	8 (4%)	117 (16%)
Extinct in the Wild	1 (100%)	0 (0%)	0 (0%)	1 (100%)	2 (100%)
Critically Endangered	7 (26%)	4 (19%)	5 (25%)	3 (5%)	19 (15%)
Endangered	13 (16%)	12 (15%)	2 (5%)	3 (3%)	30 (10%)
Vulnerable	24 (27%)	26 (23%)	15 (33%)	1 (2%)	66 (23%)
CITES-listed species	95 (50%)	121 (62%)	45 (25%)	1 (6%)	262 (45%)
Appendix I species	30 (58%)	4 (44%)	8 (80%)	1 (6%)	43 (49%)
Appendix II species	58 (44%)	112 (62%)	37 (22%)	0 (0%)	207 (43%)
Appendix III species	7 (100%)	5 (100%)	0 (0%)	0 (0%)	12 (100%)

Source: https://zims.species360.org, current as of April-2019. Compiled by Johanna Staerk (Species360).

Fortunately, ex situ facilities have responded to these concerns by developing several innovative mechanisms that enables them to contribute more to the conservation of threatened species. For example, ex situ facilities all agree that attracting more visitors attracts more funding. To attract more visitors, zoos and aquaria are increasingly keeping animals in enclosures that are representative of their natural environments; this keeps the animals healthier and providing more opportunities to exhibit natural behaviors which, in turn, leave visitors more satisfied. Some zoos and aquaria have also established special displays where visitors can feed, touch, or otherwise interact with animals. Many ex situ facilities have also started inviting local artists to display sculptures and other artwork, which adds to the experience for visitors and attracting people that might not otherwise have visited. A rather unusual—but very successful—attempt to increase foot traffic comes from the USA, where the California Academy of

Sciences hosts dance parties with laser shows, food, and drinks every Thursday night (http://www.calacademy.org/nightlife), which visitors can enjoy while visiting the Academy's aquarium and other conservation exhibits.

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15.8: Thoughts on Neglected Taxa

Most of today's species-centric conservation initiatives are biased towards species that are showy, charismatic, or economically important. Consequently, conservation efforts for the vast majority of taxa are neglected. One well-known example is known as **plant blindness**, the perception that animals take precedence above plants in conservation efforts. This isn't just a case of hurt feelings among botanists: there are likely significantly more plant than animal species that should be considered as threatened; however, thorough threat assessments are hampered because, as a group, plants receive significantly less funding compared to animals (Negron-Ortiz, 2014). One explanation for this disparity is that plants are often seen as the backdrop of the environment rather than the critical foundation (as primary producers) of every food web on Earth. While showy plant species may indeed have highly visible roles in maintaining the environment and regional economies, neglected species may play an equally—sometimes even more—important role in maintaining ecosystems and ecosystem services (Schleuning et al., 2016).

Fortunately, the number of professional and amateur societies interested in protecting neglected taxa, such as reptiles, amphibians, invertebrates, fungi, and plants are rising. Some groups of experts are also organized into Specialist Groups (https://www.iucn.org/ssc-groups) by the IUCN. These societies and expert groups highlight the plight of neglected taxa and are willing to provide in-house expertise on best practices for protecting those species.

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15.9: Summary

1. A species may be threatened by a combination of many factors, all of which must be addressed in a comprehensive conservation plan that considers its natural history.
2. New populations of threatened species can be established in the wild using either captive-raised or wild-caught individuals. Animals used in translocation projects sometimes require special care and behavioral training before release as well as care and monitoring after release.
3. Maintaining and facilitating movement dynamics is very important for protecting wildlife in their natural ecosystems. To do this, connectivity must be preserved by ensuring that habitat linkages such as wildlife corridors and stepping stone habitats that are intact, functional, and free from human-made obstacles.
4. Preventing biodiversity losses under climate change requires ecosystem preservation, maintaining and restoring climate corridors and refugia, and assisted colonisation for species unable to adapt their ranges quick enough.
5. Some species that are in danger of going extinct in the wild can be maintained in zoos, aquaria, botanical gardens, and seed banks; this strategy is known as ex situ conservation. Ex situ conservation contributes to field conservation through research, skills development, public outreach, conservation education, fundraising, captive breeding, and head-starting.

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15.10: Topics for Discussion

1. How do you judge whether a reintroduction project is successful? Develop simple and then increasingly detailed criteria to evaluate a project's success.
2. Tying concepts from different chapters together, what are the biggest challenges standing in the way of conserving migratory birds?
3. Use the advanced search functions on the IUCN Red List website (https://www.iucnredlist.org) to pick one species occurring in your country that is threatened by climate change. Referring to Chapter 10, how does climate change threaten this species? What strategies can be used to prevent this species' extinction?
4. What roles do ex situ facilities play in the conservation of threatened species in your region? Discuss two or three different roles. Do you think there are certain aspects in conservation that they can make a larger contribution to than is currently the case?

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CHAPTER OVERVIEW

16: Biodiversity and the Law

16.1: Introduction to Biodiversity and the Law
16.2: Identifying Legislative Priorities
16.3: Environmental Laws and Policies
16.4: National and State Laws
16.5: The Limits of Environmental Laws and Regulations
16.6: Conclusion
16.7: Summary
16.8: Topics for Discussion
16.10: Bibliography

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16.1: Introduction to Biodiversity and the Law



One hundred and five tons of confiscated ivory and one tonne of confiscated rhino horn ablaze in Nairobi National Park, Kenya. The Presidents of the Republic of the Congo, Kenya, and Chad have personally set such stockpiles of seized contraband ablaze as a symbolic illustration of their support for efforts to stamp out wildlife crimes. Photograph by Mwangi Kirubi, https://commons.wikimedia.org/wiki/File:Nairobi-Ivory-Burn-by-Mwangi-Kirubi-7.jpg, CC BY-SA 4.0.

The negative impact of human activities on the natural environment is apparent wherever you look. Some impacts are an unavoidable consequence of human activities; vast resources are currently invested in finding ways to mitigate those impacts. Other impacts, often entirely preventable, are rooted in greed. Consider how the worst polluters are corporations that prioritize profits over environmental and human health. Similarly, many threatened species continue to be illegally exploited in an unsustainable manner; in the worst cases, the profits from poaching are funding human-rights atrocities and organized criminal networks. Because society pays the price for environmental crimes—which generally benefit only a few people—there is broad interest in preventing environmental abuse, and to punish the perpetrators.

> Because society pays the price for environmental crimes—which benefit only a few people—there is broad interest in preventing environmental abuse, and to punish the perpetrators.

Environmental crimes are generally divided into two categories: wildlife crimes—the illegal exploitation of biodiversity (including but not restricted to **wildlife trafficking** and biopiracy), and pollution crimes—the illegal trade and disposal of waste and hazardous substances. As with other crimes, environmental crimes are generally defined by legislative action, when governments pass environmental laws and regulations that restrict certain kinds of activities. The effectiveness of these laws and regulations in protecting the environment relies on three main factors: (1) identifying conservation priorities, (2) establishing regulations that addresses those needs, and (3) enforcing environmental laws and regulations.

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16.2: Identifying Legislative Priorities

Humans have always depended on the environment to fulfill their most basic needs. Before the Industrial Revolution, fulfilling those basic needs generally occurred at sustainable levels. Over the last few centuries, however, exponential human population growth and rates of resource extraction have put enormous pressure on the environment. Today, many wildlife populations and ecosystems are unable to cope with these pressures. Increased globalization has exacerbated many of these problems. For example, with most Asian rhinoceros and pangolin populations on the brink of extinction (IUCN, 2019), Asian traders are increasingly filling their orders for elephant (Figure 16.2.1), rhinoceros, and pangolin body parts from African suppliers (Biggs et al., 2013; Wasser et al., 2015; Heinrich et al., 2016).

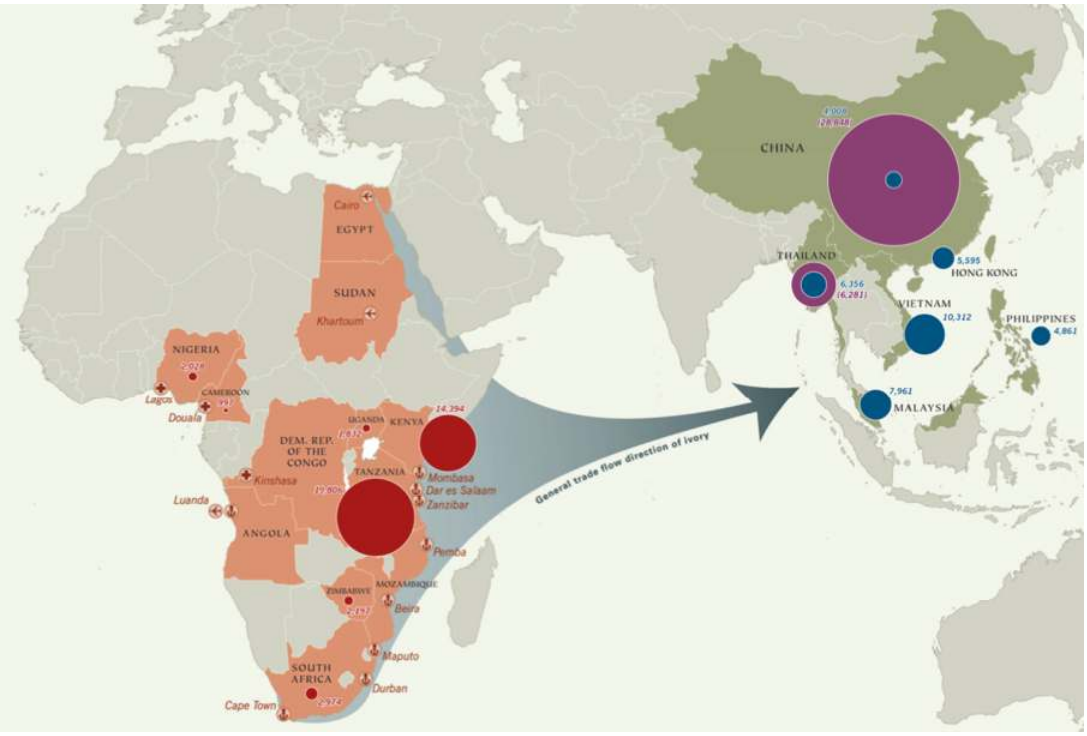


Figure 16.2.1 Key global ivory smuggling routes from 2009–2011, based on seizure data. More recent work has shown that poached elephants continue to originate from Tanzania, Mozambique, and Cameroon, while several seizures were now also from Gabon and the Republic of the Congo (Wasser et al., 2015). Map by CIA, https://www.flickr.com/photos/ciagov/30885483595, CC0.

Identifying which species and ecosystems need to be prioritized for legislative action can be confusing, and sometimes even seems in conflict with more readily available information at hand. For example, many hunters believe that the animals they target persist in healthy numbers despite claims to the contrary from conservation biologists. In other areas, logging companies claim they operate sustainably, yet tropical forests continue to shrink. In the face of conflicting information, it is critical for conservation biologists to rely on consistent, repeatable, and transparent methods to identify those populations, species, and ecosystems that may need (additional) regulatory protections.

Currently, the most popular method to identify legislative priorities is to use the **IUCN's Red List criteria**, developed to reflect a taxon's risk of extinction. Following these criteria (which can be applied on a global or local scale), species that are considered *Extinct in the Wild*, *Critically Endangered*, *Endangered*, and *Vulnerable* are officially considered "threatened with extinction" and would thus receive higher priority than species that are *Near Threatened* or *Least Concerned*.

Although coarse filter approaches, which focus on groups of species and threatened ecosystems, have been a catalyst for many international treaties and protected areas, legal mechanisms at the national and regional level do not always allow for its use. Through lobbying and education, these legislative branches will hopefully improve their receptiveness for coarse filter approaches in setting future legislative agendas.

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16.3: Environmental Laws and Policies

When conservation priorities have been identified, there are several options available to preserve biodiversity. One option could involve the establishment of protected areas where ecological restoration and species conservation projects can be carried out. Conservation biologists could also start an environmental education program that would help people live more sustainably on unprotected lands. Under certain conditions, however, especially when control and protection measures fail, restrictions or outright bans of some human activities may be necessary (Keeley and Scoones, 2014). The most effective restrictions and bans involve legislative actions that also establish mechanisms to enforce environmental laws and regulations, and mechanisms that reduce consumer demand (Challender and MacMillan, 2014).

Environmental laws and regulations are implemented at three different levels: international treaties, national laws, and local laws. While the scope of each of these levels differs, they are intricately connected with one another. International treaties influence national laws, but also depend on their enforcement to succeed, while national laws are guided by local needs as well as customary laws that have been in place for generations. Ideally speaking, international and national laws set minimum benchmarks, which regional and local governments adopt and enforce. Local and regional laws may sometimes set stricter standards in areas where the environment is more sensitive, more damaged, or more important for human well-being. Local and national legislatures may also choose to ignore broader legislation, through non-cooperation and non-enforcement. But this is not advisable as it may lead to further environmental deterioration, loss of funding, and even trade embargoes and sanctions that could harm local economies.

International agreements

International agreements provide frameworks that allow countries to work together to protect biodiversity (Sands and Peel, 2012). These international agreements, called treaties or conventions, are needed for five important reasons: (1) many species migrate and disperse across administrative borders, (2) ecosystems do not follow administrative boundaries, (3) pollution spreads by air and water across regions and around the globe, (4) many biological products are traded internationally, and (5) some environmental problems (e.g. climate change and pollution) require global cooperation and coordination. To pass international treaties, agreements are negotiated at international conferences under the authority of international bodies such as the UN, UNEP, or IUCN and come into force when they are ratified by an agreed-upon number of countries. These treaties are then implemented at the local level when signatory countries pass national laws to enforce them.

> International agreements provide frameworks that allow countries to work together to protect biodiversity.

One of the most important international environmental treaties is the ***Convention on Biological Diversity*** **(CBD**, https://www.cbd.int). The CBD formulated and signed following the UN **Earth Summit** (also called Rio Summit) held in Rio de Janeiro, Brazil in 1992, has played a major role in raising awareness of the value of biodiversity to humanity. At this meeting, representatives from 178 countries formulated and eventually signed the CBD, obligating signatory countries to protect biodiversity through careful management of nature for the benefit of humans. The CBD was expanded in 2010 to also include recommendations for the protection of IUCN Red Listed species and ecosystems, as part of the **Aichi Biodiversity Targets** (Table 16.3.1).

Table 16.3.1 The UN, with governments across the world, have agreed to work on five strategic goals and 20 specific targets (collectively known as Aichi Biodiversity Targets) to halt the loss of biodiversity and protect and restore what remains.

CBD strategic goal		Aichi Target
A.	Address underlying causes of biodiversity losses	1. Improve awareness of biodiversity values 2. Integrate biodiversity values into development 3. Eliminate perverse subsidies; incentivize sustainability 4. Implement plans for sustainable consumption and production
B.	Reduce pressures on biodiversity	5. Reduce the rate of habitat loss by at least 50% 6. Ensure sustainable use of marine resources 7. Ensure sustainable agriculture, aquaculture, and forestry 8. Reduce pollution to non-detrimental levels 9. Identify and control priority invasive species 10. Reduce pressures on climate-sensitive ecosystems
C.	Safeguard ecosystems, species, and genetic diversity	11. Increase coverage of well-managed protected areas 12. Prevent the extinction of threatened species 13. Prevent genetic erosion of biodiversity
D.	Enable more people to enjoy the benefits of biodiversity	14. Restore and safeguard ecosystems and essential services 15. Restore and enhance resilience of degraded ecosystems 16. Ensure fair and equitable sharing of ecosystem services
E.	Implement participatory biodiversity strategies	17. Implement participatory national biodiversity strategies 18. Respect and conserve traditional knowledge 19. Improve, share, and apply biodiversity knowledge 20. Mobilize resources to address Aichi Targets

Source: https://www.cbd.int/sp/targets

There are also several international agreements seeking the direct protection of targeted threatened species. One of the most important treaties of this nature is CITES ***(Convention on International Trade in Endangered Species of Wild Fauna and Flora***, https://cites.org), agreed upon in 1973 in Washington, DC. This treaty, ratified by 175 countries, establishes lists (known as Appendices) of species for which member nations agree to ban, restrict, control, and monitor international trade. Over 35,000 species of plants and animals appear on these appendices, many also listed as threatened by the IUCN. The treaty is limited in its reach because it only deals with international movement of organisms or their parts. It is also limited by various countries' ability or willingness to enforce the treaty and supporting legislation.

Species can be listed in one of three CITES appendices. Trade is banned for Appendix I species, which are threatened with extinction. For example the trade of ivory is banned by CITES. Trade is regulated for Appendix II species, such as the meat and shells of the queen conch or big-leaf mahogany (figure 16.4.b16.4.b). Appendix III species are protected in at least one country, and the local government needs a coordinated response through CITES. For example, several species of red and pink corals have been added to Appendix III at the request of China.



Figure 16.3.1: Big-leaf mahogany (*Swietenia macrophylla*) timber is used to make furniture, musical instruments, boats, and other products. It listed in CITES Appendix II, meaning that it is regulated. Specifically, a permit is required to ship big-leaf mahogany timber. Image by Forest and Kim Starr (CC-BY).

The **Migratory Bird Treaty Act** (MBTA) is an agreement between the United States and Canada that was signed into law in 1918 in response to declines in North American bird species caused by hunting. Figure 16.3.2 depicts the migratory routes for North American birds. The Act now lists over 800 protected species. It makes it illegal to disturb or kill the protected species or distribute their parts (much of the hunting of birds in the past was for their feathers). Examples of protected species include northern cardinals, the Red-tailed Hawk, and the American Black Vulture.

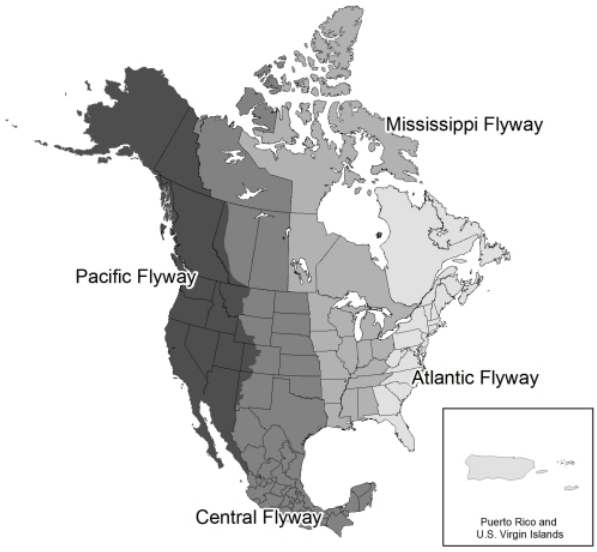


Figure 16.3.2: North American Flyways used by migratory birds. (US Fish and Wildlife Service)

The Convention on the Conservation of Migratory Species of Wild Animals (sometimes shortened to Bonn Convention, http://www.cms.int) is another important treaty that seeks the protection of specifically targeted species. The Bonn Convention came into force in 1983, and has over 120 Parties. As with CITES, the Bonn Convention categorizes species under Appendices. Species on Appendix I are threatened with extinction; "Range States" to Appendix I species are obliged to afford those species' strict protections. Appendix II lists species whose populations would significantly benefit from international cooperation.

Several international agreements seek the protection of important ecosystems. Perhaps the most prominent is *Convention Concerning the Protection of the World's Cultural and Natural Heritage* (http://whc.unesco.org), which protects natural (and cultural) areas of international significance. As of mid-2021, **UNESCO** (the organization managing the list of **World Heritage Sites**) recognized 1,154 World Heritage Sites across 167 countries; this includes 218 natural sites (Figure 16.3.3), 897 cultural sites and 39 mixed properties. There are 24 sites in the United States including Yellowstone, Yosemite and Everglades National Parks.



Figure 16.3.3 The Maloti-Drakenberg Park World Heritage Site, on the borders of South Africa and Lesotho, protects globally significant natural and cultural heritage. Photograph by Diriye Amey, https://commons.wikimedia.org/wiki/File:South_Africa_-_Drakensberg_(16261357780).jpg, CC BY 4.0.

Another important treaty that seems ecosystem protection is the ***Ramsar Convention on Wetlands*** (http://www.ramsar.org), which recognizes the ecological, scientific, economic, cultural, and recreational value of freshwater, estuarine, and coastal marine ecosystems. This binds each member country to conserve and sustainably utilize its wetlands (particularly those that support migratory waterfowl), and to officially declare at least one internationally significant wetland as protected. As of 2021 2,435 sites were designated 'Ramsar sites," covering 2.5 million km2 worldwide with 420 sites are in Africa, covering over 1 million km2 and 220 sites in North America totaling 236,000 km2.

International treaties are particularly important to the marine environment, since about two-thirds of the world's oceans (50% of the planet) are considered international waters—that is, being outside any country's **exclusive economic zone** (EEZ), all states have

the freedom to fish, travel, do research, etc. in these areas. Three examples of international agreements protecting such marine ecosystems are (1) the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (http://www.imo.org/en/OurWork/Environment/LCLP) which regulates pollutants into the marine environment, (2) the 1982 Convention on the Law of the Sea (http://www.un.org/Depts/los) which establishes guidelines for management of marine natural resources, and (3) the 2009 Agreement on Port State Measures (http://www.fao.org/port-state-measures) which sanctions monitoring for illegal, unreported, and unregulated fishing at shipping ports.

The 2016 ***Paris Agreement***, which deals with greenhouse gas emission reduction and climate change mitigation, serves to illustrate the difficult political negotiations (Figure 16.4.4) involved in the adoption of an international treaty. Although the negative effects of climate change have been known for several decades (Section 6.1), until recently there has been a distinct lack of action to curb global greenhouse gas emissions. For example, as an early call to action on reducing greenhouse gas emissions, representatives from 154 countries signed the UN Framework Convention on Climate Change (UNFCCC) at the Earth Summit in May 1992. In the following years, negotiations during annual UNFCCC conferences (formally known as "Conference of the Parties", or COPs) led in the Kyoto Protocol, adopted in Japan in 1997, which marked the first attempt to set legally binding emission reduction targets. Despite broad appeal among its 192 parties, the Kyoto Protocol faced an uphill battle from the start because the USA (the world's biggest greenhouse gas emitter at the time) refused to ratify it, and China (which recently overtook the USA as the biggest emitter) was exempted from compliance. While this has left the ***Kyoto Protocol*** largely a failure, it provided important lessons that contributed to the successful passing of the Paris Agreement (http://unfccc.int), which was negotiated and adopted through consensus by 195 countries (this time including the USA and China) in December 2015. The Paris Agreement went into effect on 4 November 2016 after the minimum 55 countries ratified it, marking a breakthrough in the decades-long battle to curb global greenhouse gas emissions. By mid-2019, all but one country in the world (the non-signatory being the Holy See, who as UNFCCC observer nation that cannot sign but strongly support the Agreement) have signed and/or ratified the Agreement. Most relevant to African member states are the mechanisms set up to provide developing countries with large amount of aid for climate change mitigation and adaption, much of which involves ecosystem conservation.



Figure 16.3.4 A small group of COP21 delegates, led by UNFCCC Executive Secretary Christiana Figueres, negotiating the final terms of the Paris Agreement before its adoption on 12 December 2015. Photograph by Benjamin Géminel, https://www.flickr.com/photos/cop21/23596677582, CC0.

While it is still too early to judge the effectiveness of the Paris Agreement, the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (http://ozone.unep.org) illustrates how international cooperation can be effective in preventing environmental disasters. In the 1970s, scientists discovered that a range of chemicals (primarily chlorofluorocarbons, or CFCs) commonly used in agriculture, energy production, and even common household items (such as refrigerators and aerosol spray canisters) were depleting the atmospheric **ozone layer**. The ozone layer is critical for human life; by cutting the amount of harmful ultraviolet radiation from the sun that reaches the Earth's surface, protection from the ozone layer reduces skin cancer, cataracts, and crop damage. In response to this threat, the Montreal Protocol aimed to phase out those substances that were responsible for ozone depletion. Since then, the ozone layer has steadily recovered; current projections suggest that the ozone layer will return to 1980 levels in the second half of the 21st century. Towards the end of his tenure as Secretary General of the UN (1997–2006), Ghana's

Kofi Annan declared, “Perhaps the single most successful international agreement to date has been the Montreal Protocol”. The Montreal Protocol’s success is directly due to this widespread adoption and implementation.

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16.4: National and State Laws

National and State Laws

Within many countries there are laws that protect endangered species and regulate hunting and fishing. For example, the **Endangered Species Act** (ESA) was enacted in 1973 in the United States. The ESA does not automatically protect species categorized as threatened on the Red List. Instead, the U.S. Fish and Wildlife Service (FWS), which enforces the ESA, assesses candidates for protected status as threatened or endangered (figure 16.4.*a*). Consideration of candidate species can be initiated by the FWS itself or at the request of the public. Through the Species Status Assessment Framework, the FWS compiles biological data, such as habitat and population information and current threats to the species. This biological data is used to inform decisions.



Figure 16.4.*a*: Public Affairs Specialist for the U.S. Fish and Wildlife Service, Joanna Gilkeson, takes photos of federally endangered San Diego fairy shrimp in a vernal pool in Otay Mesa, California. Vernal pools are shallow seasonal ponds, and vernal pool species are uniquely adapted to changes in water availability. Image by Maideline Sanchez/USFWS (public domain).

Once a species is listed, the FWS is required by law to develop a management plan to protect the species and bring it back to sustainable numbers. The ESA, and others like it in other countries, is a useful tool, but it suffers because it is often difficult to get a species listed or to get an effective management plan in place once a species is listed.

The 1972 **Marine Mammals Protection Act** prohibits the "take" of marine mammals—including harassment, hunting, capturing, collecting, or killing—in U.S. waters and by U.S. citizens on the high seas. The act also makes it illegal to import marine mammals and marine mammal products into the United States without a permit.

State laws can also aid in conservation. Through **California Endangered Species Act** (CESA), originally passed in 1970 and subsequently amended, the California Fish and Game Commission assesses species to be listed as threatened or endangered by the state. A listed species, or any part or product of the plant or animal, may not be imported into the state, exported out of the state, "taken" (killed), possessed, purchased, or sold without proper authorization.

Note that endangered is a subcategory of threatened on the Red List, but for ESA and CESA, threatened and endangered are separate categories, with the latter representing at the greater risk of extinction.

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16.5: The Limits of Environmental Laws and Regulations

Despite all the efforts to protect biodiversity through laws and regulations, the scale of environmental crimes continues to increase year after year. Today, the US $91–258 billion environmental crime industry is the world's fourth largest illegal enterprise, after drug smuggling, counterfeiting, and human trafficking (Nellemann et al., 2016). Increased financial support for environmental law enforcement could certainty help: current spending to combat environmental crimes, globally estimated at US $20–30 million a year, is a mere drop in the bucket compared to the losses incurred from these same crimes, which are 10,000 times greater (Nelleman et al., 2016). There is also a need to prevent environmental crimes before they happen, given that the damages incurred cannot always be undone by punishing the offenders.

> Environmental crime is the world's fourth largest illegal enterprise, after drug smuggling, counterfeiting, and human trafficking.

An important step towards reducing the scale of environmental crimes is to address the ineffectiveness of environmental regulations. That includes addressing the range of tactics that criminals use to facilitate non-compliance (Chapron et al., 2017), but also ensuring there are mechanisms that remove the incentives for people to engage in environmental crimes. In the following section, we look at some of the most prominent challenges that complicate environmental law enforcement.

Lack of capacity

The foremost reason why environmental laws fail is that authorities often lack the capacity for effective monitoring and enforcement. Lack of capacity is a major problem in the marine fisheries industry due to the size of the oceans and the cost of patrolling them.



Figure 16.5.1 Fishermen from Tanji fishing village in The Gambia fixing their nets after a day out at sea. Intensive harvesting has reached crisis level off West Africa, where a largely unregulated fisheries industry threatens not only fish populations and the people relying on fish, but also seabirds, marine turtles, whales, and dolphins. Photograph by Jan Kruithof, https://www.flickr.com/photos/jankruithof/30426220994, CC BY 2.0.

Lack of capacity is exacerbated by law enforcement officers that turn a blind eye to actions they deem innocuous, or when prosecutors fail to indict criminals out of fear of reprisals. Regulatory controls may also no longer exist or be enforced in regions that experience substantial political instability, economic hardship, civil unrest, or war (Hanson et al., 2009; Beyers et al., 2011). But even in areas where regulatory controls exist, prosecution can be complex, and thus very hard, especially when the illegal activities cross international boundaries and different legal jurisdictions. Such a breakdown of legal mechanisms often leaves natural resources vulnerable to whoever can exploit them.

Conflicting government priorities

Clashing priorities between different government structures complicate the enforcement of environmental laws. We see this when agencies overseeing mining activities issue inappropriate permits because of pressure for economic development, or because of corrupt agreements between businesses and government officials (Mascia and Pailler, 2011). Another example of mixed priorities occurs when a national government gives permission to extractive companies to exploit protected areas or communal lands without first consulting and obtaining local input and consent. Such government-sanctioned violations are generally very difficult to prosecute and require an active and caring citizenry to take their governments to task.

One of the most popular methods for citizens to make themselves heard is activist activities, such as public protests. Concerned individuals can also launch petitions on websites such as https://www.change.org, http://www.greenpeace.org, and https://www.avaaz.org. There is even a website for whistle-blowers (https://wildleaks.org) who want to report environmental crimes anonymously. Another positive development is the growing number of successful lawsuits that concerned citizens and environmental justice organizations have brought against their governments for environmental violations (e.g. CER, 2017; Yende, 2017).

Informal economies, traditional activities, and the law

Law enforcement can at times be counterproductive. This is true especially in areas where the separation between informal/unreported and illegal activities is blurred. For example, traditional people who graze their livestock, collect medicinal plants, or hunt and trap animals in protected areas that were established on ancestral land seldom have criminal intent. But because formal law systems seldom account for these informal activities, those people are engaging in illegal activities.

> When dealing with vulnerable people, conservation initiatives must also consider impacts on livelihoods and the potential for sustainable utilization

When dealing with vulnerable peoples whose livelihoods are threatened, an approach that involves sensitivity and compassion generally offers more effective and enduring resolutions. Many conservation initiatives have not only failed but have also created long-lasting negative attitudes by preventing traditional peoples from sustaining their livelihoods. Before implementing new regulations, governments should carefully consider if they would disrupt livelihoods. If so, it might be wise to consider if some form of sustainable utilization isn't possible.

Trade embargoes and sanctions

The basic premise of CITES is that, so long as participating countries abide by agreed-upon regulations, trade involving species of concern will not be stopped, only monitored. However, when agreements are not met, or compliance falls short, then trade is banned in part or in whole. For example from 2016: after various high-profile environmental crimes that involved CITES-regulated species, the USA afforded protection to lions and elephants under their Endangered Species Act (https://www.fws.gov/endangered). Trophy hunters from the USA now face significant regulatory and logistical barriers which has all but eliminated hunting of these species for wealthy American hunters, threatening a US $500 million per year industry that supports over 53,000 jobs and protects over 1.4 million km2 of land (SCIF, 2015). In this example, businesses operating within the law are unfortunately also impacted.

> Many formerly destructive companies are now voluntarily pursuing opportunities to prove, through special certifications, that their products are harvested responsibly and sustainably.

To avoid scenarios such as these, it is much more advantageous for pressure to mount from within non-complying countries and industries before outside pressure takes effect. To that end, many formerly destructive companies are now voluntarily pursuing opportunities to prove, through special certifications, that their products are harvested responsibly and sustainably. Four prominent certification agencies are the Forest Stewardship Council (FSC) which sets guidelines for the responsible management of forests, the Marine Stewardship Council (MSC) which sets standards for sustainable fisheries, the Roundtable on Sustainable Palm Oil (RSPO) which promotes sustainable production of palm oil, and the Rainforest Alliance which promotes sustainable agriculture (For a more complete treatment of sustainability standards, see https://www.isealalliance.org, https://www.evidensia.eco, and

https://www.iisd.org/ssi). Given that most certification schemes were established relatively recently, they are not without their flaws, but collaborations with conservation biologists (e.g. Christian et al., 2013; WWF, 2013) play a major role in ensuring continued improvements.

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16.6: Conclusion

Challenging problems are often solved when a diverse group of people from different backgrounds and viewpoints come together for mutual benefit. Solving environmental crime is no different: history shows that building trust and respect for fellow human beings and future generations is more powerful than the threat of force. Effective law enforcement efforts, which require multi-level cooperation from international structures down to individual people (Box 16.7), are often characterized by partnerships between wildlife agencies and local people (Biggs et al., 2016). These partnerships may take the form of environmental educational campaigns to incentivize conservation action and sustainable resource use (Abensperg-Traun, 2009). Cooperation between different individuals at the grassroots level is another very effective means to ensure sustainable resource use. These efforts may take many forms, but they begin with individual and group decisions to prevent the destruction of habitats and species to preserve something of perceived economic, cultural, biological, scientific, or recreational value. Through collaboration and cooperation, both from the grassroots level up, and governments down, conservation biologists can achieve their goals, by ensuring free and fair treatment of all citizens regardless of their diverse and sometimes opposing viewpoints on natural resource management.

Box 16.6 Thoughts on Poaching and Illegal Wildlife Trafficking in Sub-Saharan Africa

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The two main causes of the alarmingly rapid wildlife loss in Africa today are: (1) unsustainable use of land and natural resources, mostly related to decision making that does not prioritize conservation considerations; and (2) overharvesting of wild animals and plants through poaching and illegal logging.

Poaching and illegal logging can be locally driven for subsistence use, resulting from poverty; for lack of other protein, energy, and income sources; and, at times, by the intensifying impact of armed conflict or post-conflict situations. In a country like Angola, for example, where war has significantly diminished wildlife populations, the continuous impact of intensive bushmeat poaching may well lead to the extinction of remnant core populations of species that have initially survived the armed conflict. It is severely impacting even the iconic and endemic giant black sable (*Hippotragus niger variani*, CR). Bushmeat poaching is typically unselective; it targets mainly large and medium sized mammals, but also smaller mammals, birds, reptiles and freshwater fish. Similarly, illegal logging for wood, charcoal, or slash-and-burn-based cultivation, results in rapid and irreversible biodiversity degradation and loss.

In contrast, commercial poaching is often driven by international trafficking, whether of live animals (Figure 16.6.1) or animal and plant products, from source countries to destination markets. Illegal traffickers are often well financed, sophisticated, and involved in other forms of serious crime, at times even in terrorism (e.g. Nellemann et al., 2014). Illegal wildlife trade is selective and forms an imminent threat to iconic species with commercial value, such as elephants, rhinoceros, big cats, great apes, pangolins, sea turtles, parrots, and rosewood, to name a few.



Figure 16.6.1 In 2004, Angolan authorities confiscated Massamba, an orphaned chimpanzee (*Pan troglodytes*, EN), from poachers, as part of a crackdown on the illegal wildlife trade. Photograph by Tamar Ron, CC BY 4.0.

While the core causes, nature, and impacts of subsistence and commercial poaching are different, local community members are a centerpiece of both. Their intimate acquaintance with local wildlife and their habitats is vital; therefore, effective wildlife protection is based on their active engagement. After many generations of alienation, local community members must be included in the decision-making process for the sustainable management of natural resources. The Namibian conservancies offer a model of success in engaging communities in conservation, by protecting their rights, securing their fair benefits as the resource owners and not merely as workers, and providing them with adequate training.

Wildlife crime is a serious threat to biodiversity and while local influences should be recognized and addressed, these crimes should be treated as a global enforcement priority. Continuous and coordinated national efforts of all relevant sectors, and with global cooperation, are essential to success. Such efforts must include: (1) improving awareness at all levels; (2) adequate legislation and policies; (3) realistically deterring punishments and forfeiture of wildlife crime revenues; (4) strengthening enforcement and intelligence capacities in all source, destination, and transit countries; (5) addressing governance challenges; and (6) trying to eradicate the markets, or at least to reduce the demand for illicit wildlife products. The poaching drivers, international crime syndicates, and middlemen, must be targeted. Enforcement focused mostly at the poachers' level can never achieve the desired results. Often, they are no less victims than their target species. Further, if the world wants to protect iconic species, it cannot be expected that the burden of their conservation, and human-wildlife-conflict damages, should fall solely on those communities that happen to share their habitat. The global effort and substantive support required should not be viewed as a contribution, but as mutual responsibility for achieving a global goal.

Lastly, we may have to accept that total eradication of wildlife crime may not be achievable. There is no magic remedy, nor a single perpetrator. Nevertheless, integrated efforts to reduce these crimes must be strengthened at all levels. We simply cannot give up on our fellow species.

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16.7: Summary

1. Environmental laws and regulations are implemented at three different levels: international treaties, national laws, and local laws. Each of these levels is intricately connected: international treaties influence—but also depend on—national laws to succeed, while national laws are guided by local needs and customary laws that have been in place for generations.
2. International treaties and conventions provide frameworks for countries to cooperate on protecting species, ecosystems, and other levels of biodiversity. International agreements are important because: (1) many species migrate and disperse across borders, (2) ecosystems do not follow administrative boundaries, (3) pollution spreads by air and water across regions and around the globe, (4) many biological products are traded internationally, and (5) some environmental problems require global cooperation and coordination.
3. National governments protect biodiversity by regulating natural resource use and preventing pollution. Subsidies and tax incentives can also be used to reward citizens and businesses that engage in environmentally-responsible behaviors.
4. There is a constant need to evaluate environmental laws and regulations to ensure that they are enforced, violators are prosecuted, and new laws and amendments are passed as and when needed. Law enforcement agencies and scientists are constantly looking for new ways to address enforcement shortcomings.
5. When banning environmentally detrimental activities that are not compatible with conservation goals, it is critical to help the affected people to transition toward sustainable activities. Failing that, conservation activities may unintentionally force those people to resort to illegal activities such as poaching out of desperation to obtain food and income.

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16.8: Topics for Discussion

1. Identify two or three environmental laws regulating human activities in your country. Discuss how these national laws relate to international laws and local laws.
2. A wide range of international and national laws protect threatened species and ecosystems. Why do species and ecosystems covered by such laws not recover?
3. Trapping birds and small mammals are traditional activities for boys and young men across Africa, and traditional hunting is seen as a competitive sport to sharpen the mind. These activities are also important to meet local income and nutritional needs. How should we deal with the hunting of threatened species outlawed by national governments, but encouraged by local traditions? Should people be allowed to hunt for bushmeat, even if it includes great apes and other rare species, to pay for necessities, such as schooling and medicine?

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CHAPTER OVERVIEW

17: The Importance of Protected Areas

17.1: Introduction to the Importance of Protected Areas
17.2: Establishing Protected Areas
17.3: Classification of Protected Areas
17.4: Government Protected Areas in the US
17.5: Non-profit Organizations
17.6: Prioritization - What Should be Protected?
17.7: Designing Protected Areas
17.8: Challenges for Protected Areas
17.9: Summary
17.10: Topics for Discussion
17.11: Bibliography

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17.1: Introduction to the Importance of Protected Areas



Sea anemones and cold-water corals are among the species that enjoy protection in the 1000 km2 Table Mountain National Park Marine Protected Area (MPA), South Africa. The MPA is divided into several no-take zones which act as breeding and nursery areas for marine life, as well as zones where harvesting is allowed under certain conditions. Photograph by Andrew Beard, https://www.flickr.com/photos/andrewbeard/13268749044, CC BY 2.0.

In light of increasing human populations that need an increasing amount of natural resources each year, safeguarding the region's biodiversity is a major challenge. One of the best ways to meet this challenge is to designate protected areas—regions where human activities are regulated or, at times, even prohibited by law.

> Protecting existing wild populations in their natural ecosystems not only protects ecological communities and interactions, but also natural processes and ecosystem services.

Biodiversity conservation is most effective when we maintain healthy, functioning, and intact ecosystems. Although it is true that many species and populations live outside protected areas, and some wildlife populations (Craigie et al., 2010) and natural communities (Lindsey et al., 2014) are declining even when protected, well-managed protected areas continue to be the most effective method to safeguard biodiversity (Brooks et al., 2009; Ihwagi et al., 2015). Illustrating the point, a global meta-analysis found that wildlife populations are 15% larger and species richness is 11% higher inside protected areas compared to populations directly outside (Gray et al., 2016). Studies have also shown how wildlife in protected areas are more resilient to climate change (Beale et al., 2013a), because habitat loss and fragmentation occur at four times their respective rates outside protected areas relative to inside them (see also Potapov et al., 2017). Consequently, until such a time that we can live more sustainably on unprotected lands, protected areas will remain an important cornerstone in our efforts to protect biodiversity. But how do we know what or where to protect, how much to protect, or how to effectively manage a protected area?

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17.2: Establishing Protected Areas



Figure 17.2.1 Land clearing and agricultural development pushes right up to the eastern edge of Bwindi Impenetrable National Park, Uganda. It is important for protected areas—and zones within those areas—to have clearly defined boundaries to avoid confusion on where and how human activities are regulated. Photograph by Jason Houston/USAID, https://www.flickr.com/photos/usaid-biodiversity-forestry/38484053220, CC0.

A **protected area** is "a clearly defined geographical space (Figure 17.2.1), recognized, dedicated and managed through legal or other effective means to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008). Given this broad definition, it comes as no surprise that governments, organizations, and local communities use a variety of mechanisms to establish protected areas. The most popular of these mechanisms are:

- Government action, which can occur at a national, regional, or local level.
- Community-based initiatives by local people and traditional groups.
- Land purchases and holdings by private individuals and organizations.
- Protected areas established through co-management agreements.
- Development of biological field stations or marine laboratories.

Government protected areas

Government actions are generally considered the most secure form of protection because they involve passage of laws and buy-in from multiple levels of society. Of course, legislation establishing a protected area does not guarantee that the species and ecosystems therein are adequately preserved. Small populations, especially those living in small protected areas, often require active management to ensure their continued survival. Another concern is that laws protecting national parks and other wildlife sanctuaries are not strictly enforced, leading to so-called paper parks—parks that appear on official government lists, but with wildlife monitoring, law enforcement, and ecosystem management lacking on the ground (Laurance et al., 2012). However, government-sanctioned protected areas do lay a solid foundation for partnerships among governments, international conservation organizations, multinational banks, research institutes, and educational organizations. Such partnerships can bring together funding, training, and scientific and management expertise to maximize the potential value of those protected areas.

Community conserved areas

In many areas, local people already protect biological communities, forests, wildlife, rivers, and coastal waters in the vicinity of their homes. Protection on these **community conserved areas** is enforced by village elders and councils to ensure the sustainable use of natural resources such as food supplies and drinking water. Natural areas have also been set aside by royal families and churches to provide a space for spiritual activities and sustainable harvesting of medicinal plants. Because human activities are highly restricted in these sacred spaces, they provide an important refuge for biodiversity. Today, an increasing number of traditional communities link cultural advocacy directly to conservation through the establishment of protected areas on their lands

as a safeguard against developments that would compromise their way of living. Other communities establish protected areas to attract tourists and ensure the protection of special wildlife.

> Traditional communities may link cultural advocacy to conservation by establishing protected areas as a safeguard against developments that would compromise their way of living.

Privately protected areas

Over the last few decades, many countries have adopted a more Western form of land tenure under private ownership. Wealthy individuals or groups of people have taken advantage of this opportunity by acquiring large tracts of land for ecotourism purposes (de Vos et al., 2019). Because the ecotourism potential of these privately protected areas depends on how well the property is managed (Clements et al., 2016), private landowners often invest considerable effort to maintain and even increase wildlife populations on their land. Privately protected areas have unique advantages over government-protected areas. For example, they have local buy-in from landowners and their employees by design; this is often a significant stumbling block for government-protected areas. Private sites could also employ innovative funding mechanisms that allow them to fast-track land acquisition, perhaps in response to threats such as development. In some areas, privately protected areas may even employ more people, pay better wages, and contribute more to local economies that government protected areas (Sims-Castley et al., 2005). Privately protected areas can, therefore, play a significant role in overall conservation efforts, particularly in areas where threatened species (Cousins et al., 2010) and ecosystems (Gallo et al., 2009) are underrepresented in government-protected areas.

> Because the ecotourism potential of private protected areas depends on how they are managed, landowners prioritize maintaining and even increasing wildlife populations on their land.

Despite the advantages of privately protected areas, we must also consider the drawbacks. Like many community conserved areas, privately protected areas are not permanently protected by the same mechanisms and oversight as government protected areas are. Ownership and management style can also change at the whim of the landowner, or perhaps the heirs. At times, management practices may be detrimental to the species and ecosystems these privately protected areas claim to protect, for example, through introduction of invasive species and harmful breeding practices (Milner et al., 2007), and by resisting regulatory controls (Cousins et al., 2010). Innovative strategies will thus be required to ensure that these areas do contribute to biodiversity protection, which include education, support, and methods that balance financial gains with conservation goals.

Co-managed protected areas

Local people who support conservation and the protection of their local natural resources are often inspired to take the lead in protecting their local biodiversity. Governments and conservation organizations can assist such initiatives by allowing local people to access specialist expertise and obtain financial assistance to develop conservation and ecotourism infrastructure. These conservation areas, characterized by partnerships between different levels of society that share decision-making responsibilities and consequences of management actions, have been termed co-managed protected areas. One of the biggest strengths of **co-management** is that, with proper consultation and engagement, it avoids **eco-colonialism**—the unfortunate practice by some governments and conservation organizations of disregarding the rights and practices of local people during the establishment and management of new conservation areas or environmental laws and regulations.

Contractual parks offer a good model on how to avoid eco-colonialism. These protected areas are established and managed through agreements with private or communal landowners whose land forms part of a protected area (usually a national park). This not only allows a larger area to be protected, but also allows local people to benefit from biodiversity conservation through benefit sharing and job generation initiatives. Contractual parks play an important role where it is used as a tool to meet both conservation goals and restitution of previously dispossessed land.



Figure 17.2.2 A lone giant quiver tree (Aloidendron pillansii, CR) stands guard over a desert valley in |Ai-|Ais/Richtersveld TFCA, on the border between South African and Namibia. This TFCA is special in that it is an agreement park, established through the cooperation between governments and private landowners. Photograph by Vincent van Oosten, https://pixabay.com/en/richtersveld-south-africa-desert-758235, CC0.

Field stations and marine laboratories

Biological field stations and marine laboratories are a special kind of protected area that provide a dedicated stable space for scientists, students, and even the general public to pursue research projects on all kinds of natural phenomena in an intact environment (Tydecks et al., 2016). By facilitating collaboration and long-term observation, work done at field stations have led to several fundamental scientific advances, including improved understanding of environmental responses to climate change and acid rain, as well as advances in social development through conservation activities.

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17.3: Classification of Protected Areas

Protected areas vary greatly in how they are managed. For some, particularly those that protect very sensitive and/or recovering wildlife populations and ecosystems, human activity—even activities, such as photography, hiking, or bird watching (which can cause trampling and disturb shy animals)—may at times need to be forbidden except for specially arranged guided tours. For others, extraction of natural resources may be permitted albeit regulated.

To distinguish how protected areas are managed, the IUCN developed six categories to classify protected areas based on how the land is used (Table 17.3.1). Of these categories, the first five can be defined as true protected areas, because the environment is managed primarily for biological diversity. The sixth category, Protected area with sustainable use of natural resources, refers to **extractive reserves** that are managed primarily for the sustainable production of natural resources, such as timber and grazing lands. Nevertheless, extractive reserves can play an important role in conservation: (1) they frequently protect much larger areas than do other types of protected areas; (2) they still provide habitat for many species that were present pre-extraction; and (3) they often border and can thus provide a buffer around, and wildlife linkage between, category I–V protected areas.

Managers of extractive reserves must seek balance between the harvest of natural resources and risking environmental degradation from unsustainable practices.

Table 17.3.1 Description of Categories I–VI of the IUCN's classification of protected areas.

Category		Description
Ia	Strict nature reserve	Managed strictly for biodiversity conservation. Serves as reference sites for research and monitoring. Human visitations and impacts highly regulated.
Ib	Wilderness area	Generally large and relatively unmodified natural areas without significant human habitations. Managed to preserve the area's natural character and ecological integrity.
II	National Park	Large natural areas set aside for protection of biodiversity and ecosystem processes. Also managed to support human activities (spiritual, education, scientific, recreation) compatible with biodiversity protection.
III	National monument of feature	Managed to protect a natural feature (e.g. seamount, geological feature, ancient grove) with outstanding cultural and/or natural significance. Can cover a small area, and often have high visitor value.
IV	Habitat/species management area	Protected area dedicated to the protection of a specific species of habitat. May at times required regular and active intervention to ensure primary management goals are met
V	Protected landscape/seascape	An area with a significant natural or cultural value, created by the interaction between people and nature. Managed to safeguard the interactions that sustains the area's value. Often act as model for sustainability
VI	Managed-resource protected area	Managed primarily for the low-level, non-industrial, sustainable use of natural resources. Generally large, with most of its ecosystems intact.

Source: After Dudley, 2008

It is important to note that not all protected areas are covered under the IUCN's six-category system. Prominently are RAMSAR wetlands which are not incorporated under formal protected areas, but still protected under international law. Other examples include locally-managed marine areas and indigenous reserves, some of which are as effectively managed as formal protected areas. The IUCN is currently working on a new classification, called 'other effective area-based conservation measures' (OECM; IUCN WCPA, 2018), to officially recognize the contribution of areas falling outside formal protected area networks to biodiversity conservation efforts.

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17.4: Government Protected Areas in the US

It is important to protect natural areas for several reasons. Some people feel a cultural or spiritual connection to the wilderness. Every year, millions of people visit recreational lands such as parks and wilderness areas to experience attractions of the great outdoors: hiking among the giant sequoias in California, traveling on a photo safari in Kenya or just picnicking at a local county park. Besides providing people with obvious health benefits and aesthetic pleasures, recreational lands also generate considerable tourist money for government and local economies. Outdoor recreation activities such as hiking and camping benefit tourist industries and manufacturers of outdoor clothes and equipment.

Establishment of preserves is one of the key tools in conservation efforts. A **preserve** is an area of land set aside with varying degrees of protection for the organisms that exist within the boundaries of the preserve (figure 17.4.a). Governments or private organizations establish nature preserves. In 2016, the IUCN estimated that 14.7 percent of Earth's land surface was covered by preserves of various kinds. This area is large, but only 20% of the key biodiversity areas identified by the IUCN were sufficiently protected.



Figure 17.4.a: Mequon Nature Preserve in Wisconsin. Image by Jennifer Tomaloff (CC-BY-NC-SA).

There has been extensive research into optimal preserve designs for maintaining biodiversity. Preserves can be seen as "islands" of habitat within "an ocean" of non-habitat. In general, large preserves are better because they support more species, including species with large home ranges; they have more core area of optimal habitat for individual species; they have more niches to support more species; and they attract more species because they can be found and reached more easily. One large preserve is better than the same area of several smaller preserves because there is more core habitat unaffected by less hospitable ecosystems outside the preserve boundary. For this same reason, preserves in the shape of a square or circle will be better than a preserve with many thin "arms." If preserves must be smaller, then providing wildlife corridors between two preserves is important so that species and their genes can move between them. All of these factors are taken into consideration when planning the nature of a preserve before the land is set aside. In addition to the physical specifications of a preserve, there are a variety of regulations related to the use of a preserve. These can include anything from timber extraction, mineral extraction, regulated hunting, human habitation, and nondestructive human recreation.

The public lands described below differ in their level of protection. For example, national parks and forests allow camping whereas wildlife refuges place more limitations on human activities.

Wilderness Areas

Wilderness areas, comprise ecosystems in which human activity has not significantly affected the plant and animal populations or their environment. Natural processes predominate. According to the "Wilderness Act of 1964," wilderness areas are defined as being those areas where the nearest road is at least five miles away and where no permanent buildings stand. Activities that could

disrupt native species, such as the use of motorized vehicles is prohibited. More than 100 million acres of land are now preserved as wilderness under this act. Sparsely populated Alaska contains the largest chunk of wilderness areas, over half of it. Although wilderness areas are scattered among most of the lower 48 states, the largest percentage is found in the western states. Few undesignated areas in the contiguous states remain that would qualify as wilderness.

National parks and forests and wildlife refuges can contain wilderness areas. California contains significant wilderness areas, with over 4 million acres of National Forest Wilderness areas, and 1.5 million acres of mostly desert wilderness in the Mojave Desert National Preserve (figure 17.4.*b*).



Figure 17.4.*b*: A variety of unique plant life grows at Mojave Desert National Preserve. Image by John Fowler (CC-BY).

Wilderness areas provide an essential habitat for a wide array of fish, wildlife, and plants, and are particularly important in protecting endangered species. For scientists, wilderness areas serve as natural laboratories, where studies can be performed that would not be possible in developed areas.

National and State Parks

The United States has set aside more land for public recreational use than any other country. The **National Park System** manages more than 380 parks, recreation areas, seashores, trails, monuments, memorials, battlefields, and other historic sites. It consists of more than 80 million acres nationwide (figure 17.4.*c*). The largest national park is Wrangell–St. Elias National Park and Preserve in Alaska with over 13 million acres. California has eight national parks: Channel Islands, Death Valley, Joshua Tree, Lassen, Redwood, Sequoia, Kings Canyon, and Yosemite. Many national parks such as Yosemite, Yellowstone and the Grand Canyon are such popular recreation destinations that the ecosystems of those parks are being severely tested by human activities.



Figure 17.4.*c*: National parks, such as Grand Teton National Park in Wyoming, help conserve biodiversity. (credit: Don DeBold)

Every state has also set aside significant amounts of land for recreational use. The **California State Park System** manages more than one million acres of parklands including: coastal wetlands, estuaries, scenic coastlines, lakes, mountains and desert areas. California's largest state park is Anza-Borrego Desert State Park, which is the largest state park in the United States with 600,000 acres. The stated mission of the California State Park System is "to provide for the health, inspiration and education of the people

of California by helping to preserve the state's extraordinary biological diversity, protecting its most valued natural and cultural resources and creating opportunities for high-quality outdoor recreation".

National Forests

The **National Forest System**, managed by the U.S. Forest Service (part of the United States Department of Agriculture), consists of more than 170 forestlands and grasslands, which are available for activities such as camping, fishing, hiking and hunting. These are managed as multiple use lands, which balance the needs for recreation, grazing, timber, watershed protection, wildlife and fish, and wilderness.

Some examples of national forests are the Sierra National Forest in California and the White Mountain National Forest in New Hampshire. The Coronado National Forest in Arizona is famous for "sky islands", or steep mountain ranges surrounded by low-lying areas. The dramatic increase in elevation is associated with changes in the flora and fauna (figure 17.4.*d*). Explore national forests using this interactive map.



Figure 17.4.*d*: The Santa Teresa Mountains of the Coronado National Forest form "sky islands". Image by Jstuby (public domain).

Wildlife Refuges

The U.S. Fish and Wildlife Service manage more than 500 national **wildlife refuges** (figure 17.4.*e*), which not only protect animal habitats and breeding areas but also provide recreational facilities. Find a Refuge is an interactive map for locating wildlife refuges.



Figure 17.4.*e*: Bobcat at Sonny Bono National Wildlife Refuge in southern California. Image by Mark Stewart/USFWS (public domain).

Supplemental Reading

America's Public Lands Explained. 2016. U.S. Department of the Interior.

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17.5: Non-profit Organizations

The private non-profit sector plays a large role in the conservation effort both in North America and around the world. For example, the World Wildlife Fund raised over $300 million in the 2017-2018 fiscal year to protect endangered animals, their habitats, and natural resources. Some non-profit organizations are species specific, like the Orangutan Foundation, and others are broadly focused, such as the IUCN and Trade Records Analysis of Flora and Fauna in Commerce (TRAFFIC). Illegal wildlife trade is monitored by TRAFFIC. The Nature Conservancy (figure 17.5.a) takes a novel approach. It purchases land and protects it in an attempt to set up preserves for ecosystems.



Figure 17.5.a: Jo-Ellen Darcy (left), Assistant Secretary of the Army for Civil Works, discusses the Hamilton City with Ryan Luster, project director for The Nature Conservancy, during a site tour in Hamilton City, Calif., June 3, 2014. The U.S. Army Corps of Engineers Sacramento District's Hamilton City project will let nature help do the work of reducing flood risk by restoring 1,500 acres of native habitat between the Sacramento River and a new setback levee to be built near the town. The Nature Conservancy assisted the project partners by helping acquire the land planned for restoration. Image by US Army Corps of Engineers (public domain).

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17.6: Prioritization - What Should be Protected?

Historically, the boundaries of protected areas was often determined through pragmatic considerations, such as the availability of funds and land, and political influence, rather than ecological considerations. Many conservation areas were thus established on “lands that nobody wants”: marginal areas with little agriculture and development potential, or areas that were too remote to have high commercial value (a trend that continues even today: Venter et al., 2018). Other protected areas were established in locations with charismatic megafauna, so ecosystems without those species remained unprotected. Consequently, some of Earth's most threatened species and ecosystems remain under-protected (Beresford et al., 2011).

> In a crowded world with finite natural resources and limited funding, it is increasingly important to be strategic about where protected areas are established.

In a crowded world with finite natural resources and limited funding, it is becoming increasingly important to be strategic about where protected areas are established. To do this, conservation biologists and policy makers must answer three key questions: (1) What is most important to protect? (2) Where would it be best protected? (3) How could it be most effectively protected? Three criteria can be used to answer the first two of these questions:

- *Distinctiveness (or irreplaceability)*: Ecosystems with species that are distinct in their taxonomy (e.g. ecosystems that contain the only species in a taxonomic group) or geographic distribution (e.g. endemic species), or ecosystems with unique attributes (e.g. scenic landscapes, unusual geological features).
- *Endangerment (or vulnerability)*: Areas that contain concentrations of species threatened with extinction, or ecosystems in danger of being destroyed.
- *Utility*: Species and ecosystems that people value, including culturally significant species, economically valuable species or ecosystems, or areas that can contribute to combating climate change.

Using these criteria, scientists have developed several broadly complementary methods to prioritize areas for protection. The approaches differ more in what traits they emphasize rather than in their fundamental principles. Thus, although some people may argue about which approach is better, each approach contributes to the protection of biodiversity.

Species approach

Many protected areas are created to protect (e.g. threatened, culturally significant, or keystone) species. Species that provide the motivation to establish a protected area are known as **focal species**. As a prominent example using the focal species concept, the Alliance for Zero Extinction (http://www.zeroextinction.org) identified 853 priority sites globally that contain the last remaining populations of one or more Endangered or Critically Endangered species. **Flagship species**, such as gorillas, are a special kind of focal species because they capture public attention, have symbolic value, and are important for ecotourism purposes. Many flagship species and focal species are also **umbrella species**, because their protection indirectly benefits other species and ecosystem components with which they share their landscape (Figure 17.6.1).



Figure 17.6.1: The Southern Sea Otter, *Enhydra lutris nereis*, is an endangered sea mammal that lives in kelp forest and estuary habitats along the coast of California. The California sea otter eats sea urchins and other invertebrates that feed on the kelp. The sea otter plays a vital role in the health of the kelp forest by keeping the populations of urchins in check which would otherwise overgraze the kelp. It is a keystone species for the kelp forest and also a focal, flagship and umbrella species drawing two million visitors to the Monterey Bay Aquarium each year. (Photo by Mike Baird via flickr, CC-BY-2.0)

Ecosystem approach

There is debate among conservation biologists over whether ecosystems rather than individual species should be the primary target of conservation efforts. Supporters of an ecosystem approach argue that protecting and managing ecosystems can preserve more species and provide more value to people than spending the same amount of money to protect individual species. Focusing on ecosystems also allows for greater flexibility in justifying conservation efforts, because it can be easier to demonstrate the economic value of ecosystems for helping to control floods, filtering water, and providing opportunities for recreation. To that end, the WWF has identified 238 ecoregions across the globe (the “Global 200”) that are most crucial to the biodiversity conservation (Olson et al., 2002). This Global 200 analysis formed the basis of a more recent global assessment that identified 41 at-risk ecoregions—areas of high conservation priorities because they are undergoing high levels of habitat conversion and have low protected areas coverage (Watson et al., 2016). The IUCN Red List of Ecosystems (RLE) is another example of an ecosystem-focused prioritization for conservation. While the ecosystems approach overcomes several limitations of the species approach, some conservationists argue that focussing on distinct ecosystems may, in itself, be detrimental, and that the scope of conservation should be expanded, for example by also including biogeographic transition zones (van Rensburg et al., 2013).

Wilderness approach

Wilderness areas are large areas where people have had little influence on the environment (relative to other areas), they have few people living in them, and are unlikely places for human development in the short term. These areas are conservation priorities because they may be the only places where animals that require large home ranges can continue to survive in the wild. Further, wildernesses can serve as controls or benchmarks for researchers to measure the effect of human disturbance on nature. The most popular way to identify wilderness areas is to identify areas without roads. While very few roadless areas remain, many of the world’s most important roadless wildernesses, some larger than 10,000 km2, are in Africa (Ibisch et al., 2016). Of concern is that, second to South America, Africa also leads the world in wilderness losses over the past decade (Potapov et al., 2017). It is worth emphasizing that even wilderness areas have had a long history of human activity (Roberts et al., 2017). It is not always necessary or even possible to eliminate all human activity from such areas, if those activities do not obstruct conservation goals.

Hotspot approach

Multiple prominent initiatives have prioritized conservation in areas where large concentrations of species can be protected in a relatively small area. Perhaps the most prominent example is the Global Biodiversity Hotspots initiative. Combining a species approach with an ecosystem approach, **Global Biodiversity Hotspots** are areas with exceptionally high levels of biological diversity and endemism—that is, irreplaceable biodiversity—that are threatened with imminent habitat destruction. Conservation

International (CI) has identified an expanded set of 36 Biodiversity Hotspots (Mittermeier et al., 2005). This expanded set of Biodiversity Hotspots covers only 2.3% of Earth's surface yet contains over 50% of all plant species and over 40% of all terrestrial vertebrate species.

https://www.cepf.net/our-work/biodiversity-hotspots.

While the Global Biodiversity Hotspots highlight some of the most important global conservation priorities, none of these Hotspots are small enough to be contained in a single protected area—in fact, most of these Hotspots identify whole regions, not projects, requiring conservationists to still make decisions for prioritizing protection within them. To create actionable priorities from within regional hotspots, several initiatives aim to identify local hotspots of species richness that can be conserved as one protected area of a manageable size. One such approach is the **Key Biodiversity Areas (KBA)** program (Eken et al., 2004), which identifies conservation priorities using standardized criteria and thresholds that account for concentrations of threatened species and/or globally significant population aggregations. The KBA program functions as an umbrella designation for several taxon-specific approaches, most prominently BirdLife International's Important Bird and Biodiversity Areas (IBA) program (Fishpool and Evans, 2011). Other KBA programs include PlantLife International's Important Plant Areas program (e.g. Smith and Smith 2004), as well as the Important Sites for Freshwater Biodiversity program (Darwall et al., 2005).

Gap analysis approach

Assessing the performance of existing protected areas can be done by spatially comparing their footprint to prioritized conservation areas (as above). Such an assessment offers not only an assessment of existing protected areas performance, but also offers a means to identify conservation gaps—important areas that still need to be protected to meet broader conservation goals. Such assessments, which systematically evaluate whether different aspects of biodiversity are adequately protected, are collectively known as **systematic conservation planning** assessments (McIntosh et al., 2017). Perhaps the most popular systematic conservation planning method is gap analysis, during which scientists overlay maps of species (or ecosystem) distributions with maps of protected areas to identify species (called gap species) or ecosystems that are not adequately protected in existing protected areas networks (Box 17.6.1).

When identifying conservation gaps, it is important to think carefully about the taxa or ecosystem used to make the assessment. Many conservation assessments assume that one well-known species group can act as a **biodiversity indicator** (also known as a biodiversity surrogate or **surrogate species**) for lesser-known taxa, so establishing a protected area to protect one gap species will also afford protection to other under-protected taxa. While this is true to some level, several studies have shown that this may not always be the case (Rodrigues and Brooks, 2007; Carwardine et al., 2008; Jones et al., 2016).

> Gap analysis enables conservation planners to identify species or ecosystems that are not adequately protected in existing protected areas networks.

Box 17.6.1 Identifying Key Sites for Conservation in the Albertine Rift

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The Albertine Rift is one of the richest regions on Earth for vertebrate diversity (Figure 17.6.1). Spanning about 100 km either side of the international border of the eastern DRC, it includes forests, wetlands and savannahs from eastern DRC and western Uganda, Rwanda, Burundi, and Tanzania, and runs from the northern end of Lake Albert to the southern end of Lake Tanganyika. It contains more than 40% of Africa's mammals, 52% of Africa's birds, as well as 19% of its amphibians and

plants, in only 1% of the continent's surface area. It also contains more endemic and globally threatened species than any other ecoregion in Africa (Plumptre et al., 2007). Endemic large charismatic species include the eastern gorilla (*Gorilla beringei*, CR), golden monkey (*Cercopithecus kandti*, EN), Congo bay owl (*Phodilus prigoginei*, EN), and Ruwenzori turaco (*Ruwenzorornis johnstoni*, LC). The lakes in the Albertine Rift each also contain several hundred unique fish species. Unfortunately, this rich biodiversity also occurs in one of the most densely populated parts of Africa, and the threats to existing protected areas are high.



Figure 17.6.1 (Top) Mubwindi Swamp, in Bwindi Impenetrable National Park, an important site for mountain gorillas and the Albertine Rift endemic Grauer's Rush Warbler (*Bradypterus grayeri*, EN). (Bottom) A Grauer's gorilla, the largest of the four gorilla subspecies and a flagship for conservation efforts in the Albertine Rift. Photographs by A.J. Plumptre/WCS, CC BY 4.0.

The Wildlife Conservation Society (WCS) has been working to support the conservation of six key landscapes in the Albertine Rift (ARCOS, 2004), particularly focusing on (a) identifying critical areas for conservation of threatened and endemic species; (b) undertaking research and monitoring of species and key landscapes; and (c) supporting the conservation of critical sites and the creation of new protected areas to conserve large and small mammals, birds, reptiles, amphibians and plants in all protected areas, as well as sites where new protected areas might be established. These surveys have identified critically important areas in eastern DRC, such as the Itombwe and Kabobo Massifs where new species have been identified and some species were rediscovered, having been last seen more than 50 years ago. Working with local communities, the surveys have been used to design the boundaries of newly established protected areas to ensure that they capture as much of the biodiversity as feasible. Once the local people in the area are presented with survey results and options for protection discussed, they often realize the importance of their site and propose more stringent protection measures than conservationists initially thought possible.

Using species distribution models (SDM) of the region's endemic and globally threatened species, WCS gained an understanding of where these species should occur both now and under future climate change scenarios (Ayebare et al., 2018). Using Marxan software (Possingham et al., 2000), WCS then identified those areas that would conserve all the species of conservation interest at minimum cost (Plumptre et al., 2019). This procedure identified the Itombwe and Kabobo Massifs together with the Sitebi Hills east of Mahale Mountains National Park in western Tanzania as being critical for conservation of species that are currently not adequately protected (Figure 17.6.2).

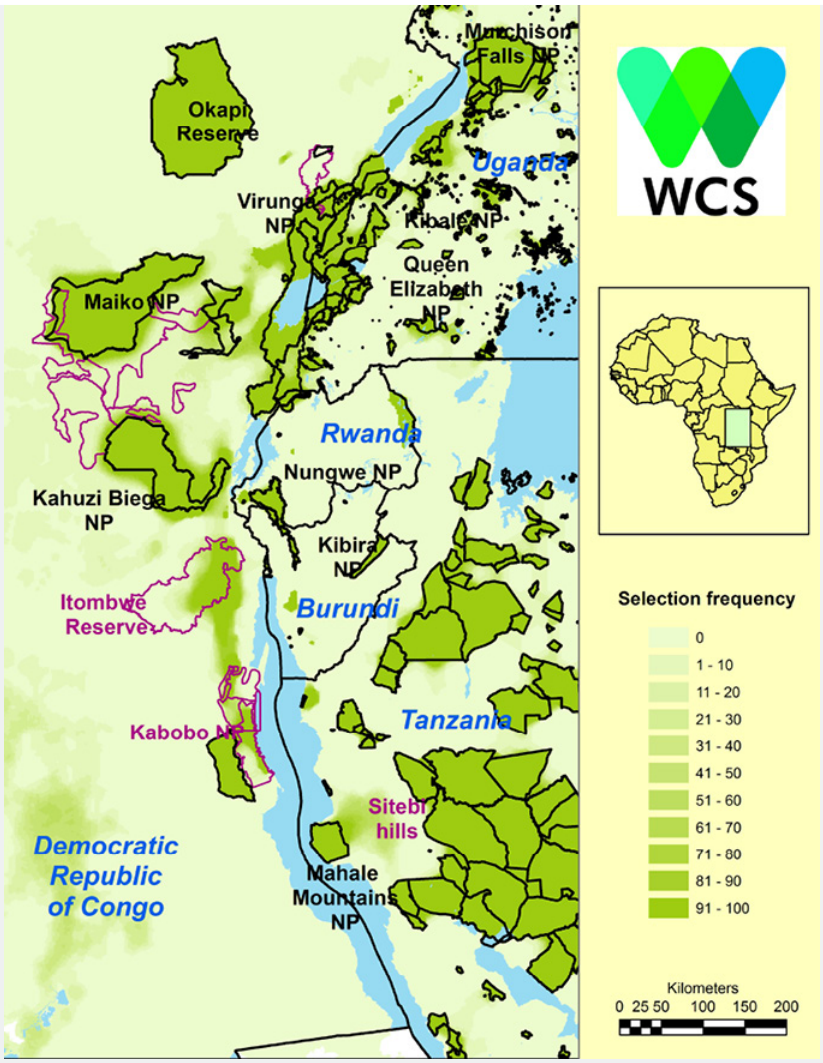


Figure 17.6.2 Selection frequency of 5 km2 cells in the Albertine Rift from Marxan analysis, indicating priority areas for the conservation of endemic and threatened mammals, birds, reptiles, amphibians, and plants. Existing protected areas (all highlighted) were locked in but proposed protected areas such as Itombwe and Kabobo and community reserves (purple boundary) were not. Darker green areas indicate priority conservation sites. Image courtesy of WCS Albertine Rift Program, CC BY 4.0.

These results were used to develop an Albertine Rift Action Plan (Plumptre et al., 2016), together with detailed conservation action plans for the preservation of the six core landscapes and their unique and threatened species, both inside and outside of protected areas, now and into future.

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17.7: Designing Protected Areas

The unplanned way in which protected areas have historically been established means that their design may at times impede rather than aid their goals. For example, many protected areas are too small to sustain viable populations of the species they are meant to protect. To avoid and mitigate such mistakes, conservation biologists are increasingly exploring methods to design more efficient protected areas networks.

Conservation biologists often start the process of designing protected areas networks by considering “the four Rs”:

- *Representation*: A network of protected areas should protect as much of the biodiversity (including species, ecosystems, genetic diversity, ecosystem processes, etc.) of a region, country, or subcontinent (depending on the scale of planning) as possible.
- *Resiliency*: Protected areas should be large enough that they can maintain biodiversity (including species, ecosystems, genetic diversity, etc.) for the foreseeable future, including in the face of climate change and natural disasters such as cyclones/hurricanes and uncontrollable wildfires.
- *Redundancy*: A network of protected areas should not rely on a single protected area to conserve key aspects of a region’s biodiversity; rather important aspects of biodiversity should be included in multiple protected areas to ensure their long-term existence.
- *Reality*: Each protected area requires sufficient funding, political will, defensibility, and local buy-in to support biodiversity over the long term.

In addition to the four Rs (which can also be applied to species protection), the following questions can also help guide planning of protected area networks (Figure 17.7.1):

- How large of an area must be protected and what landscape features must it include to effectively and sustainably protect biodiversity that may not be able to persist outside it?
- Is a single large protected area better, or are multiple smaller reserves more effective?
- What shape should a protected area be?
- When creating multiple protected areas, should conservation managers create them near one another or far apart? Should they be connected in some way, or should they be isolated from one another?
- How should human activities be accommodated? What activities should be allowed?

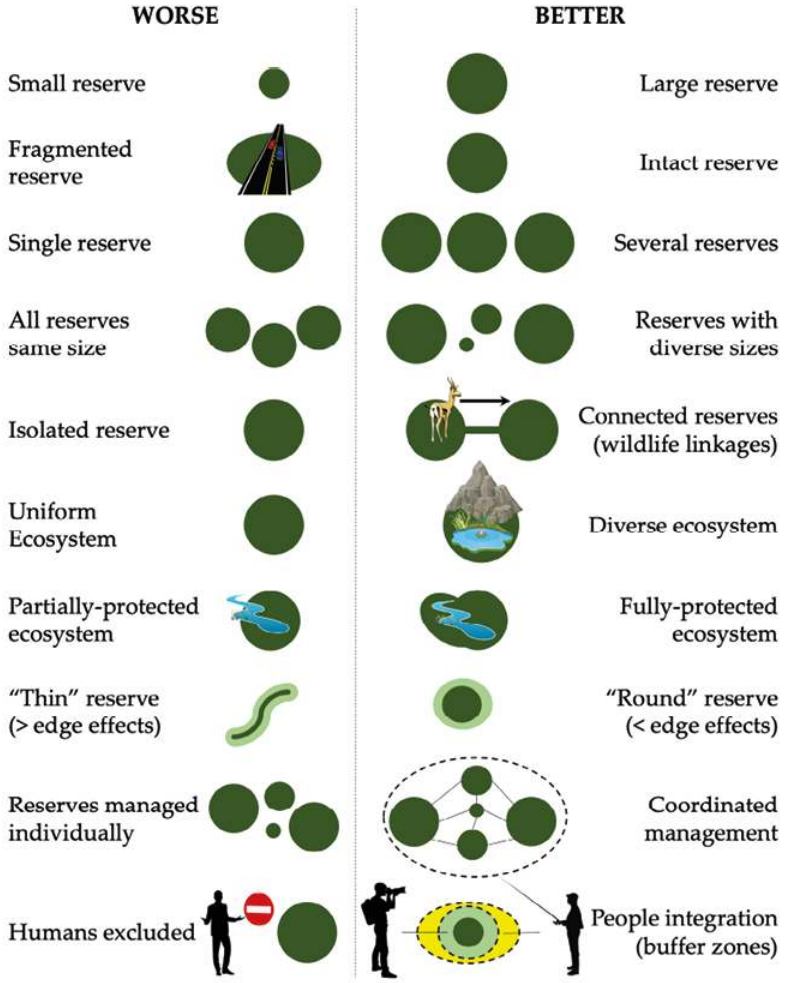


Figure 17.7.1 There are several major principles of reserve design to consider when establishing a new protected area or redrawing the boundaries of an existing protected area. While addressing all these principles is not always possible, the designs on the right are generally considered preferable to those on the left. After Shafer, 1997, CC BY 4.0.

What size should a protected area be?

The design of protected areas, and their size, is often addressed through the lens of the island biogeography model that states that large islands can accommodate more species and larger populations than small islands. Research on extinction rates of populations (Newmark, 1996; Woodroffe and Ginsberg, 1998) and species richness (Harcourt et al., 2001; Brashares et al., 2001) has shown that protected areas function very much like islands. Specifically, because large protected areas contain greater habitat diversity than small protected areas, larger protected areas can accommodate (a) more species, (b) a larger range of ecosystem processes, and (c) viable populations of large species that range over large areas and live at low densities.

Given the range of costs and benefits of establishing large protected areas, conservation biologists have debated whether creating a single large reserve or several small reserves of the same total area—known as the **SLOSS (Single Large Or Several Small) debate**—is better. As discussed previously, habitat fragmentation is currently one of the main drivers of species extinctions; it divides large populations into more vulnerable subpopulations, leads to undesirable edge effects, creates barriers to dispersal, and provides entry points for invasive species. These negative impacts are also of concern for protected areas, especially those that are small and fragmented (leading to larger perimeter:area ratios). For example, fragmentation concentrates elephants (Vanak et al., 2010) and apex predators (Cozzi et al., 2013) in the core of protected areas, greatly limiting the effective protected area for these taxa. However, these same impacts do not alter ungulate foraging (Kiffner et al., 2013), leading, potentially, to overgrazing near reserve borders. Studies have also shown how wildlife experience higher levels of mortality near protected area boundaries (Balme et al., 2010). Ignoring such edge effects could disrupt the long-term conservation value of a protected area, particularly small ones that could effectively function as edge habitat in its entirety. Because one big fragmented reserve has many of the characteristics of

several small protected areas, conservation planners should aim to establish properly-placed large protected areas and to keep them as intact as possible. It is thus good practice to restrict and even remove highways, fences, farms, logging operations, and other human activities inside protected areas because of how they fragment habitats and reduce habitat availability overall.

But how do we know when a protected area is big enough? Ultimately, optimal size depends on the area over which important natural processes take place, which varies depending on the ecosystem. In some cases, the functional size may be quite small, such as a desert spring, a mountain bog, or a rocky outcrop. In contrast, the functional size of tropical forests, seasonal drylands, and desert communities are typically quite large, possibly spanning across country borders. Understanding and planning for protecting these different targets thus requires a familiarity with the functioning and ecology of each ecosystem.

When considering the size of a proposed protected area, conservation managers must also consider how well the area can be monitored and defended from threats. In some instances, an entire community may be incorporated into a relatively small protected area that is easy to monitor and defend against pollution, invasive species, and so forth. More often however, only a portion of the target community can be protected. In such cases it is important to consider how secure the conservation target will ultimately be. For example, if an aquatic organism needs protection, clearly the protection of its immediate habitat is critical. However, if a major threat is upstream from its habitat, then protection of the immediate habitat alone will be insufficient. Instead, managers would need to find ways to prevent outside threats from impacting populations inside the protected area.

Zoning as a solution to conflicting demands

While the general consensus seems to be that larger protected areas are better than smaller ones, establishing a properly-placed large protected area can be an imposing challenge. In a few special cases, large protected areas may be established through cooperation between multiple levels of society. More often, however, conservation biologists are faced with limited resources, and stakeholders can reasonably ask why a large park is required in an area that can otherwise be used to support agriculture or other types of businesses that may provide quick profits and jobs.

One way to deal with such conflicting demands while still achieving the target of protecting a large area is through a method called **mixed-use zoning**. Mixed-use zoning prioritizes the overall conservation objectives for a protected area but also sets aside designated areas where certain regulated human activities are permitted. In this way, some areas (or zones) may be designated for subsistence agriculture, shade-grown crops, timber production, hunting, ecotourism, or water management. Other areas are designated are dedicated to recovery of threatened species, ecotourism, ecosystem restoration, and scientific research.

> Mixed-use zones sets aside areas for certain regulated human activities within a larger conservation area. This approach helps abate conflicting land use pressure.

Through its Biosphere Reserves program, UNESCO has pioneered a formal zoning approach that integrates human activities, scientific research, biodiversity conservation, and tourism at a single location (Coetzer et al., 2014). A **biosphere reserve** is divided into three zones to delineate different levels of human use (Figure 17.7.2). The core of a typical biosphere reserve is a **no-take zone** (also called a core zone), strictly protected for biodiversity and ecosystem functioning. Around the core area is a restricted-use buffer zone, where people can conduct traditional, low-impact activities, such as collecting edible plants and small amounts of wood for fuel, and scientists can conduct non-destructive research. Outside of the buffer zone is a transition zone that allows some sustainable development (such as small-scale farming) and some medium-impact natural resource extraction (such as selective logging and fishing). As of 2021, there were 727 UNESCO Biosphere Reserves in 131 different countries (http://www.unesco.org/new/en/natural-sciences); new reserves are regularly being added.

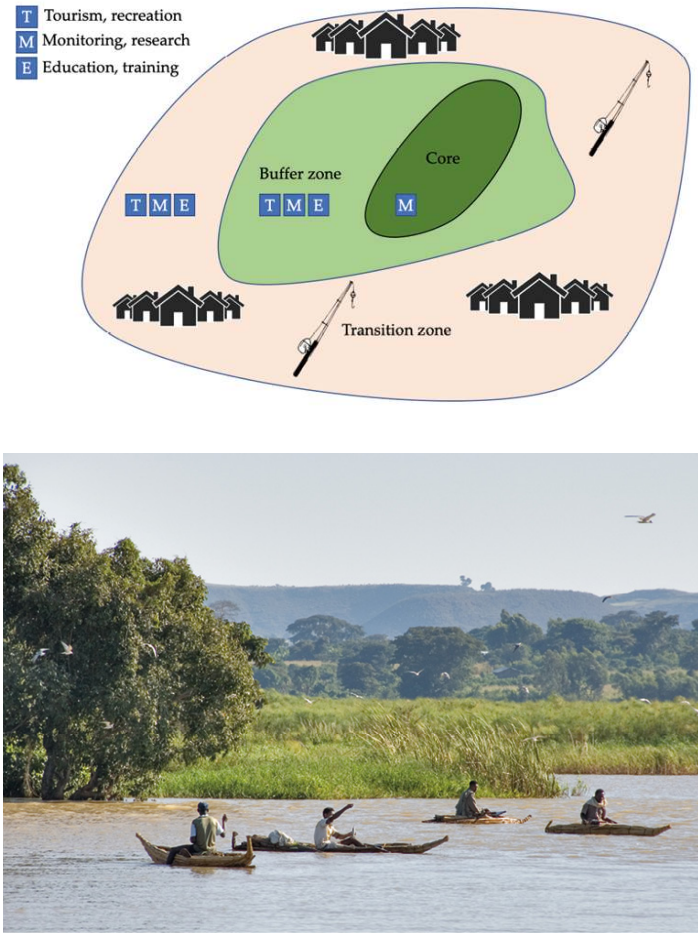


Figure 17.7.2 (Top) The general zones of a biosphere reserve: a core area set aside strictly for biodiversity conservation; a restricted-use buffer zone where human activities compatible with conservation are carried out; and a buffer zone dedicated to sustainable development. (Bottom) Fishermen on their traditional fishing boats in the buffer zone of Ethiopia's Lake Tana Biosphere Reserve. Photograph by Alan Davey, https://www.flickr.com/photos/adavey/2260748777, CC BY 2.0.

Zoning is also proving effective in resolving conflicting demands over marine environments. Like terrestrial biosphere reserves, zoned MPAs consist of core zones where marine organisms can escape and recover from human disturbances, and multiple-use zones where activities such as harvesting of natural resources are permitted. Of course, harvesting fish and other marine species is not the only human activity that needs to be regulated. For example, many marine organisms are sensitive to anthropogenic noise, which interferes with communication and other important behaviors (Shannon et al., 2015). Creating multiple types of multiple-use areas can allow for different intensities of human activities. The is well illustrated at Eritrea's Sheik Said Marine National Park; here, only approved scientific research is allowed in the restricted zone, low-impact ecotourism activities such as snorkelling and spiritual activities are allowed in the sanctuary zone, while noisy motorboats and limited take are allowed in the habitat protection zone (Habtemariam and Fang, 2016).

> Zoned marine protected areas include core zones where marine organisms can escape human disturbance, and multiple-use zones where certain activities are permitted.

While resolving conflicting demands for space, zoning also provides benefits to biodiversity and people. For example, when compared to nearby unprotected sites, zoned MPAs typically have greater total weight of commercially important fish, greater numbers of individual fish, and greater coral reef cover (Lester et al., 2009). Conditions that allow marine organisms within MPAs to thrive, in turn, create opportunities for fish and other sea creatures to spill from the MPA into adjacent unprotected areas where they can be caught by local fishers, with a goal of a more sustainable harvest overall.

Connectivity among protected areas

Although large protected areas are preferable to smaller ones, sometimes small protected areas are the only available option, and conservation biologists must figure out how to protect biodiversity in these small areas. To help conservation biologists meet this challenge, there is a growing body of evidence showing that small protected areas, even ones less than a hectare, can in fact be effective at maintaining viable wildlife populations. But how can that be? Does it suggest that small conservation areas are also useful for conservation purposes?

One of the main reasons why some wildlife populations can persist in small protected areas is that these areas violate an important assumption—that protected areas are isolated from one another. But we now know that wildlife populations often disperse between protected areas through the surrounding **habitat matrix** (Pryke et al., 2015). This dispersal maintains both metapopulation dynamics and reduces the risk of deleterious genetic effects, allowing a network of small protected areas to effectively function as one large conservation area (Wegmann et al., 2014). In contrast, reserve isolation create population sinks for wildlife meant to be protected (Newmark, 2008). Consequently, re-establishing or maintaining connectivity within protected areas networks, and particularly among small reserves, has become an important strategy for enhancing their conservation value

> Landscape connectivity may enable a network of small protected areas to effectively function as one large conservation area.

Many of the strategies used to maintain and restore ecosystem connectivity can be applied to protected areas management. However, this can be challenging given that administrative boundaries seldom consider natural ecosystem boundaries (Dallimer and Strange, 2015). Consequently, many ecosystems are artificially divided between different countries, each with its own development needs and management styles. Furthermore, many border barriers meant to restrict movement of people also restrict wildlife movement.

Bioregional management seeks to conserve such large ecosystems that cross political borders. One way to accomplish this is to establish a **transfrontier conservation area** (TFCA) (also known as Peace Park or transboundary protected area), in which two or more countries collaboratively manage a shared ecosystem for mutual benefit (Hanks, 2008). In addition to pooling scarce resources, this cooperative management style often includes removal of human-made physical barriers such as fences to allow free movement of animals (and sometimes also people, such as pastoralists) within the TFCA.

What about small isolated reserves?

At times, there will be no other choice than to accept that a small reserve is the only option available to achieve in situ conservation. In those cases, it is certainly better to accept the challenge. For many species, especially plants, a small protected area is the only buffer they have against extinction (Wintle et al., 2019). Small reserves, especially those located in or near populated areas, can also serve as locations for public outreach, conservation education, recreation, and citizen science that can improve public engagement with nature and awareness of conservation issues (Miller and Hobbs, 2002). Lastly, in addition to serving as stepping stones, even small protected areas in urban areas provide various ecosystem services, including mitigating the urban heat island effect and reducing flooding (Feyisa et al., 2014). In each of these cases, conservation biologists must creatively consider how to replicate natural processes across a small and/or fragmented protected areas network to ensure that they function on a scale that will maintain the target populations and communities.

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17.8: Challenges for Protected Areas

The biggest challenges that park managers will face in the coming decades stem from a growing human population. When key natural resources, such as firewood and bushmeat, and medicinal plants, become harder to find, conflict is inevitable as more people look for new lands where they can fulfill their needs. As more people encroach into protected areas, so too will habitat loss, pollution, invasive species, and diseases. Despite conservationists' best efforts to build collaborations with nearby communities, park managers need to anticipate that this ever-greater demand for space and natural resources will add additional challenges to their work plans. Below, we discuss three challenges that will likely continue to pose threats in future, and for which there are not always easy solutions.

Poaching

People will continue to harvest resources illegally from protected lands especially when these resources are necessary for survival. Enforcement of regulations within protected areas and addressing poverty will be the most important factors in reducing poaching.

Funding limitations

To enable protected areas to achieve their full potential, there must be adequate funding to support a team of well equipped, properly trained, and motivated staff (James et al. 2001; Gill et al., 2017). There is also a need for buildings, vehicles, communications equipment, and other appropriate infrastructure and resources to enable the staff to fulfill their duties, and for tourists to have a memorable time. The cost of these resources can quickly add up. Some of these challenges can be solved with an adequate ecotourism plan, which can be facilitated from the grassroots level up or government level down. A growing number of funding mechanisms, including private and international donors, have also started to fill funding gaps which, in turn, has allowed more NGOs to assist in conservation areas management (Tranquilli et al., 2012; Lindsey et al., 2014). Above all, a carefully assembled management and monitoring plan, which is adequately funded, is key to the success of protected areas.

Planning for climate change

Because protected areas are fixed in space and time, many species that are currently protected will adjust their ranges beyond the borders of existing protected areas due to climate change. To ensure the future protection of species vulnerable to climate change, we must incorporate species' predicted distribution ranges into the planning of protected areas networks. For species that disperse easily, this requires protecting gaps in their current and future ranges (Hole et al., 2011), as well as protecting, maintaining, and restoring potential dispersal pathways. For poor dispersers, conservationists could start experimenting with assisted colonizations, or identify and protect their climate refugia. For many species, however, establishing protected areas in their future ranges will be nearly impossible simply because no land is available. These species will greatly depend on conservation efforts outside protected areas.

Facing degazettement

It may be reasonable to assume that protected areas (especially government protected areas, established by law) afford permanent protection to biodiversity on those lands. Unfortunately, that is not the case—between 1950 and 2017, at least 227 different protected areas in Sub-Saharan Africa lost (partially or fully) lost their legal protected status (WWF and CI, 2016), in a process formally known as **protected area downgrading, downsizing, and degazettement (PADDD**, http://www.padddtracker.org). There are a variety of reasons behind PADDDs. For example, some protected areas have been PADDDed because of environmental degradation caused by conflicting land uses, including illegal logging, illegal agriculture, and land invasions; in such cases governments (in consultation with conservation managers) may determine that the resources needed for land rehabilitation are better spent protecting other sites (Fuller et al., 2010). Others have been PADDDed because incorrect procedures were followed during establishment—in such cases, it might be prudent to carefully consider if a compromise could be reached that combines the goals of conservation and development. However, the vast majority of African PADDDs are enacted because of more sinister motives, such as to undercut conservation restrictions (Mascia and Pailler, 2011). For example, when examining each threat individually, data from WWF and CI (2016) suggest that mining pressure was the leading cause of previous African PADDDs. Considering that nearly 30% of African protected areas are still earmarked for oil and gas exploration (Leach et al., 2016), the threat from mining will likely also continue in the foreseeable future (Durán et al., 2013; Edwards et al., 2013).

> Mining pressure is currently the leading cause for downgrading and degazettement of African protected areas.

Most conservationists consider the PADDD process a bad precedent that should be avoided unless necessary. While there are legitimate reasons behind some PADDDs (Fuller et al., 2010), few are enacted with conservation goals in mind. In many cases, government officials remove the protected status of lands without even consulting conservation scientists and park managers. Such decisions are particularly frustrating when important areas that protect threatened species and ecosystems are affected. Combating the continuing threat of PADDDs will depend on national and international conservation organizations partnering with vigilant citizens who take ownership of their natural treasures. Until citizenry can trust that government officials have the interests of their natural heritage at heart, protected areas PADDDs will remain a highly controversial topic.

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17.9: Summary

1. Establishing protected areas is the most effective method for safeguarding biodiversity.
2. Government agencies and conservation organizations set priorities for establishing new protected areas based on the relative distinctiveness, endangerment, and utility of a species or ecosystems. Many protected areas are established to preserve species of special significance, unique ecosystems, wilderness areas, and concentrations of threatened species. Gap analysis is used to identify elements of biodiversity not accommodated in existing protected area networks.
3. While protected areas have previously been designed haphazardly, conservation biologists are developing guidelines for designing more effective protected areas. As general guidelines, protected areas should be large whenever possible, and should not be fragmented. Conservation planners should also aim to create linked networks of conservation areas to encourage wildlife dispersal.
4. Protected areas must be actively managed to maintain biodiversity. Monitoring provides much needed information to evaluate whether management activities are achieving their intended objectives or need to be adapted.
5. Managing interactions with local people and visitors is critical to the success of protected areas and should be part of a management plan. To obtain and maintain local support, managements plans should consider benefit sharing and co-management partnerships.

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17.10: Topics for Discussion

1. Obtain a map of your region's protected areas (e.g. nature reserves and national parks) and multiple-use managed areas (e.g. hunting and logging concessions). (https://protectedplanet.net is a good source.) If you could designate an additional protected area, where would it be? What shape would your protected area be? What would the management goals be for these additional areas? Explain all your answers.
2. Think about a protected area that you have visited. What is the main goal of this protected area? Do you think park management is succeeding in the goal? What are they doing particularly well? What could they do to manage the protected area better?
3. Think of a protected area near you that safeguards an aquatic environment, such as a beach, estuary, or lake. What unique challenges do you think the people managing that protected area face that managers of a terrestrial protected area do not face?
4. Many countries are developing protected areas that cross international borders. What are the main goals of these parks? Are they achieving their goals? What are the main challenges?
5. How can national parks continue to function optimally in countries where the central governments have largely ceased to function, and where corruption is rampant?

Suggested Readings

de Vos, A., H.S. Clements, D. Biggs, et al. 2019. The dynamics of proclaimed privately protected areas in South Africa over 83 years. Conservation Letters 12: e12644. https://doi.org/10.1111/conl.12644 Tracking the growth of privately protected areas in South Africa as a function of national legislation.

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CHAPTER OVERVIEW

18: Conservation on Unprotected Lands

18.1: Introduction to Conservation on Unprotected Lands
18.2: Human-Dominated Landscapes
18.3: Sustainable Agriculture
18.4: Smarter Infrastructure
18.5: Confronting Human-Wildlife Conflict
18.6: Data Dive- Landslides and Ag Terraces
18.7: Summary
18.8: Topics for Discussion
18.10: Bibliography

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18.1: Introduction to Conservation on Unprotected Lands



Farm workers tending rice fields near Monrovia, Liberia. Agricultural expansion is a major contributor to habitat loss, but is also a common cause of pollution, invasive species, and at scale, even climate change. There is an urgent need to adopt more sustainable agricultural practices and policies to ensure this sector continues to sustain food security and economic activity, but not at the expense of biodiversity. Photograph by blk24ga, https://commons.wikimedia.org/wiki/File:Liberia,_Africa_-_panoramio_(103).jpg, CC BY 3.0.

Well-managed protected areas are essential tools for securing intact ecosystems and the biodiversity they sustain. However, it will not be sufficient to rely solely on protected areas to preserve biodiversity. Harming ecosystems such as rivers and streams on unprotected lands has repeatedly been shown to decrease biodiversity also within protected areas (Colvin et al., 2011; Woodborne et al., 2012). Furthermore, many species only occur on unprotected lands (Beresford et al. 2011), and some species even fare better outside protected areas (Murgatroyd et al., 2016). Other species need to move out of protected areas to access important seasonal resources. Lastly, restoring damaged areas and maintaining intact ecosystems inside and outside of protected areas provides ecosystem services such as water and air purification. And so, while we must continue to pursue protected areas for the many benefits they do offer, we must not forget about the value of the spaces between protected areas. In this chapter, we will explore how efforts on unprotected lands can complement conservation efforts in protected areas.

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18.2: Human-Dominated Landscapes

In every country on Earth, significant portions of unprotected lands still harbor some of their original biota. Consider, for example, remote regions that are considered “wilderness” by governments and the general public. Most of these areas are inhabited by low-density human societies that practice a traditional way of life. With relatively little outside influence from modern technology, these traditional peoples are often dependent on—and thus highly concerned with—the health of their environment. More importantly, traditional peoples have been an integral part of their environments for thousands of years. The present mixture and relative densities of wildlife in these “wildernesses” thus reflect the historical activities (e.g. fishing, hunting, fire management, land clearing, and planting of useful plant crops) of the people living in those areas (Roberts et al., 2017). These activities do not degrade the environment if human population densities remain low and natural resources are harvested sustainably. To regulate these activities, most traditional societies have an established system of rights to natural resources, known as customary laws, which an increasing number of governments recognize. Conservation biologists should follow this example: rather than being considered a threat to the “pristine” environments in which they live, traditional peoples should be seen as important partners in conservation efforts because protecting their lifestyles also ensures the protection of biodiversity.

Urban Areas

People who live in rural areas and sell natural resources that they extract from healthy ecosystems also play an important role in conservation by engaging in sustainable natural resource management. Consider all the unprotected estuaries and marine areas that support commercial fisheries for a moment. When fisheries are managed in a sustainable way, not only does this benefit the people that depend on these commercially important species, but other native species can also thrive.

People living in urban centers can also contribute to conservation efforts by raising environmental awareness among fellow citizens, participating in activism, lobbying, and fundraising activities, and generating knowledge through citizen science projects. They can also help reduce the multiple pressures that their cities exert on the surrounding environment. Among the most exciting recent developments have been the development and installation of **green infrastructure**, such as urban forests, green roofs, urban wetlands, permeable sidewalks, urban farms, and rain gardens (Figure 18.2.1). Not only does green infrastructure save money by reducing energy consumption and pollution clean-up costs, it also reduces overall maintenance (Odefey et al., 2012) and improves overall well-being (Demuzere et al., 2014). Consequently, green infrastructure is increasingly being integrated in urban planning across the world, including North America (EPA, 2018), Europe (Natural England, 2009), Asia (e.g. Kennedy et al., 2016), and in South Africa (Culwick et al., 2016).

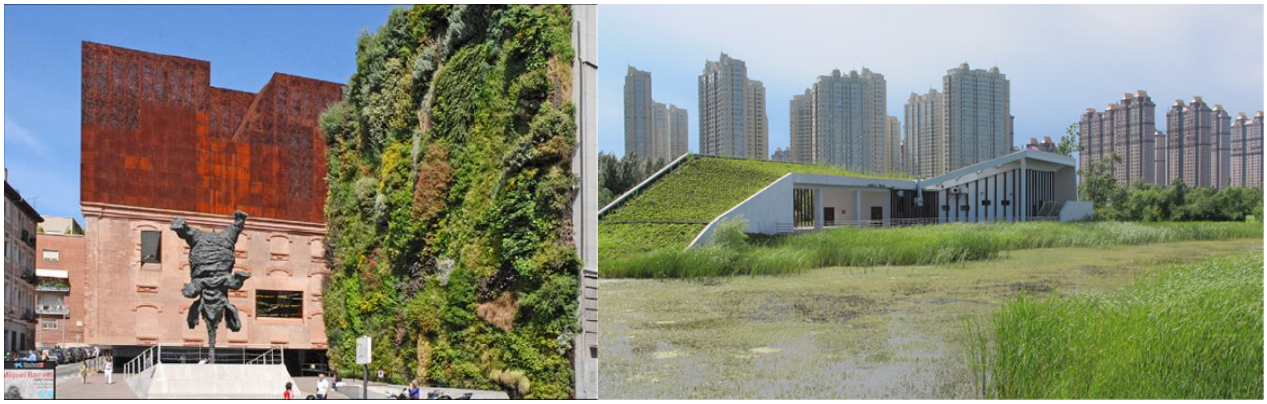


Figure 18.2.1 Green infrastructure enables people living in urban centres to reduce their pressure on natural ecosystems and live more comfortable lives. (Top) A green wall to provide cooling and air purification in Madrid, Spain. Photograph by Jean-Pierre Dalbéra, https://www.flickr.com/photos/dalbera/4657766022, CC BY 2.0. (Bottom) A constructed wetland in Harbin, China, built to provide flood control, a wildlife refuge, and a nature experience. Photograph by Richard Primack, CC BY 4.0.

Many urbanites are also eager to work with government agencies and conservation NGOs to make their cities more biodiversity friendly by restoring urban waterways and wetlands, and replanting abandoned industrial sites and other damaged urban areas with native vegetation that can support pollinators, birds, and other wildlife. Such efforts foster neighborhood pride, create a sense of community, and provide a sense of satisfaction to people who like to be close to nature. These restored areas, and other urban green spaces, can also serve to highlight the links between human well-being and nature, which may make those city dwellers who

remain on the side-lines of conservation more receptive to the more challenging aspects of conservation, such as prescribed fire and invasive species management (Gaertner et al., 2016). Establishing and maintaining areas to protect biodiversity where people live and work, termed **reconciliation ecology** (Rosenzweig, 2003), will increase in importance as urban centers continue to expand over the next decades (Seto et al., 2011). Reconciliation ecology can improve biodiversity by providing habitat stepping stones between protected areas.

The Monarch Butterfly, *Danaus plexippus*, is an example of a specialist species in decline (Figure 18.2.2) that can be helped by reconciliation ecology efforts. The north American populations migrate great distances from summer to winter ranges and rely specifically on milkweed, *Asclepias* spp., for reproduction. Caterpillars eat and develop on milkweed and toxins in the plant provide protection for the developing butterfly. Multiple generations are produced during one breading season and require milkweed and nectar sources along the migratory route. Factors causing the decline of Monarch populations in North American are grassland conversion to agriculture, herbicide use, drought, logging in the winter range, and urban development (U.S. Fish and Wildlife Service, 2020, Monarch (*Danaus plexippus*) Species Status Assessment Report). Planting native milkweed species and pesticide-free nectar sources in rural and urban areas can improve habitat for migrating monarchs.

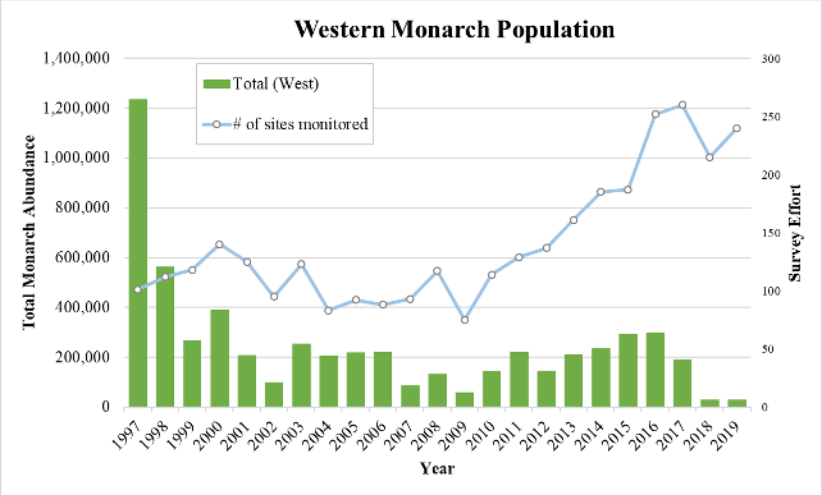




Figure 18.2.2: Top: Monarch butterfly (*Danaus pexippus*) populations rely on Milkweed for reproduction. Two important North American populations migrate great distances between their winter and summer habitat. (Top: Caterpillar on milkweed. Photo by Ashley Spratt, USFWS Pacific Southwest Region from Sacramento, US, Public Domain via Widimedia Commons, Middle: Adult monarch on milkweed. Photo by Jim Hudgins, USFWS Midwest, Public Domain via Wikimedia Commons, Bottom: Overwintering monarchs on the central California coast. Agunther, CC BY 3.0, via Wikimedia Commons) Graph: Thanksgiving counts showing the number of western North American monarch butterflies observed at overwintering sites (green bars). Blue line shows the number of sites monitored (survey effort) for a given year. (U.S. Fish and Wildlife Service. 2020. Monarch (*Danaus plexippus*) Species Status Assessment Report., Data from The Xerces Society for Invertebrate Conservation 2020, entire)

Lessening impacts of agriculture

Habitat loss from agricultural expansion is one of the biggest current challenges to biodiversity conservation in many parts of the world (Balmford et al., 2012; Laurance et al. 2013; Maxwell et al., 2016). At the root of this problem is the need to supply food and other resources to a growing human population. Exacerbating the situation, much of the Earth's arable land has already been degraded to such a degree that it cannot sustain viable food production anymore (Drechsel et al., 2001). Most of these losses are not due to natural factors, but to poor land management practices, such as overgrazing, continual plowing of fields, and heavy use of fertilizers. These practices release nitrogen, carbon, and oxygen into the atmosphere and compromise the soil's ability to hold water, leading to erosion, soil salinization, desertification, and even climate change (Vågen et al., 2005). This not only lead to collapsing ecosystem services, but also increased competition for space as even more land must be converted for agriculture, and to accommodate people and their activities. Such land conflicts are only going to become worse with climate change (Zabel et al., 2014).

In light of the seemingly irreconcilable conflict between agriculture and conservation, some conservation biologists have suggested that the only way in which we can secure a future for biodiversity is through a **land sparing** approach, in which agricultural investments are focused on intensifying practices on land already dedicated to farming and no more. One of the main drawbacks of such a high-yield approach is that the impact of intensive agricultural practices degrades natural ecosystems even far from the immediate area, for example through nutrient and pesticide pollution. For that reason, others support a **land sharing** approach that promotes biodiversity-friendly agricultural practices, even if that means agricultural lands continue to expand. One of the main drawbacks of this land-sharing approach is that it still alters ecosystem composition, which would threaten species that need large territories and habitats, in addition to leading to more human-wildlife conflict. Agricultural land use in the United States has declined slightly from 1959 to 2017 (Figure 18.2.3).

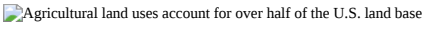


Figure 18.2.3. *Land use for agriculture in the US declined between 1959 (59%) and 2017 (53%). Total land area is 2.26 billion acres. Urban land use has more than tripled in the same time period to 74 million acres (USDA Public Domain).*

While the land-sparing versus land-sharing frameworks make for good intellectual debate, the reality is that both are undesirable scenarios when carried out as opposite extremes. There is no denying that agriculture is important, and critical for food security. But because there is a finite amount of land available for food production, we have no choice but to develop methods that will allow greater yields on existing agricultural lands without depleting the soil or damaging more ecosystems. In other words, we need to adopt a hybrid approach where some lands are dedicated to large protected areas where human activities are restricted, some lands are dedicated to wildlife-friendly agro-ecosystems, and some lands are used for intensive food production (Fischer et al., 2014; Law et al., 2017). Traditional farming systems offer many strategies showing how natural ecosystem services can be used to improve yields, including the use of biocontrol and crop diversification to keep pests and diseases at bay, and planting of nitrogen-fixing legumes to improve soil fertility. This is in stark contrast to intensive modern agricultural practices dedicated to single crop specialization; these impoverished ecosystems cannot maintain themselves but rather rely on continuous use of fertilizers and pesticides to remain productive.

> Biodiversity-friendly farming practices can also produce economic benefits; and so, many government programs are now promoting sustainable agricultural intensification.

With the increased realization that biodiversity-friendly farming practices can also produce economic benefits, many government programs have begun to promote and subsidize the adoption of **sustainable agricultural intensification** (see also Pretty et al., 2011; Garnett et al., 2013). Also known as **conservation agriculture**, this farming approach blends traditional agricultural practices with improved and locally adapted crops, as well as integrated crop and pest management strategies (Figure 18.2.4) to boost yields on existing farmland while creating cost and labor savings; it may even reduce the amount of land under cultivation (Stevenson et al., 2013). Some of these strategies include minimal tilling, crop rotation, intercropping, and terracing (to prevent agricultural runoff which, in turn, prevents erosion). Soil nutrient levels are enhanced through **fertilizer microdosing**, and by planting legumes, encouraging decomposition by termites, and using crop residues as mulch before composting it directly into the soil. Crop yields are further improved by maintaining windbreaks such as riparian buffer zones, which have the added benefit of enhancing the diversity of seed dispersers, biocontrol agents, and pollinators. It is important to remember that conservation agriculture is a departure from both traditional and intensive monocrop farming techniques. Adequately training farmers in best practices and new techniques is therefore crucial to program success (Gatare et al., 2013).



Figure 18.2.4 A vegetable farm maintained by a local community living adjacent to Gorongosa National Park, Mozambique. The farm is maintained following several conservation agriculture principles. For example, to conserve water, the ground is covered in mulch obtained from a nearby grassy field, while a drip irrigation system was installed by park staff and a local women's association. To further strengthen local development and collaboration, part of the crop is also sold at the tourist restaurant inside the park. Photograph by Iñaki Abella Gutiérrez/Bio+, CC BY. 4.0.

To take advantage of the multiple benefits to be gained from integrated, biodiversity-friendly farming techniques, entire industries have started adopting such practices. Among the most prominent are cacao and coffee, where many growers now produce their crops under native shade trees (Box 18.2.1). While Africa has had a long history of shade-grown cacao and coffee production, recent decades have seen many farmers transitioning towards intensive farming in full sun, which allows for easier mechanisation. But crops grown in full sun are generally also of lower quality and more susceptible to pest outbreaks (Kellerman et al., 2008; Bisseleua et al., 2009; Tscharntke et al., 2011). In contrast, shade-grown cacao and coffee benefits both the farmers and biodiversity: a study from Ethiopia found that shade coffee farms had over double the number of bird species in comparison with nearby forest sites (Buechley et al., 2015). Shade farming could also be a strategy for farmers trying to cope with increasing temperatures due to climate change (Blaser et al., 2018). Considering the large global markets for cacao and coffee, reverting to traditional growing methods here would have a large positive impact on the environment simply due to the economy of scale.

Box 14.3 Preserving Biodiversity Through Shaded Agroforestry

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Chocolate is one of the most universal treats in the world, but could your sweet tooth be increasing biodiversity loss? The chocolate tree (Theobroma cacao) is traditionally grown in areas with dense and diverse canopies of shade trees, home to an abundant variety of plants and animals (Figure 18.2.5). The chocolate industry is strongly dependent on small-scale agriculture, but also highly vulnerable to pest and disease outbreaks, and climate change. These production challenges combined with increasing global demand for chocolate has increased economic and social pressures to achieve higher yields within a shorter timeframe. Higher yields could be achieved through reduced shade tree management and increased use of chemical pesticides and fertilizer. But these techniques lead to deforestation, biodiversity loss, and loss of ecosystem functioning. Higher yield techniques in the short term are also not sustainable over the long term: work in Cameroon and elsewhere showed that the promotion of high-yielding hybrid cacao varieties under direct full sun have contributed to more frequent outbreaks of pests and diseases (Kellerman et al., 2008; Bisseleua et al., 2009; Tscharntke et al., 2011).

To achieve more sustainable cacao production, and to benefit from ecosystem services, such as enhanced biological control of pests and diseases, and increased soil fertility, West Africa's cacao farmers are now gradually returning to agroforestry practices that embrace increased shade tree diversity. Farmers adopting these techniques are already reaping benefits. For instance, in Ghana and Cameroon, cacao yields from shaded cacao agroforestry systems are 12–23% higher compared to full sun systems (Bisseleua et al., 2009; Asare and Raebild, 2016). In eastern Côte d'Ivoire, the use of leguminous trees as shade in

rehabilitated cacao plantations is also reported to increase the survival rate and yield of cacao trees (Smith Dumont et al., 2014). Cacao grown in shade may produce for 60–100 years, whereas production may only last for 20 years without shade (Obiri et al., 2007). In addition to environmental services, diversified shade trees may also provide additional income opportunities, such as timber and firewood production, medicine, local spices, and fruit, from native shade trees such as the njangsang tree (Ricinodendron heudelotii) and bush mango (Irvingia gabonensis) (Smith Dumont et al., 2014). Importantly, in all these multi-strata systems, a higher density and diversity of shade trees means higher densities and diversity of pollinators and biological pest control agents such as ants and social wasps, which in turn increase cacao yields even more (Bisseleua et al., 2017).

In conclusion, better land management practices, such as allowing a diversity of shade trees to grow among the cacao crop, increases both biodiversity and revenue for farmers. Tropical agroforestry is thus a promising approach to reconcile biodiversity conservation and economic development. Educating farmers on shaded agroforestry systems and creating complimentary economic incentives and policies would help farmers adapt to better management practices faster, ultimately allowing agroforestry systems to contribute more to biodiversity conservation. A guilt-free sweet tooth, indeed!



Figure 18.2.5 (Top) Cacao grown as a monoculture, without shade trees, in Ghana. Biodiversity is greatly reduced and the cacao trees are more susceptible to pests and diseases in this framework. Photograph by Phillip Allman, CC BY 4.0. (Bottom) Coffee grown under a diverse canopy of trees in Ethiopia. Like cacao, coffee cultivated under shade provides a forest structure in which birds, insects, and other wildlife can flourish. Photograph by Evan Buechley, CC BY 4.0.

Improved logging practices

> Conservationists are also dependent on extractive industries. Rather than criticize, it is more productive to partner with and influence these industries to contribute to conservation efforts.

As with intensive agriculture, high-impact resource extraction industries have not traditionally been compatible with conservation needs. These include mining, oil and gas extraction, dredging, quarrying, and logging, which have often been associated with complete ecosystem destruction. While it is easy to criticize these industries for their impact on nature, it is important for conservationists to remember that we are all dependent on those industries in some way or other, even to perform our conservation activities. Rather than criticize, it is more productive to partner with and influence with industries to contribute to conservation efforts.

There are many examples illustrating how partnerships between conservation biologists and extractive industries can benefit conservation. One of the best examples comes from the timber industry, which has the potential to greatly increase forest conservation opportunities (Clark et al., 2009). Traditionally known for leaving unsightly clear-cuts behind them, research has shown that improved logging techniques facilitate quicker ecosystem recovery after harvesting, which in turn also benefits biodiversity. For example, while the response of wildlife to logging differs depending on the harvesting method and forest type (Ofori-Boateng et al., 2013), primates (Stokes et al., 2010; Morgan et al., 2018), amphibians (Ofori-Boateng et al. 2013), and birds (Şekercioğlu, 2002) can all tolerate responsible-done light-touch logging techniques (but see also Bicknell et al., 2013; Gatti et al., 2015).

Guided by this research, some sectors of the timber industry have been keen to adopt more sustainable logging techniques (Figure 18.2.6) that focus on reducing damage to the soil, stream banks, and remaining trees, while removing just the largest trees. This approach reduces soil disturbance, erosion, waste, and carbon emissions. **The Forest Stewardship Council (FSC)** and other similar organizations are setting certification standards for sustainable logging, which enable certified logging operations to sell their products at higher prices on world markets. In addition to impact reduction within logged areas, certification schemes typically also require timber companies to avoid logging high conservation value forests, which is a good strategy for protecting ecosystem services and biodiversity in general. Some agroforestry companies also allow local people to cultivate rare medicinal and aromatic plants in the shaded areas on their concessions which reduces harvesting pressure on wild populations (Rao et al., 2004). Lastly, a key element for wildlife management in logged forests is to stop hunters, fishers, trappers, and plant collectors from entering the impacted area after timber harvest by closing unused logging roads. (For more discussion on the impact of the logging road on biodiversity, see Laurance et al., 2014 and Benítez-López et al., 2017.)



Figure 18.2.6 Reduced impact logging techniques facilitate quicker ecosystem recovery. In this example from Mozambique, foresters took only the largest trees, and left some scattered logging slash (i.e. cut branches) to provide shelter for wildlife and to promote natural seed germination. Logged areas are also surrounded by stands of intact forest to promote wildlife and seed dispersal. Photograph by Johnny Wilson, CC BY 4.0.

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18.3: Sustainable Agriculture

Sustainable agriculture is a method of farming that does not deplete natural resources or degrade the environment and can therefore be continued indefinitely. Sustainable farms often rely on components of local ecosystems. For example, they might promote conditions for natural decomposition of wastes or employ natural enemies to control pests through predation or competition. More specifically, the 1977 and 1990 “Farm Bills” describe sustainable agriculture as "an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- satisfy human food and fiber needs;
- enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- sustain the economic viability of farm operations;
- enhance the quality of life for farmers and society as a whole."

Promoting biodiversity is key to sustainable agriculture, and high biodiversity results intact ecosystem services such as nutrient cycling and regulation of pest populations. This is consistent with the goal of sustainable agriculture: to mimic the processes found in natural ecosystems. In contrast to the monocultures of industrial agriculture, **polyculture** farming (growing different species together) is a common practice in sustainable agriculture. This assists with regulating pests and maintaining soil fertility (see below). **Seed banks**, locations at which many different types of seeds are stored, are key to conserving the genetic diversity of crops. These storage sites are cold enough to keep seeds frozen naturally (figure 18.3.a).



Figure 18.3.a: The Svalbard Global Seed Vault in Norway. Image by Miksu (CC-BY-SA).

Integrated Pest Management

Integrated Pest Management (IPM) refers to a mix of farmer-driven, ecologically-based pest control practices that seek to reduce reliance on synthetic chemical pesticides. It uses several methods simultaneously to control pest populations. The steps of integrated pest management are to (1) identify true pests, (2) set thresholds and monitor (figure 18.3.b), and (3) develop an action plan. As many insects, microbes, and other organisms found in an agricultural area have a neutral or beneficial effect, it is not necessary to remove them. True pests are those that are causing economic harm, and they are managed (kept below economically damaging levels) rather than eradicated.



Figure 18.3.*b*: A retired Navy commander and landowner inspect an insect trap as part of an Integrated Pest Management (IPM) conservation practice. Image by NRCS (public domain).

An IPM Action Plan draws on four types of control: cultural, mechanical, biological, and chemical. These methods are listed in order of least to most environmental impact and are thus applied in this order. For example, cultural control is attempted first. If that is not effective, mechanical control is added to the plan, and so on. Chemical control is used as a last resort and is deemphasized in an IPM plan. When pesticides must be used, they are selected and applied in a way that minimizes adverse effects on beneficial organisms, humans, and the environment. It is commonly understood that applying an IPM approach does not necessarily mean eliminating pesticide use, although this is often the case because pesticides are often over-used for a variety of reasons.

An Alternative to Spraying: Bollworm Control in Shandong

Farmers in Shandong (China) have been using innovative methods to control bollworm infestation in cotton when this insect became resistant to most pesticides. Among the control measures implemented were:

1. The use of pest resistant cultivars and interplanting of cotton with wheat or maize.
2. Use of lamps and poplar twigs to trap and kill adults to lessen the number of adults.
3. If pesticides were used, they were applied on parts of the cotton plant's stem rather than by spraying the whole field (to protect natural enemies of the bollworm).

These and some additional biological control tools have been effective in controlling insect populations and insect resistance, protecting surroundings and lowering costs.

Cultural Control

Cultural control refers to minimizing the conditions that allow pests to thrive and spread. Examples include alternating which crops are planted each year (**crop rotation**), planting multiple types of crops near each other (**intercropping**; figure 18.3.*c*), selecting pest-resistant varieties, and planting pest-free rootstock (underground plant parts). Crop rotation prevents pests that are specialized to a particular type of crop from continuing year after year because their host plants are only available in certain years. Similarly, intercropping spatially limits the spread of pests. **Strip cropping** is a type of intercropping that involves growing different types of crops in alternating rows. Pests may infest one (or several) rows of their host species, but they would have to move past multiple rows of non-hosts to access additional host plants. Additionally, cultural control can involve optimizing irrigation and fertilizer application to promote plant defense and limit disease spread. Cultural control methods can be very effective and cost-efficient and present little to no risk to people or the environment.



Figure 18.3.*c*: *Momordica charantia* (bitter melon) intercropped with rice in the Philippines (cultural control). Bitter melon plants emerge from holes in plastic, which is used for mechanical control of weeds. Image by Judgefloro (CC-BY-SA).

Mechanical Control

Mechanical control refers to physically removing pests or excluding them with barriers (figure 18.3.*d*). Mechanical controls that remove pests include sticky insect traps, mole traps, and removing weeds by hand. Netting to exclude birds, deer fencing, and weed cloth, plastic weed barriers (figure 18.3.*c*) or mulch are additional examples of mechanical control.



Figure 18.3.*d*: This solar insect trap is an example of mechanical control. It emits ultraviolet light to attract insects and is recharged using small solar panels. Image by MGK Solar Trap (CC-BY-SA).

Biological Control

Biological control is the use of organisms to reduce pest populations (also see Invasive Species). One biological control strategy involves releasing natural enemies, such as predators, parasites, or parasitoids of the pest organisms (parasitoids are similar to parasites, but they consistently kill their hosts). Home gardeners can also rely on natural enemies by purchasing preying mantises, ladybugs (ladybird beetles), or lacewings for release (figure 18.3.*e*). Successful examples include ladybird beetles to depress aphid populations, parasitoid wasps to control whiteflies, and fungi, such as *Trichoderma*, to suppress fungal-caused plant diseases.



Figure 18.3.*e*: Lacewings are natural predators of garden and crop pests. Image by artsehn/Pixabay (Pixabay license).

If not used carefully, chemical control can have unintended negative consequences for biological control. In 1887, the cottony cushion scale (native to Australia) was devastating the citrus groves of California. A U.S. entomologist went to Australia to find a natural enemy and came back with the **vedalia beetle**, a species of ladybird beetle. Released in California, the beetle quickly brought the scale under control, at least until 1946. In that year, the pest made a dramatic comeback. This coincided with the first use of the now-banned pesticide dichlorodiphenyltrichloroethane (DDT) in the groves. Not only did DDT kill the target pest insects, but it killed the vedalia beetle as well. Only by altering spray procedures and reintroducing the beetle was the scale insect again controlled.

Another strategy for biological control involves releasing sterile males, which compete with fertile males for mates, ultimately decreasing pest population size. This technique was first applied against the screwworm fly, a serious pest of cattle (figure 18.3.*f*). The female flies lay their eggs in sores or other open wounds on the animals. After hatching, the larvae eat the tissues of their host. As they do so, they expose a still larger area to egg laying, often finally killing the host.



Figure 18.3.*f*: Thought to be eradicated in the United States by 1966, the screwworm fly, a cattle pest, reemerged in deer at Key Deer National Refuge in Florida in 2016. Sterile males were again released, and the pest was eradicated from Florida in 2017. Image by Judy Gallagher (CC-BY).

Prior to its eradication from the southeastern United States, the screwworm was causing huge annual livestock losses. The sterile male technique involves releasing factory-reared and sterilized flies into the natural population. Sterilization is done by exposing the factory flies to just enough gamma radiation to make them sterile but not enough to reduce their general vigor.

Starting in early 1958, up to 50 million sterilized flies were released each week from aircraft flying over Florida and parts of the adjoining states. Each time a fertile female in the natural population mated with a sterile male, the female layed sterile eggs. Since the females mate only once, her reproductive career was at an end. By early 1959, the pest was totally eliminated east of the Mississippi River. The problem in southwestern states was more challenging because the fly winters in Mexico and could move across the border with each new season. Even so, by expanding the program to include Mexico as well, the screwworm fly was finally eliminated from Mexico in 1991.

The sterile male technique also successfully controlled the Mediterranean fruit fly ("medfly"), a destructive fruit fly of citrus, peaches, pears, and apples in California.

Chemical Control

Chemical control refers to the use of pesticides. If chemical control is needed, IPM favors highly targeted chemicals, such as pheromones to disrupt pest mating. **Pheromones** are chemical signals released by animals to communicate with other members of their species. Humans and many insect species alike release pheromones that function in attracting mates. Releasing the pheremones of insect pests can confuse males seeking mates and ultimately hinder them from reproducing (figure 18.3.g). This "male confusion" has been successful against the pink bollworm that infests cotton and reduced the need for conventional chemical insecticides by 90%. Pheromones have also been successful against pests that attack tomatoes, grapes, and peaches. If targeted chemicals are not effective, IPM may employ conventional pesticides, ideally only applying them to the spots that they are needed and at the lowest effective concentration. Broadcast spraying of non-specific pesticides is a last resort.



Figure 18.3.g: This pheromone trap is used to control the Asiatic rice borer. The caterpillars of this moth species infest rice stems. Image by Mehdi (CC-BY-SA).

Sustainable Practices to Maintain Soil Fertility

A variety of sustainable practices can maintain soil quality. Many of these strategies have additional benefits such as regulating pests, limiting climate change, and preventing water pollution. These methods enrich the soil with nutrients, ensure proper water holding capacity (ability of the soil to retain water), and limit soil-degrading processes such as erosion and compaction.

Crop Rotation

As previously mentioned, **crop rotations** are planned sequences of different crops over time on the same field (figure 18.3.h). Rotating crops provides productivity benefits by improving soil nutrient levels and breaking crop pest cycles. Farmers may also choose to rotate crops in order to reduce their production risk through diversification or to manage scarce resources, such as labor, during planting and harvesting. This strategy reduces the pesticide costs by naturally breaking the cycle of weeds, insects and diseases. Also, grass and legumes in a rotation protect water quality by preventing excess nutrients or chemicals from entering water supplies.



Figure 18.3.*h*: Crop rotation can be used at a large agricultural scale (left) or in a smaller garden (right). In each situation, which crop species are planted in each location changes year to year. Left image by USDA (public domain) and right image by Sten Porse (CC-BY-SA).

Intercropping

Intercropping means growing two or more crops in close proximity to each other during part or all of their life cycles to promote soil improvement, biodiversity, and pest management. Incorporating intercropping principles into an agricultural operation increases diversity and interaction between plants, arthropods, mammals, birds and microorganisms resulting in a more stable crop-ecosystem and a more efficient use of space, water, sunlight, and nutrients (figure 18.3.*i*). This collaborative type of crop management mimics nature and is subject to fewer pest outbreaks, improved nutrient cycling and crop nutrient uptake, and increased water infiltration and moisture retention. Soil quality, water quality and wildlife habitat all benefit.



Figure 18.3.*i*: Intercropping of beans and maize (corn). Beans have root nodules that house nitrogen-fixing bacteria, enriching the soil. Image by AnnaJB (CC-BY-SA).

A common example of strip cropping (a type of intercropping; see above) involves alternating a row crop such as corn with a ground-covering crop such as alfalfa. The ground-covering crop helps reduce water runoff and traps soil eroded from the row crop. If this ground-covering crop is a member of the legume family such as alfalfa or soybeans and is associated with nitrogen-fixing bacteria, then alternating the strips from one planting to the next can also help maintain topsoil fertility.

Cover Crops

Cover crops are those that are planted in the off-season to avoid leaving the soil bare. They can prevent soil and wind erosion, improve soil's physical and biological properties, supply nutrients, suppress weeds, improve the availability of soil water, and break pest cycles along with various other benefits. Cover crops are often members of the legume family and help enrich the soil with usable nitrogen. A single species or mix of cover crop species may be planted (figure $18.3.j$).



Figure $18.3.j$: A roller (crimper) on a tractor being used to roll down a rye and hairy vetch cover crop in April in the United States. While hairy vetch can limit soil erosion and add nitrogen to the soil, it is also an invasive species that must be carefully managed. Image and caption (modified) from Mr. 1032 (CC-BY-SA).

Agroforestry

Agroforestry is the process of planting rows of trees interspersed with a cash crop (figure $18.3.k-l$). Besides helping to prevent wind and water erosion of the soil, the trees provide shade which helps promote soil moisture retention. Decaying tree litter also provides some nutrients for the interplanted crops. The trees themselves may provide a cash crop. For example, fruit or nut trees may be planted with a grain crop. You can learn more about agroforestry using this interactive site by the United States Department of Agriculture and Forest Service.



Figure 18.3.*k*: Through agroforestry, high-value non-timber crops (food, medicinal plants, woody florals, and crafts) can be cultivated under the protection of a forest canopy that has been managed to provide a favorable crop environment. Image and caption (modified) from USDA/UFS (public domain).

Contour and Terrace Farming

Contour farming involves plowing and planting crop rows along the natural contours of gently sloping land (figure 18.3.*l*). The lines of crop rows perpendicular to the slope help to slow water runoff, inhibit the formation of channels of water, and limit soil erosion (and the resultant loss of nutrients). **Terracing** is a common technique used to control water erosion on more steeply sloped hills and mountains (figure 18.3.*l*). Broad, level terraces are constructed along the contours of the slopes, and these act as dams trapping water for crops, reducing runoff, and limiting erosion.



Figure 18.3.*l*: Contour farming (left) and terracing (right). In contour farming, rows of crops wave perpendicular to the slopes of the land. This example (left) also employs agroforestry. Terrace farming involves making step-like structures (terraces) perpendicular to the incline of a slope to reduce erosion. Left image by Pixture2016 (CC-BY-SA). Right image by USDA (public domain).

Minimal Tillage and No-till Agriculture

In modern agricultural practices, heavy machinery is used to prepare the seedbed for planting, to control weeds, and to harvest the crop. The use of heavy equipment has many advantages in saving time and labor, but can cause compaction of soil and disruption of the natural soil organisms. The problem with soil compaction is that increased soil density limits root penetration depth and may inhibit proper plant growth. Another aspect of soil tillage (mixing the soil) is that it may lead to more rapid decomposition of organic matter due to greater soil aeration. Over large areas of farmland, this has the unintended consequence of releasing more carbon and nitrous oxides (greenhouse gases) into the atmosphere, thereby contributing to climate change.

One of the easiest ways to prevent these problems is to minimize the amount of **tillage**, or turning over of the soil. In **minimal tillage** (conservation tillage) or **no-till agriculture**, the land is disturbed as little as possible by leaving crop residue in the fields (figure 18.3.*m*). Special seed drills inject new seeds and fertilizer into the unplowed soil. Tillage of fields does help to break up clods that were previously compacted, so best practices may vary at sites with different soil textures and composition. With proper planning, minimal tillage and no-till agriculture can simultaneously limit soil erosion and compaction, protect soil organisms, reduce costs (if performed correctly), and promote water infiltration. Furthermore, carbon can actually become sequestered into the soil with these methods, thus mitigating climate change. Minimal or no-till agriculture have proved a major success in Latin America and are being used in South Asia and Africa. However, a drawback of this method is that the crop residue can serve as a good habitat for insect pests and plant diseases.



Figure 18.3.m: No-till agriculture is an important tool to prevent loss of soil moisture. Image by USDA (public domain).

Windbreaks

Creating **windbreaks** by planting tall trees along the perimeter of farm fields can help control the effects of wind erosion of soil (figure 18.3.n). Windbreaks reduce wind speed at ground level, an important factor in wind erosion. They also help trap snow in the winter months, leaving soil less exposed. As a side benefit, windbreaks also provide a habitat for birds and animals. One drawback is that windbreaks can be costly to farmers because they reduce the amount of available cropland.



Figure 18.3.n: Windbreaks are rows of trees and shrubs that reduce wind speed. They improve crop yields, reduce soil erosion, improve water-efficiency, protect livestock, and conserve energy. Image and caption (modified) from USDA/UFS (public domain).

Organic Agriculture

Organic agriculture is often incorporated into sustainable agriculture (figure 18.3.o). To be certified as organic, farms must avoid using synthetic pesticides, synthetic fertilizers, and genetically modified organisms (figure 18.3.p). Organic meat, poultry, eggs, and dairy products come from animals that are given no antibiotics or growth hormones. Pests may instead be controlled by natural enemies or naturally produced substances such as neem oil or diatomaceous earth. Some organic alternatives to synthetic pesticides have relatively low environmental impact (such as salt spray), but there are many naturally produced compounds that are still toxic to people or cause ecological harm when widely used. Interestingly, external application of Bt toxin is approved for organic farming, but use of genetically engineered Bt crops is not. The latter results in lower concentrations of Bt toxin in the environment because it is locally produced directly by the plants themselves. In summary, although many practices of organic agriculture benefit the environment and meet sustainability goals, some organic farms are not sustainable and some sustainable farms are not organic.



Figure 18.3.*o*: United States Department of Agriculture (USDA) Conservationist Shemekia Mosley (right) works with Nuri Icgoren (left) who operates Urban Sprout Farms, a biodynamic, certified organic urban farm Lakewood Heights, Georgia. Image and caption (modified) by Preston Keres/USDA (public domain).



Figure 18.3.*p*: The USDA certified organic label. Modified from image by nikoretro (CC-BY-SA).

Consumer Choices that Support Sustainable Agriculture

Even if you're not a farmer or lawmaker, you have the power to promote sustainable agriculture as a consumer. As discussed in Food Chains and Food Webs, it generally requires more land and more energy to produce meat compared to plant-based foods due to the inefficient transfer of energy from one trophic level to the next. For this reason, plant-based diets tend to be more sustainable, but this depends on the types of foods consumed and how they were produced.

Local food is not only fresher, but it requires fewer food miles (figure 18.3.*q*). In some ways, **organic food** causes less environmental degradation, but note that organic does not necessarily mean sustainable (see above). Because it limits machinery, synthetic pesticides, and synthetic fertilizers, it has a smaller **carbon footprint** (meaning it minimizes contribution to climate change). The Clean 15 is a list of produce that is low in pesticide residues. If you can't afford all organic foods, these are the best items to purchase non-organic. Examples include avocados, sweet corn, and pineapple. The Dirty Dozen lists produce that has the most pesticide residues. If you can only afford a few organic items, these are best to purchase organic. Examples include strawberries, spinach, and nectarines. Finally, some foods, such as beef, have higher **carbon footprint** and **water footprint** than others.



Figure 18.3.*q*: Farmers' markets are one option for purchasing locally grown foods. Image by NatalieMaynor (CC-BY).

The Future of the Sustainable Agriculture Concept

Many in the agricultural community have adopted the sense of urgency and direction pointed to by the sustainable agriculture concept (figure 18.3.*r*). Sustainability has become an integral component of many government, commercial, and non-profit agriculture research efforts, and it is beginning to be woven into agricultural policy. Increasing numbers of farmers and ranchers have embarked on their own paths to sustainability, incorporating integrated and innovative approaches into their own enterprises.

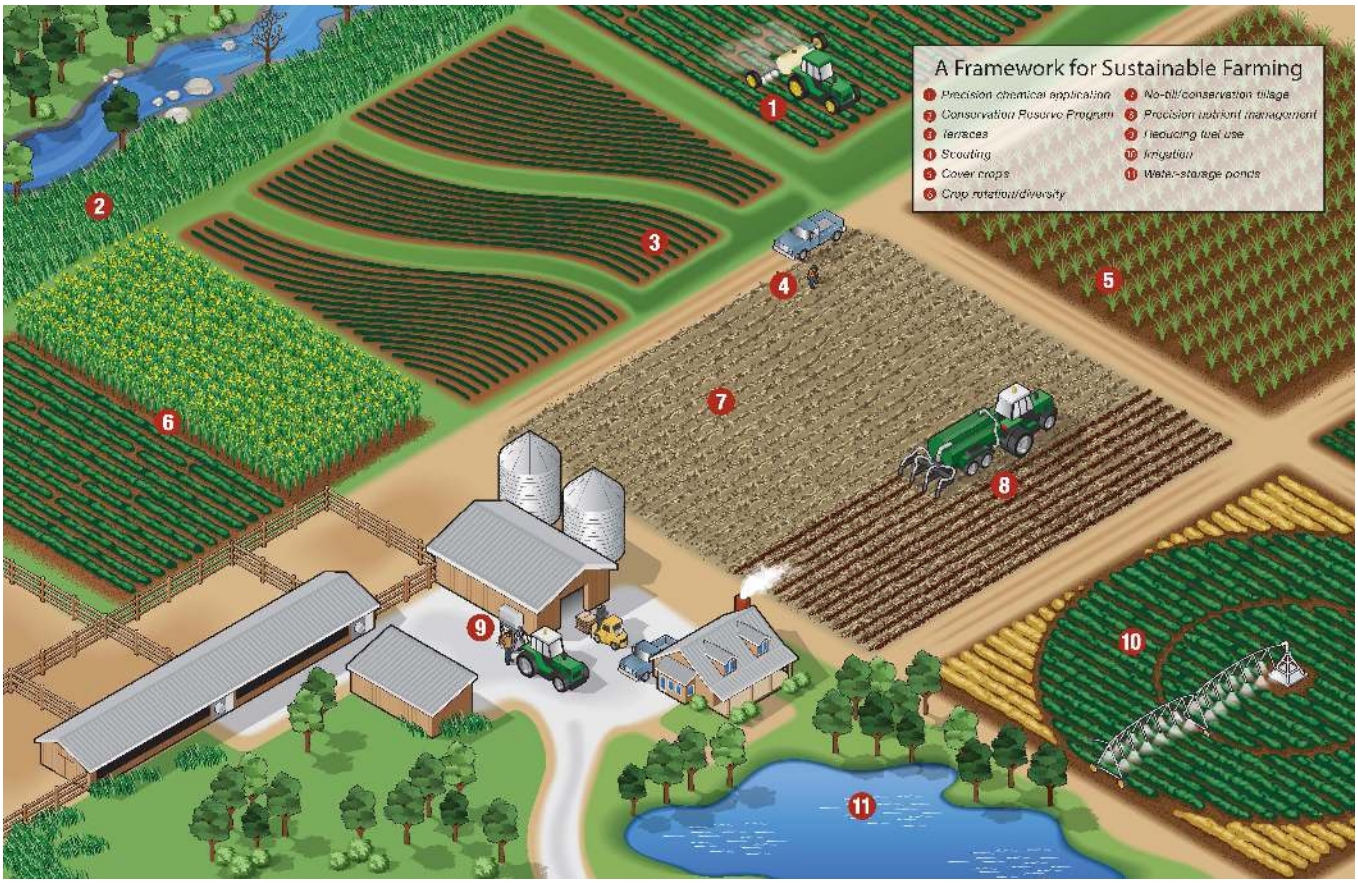


Figure 18.3.r: Sustainable agriculture combines many approaches. (1) If chemical are used, they are applied only where needed. (2) Through the Conservation Reserve Program, the most ecologically important patches are left intact. (3) Terraces on slopes reduce soil erosion. (4) Crops are scouted for pests as part of monitoring, a component of integrated pest management. (5) Cover crops prevent erosion and enrich the soil during off-seasons. (6) Different types of crops are included are planted in close proximity (intercropping) or in different years (crop rotation). (7) Land is either not tilled at all or tilled minimally (conservation tillage). (8) Through precision nutrient management, soil is sampled at different locations, and fertilizer is only applied where needed. (9) Heavy equipment is used only as needed and in such a way that conserves fuel. (10) Irrigation is precisely timed to conserve water. (11) Water storage ponds help recharge groundwater. Image by the United Soybean Board (CC-BY).

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18.4: Smarter Infrastructure

Infrastructure development poses a significant and escalating challenge to biodiversity conservation efforts. Dams and fences impede wildlife dispersal and migrations, power distribution lines and high-rise buildings pose a collision hazard to birds and bats (Rushworth et al., 2014; Frick et al., 2017), and city expansions compete with biodiversity for space. Expanding road networks are particularly harmful because roads open new areas for deforestation, urban sprawl, agricultural expansion, and unsustainable hunting (Laurence et al., 2006; Benítez-López et al., 2017).

Conservation versus development is not a zero-sum game. Rather, biodiversity conservation improves our own well-being by enabling us to obtain the necessary resources to support our livelihoods and our industries' profit margins. One way to maintain these benefits while also promoting economic development is to focus on improving existing infrastructure in disturbed and populated areas, rather than creating new developments that bisect marginal lands, protected areas, and wilderness areas. Developing marginal lands and wildernesses seldom makes sense, not only because these areas are sparsely populated, but also because many are low-nutrient environments that would never support sustainable agriculture (Balmford et al., 2001; Laurance et al., 2015).

There are also opportunities to make existing infrastructure more wildlife friendly. Of interest is the maintenance of connectivity despite the presences of potential barriers such as fences and roads. For example, strategically placed fence-gaps and exclusionary fences, as well as tunnels placed under fences can be used to facilitate continued dispersal of selected species in fenced areas (Dupuis-Desormeaux et al., 2018). Similarly, warning signs (Figure 18.4.1), overpasses (e.g. Ford et al., 2009) and underpasses (e.g. Dell'Amore 2012) along paved roads can keep motorists safe from collisions with large animals. One study from Canada found that strategically placed wildlife crossings could reduce vehicle collisions involving large mammals by 96% (Ford et al., 2009), also reducing the chance of human injuries and damage to vehicles (Huijser et al., 2009). While this field of research is still relatively new, much headway has been made in making wildlife crossings cost-effective (https://arc-solutions.org) and determining their optimal placement (Bastille-Rousseau et al. 2018).



Figure 18.4.1: A toad tunnel in Northern Germany to allow the European toad, *Bufo bufo*, to safely cross under a road.



A fish ladder on Japan's Nishiotaki Dam. Fish ladders can provide migrating fish such as salmon with a way to bypass the dam.

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Signs warning motorists to watch out for wildlife can be effective. This sign warns of moose on the highway in Newfoundland, CA. Photo by DragonWoman, Flickr, CC-BY-NC-ND-2.0

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18.5: Confronting Human-Wildlife Conflict

As a growing human population continues to encroach on the last remaining wildernesses, wildlife populations are facing increased competition for space and food. Inevitably, as animals are being displaced from degraded ecosystems, they will increasingly meet humans. Some of these interactions will be negative ranging from direct conflict (e.g. injury and even death to one or both participants) and indirect conflict (e.g. transmission of diseases) to opportunity costs (e.g. loss of income due to crop damage and livestock predation). Managing **human-wildlife conflict** is thus an important issue to consider in the management of potentially dangerous species, especially near protected area borders.

Dealing with predators

When wildlife impedes human activities, the traditional solution is to either kill the animal or to exclude it from the area with a barrier such as a fence. Killing problem animals can take the form of pro-active lethal control to avoid losses, or retaliatory killings in response to losses. While there is a sense of instant gratification after killing a problem animal, it provides only a temporary solution at best, and may even give rise to a new set of challenges. For example, work on black-backed jackals (Canis mesomelas, LC) showed that killing territorial individuals may cause a breakdown in their local social structure, in turn allowing multiple roaming sub-adult animals to take advantage of the vacant territory (Minnie et al., 2016). Killing apex predators could also give rise **mesopredator release**, where medium-sized carnivores and omnivores flourish in the absence of their natural enemies (Brashares et al., 2010). Indiscriminate poisoning and trapping also kills beneficial non-target animals that opportunistically scavenge, such as owls, vultures, and harmless ant-eating mammals (Brown, 2006; Ogada et al., 2015). Thus, while killing problem animals may seem an intuitive solution, it is seldom the best strategy.

> Non-lethal control of problem animals involved in human-wildlife conflict may provide more benefits than lethal control.

Livestock on commercial and smallholder farms are also vulnerable to predation when foraging away from protective structures. Non-lethal options to reduce livestock losses under these circumstances include predator-proof fences using native thorny plants, corralling pregnant females and calves during their vulnerable periods (Schiess-Meier et al., 2007), and setting up visual, chemical, or acoustic repellents in predation hotspots. Eliminating poor livestock husbandry (Woodroffe and Frank, 2005; Gusset et al., 2009; Newsome et al., 2015) and tardy disposal of deceased animals (Humphries et al., 2015) can also avoid situations where predators are attracted to domestic animals in the first place. But perhaps one of the most successful programs has been the use of livestock guarding animals, which could be dogs (Figure 18.5.1), donkeys, and other domesticated animals trained to protect livestock. A study from South Africa found that livestock depredation was eliminated on 91% of farms after the placement of guardian dogs, saving each of the 94 participant farms US $3,189 per year (Rust et al., 2013). While there is an upfront cost involved in obtaining a guardian animal, recent work found that their deployment is generally more efficient and cost-effective than the cost of lethal options (McManus et al., 2015).



Figure 18.5.1 Placing large guard dogs with livestock is a highly effective, non-lethal strategy to reduce predator attacks. The mere presence of the dog is often enough to keep predators away. Several conservation organizations are now providing trained guard dogs to reduce instances of human-wildlife conflicts involving predators. Photograph by Cheetah Conservation Fund, https://en.Wikipedia.org/wiki/File:Kangal_Shepherd_(livestock-guarding_dog)_and_flock_of_goats_in_Namibia.jpg, CC BY-SA 3.0.

The collaborations between farmers and conservation biologists to reduce livestock predation have benefited biodiversity conservation as well. Populations of African wild dogs (*Lycaon pictus*, EN) and lions are rebounding on some unprotected lands (Woodruffe, 2011; Blackburn et al., 2016), while farmers using guardian animals are also more tolerant of some predators on their properties (Rust et al., 2013). Not only do these farmers enjoy seeing native wildlife on their properties; some have even completely switched focus away from livestock to more profitable ecotourism (Sims-Castley et al., 2005) and wildlife ranching endeavors (Lindsey et al., 2013).

Concluding thoughts on human-wildlife conflict

> One of the most effective mechanisms for dealing with human-wildlife conflict is to develop awareness and opportunities for at-risk people to benefit from potentially harmful animals.

Whether dealing with dangerous animals or crop raiders, one of the most effective mechanisms for dealing with human-wildlife conflict is to develop awareness and opportunities for at-risk people to benefit from potentially harmful animals (Blackburn et al., 2016). Studies found that most people—even those who have been victims of human-wildlife conflict—have positive attitudes towards wildlife and believe that they can co-exist (Eshete et al., 2015). The reason for such positive attitudes is that a substantial portion of the affected people are aware of benefits from ecosystem services, including ecotourism opportunities. Such positive attitudes toward wildlife play a crucial role in the protection of a range of endemic species in this Global Biodiversity Hotspot, including the Walia ibex (*Capra walie*, EN) and Ethiopian wolf (*Canis simensis*, EN).

As discussed earlier, both ICDPs and CBNRM programs offer opportunities for local people to gain direct benefits from local wildlife, even potentially dangerous species. There are also research opportunities to further human-wildlife conflict mitigation beyond direct benefits to local people. An increasing number of resources are available to aid these and other efforts. The IUCN Human-Wildlife Conflict Task Force has taken the lead to collate much of this information; their library (http://www.hwctf.org/resources/document-library) is sorted by species and topic. They also provide free training manuals (e.g. Parker et al., 2007) and host regular workshops.

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18.6: Data Dive- Landslides and Ag Terraces

Overview

The beauty of terraced agriculture almost makes the observer forget that it is still a form of habitat destruction and landscape modification. A 2019 study investigated the risk to terraced landscapes with varying states of upkeep after severe rainfall events, which increase chances of serious damage due to landslide events. The authors compared three classes of upkeep:

- Succession on terrace: Which includes all terraced areas in which cultivation activities ceased, and is currently substituted by both wood and shrub cover.
- Cultivated terrace: Which includes all areas which are still under any kind of cultivation, from olive groves, to vineyards, to other crops
- Vegetated natural slopes: Which refer to those areas covered by spontaneous vegetation which have never been terraced.

Landslide mapping was used to estimate the size of damage after a landslide event took place. Below is a graph for some of the published results:

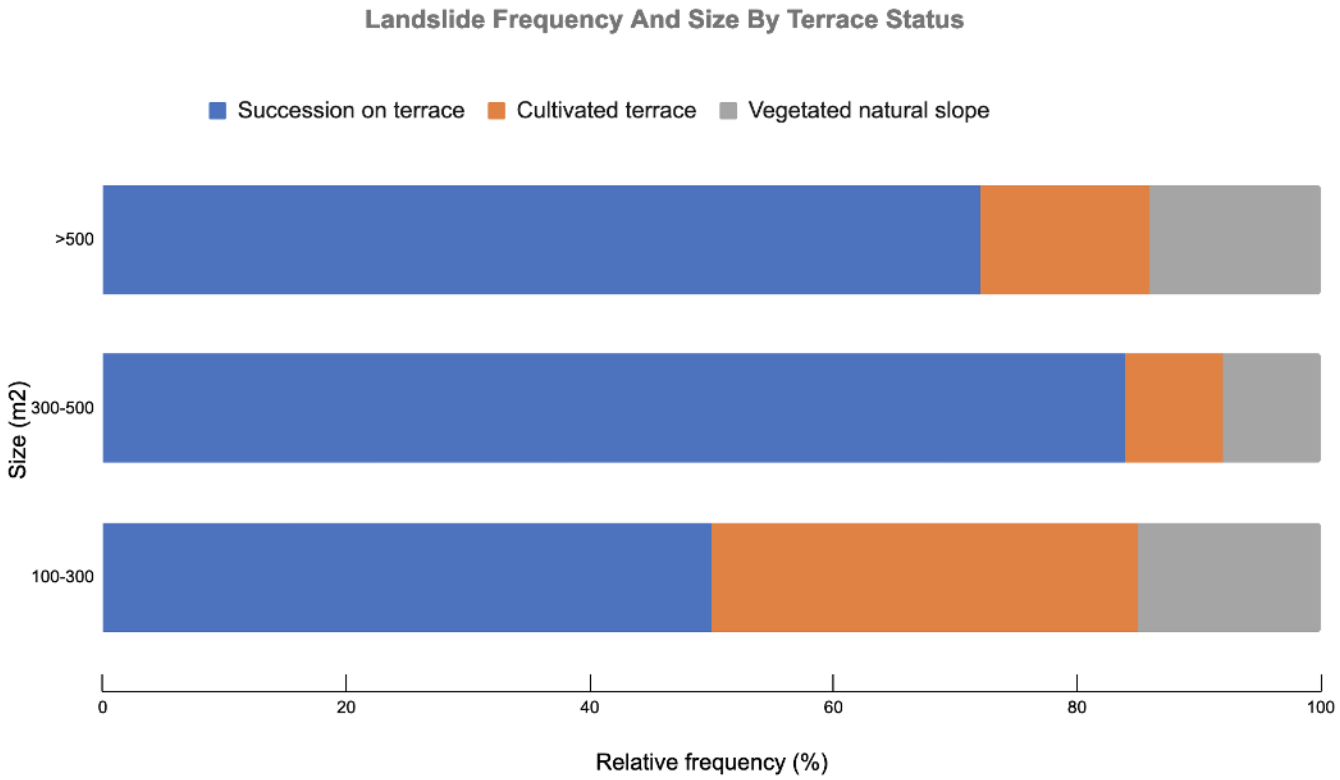


Figure 18.6.*a*: Percent breakdown of landslide frequency and size by terrace status. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Agnoletti M, Errico A, Santoro A, Dani A, Preti F 2019.

Questions

1. What is the independent (explanatory) variable and the dependent (response) variable?
2. What question(s) are the authors trying to answer with this graph?
3. Do the authors use any control category/variable to help clarify the patterns observed? If so, what?
4. Which status has the most consistent increased landslide frequency?
5. What landslide frequency patterns can you observe across the three size?
6. How can the results of this graph to inform future projects/restoration efforts when a terrace is abandoned?

Raw Data For Above Graph(s)

Table 18.6.*a***:** Raw data for percent breakdown of landslide frequency and size by terrace status. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Agnoletti M, Errico A, Santoro A, Dani A, Preti F 2019.

Terrace Status	100-300	300-500	Over 500
Succession On Terrace	50	84	72
Cultivated Terrace	35	8	14
Vegetated Natural Slope	15	8	14

Attribution

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18.7: Summary

1. Many species persist outside protected areas, in areas such as traditional farmland, sustainably logged forests, and unprotected rangelands. These areas can and must play a more important role in ongoing conservation efforts.
2. Traditional peoples that live on undeveloped land have beliefs that are compatible with biodiversity conservation. There are conservation strategies that can benefit traditional people and protect biodiversity.
3. Areas intensively used by humans can also contribute to conservation efforts. Biodiversity-friendly techniques are being developed and implemented for the agriculture, logging, and fisheries industries, many which have been adopted. Mines and other extractive industries can participate in biodiversity offset programs, and partner with conservation organizations to contribute to local biodiversity protection. But there remains a need to monitor the activities of extractive industries to ensure that cost-cutting measures do not lead to biodiversity losses.
4. Integrated conservation and development projects (ICDPs) and community-based natural resource management (CBNRM) projects link biodiversity conservation with economic development. There is however a need to ensure these approaches remain resilient to challenges that may threaten their long-term success.
5. Human-wildlife conflict, such as livestock predation and crop raiding, remains a major conservation challenge. Multiple mechanisms have been developed to help victims overcome or mitigate such losses. Some of these mechanisms have even allowed victims to benefit from the animals they previously thought of as nuisances.

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18.8: Topics for Discussion

1. Imagine that the government informs you that a highly threatened species lives on land that you planned to develop. Would you be happy, angry, confused, or proud? What are your options in terms of the planned development? What would be a fair compromise that would protect your rights and interests, the rights of the public, and the well-being of the species?
2. Imagine your country builds an expensive dam to provide hydroelectricity and water for irrigation. It will take decades to pay back the costs of construction and lost ecosystem services; some of those costs may never be recovered. Who are the winners of such a project, and who are the losers? How are each of these groups (consider both people and wildlife groups) affected? What do you think can be done to make the project more worthwhile?
3. Do you think that the purchase of “green” (environmentally-responsible) products is an effective way to promote biodiversity conservation? Would you be willing to spend more money for timber, fuelwood, coffee, chocolate, palm oil, and other products that have been produced in a sustainable way, and if so, how much more? How could you determine whether the purchase of such products was really making a difference?
4. Think of a family (someone you know or heard of) that has been a victim of human-wildlife conflict or contracted a disease while being in nature. What happened? What did the family lose? Was the family compensated for their losses? How and by whom? If you had the opportunity to establish a plan to prevent or mitigate future conflicts, what would you do?

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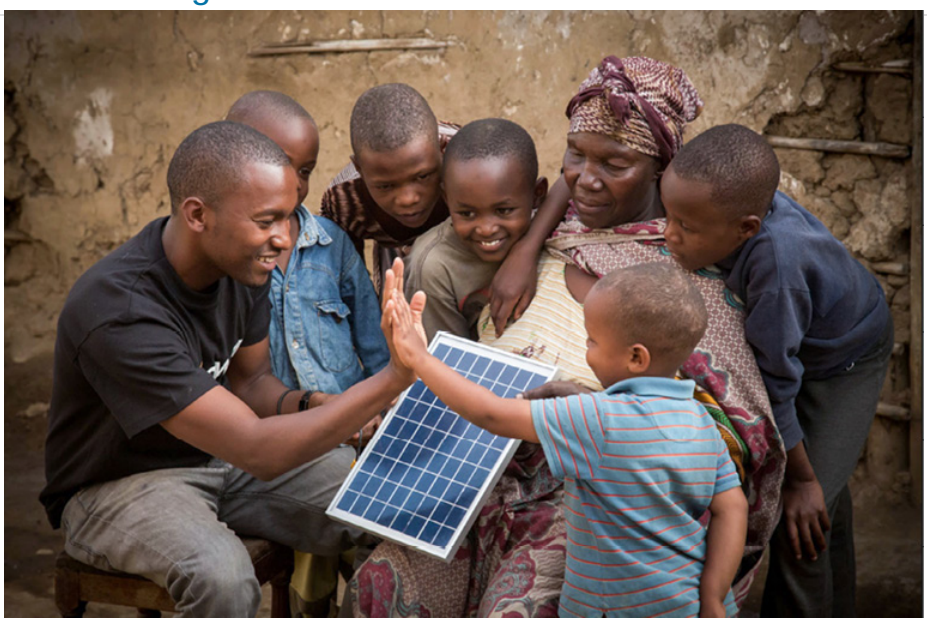
CHAPTER OVERVIEW

19: An Agenda for the Future

19.1: Introduction to An Agenda for the Future
19.2: Individual Choices
19.3: Introduction to Sustainability
19.3.1: History of Sustainability
19.4: Achieving Sustainable Development
19.4.1: Sustainable Cities
19.4.2: Sustainability and the Future
19.5: Dealing with Technological Advances
19.6: Funding Conservation Activities
19.6.1: Data Dive- Sustainable Investments
19.7: Building Lasting Partnerships
19.8: Environmental Education and Leadership
19.9: Summary
19.10: Review
19.11: Topics for Discussion
19.13: Bibliography

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19.1: Introduction to An Agenda for the Future



A family in rural Tanzania celebrating solar power arriving in their village. New technologies provide great opportunities for more sustainable lifestyles. Photograph by Power Africa, https://www.flickr.com/photos/usaidafrica/26570196501, CC0.

The field of conservation biology has set itself some imposing—but critical—goals: to describe Earth's biological diversity, to protect what remains, and to restore what is damaged. With wildlife declines showing no sign of halting, we are in a race against time to prevent catastrophic losses. Conservation biology is a truly crisis discipline (Soulé, 1985; Kareiva and Marvier, 2012), because decisions often need to be made under pressure, with limited resources, and constrained by tight deadlines. At the same time, the discipline needs to offer a long-term conservation vision that extends beyond the immediate crisis, despite unreliable commitments to seeing such plans through to completion.

Despite the challenges we face, there are many positive signs for cautious optimism. Some threatened species are recovering, the number of well-managed protected areas is increasing, and, in some cases, natural resources are being used more prudently on unprotected lands. We have also increased our capacity to restore degraded ecosystems to such a level that we are now reintroducing species that were once extinct in the wild. Our improved ability to protect biodiversity is in no small way attributable to the wide range of productive local, national, and international collaborative efforts that have been cultivated over the past few decades. It is also because the field of conservation biology has expanded for the better, by developing linkages with rural development, economics, the arts, social sciences, and government policy, to name a few.

Make no mistake, many challenges remain unaddressed and under-addressed, and new ones will surely also arise. These challenges all need to be faced head-on, because there is no "Planet B": Earth is our one and only planet. There will be times when the biodiversity crisis will feel insurmountable. When that happens, it is important to remember that every individual human can play a role in saving our natural heritage. If just one-tenth of Sub-Saharan Africa's 1 billion people use one less plastic item (e.g. plastic bags, drinking straws, food wrappers) a week, there would be a reduction of 100,000,000 plastic items each week. People operating at the regional and global scales, such as company executives and government officials, also have an important task—ensuring that mechanisms are in place for all citizens to contribute to ensuring that future generations will inherit a healthier environment. Below, we offer a few holistic strategies towards a sustainable future.

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19.2: Individual Choices

Many of the strategies for preserving biodiversity operate at the level of whole governments or large organizations; however, your choices as an individual also play a role in conservation.

Consumer Choices

The products you purchase have differing impacts on biodiversity. Educating yourself on the origin of products and food that you purchase and choosing the sustainable options can help preserve biodiveristy. For example, arabica coffee can be grown in the shade, meaning there is no need to fully clear rainforest vegetation when growing this species (figure 19.2.a). However, robusta coffee requires full sun, and cultivating it has a greater impact or rainforest biodiversity. Monterey Bay Aquarium provides a sustainable seafood guide, which identifies seafood choices that have a lower environmental impact. Choosing local products reduces the amount of fossil fuels that were burned to transport them to you, thus reducing carbon emissions that contribute to climate change.



Figure 19.2.a: Shade-grown coffee at a Columbian farm. Image by Brian Smith/American Bird Conservancy/U.S. Fish and Wildlife Service Northeast Region (CC-BY).

Some products have special certifications that indicate their impact on biodiversity. For example, certified organic products must be cultivated without the use of synthetic pesticides, herbicides, and fertilizers, which pollute the surrounding areas. Additionally, they cannot contain genetically modified organisms (GMOs), which have both positive and negative environmental implications. If you cannot afford to buy all organic produce, see the Environmental Working Group's lists of the Clean Fifteen™ (for which pesticide use is already limited) and Dirty Dozen™ (which are high priority to purchase organic or avoid due to high pesticide residues). The Roundtable on Sustainable Palm Oil (RSPO) certifies oil palm plantations that follow standards such as avoiding deforestation and using fire to clear land. Additionally, RSPO-certified business must follow guidelines to compensate their employees sufficiently. Fair Trade Certified™ goods must meet social and environmental standards that support the United Nation's Sustainable Development Goals.

Resource Conservation

Resource conservation is individual choice that can promote biodiversity. In this case, conservation refers to limiting one's use of resources, such as water, electricity, and gasoline. Landscaping with drought-tolerant plants to limit the need for irrigation or using a low-flow shower head are examples of water conservation. Because much electricity is generated from burning fossil fuels, such as coal and natural gas, conserving electricity reduces carbon emissions associated with climate change. Turning off lights and appliances when not in use and insulating one's home to reduce electricity spent on heating and cooling save money and benefit the environment. Similarly, transportation choices such as carpooling, biking, or taking public transportation can limit carbon emissions. Reusing items or not purchasing unnecessary ones also conserves the energy needed to produce and transport these

goods and reduces plastic waste, which is particularly harmful to aquatic ecosystems. See chapters about Water Resources, Renewable Energy, and Solid Waste Management for more about resource conservation.

Guide to Planting a Pollinator Garden

Whether you have a few feet on your apartment balcony or several acres, you can promote populations of native bees, butterflies, and other pollinators by building a **pollinator garden** (figure 19.2.*b*). The first step is to choose a location. While flowering plants can grow in both shady and sunny locations, consider your audience. Butterflies and other pollinators like to bask in the sun and some of their favorite wildflowers grow best in full or partial sun with some protection from the wind. The next step is to identify your soil type. Take a look at your soil - is it sandy and well-drained or more clay-like and wet? You can turn over a test patch or check out a soil mapper to learn more. Your soil type and the amount of sunlight it gets will help determine the kinds of plants you can grow.



Figure 19.2.*b*: A diversity of plant species support native pollinators in this pollinator garden. Image by Sara "Asher" Morris (CC-BY-NC).

Next, research which varieties of milkweed and wildflowers are native to your area and do well in your soil and sunlight conditions. **Native plants**, those that have historically occurred in the area, are the ideal choice, because they require less maintenance and tend to be heartier because they are well adapted to conditions in a particular area. In addition, native plants can support native wildlife including pollinators, beneficial insects and birds. Find a nursery that specializes in native plants near you - they'll be familiar with plants that are meant to thrive in your region. Calscape.org is a web service created by the California Native Plant Society that allows users to search native plant lists by zip code or area in California. Some examples of pollinator-friendly plants native to California, include the California poppy, California lilac, milkweed, and foothill penstemon. The California Native Plant Society and UC Berkeley Urban Bee Lab have additional plant suggestions. It's essential to choose plants that have not been treated with pesticides. Choosing **perennials** will ensure your plants come back each year, reducing the need for maintenance.

Remember to think about more than just the summer growing season. Pollinators need nectar early in the spring, throughout the summer and even into the fall. Choosing plants that bloom at different times will help you create a bright and colorful garden that both you and pollinators will love for months!

Some native bee species use bare soil for nesting. While applying mulch can help control weeds, leaves some bare soil if possible. Some native pollinators also nest in tiny cavities, which may already occur naturally in or near your garden or can be provided with bee boxes.

Make sure to weed and water your garden to keep it healthy. It may take some time, but you will eventually see butterflies and other pollinators enjoying your garden.

Modified by Melissa Ha from the U.S. Fish and Wildlife Service (public domain).

Citizen Science

Finally, citizen science provides the opportunity to be directly involved in biological conservation efforts. For some opportunities like Globe at Night, which assess light pollution, or the Lost Ladybug Project, data can be collected independently and submitted online. Others, like bird banding, are scheduled events in which experts train a group of volunteers to complete fieldwork (figure 19.2.c). The federal government's citizen science database lists many such opportunities.



Figure 19.2.c: Left: Students returning from taking phenology measurements on native trees in a native forest conservation area on Hawaii Island. Phenology refers to the timing of events in an organism's life cycle. Right: Americorp members preparing ʻōhiʻa tree cuttings for rooting and propagation – with plants to be used for disease resistance screening. Left image by UFS/USDA (public domain). Right image by USFS (public domain).

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19.3: Introduction to Sustainability

Section Hook

Cities in today's modern world are struggling to balance a sustainable society, economy, and environment. According to a 2016 report that rated sustainability across 32 indicators, Zurich, Switzerland, was ranked number one. Zurich invests in renewable energies, sustainable public transport, public green space, and public education. One of the most notable ways Zurich is leading global sustainability efforts is their dedication to keeping their carbon dioxide emissions low. Figure 19.3.a below shows the difference in emissions for the United States and Switzerland:

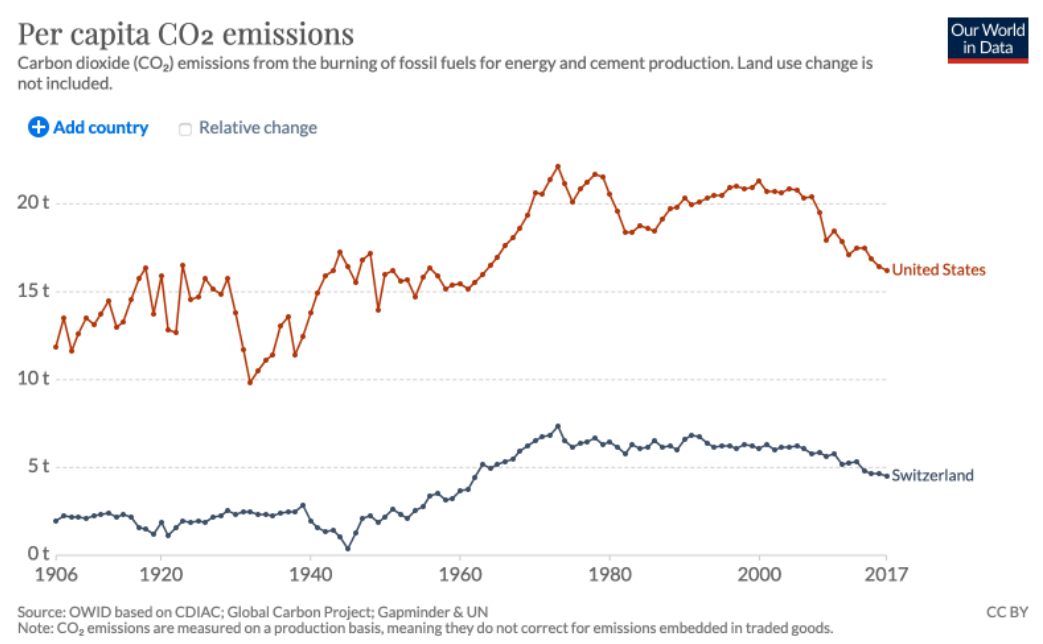


Figure 19.3.a: Per capita emissions of carbon dioxide between the United States and Switzerland. Graph by Our World in Data (CC-BY4.0)

Introduction

Sustainability is derived from two Latin words: *sus* which means up, and *tenere* which means to hold. Thus, sustainability is essentially about holding up human existence by meeting the needs of the present without compromising the ability of future generations to meet their needs.

There are three dimensions that sustainability seeks to integrate: economic, environmental, and social (including sociopolitical).

- Economic interests define the framework for making decisions, the flow of financial capital, and the facilitation of commerce, including the knowledge, skills, competences and other attributes embodied in individuals that are relevant to economic activity.
- Environmental aspects recognize the diversity and interdependence within living systems, the goods and services produced by the world's ecosystems, and the impacts of human wastes.
- Social/Socio-political refers to interactions between institutions/firms and people, functions expressive of human values, aspirations and well-being, ethical issues, and decision-making that depends upon collective action.

The intersection of social and economic elements can form the basis of social "equitability". In the sense of enlightened management, "viability" is formed through consideration of economic and environmental interests. Between environment and social elements lies "bearability," the recognition that the functioning of societies is dependent on environmental resources and services. At the intersection of all three of these lies sustainability (figure 19.3.b).

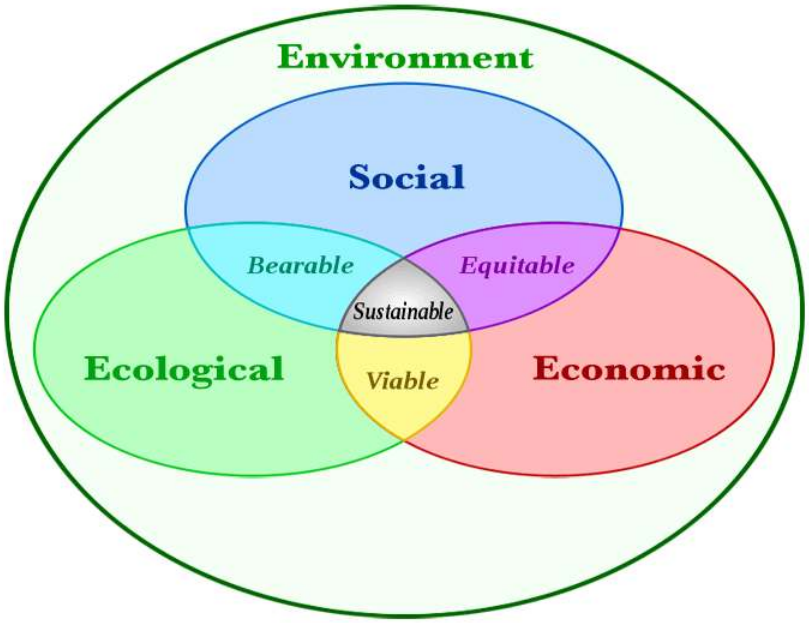


Figure 19.3.*b*: Venn diagram of defining the components of sustainability. Image by Andrew, Sunray, based on "File:Sustainable development.svg" by Johann Dréo in Wikimedia Commons (CC-BY-SA4.0)

The three main elements of the sustainability paradigm are thought of as equally important, however, tradeoffs occur depending on the local/global objective. For example, in some instances it may be deemed necessary to degrade a particular ecosystem in order to facilitate commerce, or food production, or housing. In reality, the extent to which tradeoffs can be made before irreversible damage results is not always known, and in any case there are definite limits on how much substitution among the three elements is wise (to date, humans have treated economic development as the dominant one of the three). This has led to the notion of strong sustainability, where tradeoffs among natural, human, and social capital are not allowed or are very restricted, and weak sustainability, where tradeoffs are unrestricted or have few limits. Whether or not one follows the strong or weak form of sustainability, it is important to understand that while economic and social systems are human creations, the environment is not. Rather, a functioning environment underpins both society and the economy.

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19.3.1: History of Sustainability

Taking The Long View: Sustainability an Evolutionary and Ecological Perspective

Of the different forms of life that have inhabited the Earth in its three to four billion year history, 99.9% are now extinct. Against this backdrop, the human enterprise with its roughly 200,000-year history barely merits attention. As the American novelist Mark Twain once remarked, if our planet's history were to be compared to the Eiffel Tower, human history would be a mere smear on the very tip of the tower. But while modern humans (*Homo sapiens*) might be insignificant in geologic time, we are by no means insignificant in terms of our recent planetary impact. A 1986 study estimated that 40% of the product of terrestrial plant photosynthesis — the basis of the food chain for most animal and bird life — was being appropriated by humans for their use. More recent studies estimate that 25% of photosynthesis on continental shelves (coastal areas) is ultimately being used to satisfy human demand. Human appropriation of such natural resources is having a profound impact upon the wide diversity of other species that also depend on them.

Evolution normally results in the generation of new lifeforms at a rate that outstrips the extinction of other species; this results in strong biological diversity. However, scientists have evidence that, for the first observable time in evolutionary history, another species — *Homo sapiens* — has upset this balance to the degree that the rate of species extinction is now estimated at 10,000 times the rate of species renewal. Human beings, just one species among millions, are crowding out the other species we share the planet with. Evidence of human interference with the natural world is visible in practically every ecosystem from the presence of pollutants in the stratosphere to the artificially changed courses of the majority of river systems on the planet. It is argued that ever since we abandoned nomadic, gatherer-hunter ways of life for settled societies some 12,000 years ago, humans have continually manipulated their natural world to meet their needs. While this observation is a correct one, the rate, scale, and the nature of human-induced global change — particularly in the post-industrial period — is unprecedented in the history of life on Earth.

There are three primary reasons for this:

1. Mechanization of both industry and agriculture in the last century resulted in vastly improved labor productivity which enabled the creation of goods and services. Since then, scientific advance and technological innovation — powered by ever-increasing inputs of fossil fuels and their derivatives — have revolutionized every industry and created many new ones. The subsequent development of western consumer culture, and the satisfaction of the accompanying disposable mentality, has generated material flows of an unprecedented scale. The Wuppertal Institute estimates that humans are now responsible for moving greater amounts of matter across the planet than all natural occurrences (earthquakes, storms, etc.) put together.
2. The sheer size of the human population is unprecedented. Every passing year adds another 90 million people to the planet. Even though the environmental impact varies significantly between countries (and within them), the exponential growth in human numbers, coupled with rising material expectations in a world of limited resources, has catapulted the issue of distribution to prominence. Global inequalities in resource consumption and purchasing power mark the clearest dividing line between the haves and the have-nots. It has become apparent that present patterns of production and consumption are unsustainable for a global population that is projected to reach between 12 billion by the year 2050. If ecological crises and rising social conflict are to be countered, the present rates of over-consumption by a rich minority, and under-consumption by a large majority, will have to be brought into balance.
3. It is not only the rate and the scale of change but the nature of that change that is unprecedented. Human inventiveness has introduced chemicals and materials into the environment which either do not occur naturally at all, or do not occur in the ratios in which we have introduced them. These persistent chemical pollutants are believed to be causing alterations in the environment, the effects of which are only slowly manifesting themselves, and the full scale of which is beyond calculation. CFCs and PCBs are but two examples of the approximately 100,000 chemicals currently in global circulation. (Between 500 and 1,000 new chemicals are being added to this list annually.) The majority of these chemicals have not been tested for their toxicity on humans and other life forms, let alone tested for their effects in combination with other chemicals. These issues are now the subject of special UN and other intergovernmental working groups.

The Evolution of Sustainability Itself

Our Common Future (1987), the report of the World Commission on Environment and Development, is widely credited with having popularized the concept of **sustainable development.** It defines sustainable development in the following ways…

- …development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
- … sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the orientation of the technological development, and institutional change are made consistent with future as well as present needs.

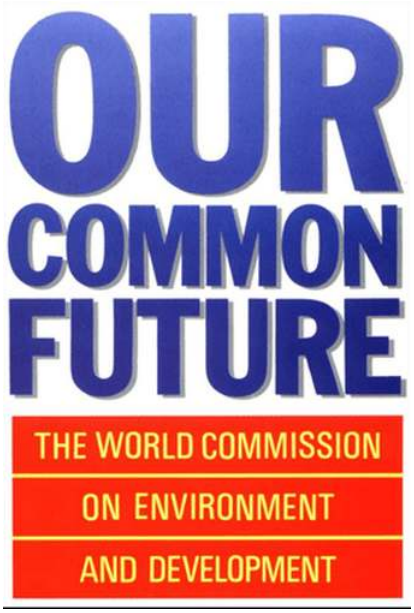


Figure 19.3.1.*a***:** Cover of Our Common Future. Image by Sigurður Kaiser in Wikimedia Commons (CC-BY-SA4.0)

The concept of sustainability, however, can be traced back much farther to the oral histories of indigenous cultures. For example, the principle of inter-generational equity is captured in the Inuit saying, 'we do not inherit the Earth from our parents, we borrow it from our children'. The Native American 'Law of the Seventh Generation' is another illustration. According to this, before any major action was to be undertaken its potential consequences on the seventh generation had to be considered. For a species that at present is only 6,000 generations old and whose current political decision-makers operate on time scales of months, or few years at most, the thought that other human cultures have based their decision-making systems on time scales of many decades seems wise but unfortunately inconceivable in the current political climate.

Precautionary Principle

The **precautionary principle** is an important concept in environmental sustainability. A 1998 consensus statement characterized the precautionary principle this way: "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically". For example, if a new pesticide chemical is created, the precautionary principle would dictate that we presume, for the sake of safety, that the chemical may have potential negative consequences for the environment and/or human health, even if such consequences have not been proven yet. In other words, it is best to proceed cautiously in the face of incomplete knowledge about something's potential harm.

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19.4: Achieving Sustainable Development

Efforts to preserve biological diversity are regularly perceived as in conflict with societal progress (Redpath et al., 2013). Perhaps the root of this conflict lies with the fact that most of the development we see today is *unsustainable*—that is, it risks depleting natural resources to a point where they will no longer be available for use or to provide ecosystem services. Moreover, governments and businesses often measure success in terms of **economic growth**, which occurs when an economy increasingly produces more goods and services (often measured as GDP). Economic policies that favor economic growth are generally based on an implicit but erroneous assumption that the supply of natural resources is unlimited. A society that aims for economic growth is therefore bound to fail at one point or another.

To overcome these perceptions and conflicts, scientists, policy makers, and conservation managers are increasingly highlighting the need for **sustainable development**—economic activities that satisfy both present and future needs without compromising the natural world (Figure 19.4.1). Sustainable development is closely linked to **economic development**, a multi-dimensional concept that describes economic activities that aim to improve income and health without necessarily increasing consumption of natural resources. We should thus all strive for sustainable development, which emphasizes economic development without unsustainable economic growth.



Figure 19.4.1 Sustainable development heals the rift between development and conservation; it aims to simultaneously meet conservation goals and human needs, CC BY 4.0.

There are many good examples that illustrate the progress made towards sustainable development. For instance, many governments are investing in national parks and their infrastructure (such as staff and facilities) to protect biological diversity and provide economic opportunities for local communities. Similarly, stakeholders in large projects are increasingly engaging with one another to mitigate the negative impacts of infrastructure developments.

Unfortunately, there are also people and organizations that are taking advantage of this positive energy by misusing the term “sustainable development” to **greenwash** industrial activities that are harming the environment. For instance, a plan to establish a palm oil plantation that would damage a forested wilderness should not be considered sustainable development simply because the company agrees to protect a small plot of forest adjacent to the damaged area. Similarly, many environmentally-destructive companies try to mislead customers with “environmentally-friendly” (often green-colored) imagery on packages which are otherwise no better than the standard manufactured products. It is, therefore, critical for scientists, policy makers, and citizens to carefully study the issues, understand why different groups make arguments, and make thoughtful decisions about which actions or policies will best meet seemingly contradictory demands.

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19.4.1: Sustainable Cities

Introduction

Sustainability, from science to philosophy to lifestyle, finds expression in the way we shape our cities. Cities are not just a collection of structures, but rather groups of people living different lifestyles together. When we ask if a lifestyle is sustainable, we're asking if it can endure. Some archaeologists posit that environmental imbalance doomed many failed ancient civilizations. What could the sustainable city look like, how would it function, and how can we avoid an imbalance that will lead to the collapse of our material civilization? While attempting to envision the "sustainable city" we must discern what factors will influence its shape and form in the future.

So what is the major hindrance for designing/updating for a "sustainable city"?

Sprawl: The outward expansion of human populations (typically in low-density residential and commercial development) into the outer edges of cities/towns.

As sprawl expands, it eats at natural and agricultural lands and isolates people. People have to travel further and further to go to work, the grocery store, a hospital, etcetera. What this means is that cities/towns have to find solutions to moving water, waste, power, services, road development/upkeep, etcetera to these communities. As such, there are chronic issues with sprawl on both sides that make opportunity and progress difficult due to economic constraints.

It's important to note that sprawl can happen at different scales:

- **Low-density sprawl:** Small 1-2 story buildings in high densities. Low-density sprawl can be further distinguished by income as neighborhoods tend to be segregated by this. (Ex: North America)
- **High-density sprawl:** High rise buildings in high densities (Ex: China)

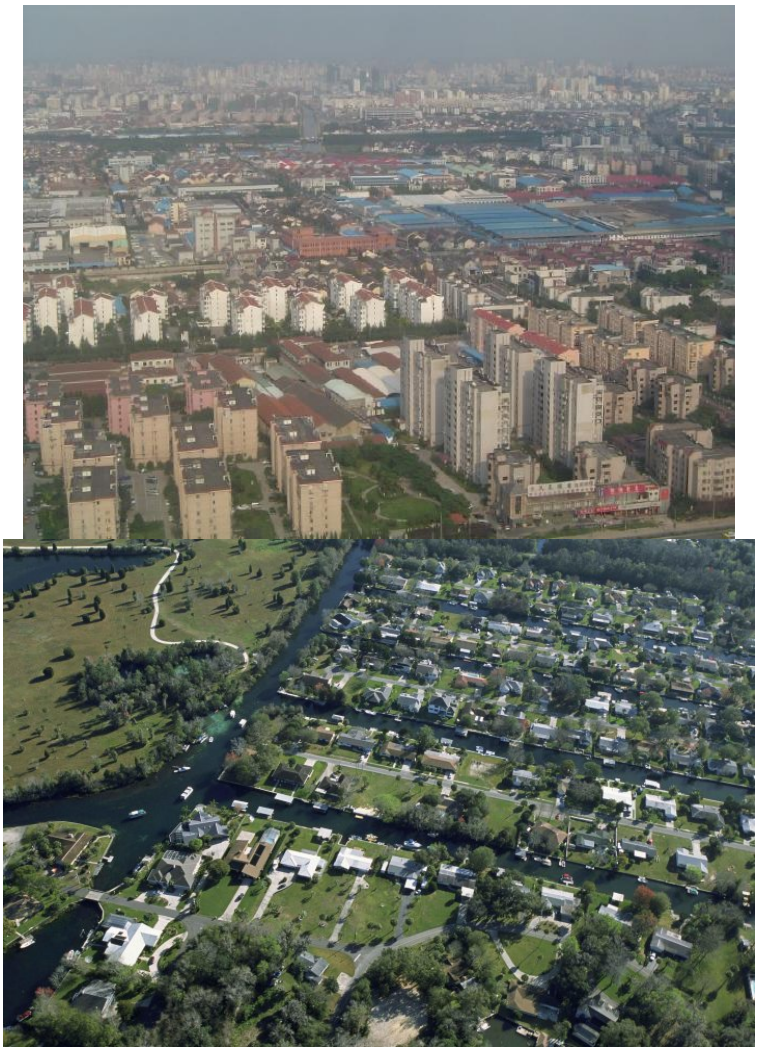


Figure 19.4.1.*a*: Left - High density sprawl in Shanghai China by John Patrick Robichaud in Wikimedia Commons (CC-BY), Right - Low density sprawl in North America by Pixnio (Public Domain).

So what can be done to design/update and move towards “sustainable cities”?

- **Mixed use development:** Lends residential, commercial, cultural, institutional, or industrial uses, where those functions are physically and functionally integrated, and that provides pedestrian connections. Making cities walkable!
- **Geographic equity:** Circulation system defined by ratios of how people move. This means more bikes, walking, public transportation (in many forms) and not cars. Equitability of the streets!
- **Preserve:** Preserve land, culture, and biodiversity as much as possible.
- **Mix**: Mix incomes, cultures, green spaces, public transport options, etcetera as much as possible. Allow people to connect and become neighbors not strangers.
- **Focus:** Match density of a community to meet transit/service needs.

Video 19.4.1.*a***:** Perspectives: Peter Calthrope describes 7 principles for building better cities.



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19.4.2: Sustainability and the Future

Ecological Footprint

The **ecological footprint** (EF), developed by Canadian ecologist and planner William Rees, is basically an accounting tool that uses land as the unit of measurement to assess per capita consumption, production, and discharge needs. It starts from the assumption that every category of energy and material consumption and waste discharge requires the productive or absorptive capacity of a finite area of land or water. If we (add up) all the land requirements for all categories of consumption and waste discharge by a defined population, the total area represents the Ecological Footprint of that population on Earth whether or not this area coincides with the population's home region.

Land is used as the unit of measurement for the simple reason that, according to Rees, "Land area not only captures planet Earth's finiteness, it can also be seen as a proxy for numerous essential life support functions from gas exchange to nutrient recycling … land supports photosynthesis, the energy conduit for the web of life. Photosynthesis sustains all important food chains and maintains the structural integrity of ecosystems."

What does the ecological footprint tell us? Ecological footprint analysis can tell us in a vivid, ready-to-grasp manner how much of the Earth's environmental functions are needed to support human activities. It also makes visible the extent to which consumer lifestyles and behaviors are ecologically sustainable calculated that the ecological footprint of the average American is – conservatively – 5.1 hectares per capita of productive land. With roughly 7.4 billion hectares of the planet's total surface area of 51 billion hectares available for human consumption, if the current global population were to adopt American consumer lifestyles we would need two additional planets to produce the resources, absorb the wastes, and provide general life-support functions.

Common Cause and Sustainability

Common cause: Brings about change in all people/interest groups/world leaders because of common goals. Below are a list of sustainability goals across the sustainability paradigm. Most, if not all, are common cause goals for the now, and into the future.

Society

- No poverty
- Zero hunger
- Good health
- Quality education
- Gender equality
- Peace, justice, and strong institutions
- Clean water and sanitation
- Reduced inequalities

Environment

- Terrestrial life/habitats conservation and restoration
- Oceanic life/habitats conservation and restoration
- Climate action
- Reduced waste/pollution

Economy

- Affordable and clean energy
- Decent work and economic growth
- Industry, innovation, and infrastructure
- Responsible consumption and production
- Sustainable cities and communities
- Partnerships locally and globally

Sustainable Living

Sustainable living describes a lifestyle that attempts to reduce/eliminate an individuals (or societies) use of resources so as to be as close as possible to "net zero living". As such, an individual (or society) focuses on reducing their footprint (ecologically, carbon, socially, etc) through their choices/methods of:

- Use of resources (energy/diet/transportation/water/etc)
- Support of people/companies (voting/economic/social/etc)
- Practices of reducing, reusing, and recycling
- Consciousness of priority and focus for local concerns/needs versus global concerns/needs
- Sharing knowledge with their community (all ages)



Figure 19.4.2.*a*: Considerations for sustainable living goals. Image by Sustainability Week Switzerland in Wikimedia Commons (CC-BY-SA)

The thought of getting started with sustainable living can be overwhelming! However, it is important to note that although we can acknowledge all the things that need to be accomplished, that that entire burden does not lie with just one individuals control (see figure below). It takes a multi-layerd approach to appropriately take action at the individual, societal, and political levels (see figure above).

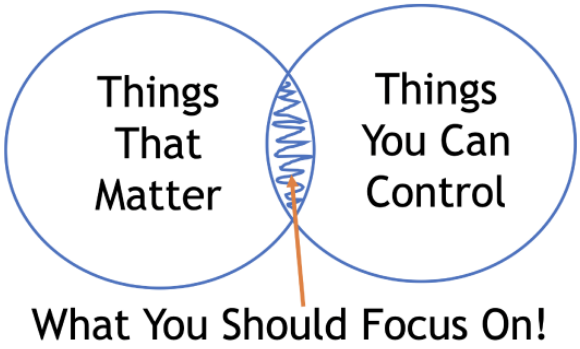


Figure 19.4.2.*b*: Focus for individual sustainability lifestyle goals. Image by Rachel Schleiger (CC-BY-NC)

The Bionic World

This book will conclude by stating a huge myth held by most of today's society, the myth of the **Bionic World**. It is the belief that science and technology will solve the pressing issues of human's impact on this earth. If society follows this logic, we have no tough choices to make about how we view and treat our surroundings, and decisions can be put off until the economic markets demand or justify a solution. Society can hope to be right…. However, until supporting evidence emerges that humanity can solve all their own problems with the ever shrinking timeline to do so, then we need to start making tough choices to ensure an equitable and sustainable future.



Figure 19.4.2.*c*: Robot arm holding up the Earth. Image by Pixabay (Public Domain)

Video 19.4.2.*a*: Perspectives: Michael Green discusses sustainability goals and what we can do moving forward (Videos from 2015 and 2018)





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19.5: Dealing with Technological Advances

Over the past several decades, we have experienced a boom in new technologies to make our lives easier, our work more efficient, and our lifestyles more sustainable. Conservation biologists have adopted many of these new technologies to great success (Pimm et al., 2015). Consider, for example, the use of unmanned aerial vehicles (UAVs) to monitor environmental changes, freely-available satellite imagery to monitor ecosystems and wildlife, and molecular methods to monitor for wildlife crimes. Hand-held devices that capture and send field data in real time are also increasing in popularity, as they enable conservation and law enforcement agencies to learn of and respond to threats much quicker than before (Wilson et al., 2019). To better streamline these efforts, there are groups such as Wildlabs which specialize in connecting the conservation community with engineers and entrepreneurs who develop such new technologies.

While conservation biologists certainly benefit from new technologies, these advances sometimes pose new challenges. Hunters now use powerful guns and motorized vehicles where historically they used bows and arrows and walked on foot. Sea fishing industries have transformed from using small wind-powered and hand-powered boats to large motorized fleets with freezers that can stay at sea for months at a time. Some technologies are so powerful that they allow for the alteration of entire ecosystems in a relatively short span of time. Some of these transformations are intentional, such as the creation of dams and the conversion of new agricultural land; others, such as pollution, are negative by-products from human activities. The impacts of these developments on ecosystems and wildlife are enormous and ominous; they have also stimulated the growth, expansion, and evolution of conservation biology.

> Renewable energy sources are needed to create a sustainable society. They must also be evaluated for their environmental impact, with systems developed to mitigate those impacts.

Technologies developed to achieve sustainable development may sometimes also present new conservation challenges. For example, to combat climate change, scientists and engineers are rushing to reduce our dependence on fossil fuels by developing carbon-neutral and **energy efficient** alternatives. As these renewable energy sources have become more assimilated into our everyday lives, their unintended consequences on the environment have also become better understood. We now know that large wind farms (Figure 19.5.1) pose a significant collision hazard to birds (Rushworth and Krüger, 2014) and bats (Frick et al., 2017), while large solar-panel arrays that concentrate sunlight can also expose wildlife to burning temperatures (Walston et al., 2016). The impacts of hydroelectric dams are cause for even more concern: in addition to harming local fisheries and freshwater biodiversity, these and other artificial reservoirs also generate large amounts of greenhouse gases that contribute to climate change (Deemer et al., 2016). Bioenergy also seems to create more problems than solutions, since it has become an important driver of habitat loss (Kleiner, 2007). Similarly, hydrological fracturing for natural gas extraction—not in itself a carbon-neutral energy alternative but claimed to do less damage than coal and petroleum—has turned out to be so damaging to the environment and human health that several governments have now banned the practice.



Figure 19.5.1 Wind power is become a popular technology representing a greener future. Yet, like other forms of carbon-neutral energy, wind power also has serious negative impacts on biodiversity that need to be mitigated to be sustainable. Photograph by Lollie-Pop, https://www.flickr.com/photos/lollie-pop/64839752, CC BY 2.0.

Despite the challenges posed by emerging technologies, none have yet posed an insurmountable threat. For example, we have already solved the ozone crisis by banning harmful chemicals such as chlorofluorocarbons (CFCs). We have also come a long way toward a sustainable fossil-fuel free world by setting guidelines for reducing the impact of wind power generation on wildlife (Reid et al., 2015; Martin et al., 2017), reducing the negative impacts of bioenergy production (Correa et al., 2017), safeguarding nuclear power stations and reusing nuclear waste (Heard and Brook, 2017), and developing more affordable solar power (Randall, 2016). It is important, however, to note that none of these emerging threats were solved by people who defended the status quo or resisted change, but by individuals who were alert and rapidly responded to new challenges before they reached a crisis point.

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19.6: Funding Conservation Activities

Economics greatly impacts conservation success. Short-term profits can incentivize individuals, companies, or governments to harvesting resources at an unsustainable rate and at the expense of ecosystem health. In impoverished regions, compromising habitat to grow high-value crops, such as coffee or oil palms, or poaching endangered species may seem like the only source of income.

Much of the Earth's biodiversity is concentrated in the tropics. While people living in the tropics may be willing and eager to preserve the wildlife around them, they are often unable to accomplish the task due to funding constraints (James et al., 2001; McClanahan and Rankin, 2016). Because many of these areas experience high levels of poverty and rapid rates of population growth, the little aid these areas receive are generally diverted to short-term socio-economic programs that ensure elected officials remain in power, rather than long-lasting sustainable solutions. In fact, one of the biggest challenges facing conservation biologists across the world is inadequate funding—many areas lack basic operational funds for protected areas, with even less for staff training, retaining top talent, keeping promises to local communities, and fulfilling the obligations set out in international treaties.

Another significant development has been the rise of NGOs that directly fund and manage conservation activities. NGOs rely on several funding mechanisms to accomplish their goals, including membership dues, donations from wealthy individuals, sponsorships from corporations, and grants from foundations and multilateral consortiums. NGOs use these funds to advance scientific research and conservation training, to implement large-scale conservation projects, and to develop locally-adapted conservation strategies (Shackeroff and Campbell, 2007), often in collaboration with local communities (Rodríguez et al., 2007). For example, BirdLife International provides alternative environmentally friendly income streams by training local guides to help tourists find rare and elusive bird species (Biggs et al., 2011) (Figure 19.6.1); other NGOs train park rangers and wildlife biologists, set up ecotourism lodges, and create opportunities to sell hand-made crafts.

> Multilateral consortiums and nongovernmental conservation organizations (NGOs) have emerged as important supporters of local conservation projects.



Figure 19.6.1: The yellow-headed rockfowl (*Picathartes gymnocephalus*, VU) is endemic to the mountain forests of West Africa from Guinea to Ghana. As one of Africa's most sought-after birds, several protected areas and nature guides tailor their businesses to showing this species to traveling birders. (Photograph by Nik Borrow, CC BY 4.0)

Another innovative funding approach, namely **debt-for-nature swaps**, leverages the huge international debt owed by developing countries to protect biodiversity. Major lenders (usually commercial banks or industrialized-country governments) have financed massive loans around the world, some of which they may never see repaid. One opportunity for the creditors to recoup some of this money is to restructure or sell the debt at a steep discount. Working with funders, investors, and development organizations, conservation groups may then buy a portion of these debts or help debtor country restructure this debt, in exchange for environmental commitments (in some cases, creditors may even directly engage with the debtor country). These conservation

efforts can also provide a new source of income for residents near the protected areas. For example, the United States forgave $20 million in debt from Costa Rica. In exchange, Costa Rica invested in expanding its protected areas and developing the ecotourism industry, which provides jobs to many of its residents (figure 19.6.2). **Ecotourism** involves visiting and enjoying natural areas while minimizing ecological damage. Ecotourism can benefit local economies and alleviate poverty especially if the earnings from it are reinvested into the communities living near tourist destinations. It generates jobs such as park operators, sellers of local crafts, and tour guides.



Figure 19.6.2: A tourist ziplines over the Costa Rican rainforest. (Khaufle at the English language Wikipedia,CC-BY-SA).

Another new strategy to obtain conservation funding is **payment for ecosystem services (PES)** schemes. Through these programs, governments, conservation NGOs, and businesses develop markets from which landowners can receive direct payments for protecting and restoring ecosystems and ecosystems services.

To combat climate change, a major international initiative financially rewards communities for preserving their carbon stocks. This initiative, established by the UN in 2007 and called Reducing Emissions from Deforestation and Forest Degradation (REDD+) receives its operational funds from individuals (such as people traveling on airplanes) and organizations seeking carbon credits to offset their carbon emissions. These funds are then used for results-based payments for conservation of carbon stocks such as forests and peatlands.

How effective is conservation funding?

Despite all these conservation resources, conservation activities continue to be underfunded due to a mismatch between funding needs and availability (Watson et al., 2014; McClanahan and Rankin, 2016; Gill et al., 2017; Lindsey et al., 2018). Exacerbating these shortfalls, conservation budgets continue to be dwarfed by spending from competing human activities and well-funded special-interest groups. For example, while the US $1.2–2.4 billion annually needed to secure Africa's protected areas with lions (Lindsey et al., 2018) is an enormous amount of money, it is much less than the US $26 billion in perverse subsidies that was paid to Africa's fossil fuel industry in 2015 (Whitley and van der Burg, 2015), which in turn is dwarfed by the whopping US $640 billion the USA budgets for military defence (DOD, 2017).

> While conservation funding is increasing, it continues to be dwarfed by perverse subsidies and spending by well-funded special-interest groups.

Many conservation projects are also constrained by weak institutional capacity, inappropriate nepotism, and even corruption in governments and NGOs. There is sometimes a tendency for conservation organizations to compete, causing them to duplicate efforts in parallel rather than cooperating efficiently. Others spend a large percentage of their funds on maintaining extensive headquarters in expensive cities; these expenses are sometimes justifiable because of work on policy or advocacy, but they are sometimes wasteful and can come at a great cost to efforts in the field. Consequently, donors are increasingly worried about how funds earmarked for conservation will be spent—will funds be used to protect biodiversity and reducing poverty, or will they be

diverted to other purposes? Thus, while new projects are often more effective, due in part to lessons learned from past experiences (Pooley et al., 2014), there is also a tendency to restrict funding to short-term cycles, and to add additional rules to prevent inappropriate spending. These additional constraints are making funding applications and accounting processes increasingly cumbersome and time-consuming, requiring even more time in the office than in the field. By focusing on short-term outcomes to meet reporting requirements, they also restrict grantees' ability to invest in organizational resilience and staff development, to adapt to changing circumstances, and to incorporate new ideas mid-cycle (Nelson et al., 2017).

Despite these conservation gains from the regulated hunting industry, legitimate concerns linger, including overcrowding and poor treatment of some animals, the ethics of trading and killing threatened species, and whether selective hunting and breeding complement or run counter to overall conservation objectives (Milner et al., 2007). The actual contribution of regulated hunting to society at large is also still being debated (IUCN/PACO, 2009; Murray, 2017), especially since some hunting concessions are established through land grabs and eco-colonialism. Similarly, there is also concerns that legal markets for threatened species may stimulate black markets and overharvesting (Lenzen et al., 2012; Hsiang and Sekar, 2016). Finding the balance between developing responsible trade opportunities in threatened species that can fund conservation activities, and risking overharvesting, is a highly emotional issue (e.g. Biggs et al., 2013a,b; Collins et al., 2013; Litchfield, 2013; Prince and Okita-Ouma, 2013) that conservation biologists will continue to grapple with in the coming years.

In the end, given the importance of nature to human well-being, it is unfortunate that conservationists continue to struggle to obtain funding and other resources. Research has shown that under-funded conservation activities run a high risk of failure (McCreless et al., 2013) while the rush to monetize nature risks weakening protection of species without immediate or realized value (Muradian et al., 2013; Balding and Williams, 2016). This contrasts with investments in protecting the natural world, which could save trillions of dollars and benefit millions of people (Costanza et al., 2014; Shindell et al., 2016). We look forward to the day when governments and individuals shift some funding from perverse subsidies to industries such as fossil fuels and unsustainable fisheries to supporting more conservation organizations and activities.

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19.6.1: Data Dive- Sustainable Investments

Overview

Climate change is the major focus of conversation across many different disciplines and interest groups. With a huge array of global sustainability challenges both now and in the future, investors are starting to re-evaluate where they want to spend their money. Today, sustainable investing is increasing exponentially! The graph below displays the global growth in sustainable investments between 2012 and 2018:

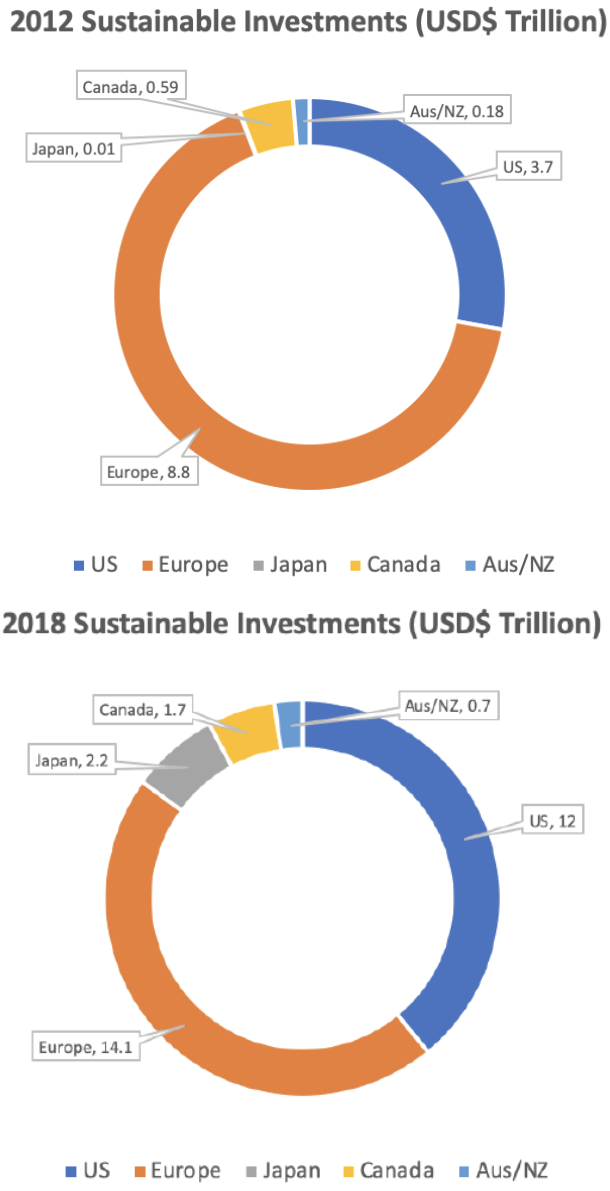


Figure 19.6.1.*a*: 2012 and 2018 global sustainable investments. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Global Sustainable Investment Alliance 2019.

Questions

1. What kind of graphs are these?
2. What major differences are there between the 2012 graph and the 2018 graph?
3. Which country(ies) is the major leader for sustainable investments?
4. Are there any countries/regions that are not represented on the graph that you would have predicted would be there?

5. Is there anything that surprises you about the results displayed in these graphs? Explain your answer.

Raw Data From Above Graph(s)

Table 19.6.1.*a*: Raw data from 2012 and 2018 global sustainable investments. Graph by Rachel Schleiger (CC-BY-NC) modified from data in Global Sustainable Investment Alliance 2019.

Country/Continent	2012 Investments (USD$ Trillion)	2018 Investments (USD$ Trillion)
United States	3.7	12
Europe	8.8	14.1
Japan	0.01	2.2
Canada	0.59	1.7
Australia/New Zealand	0.18	0.7

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19.7: Building Lasting Partnerships

Productive partnerships are one of the most important components of any successful conservation undertaking. Throughout this textbook, we have seen how successful partnerships can ensure effective law enforcement, sustainable development, ecosystem protection, and threat mitigation. Yet, many conservation projects continue to fail due to a lack of collaboration between community groups, scientists, and government leaders. Other projects fail due to unproductive partnerships, such as those relying too much on foreign consultants who lack the necessary understanding of cultural intricacies and organizational objectives in recipient countries (Mcleod et al., 2015). When considering conservation's funding deficits, it is critical to wisely use what limited funds we have by maximizing each project's prospects for success. Accomplishing this task starts with partnership composition.

Partnerships with local people

One of the most important groups to partner with is local people, particularly those individuals who are directly affected, positively and sometimes not so positively—hopefully only in the short term—by conservation projects (Redpath et al., 2013; Hall et al., 2014). Conservation projects are significantly more likely to achieve their long-term goals when they incorporate local histories and find ways to work with existing relationships between local people and their land (Waylen et al., 2010; Oldekop et al., 2016). When local people understand and buy into a project's goals and purposes, they may not only become partners in conservation, but also take on leadership roles in, or become activists for, environmental causes.

Environmental monitoring by volunteer citizen scientists provides one of the prominent success stories involving local partnerships (Figure 19.7.1). For example, using hand-held devices (e.g. smart phones) with GPS capabilities, local communities are now able to map natural resources in their forests (http://www.mappingforrights.org), wildlife distributions, and poaching hotspots (Edwards and Plagányi, 2008), as well as forest loss (DeVries et al., 2016) and human-wildlife conflict (Larson et al., 2016). Even people that lack confidence can contribute to these efforts, through platforms such as iNaturalist which have automated features to help users identify unknown organisms they may encounter.



Figure 19.7.1 Under the guidance of a conservation biologist, a group of citizen scientists monitor lesser flamingo (*Phoeniconaias minor*, NT) and black crowned crane (*Balearica pavonina*, VU) at wetlands in Guinea. Photograph by Guinea Ecology, CC BY 4.0.

There are many benefits to local involvement in biodiversity monitoring. For example, field data collected by citizen scientists—which are often as accurate as those collected by specialists (Danielsen et al., 2014; Schuttler et al. 2018)—allow biologists to obtain information from more areas more regularly and more cheaply than would be the case if specialists collected that same data. Local involvement also ensures that conservation decisions and actions are more effective and quicker to implement (Danielsen et al. 2010) and improves engagement, creating stronger advocates for conservation (Granek et al., 2008).

Partnerships among conservation professionals

Conservation biologists need to be more deliberate in fostering appropriate inter-organizational partnerships. Such partnerships enable new information to spread quicker and enable conservationists to learn from each other and to know whom to contact when

advice is sought. Strategic partnerships also enable specialization among organizations that they need not “do it all”. It allows sharing of scarce resources (e.g. trained volunteers, temporary staff, and citizen scientists) from one organization to another when not being utilized at a time. It also facilitates better coordination of activities, particularly at large scales, which improves project efficiency (Kark et al., 2015) organizational resilience (Maciejewski and Cumming, 2015), and conservation outcomes (Bonebrake et al., 2019).

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19.8: Environmental Education and Leadership

Every year, conservation biologists acquire a vast body of knowledge from projects all over the world. Yet, this information is often only communicated at small working groups and specialized meetings, published as technical papers in scientific journals with expensive subscription fees, or worse, not communicated at all. This leaves the general public detached from conservation work which, in turn, gives them (especially people living in urban centers) a sense that they live independent from nature and the knowledge gained by scientists. It also creates opportunities for willful ignorance, where citizens can normalize the environmental damage caused by their activities. To avoid these scenarios, conservation biologists need to be more proactive in outreach and environmental education, which aims to raise the public's awareness and knowledge about the environment so they can adjust to live more sustainably.

The **National Park System** in the United States consists of more than 80 million acres nationwide. Their mission is to "preserve unimpaired the natural & cultural resources & values of the national park system for the enjoyment, education, and inspiration of this & future generations". Science, conservation, and outreach are a big part of the National Park (Figure 19.8.1).



Figure 19.8.1: Shelton Johnson, a National Park Service Park Ranger, has dedicated his work at the park on connecting minorities, especially African Americans, to the natural world. He is famous for his work in sharing the history of the Buffalo Soldiers who protection public lands. (Wikipedia; Public domain)

One of the best ways to raise the public's environmental awareness is to involve them in local conservation projects, especially those that include fieldwork and site visits. Citizen science projects, as discussed above, present one of the most effective strategies. The public could also be invited to a guided tour where they are introduced to your organization's activities or provided with volunteer opportunities for stewardship workdays at a local protected area. During such workdays, ordinary citizens might help with tasks, such as invasive plant control, nest box installation, and recording wildlife behaviors. An effective public relations program can also connect people who want to engage with conservation; such a program may involve conservation exhibits in public spaces, articles written by conservation biologists for local magazines and newspapers, or public presentations.

Children and youth are one of the most important audiences for environmental education and outreach efforts. Exposing children to the wonders of the natural world instills in them a personal sense of competence, ethics, and environmental awareness that will last a lifetime (Johnson et al., 2013). These children can also influence their parents' attitudes and behavior towards environmental issues (Damerell et al., 2013). Ignoring children during outreach events, or recruiting ill-prepared teachers (Nkambwe and Essilfie, 2012), may however turn children against the environment, which they may see as a dangerous place detached from their own lives (Adams and Savahl, 2013). It could also lead to nature deficit disorder, a situation where spending less time in nature leads to behavioral problems (Louv, 2005). Consequently, many conservation organizations are now sponsoring and establishing schools to ensure young children are exposed to the importance of the environment. Others are working with children by hosting school groups, screening documentaries, publishing children's books, and offering field programs and school outings to nearby protected areas.

Reaching people who are not usually attracted to nature-based activities remains a challenge. One option is to blend conservation education and outreach with attractions and activities without an obvious conservation link. Sporting events have proven very

successful in this regard. Music concerts at botanical gardens (Figure 19.8.2) and national parks have also successfully exposed new audiences to environmental issues.



Figure 19.8.2 Conservation facilities such as Kirstenbosch Botanical Gardens, South Africa, are attracting new people to their work by hosting concerts and other types of entertainment offers. Photograph by Ivan Hendricks, courtesy of Kirstenbosch Botanical Gardens, CC BY 4.0.

The earth is in desperate need of the next generation of conservation heroes who are up to the task of addressing a growing list of complex problems. We have learnt much over the past few decades about how to better protect the natural environment in the face of growing human populations, increased consumption, and socio-economic transformations. We have also developed strong foundations in environmental education and leadership that will help us reach more people and cultivate stronger leaders. But many ecosystems continue to be in a state of distress, many species are facing extinction, and many people continue to live indifferent to their environment. The time for action is now.

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19.9: Summary

1. The field of conservation biology has set itself some imposing tasks: to describe Earth's biological diversity, to protect what remains, and to restore what is damaged. It is also a crisis discipline because decisions often need to be made under pressure, with limited resources, and under tight deadlines. A long-term conservation vision is also needed that extends beyond the immediate crisis.
2. Efforts to preserve biodiversity while overcoming conflicting human needs can be accomplished by striving towards sustainable development—economic development that satisfies both present and future needs without unsustainable economic growth that is compromising the natural world.
3. New technologies have greatly aided conservation efforts but have also created new challenges. Emerging threats are never solved by people who defend the status quo or resist change, but by individuals who rapidly respond to new challenges as soon as they arise.
4. One of the biggest challenges facing conservation biologists is inadequate funding. Fortunately, an increasing number of mechanisms are being established to fill funding voids, including multilateral funding consortiums, debt-for-nature swaps, payments for ecosystem services, and a range of grassroots initiatives.
5. To avoid leaving urban citizens detached from nature, conservation biologists need to reach out and educate the public, and particularly children, about their work. This can be achieved through citizen science projects, field programs for the public, and writing materials suitable for adults and children for newspapers, magazines, and websites.

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19.10: Review

Summary

After completing this chapter you should be able to...

- Define sustainability and the sustainability paradigm
- Describe the historic events that lead to the sustainability paradigm
- Describe how ethics and moral extensionism connect to sustainability
- Understand that true sustainability promotes environmental equity and justice, thus eliminating environmental racism
- Describe the evolution of ethics leading to the modern environmental ethic
- Understand how environmental policy has changed based on movements and need in the US
- Define what sustainable cities are
- Describe how sprawl is a hindrance to sustainable cities
- Describe how sustainable lifestyle choices influence sustainability
- Acknowledge that the Bionic World is a myth

Sustainability is focused on meeting current needs without compromising the future generations to meet theirs. Sustainability is a paradigm created out of necessity from our past negligence to society, ecology, and economy (the three main components of sustainability).

Ethics plays a large role in addressing current and future sustainability goals necessitated from historic action/inaction. This is especially true for matters of **environmental justice and racism**, in addition to **environmental policies** and movements.

Sustainable cities are also discussed to address the large-scale sustainability concerns of how humanity lives. **Sprawl** is the biggest hindrance for creating the sustainable city. There are two main types of sprawl, **low-density** and **high-density**, that can be observed in many differently populated city layouts.

The **ecological footprint** is a tool to help illustrate the imbalance between lifestyles and behaviors and what is ecologically sustainable. In order to decrease ecological footprints, in addition to environmental injustices, sustainability promotes **common cause** sustainability goals. These emphasize that most goals humanity have are the same, and that these should be what both motivate and unite us as we move towards an uncertain future. In addition, humanity should also consider how we are approaching meeting these goals. The **myth of the bionic world** warns us not to make assumptions or take the easy way out. Only through tough decisions can we ensure an equitable and sustainable future.

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19.11: Topics for Discussion

1. Think of a very important conservation challenge facing your local area. How much funding do you think would be needed to address the problem? What types of funding sources would you pursue? What are the most important benefits you would highlight to the granting agency to convince them to fund the project?
2. Several initiatives have tried to generate rural income by offering trophy hunting and wildlife viewing opportunities. Do you think these two activities are compatible with each other? What ethical, economic, political, environmental, and social issues does each initiative raise?
3. The world is moving away from fossil fuels towards renewable, carbon-neutral energy solutions, prominently solar energy, wind energy, nuclear energy, hydropower, and bioenergy. Make a list of benefits and drawbacks of each renewable energy solution. Which renewable energy solution do you think is the best, and which is the worst? What do you think is the best way to generate energy in your region and why?
4. How has studying conservation biology changed your lifestyle or level of political activity? How do you think you can make the biggest difference in protecting biodiversity?
5. Which section of this textbook appealed to you the most and why?

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Index

A

acid rain
- 11.2.3.1: Acid Deposition

adaptive radiation
- 12.2: History of Extinction

age structure
- 3.3.1: The Human Population

Aposematic Coloration
- 4.1.2: Competition

aquatic biomes
- 6.3: Aquatic Biomes

B

Batesian mimicry
- 4.1.2: Competition

biodiversity
- 12.2: History of Extinction

biodiversity hotspot
- 12.2: History of Extinction

biome
- 6.1: Climate and Biomes

biomimicry
- 8.4: Nonmaterial Contributions

C

camouflage
- 4.1.2: Competition

carrying capacity
- 3.2.3: Population Growth and Regulation

chemical diversity
- 12.2: History of Extinction

climax community
- 4.1.2: Competition

commensalism
- 4.1.2: Competition
- 4.1.4: Symbiosis

community
- 4.1: Biotic Interactions

community ecology
- 4.1: Biotic Interactions

competitive exclusion principle
- 4.1: Biotic Interactions
- 4.1.2: Competition

Crop rotations
- 18.3: Sustainable Agriculture

cultural services
- 8.4: Nonmaterial Contributions

E

ecological footprint
- 19.3.1: History of Sustainability

ecosystem diversity
- 12.2: History of Extinction

Emsleyan/Mertensian mimicry
- 4.1.2: Competition

Endemic species
- 12.2: History of Extinction

environmental disturbance
- 4.1.2: Competition

exponential growth
- 3.2.3: Population Growth and Regulation

extinction
- 12.2: History of Extinction

extinction rate
- 12.2: History of Extinction

F

foundation species
- 4.1.2: Competition

G

genetic diversity
- 12.2: History of Extinction

H

Herbivory
- 4.1: Biotic Interactions

heterogeneity
- 12.2: History of Extinction

host
- 4.1.2: Competition

human population
- 3.3.1: The Human Population

I

integrated pest management
- 18.3: Sustainable Agriculture

intercropping
- 18.3: Sustainable Agriculture

island biogeography
- 4.1.2: Competition

K

keystone species
- 4.1.2: Competition

L

logistic growth
- 3.2.3: Population Growth and Regulation

M

Müllerian Mimicry
- 4.1.2: Competition

megafauna
- 12.2: History of Extinction

Mertensian mimicry
- 4.1.2: Competition

mimicry
- 4.1: Biotic Interactions

minimal tillage
- 18.3: Sustainable Agriculture

mutualism
- 4.1.2: Competition
- 4.1.4: Symbiosis

O

organic farming
- 18.3: Sustainable Agriculture

overpopulation
- 3.3.4: Looking Ahead

P

paleosols
- 5.5: Soils

parasite
- 4.1.2: Competition

parasitism
- 4.1.4: Symbiosis

pioneer species
- 4.1.2: Competition

population growth
- 3.2.3: Population Growth and Regulation

precautionary principle
- 19.3.1: History of Sustainability

predator
- 4.1: Biotic Interactions

primary succession
- 4.1.2: Competition

pseudogenes
- 4.1.4: Symbiosis

R

relative species abundance
- 4.1.2: Competition

Remediation
- 11.2.1: Water Pollutants and Their Sources

S

secondary succession
- 4.1.2: Competition

Soil processes
- 5.5: Soils

Soil Profiles
- 5.5: Soils

species richness
- 4.1.2: Competition

sustainable agriculture
- 18.3: Sustainable Agriculture

symbiosis
- 4.1: Biotic Interactions
- 4.1.2: Competition
- 4.1.4: Symbiosis

T

terrestrial biomes
- 6.2: Terrestrial Biomes

Total Fertility Rate
- 3.3.4: Looking Ahead

Glossary

Sample Word 1 | Sample Definition 1

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- Introduction to Conservation Biology - *Undeclared*
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    - 2.5: Data Dive- California Wildfires - *Undeclared*
    - 2.6: Review - *CC BY-NC 4.0*
  - 3: Population Ecology - *CC BY-NC 4.0*
    - 3.1: Introduction to Population Ecology - *CC BY-NC 4.0*
    - 3.2: Populations - *CC BY-NC 4.0*
      - 3.2.1: Population Dispersion - *CC BY-NC 4.0*
      - 3.2.2: Population Size - *CC BY-NC 4.0*
      - 3.2.3: Population Growth and Regulation - *CC BY-SA 4.0*
      - 3.2.4: Life History - *CC BY-NC 4.0*
      - 3.2.5: Data Dive- Wildlife Corridors - *Undeclared*
      - 3.2.6: Section Review - *CC BY-NC 4.0*
    - 3.3: The Human Population - *Undeclared*
      - 3.3.1: The Human Population - *CC BY-NC-SA 4.0*
      - 3.3.2: History of Human Population Growth - *CC BY-NC-SA 4.0*
      - 3.3.3: The Rate of Human Population Growth - *CC BY-SA 4.0*
      - 3.3.4: Looking Ahead - *CC BY-NC 4.0*
      - 3.3.5: Human Impact on the Environment - *CC BY 4.0*
      - 3.3.6: Data Dive- World Population Densities - *Undeclared*
      - 3.3.7: Section Review - *CC BY-NC 4.0*
  - 4: Community Ecology - *CC BY-NC 4.0*
    - 4.1: Biotic Interactions - *CC BY-NC 4.0*
      - 4.1.1: Trophic Interactions - *CC BY-NC 4.0*
        - 4.1.1.1: Predation - *CC BY-SA 4.0*
        - 4.1.1.2: Herbivory - *CC BY-SA 4.0*
        - 4.1.1.3: Parasitism - *CC BY-NC 4.0*
        - 4.1.1.4: Food Chains and Food Webs - *CC BY-NC 4.0*
      - 4.1.2: Competition - *CC BY-SA 4.0*
      - 4.1.3: Facilitation - *CC BY-NC 4.0*
      - 4.1.4: Symbiosis - *CC BY-NC 4.0*
    - 4.2: Community Structure and Dynamics - *CC BY-NC 4.0*
    - 4.3: Data Dive- Bison Impacts In Prairies - *Undeclared*

- 4.4: Section Review - *CC BY-NC 4.0*
- 5: Ecosystems - *CC BY-NC 4.0*
  - 5.1: Ecosystem Types and Dynamics - *CC BY-NC 4.0*
  - 5.2: Matter - *CC BY-NC 4.0*
  - 5.3: Biogeochemical Cycles - *CC BY-SA 4.0*
  - 5.4: Fresh Water Supply and the Water Cycle - *CC BY-NC-SA 4.0*
    - 5.4.1: Water Usage - *CC BY-NC-SA 4.0*
    - 5.4.2: Water Scarcity and Solutions - *CC BY-SA 4.0*
  - 5.5: Soils - *CC BY-SA 4.0*
  - 5.6: Soil Degradation - *CC BY-NC-SA 4.0*
  - 5.7: Data Dive- Beaver Impacts on Wetlands - *Undeclared*
  - 5.8: Review - *CC BY-NC 4.0*
- 6: Biomes - *CC BY-SA 4.0*
  - 6.1: Climate and Biomes - *CC BY-NC-SA 4.0*
  - 6.2: Terrestrial Biomes - *CC BY-NC 4.0*
  - 6.3: Aquatic Biomes - *CC BY-SA 4.0*
  - 6.4: Data Dive- Biome Carbon Storage - *Undeclared*
  - 6.5: Review - *CC BY 4.0*
- 7: What is Biodiversity? - *CC BY 4.0*
  - 7.1: Introduction to What is Biodiversity? - *Undeclared*
  - 7.2: Classification of Earth's Species - *CC BY 4.0*
  - 7.3: Origin of Biodiversity - *CC BY 4.0*
  - 7.4: Species Diversity - *CC BY 4.0*
  - 7.5: Genetic Diversity - *CC BY 4.0*
  - 7.6: Ecosystem Diversity and Services - *CC BY-SA 4.0*
  - 7.7: Patterns of Biodiversity - *CC BY 4.0*
    - 7.7.1: Species Distribution - *CC BY-SA 4.0*
  - 7.8: Summary - *CC BY 4.0*
  - 7.9: Topics for Discussion - *CC BY 4.0*
  - 7.11: Bibliography - *CC BY 4.0*
- 8: Importance of Biodiversity - *CC BY 4.0*
  - 8.1: Introduction to the Importance of Biodiversity - *Undeclared*
  - 8.2: Material Contributions - *CC BY 4.0*
  - 8.3: Regulating Services - *CC BY 4.0*
  - 8.4: Nonmaterial Contributions - *CC BY 4.0*
  - 8.5: Option Values - *CC BY 4.0*
  - 8.6: Environmental Economics - *CC BY 4.0*
  - 8.7: Summary - *CC BY 4.0*
  - 8.8: Topics for Discussion - *CC BY 4.0*
  - 8.9: Bibliography - *Undeclared*
- 9: Habitat Destruction and Fragmentation - *CC BY 4.0*
  - 9.1: Introduction to Habitat Destruction and Fragmentation - *Undeclared*
  - 9.2: Habitat Loss Overview - *CC BY-SA 4.0*
  - 9.3: What is Habitat Loss? - *CC BY 4.0*
  - 9.4: Habitat Loss' Impact on Select Ecosystems - *CC BY 4.0*
  - 9.5: Population Growth and Consumption - *CC BY 4.0*
  - 9.6: Summary - *CC BY 4.0*
  - 9.7: Topics for Discussion - *CC BY 4.0*
  - 9.9: Bibliography - *CC BY 4.0*
- 10: Impacts of Climate Change - *CC BY 4.0*
  - 10.1: Introduction to the Impacts of Climate Change - *Undeclared*
  - 10.2: Climate Change - *CC BY-NC 4.0*
    - 10.2.1: Climate vs. Weather - *CC BY 4.0*
      - 10.2.1.1: The Greenhouse Effect and Climate Change - *CC BY-SA 4.0*
  - 10.3: Drivers of Climate Change - *CC BY 4.0*
  - 10.5: The Impact of Climate Change - *CC BY 4.0*
  - 10.6: Beneficiaries of Climate Change - *CC BY 4.0*
  - 10.7: The Overall Impact of Climate Change - *CC BY 4.0*
  - 10.8: Summary - *CC BY 4.0*
  - 10.9: Topics for Discussion - *CC BY 4.0*
  - 10.11: Bibliography - *CC BY 4.0*
- 11: Pollution, Overharvesting, Invasive Species, and Disease - *CC BY 4.0*
  - 11.1: Introduction to Pollution, Overharvesting, Invasive Species, and Disease - *Undeclared*
  - 11.2: Pollution in Its Many Forms - *CC BY 4.0*
    - 11.2.1: Water Pollutants and Their Sources - *CC BY-NC-SA 4.0*
    - 11.2.2: Mitigating Water Pollution - *CC BY-NC-SA 4.0*
    - 11.2.3: Air Pollution - *CC BY-SA 4.0*
      - 11.2.3.1: Acid Deposition - *CC BY 4.0*
    - 11.2.4: Section Review - *CC BY 4.0*
    - 11.2.5: Solid Waste Management - *CC BY-SA 4.0*
      - 11.2.5.1: Waste Generation - *CC BY-NC 4.0*
      - 11.2.5.2: Waste Disposal - *CC BY-NC 4.0*
      - 11.2.5.3: Solid Waste and Marine Life - *CC BY-NC 4.0*
      - 11.2.5.4: Data Dive- Plastic in World Oceans - *Undeclared*
      - 11.2.5.5: Waste Reduction - *CC BY-NC 4.0*
      - 11.2.5.6: Data Dive- "Flushable" Wipes - *Undeclared*

        - 11.2.5.7: Review - *CC BY-NC 4.0*
    - 11.3: Impacts of Industrial Agriculture - *CC BY-SA 4.0*
    - 11.4: Overharvesting - *CC BY 4.0*
    - 11.5: Persecution - *CC BY 4.0*
    - 11.6: Invasive Species and GMOs - *CC BY 4.0*
        - 11.6.1: Overview of Invasive Species - *CC BY-NC 4.0*
    - 11.7: Parasites and Diseases - *CC BY 4.0*
    - 11.8: Data Dive- Threats to Biodiversity - *Undeclared*
    - 11.9: Summary - *CC BY 4.0*
    - 11.10: Topics for Discussion - *CC BY 4.0*
    - 11.12: Bibliography - *CC BY 4.0*
- 12: Extinction - *CC BY 4.0*
    - 12.1: Introduction to Extinction - *Undeclared*
    - 12.2: History of Extinction - *CC BY-NC 4.0*
    - 12.3: Rates of Extinction - *CC BY 4.0*
    - 12.4: What is Extinction? - *CC BY 4.0*
    - 12.5: Which Species are at Risk of Extinction? - *CC BY 4.0*
    - 12.6: Characteristics of Threatened Species - *CC BY 4.0*
    - 12.7: Problems of Small Populations - *CC BY 4.0*
    - 12.8: Is De-extinction a Solution? - *CC BY 4.0*
    - 12.9: Summary - *CC BY 4.0*
    - 12.10: Topics for Discussion - *CC BY 4.0*
    - 12.12: Bibliography - *CC BY 4.0*
- 13: Applied Population Biology - *CC BY 4.0*
    - 13.1: Introduction to Applied Population Biology - *CC BY 4.0*
    - 13.2: Monitoring Population Size - *CC BY 4.0*
    - 13.3: Estimating Extinction Risk - *CC BY 4.0*
    - 13.4: Data Dive- Island Fox Populations - *Undeclared*
    - 13.5: Topics for Discussion - *CC BY 4.0*
    - 13.7: Bibliography - *CC BY 4.0*
    - 13.8: Summary - *Undeclared*
- 14: Conserving Ecosystems - *CC BY 4.0*
    - 14.1: Introduction to Conserving Ecosystems - *Undeclared*
    - 14.2: Measures of Biodiversity Loss - *CC BY-SA 4.0*
    - 14.3: Ecosystem Monitoring - *CC BY 4.0*
    - 14.4: Maintaining Complex and Adaptive Ecosystems - *CC BY 4.0*
    - 14.5: Restoring Damaged Ecosystems - *CC BY 4.0*
    - 14.6: Ecosystem Restoration - *CC BY-NC 4.0*
    - 14.7: Combatting Climate Change Through Ecosystem Conservation - *CC BY 4.0*
    - 14.8: Summary - *CC BY 4.0*
    - 14.9: Topics for Discussion - *CC BY 4.0*
    - 14.11: Bibliography - *Undeclared*
- 15: Preventing Extinctions - *CC BY 4.0*
    - 15.1: Introduction to Preventing Extinctions - *Undeclared*
    - 15.2: Species-level Conservation - *CC BY-NC 4.0*
    - 15.3: Studying Species and Populations - *CC BY 4.0*
    - 15.4: Saving Species Through Translocations - *CC BY 4.0*
    - 15.5: Managing and Facilitating Movement Dynamics - *CC BY 4.0*
    - 15.6: Managing Species Sensitive to Climate Change - *CC BY 4.0*
    - 15.7: Ex Situ Conservation Strategies - *CC BY 4.0*
    - 15.8: Thoughts on Neglected Taxa - *CC BY 4.0*
    - 15.9: Summary - *CC BY 4.0*
    - 15.10: Topics for Discussion - *Undeclared*
    - 15.12: Bibliography - *Undeclared*
- 16: Biodiversity and the Law - *CC BY 4.0*
    - 16.1: Introduction to Biodiversity and the Law - *Undeclared*
    - 16.2: Identifying Legislative Priorities - *CC BY 4.0*
    - 16.3: Environmental Laws and Policies - *CC BY 4.0*
    - 16.4: National and State Laws - *CC BY-NC 4.0*
    - 16.5: The Limits of Environmental Laws and Regulations - *CC BY 4.0*
    - 16.6: Conclusion - *CC BY 4.0*
    - 16.7: Summary - *CC BY 4.0*
    - 16.8: Topics for Discussion - *Undeclared*
    - 16.10: Bibliography - *Undeclared*
- 17: The Importance of Protected Areas - *CC BY 4.0*
    - 17.1: Introduction to the Importance of Protected Areas - *Undeclared*
    - 17.2: Establishing Protected Areas - *CC BY 4.0*
    - 17.3: Classification of Protected Areas - *CC BY 4.0*
    - 17.4: Government Protected Areas in the US - *CC BY-NC 4.0*
    - 17.5: Non-profit Organizations - *CC BY-SA 4.0*
    - 17.6: Prioritization - What Should be Protected? - *CC BY 4.0*
    - 17.7: Designing Protected Areas - *CC BY 4.0*
    - 17.8: Challenges for Protected Areas - *CC BY 4.0*
    - 17.9: Summary - *Undeclared*
    - 17.10: Topics for Discussion - *Undeclared*
    - 17.11: Bibliography - *Undeclared*
- 18: Conservation on Unprotected Lands - *CC BY 4.0*

- 18.1: Introduction to Conservation on Unprotected Lands - *Undeclared*
- 18.2: Human-Dominated Landscapes - *CC BY 4.0*
- 18.3: Sustainable Agriculture - *CC BY-SA 4.0*
- 18.4: Smarter Infrastructure - *CC BY 4.0*
- 18.5: Confronting Human-Wildlife Conflict - *CC BY 4.0*
- 18.6: Data Dive- Landslides and Ag Terraces - *Undeclared*
- 18.7: Summary - *CC BY 4.0*
- 18.8: Topics for Discussion - *CC BY 4.0*
- 18.10: Bibliography - *Undeclared*

19: An Agenda for the Future - *CC BY 4.0*

- 19.1: Introduction to An Agenda for the Future - *CC BY 4.0*
- 19.2: Individual Choices - *CC BY-NC 4.0*
- 19.3: Introduction to Sustainability - *Undeclared*
  - 19.3.1: History of Sustainability - *CC BY-NC 4.0*
- 19.4: Achieving Sustainable Development - *CC BY 4.0*
  - 19.4.1: Sustainable Cities - *CC BY-NC 4.0*
  - 19.4.2: Sustainability and the Future - *CC BY-NC 4.0*
- 19.5: Dealing with Technological Advances - *CC BY 4.0*
- 19.6: Funding Conservation Activities - *CC BY 4.0*
  - 19.6.1: Data Dive- Sustainable Investments - *Undeclared*
- 19.7: Building Lasting Partnerships - *CC BY 4.0*
- 19.8: Environmental Education and Leadership - *CC BY 4.0*
- 19.9: Summary - *CC BY 4.0*
- 19.10: Review - *CC BY 4.0*
- 19.11: Topics for Discussion - *Undeclared*
- 19.13: Bibliography - *Undeclared*

Back Matter - *Undeclared*

- Index - *Undeclared*
- Glossary - *Undeclared*
- Detailed Licensing - *Undeclared*