# 5

# Environmental Systems and Ecosystem Ecology

Chapter Objectives

This chapter will help you:

Describe the nature of environmental systems

Define ecosystems and evaluate how living and nonliving entities interact in ecosystem-level ecology

Outline the fundamentals of landscape ecology, GIS, and ecological modeling

Assess ecosystem services and how they benefit our lives

Compare and contrast how water, carbon, phosphorus, and nitrogen cycle through the environment

Explain how human impact is affecting biogeochemical cycles

Lecture/Reading Outline

## I. Central Case: The Gulf of Mexico's "Dead Zone"

A. The dead zone is a region in the Gulf of Mexico so depleted of oxygen that it cannot support marine organisms, a condition called **hypoxia**.

B. In 2002, the dead zone grew to its largest size ever—22,000 square km (8,500 square miles).

C. The change from productive fishery to dead zone has occurred in the last 30 years. The spread of the hypoxic zone threatens the Gulf's fishing industry, one of the most productive fisheries in the United States.

D. Scientists studying the dead zone have determined that fertilizer runoff from Midwestern farms carried through the watershed by rain and irrigation is a major cause of the hypoxia.

E. Other important causes include urban runoff, industrial discharge, fossil fuel combustion, and municipal sewage.

F. Approximately 400 coastal dead zones have been documented worldwide.

## II. Earth's Environmental Systems

A. Systems show several defining properties.

1. A **system** is a network of relationships among a group of parts, elements, or components that interact with and influence one another through the exchange of energy, matter, and/or information.
2. Systems receive inputs, process them, and produce outputs. Systems can have many inputs, processes, and outputs.
3. Sometimes a system's output can serve as an input to that same system in a circular process called a **feedback loop**.
   a. In a **negative feedback loop**, output driving the system in one direction acts as input that moves the system in the other direction. Negative feedback loops are not "bad" feedback loops. They generally stabilize a system.
   b. In a **positive feedback loop**, the output drives the system further toward one extreme. Positive feedback loops are usually not "good"; they tend to destabilize a system. Positive feedback is rare in natural systems not impacted by human behavior.
4. The inputs and outputs of a complex natural system often occur simultaneously, keeping the system constantly active. But even processes moving in opposite directions can be stabilized by negative feedback so that their effects balance out, creating a state of **dynamic equilibrium**.
5. Processes in dynamic equilibrium contribute to **homeostasis**, where the tendency of the system is to maintain stable internal conditions. Sometimes processes have to be viewed over long time periods to see this stability.
6. It is difficult to fully understand systems by focusing on their individual components because systems can show **emergent properties**, characteristics that are not evident in the system's components.
7. Systems rarely have well-defined boundaries, so deciding where one system ends and another begins can be difficult.
8. Systems may exchange energy, matter, and information with other systems, or may contain or be contained within other systems.

B. Environmental systems interact.

1. Hypoxia in the Gulf of Mexico stems from excess nutrients, primarily nitrogen and phosphorus, from the Mississippi River **watershed**. The watershed includes all the major and minor tributaries which drain all of the lands that ultimately drain to the Mississippi.
2. Excess nutrients are present in runoff from fertilized agricultural fields, animal manure, crop residues, sewage, and industrial and automobile emissions.
3. The nutrients reach the Gulf, where they boost the growth of phytoplankton; Dead phytoplankton and waste products sink toward the bottom providing food for bacterial decomposers, which flourish.
4. The decomposers consume the oxygen in the water through cellular respiration; bottom dwelling organisms, such as fish and shrimp, suffocate

and die from lack of oxygen.

5. The process of nutrient enrichment, algal bloom, bacterial increase, and ecosystem deterioration is called **eutrophication**.
6. Fresh water is less dense than the ocean water so the oxygenated river water remains in a stratified surface layer and mixes slowly with the Gulf waters as it flows out to sea.

C. We may perceive Earth's systems in various ways.

1. The **lithosphere** is everything that is solid earth beneath our feet.
2. The **atmosphere** is comprised of the air surrounding our planet.
3. The **hydrosphere** encompasses all water in surface bodies, underground, and in the atmosphere.
4. The **biosphere** consists of all the planet's living organisms, or biotic components, and the abiotic portions of the environment with which they interact.
5. All of these systems interact and their boundaries overlap. Ultimately, it is impossible to isolate any one in discussing an environmental system.

## III. Ecosystems

1. An **ecosystem** consists of all interacting organisms and abiotic factors that occur in a particular place at the same time.

A. Ecosystems are systems of interacting living and nonliving entities.

1. In the early 20th century, scientists began to recognize that biological entities were tightly intertwined with physical and chemical ones.
2. Energy flows in one direction through ecosystems; most arrives from the sun, powers the systems and its organisms, and exits in the form of heat.
3. Matter is generally recycled within an ecosystem. When organisms die and decay, their nutrients remain in the system.

B. Energy is converted to biomass.

1. Autotrophs convert the sun's energy to produce chemical bond energy in sugars through photosynthesis. This is **gross primary production**.
2. Autotrophs use some of their acquired energy to power their own metabolism by cellular respiration. The remainder is used to generate biomass and is called **net primary production**. This is the energy, or biomass available, for consumption by heterotrophs.
3. The rate at which biomass is generated is called **productivity**. Ecosystems with rapid biomass production are said to have high net primary productivity.
4. **Net primary productivity** varies widely over different ecological zones and according to nutrient availability.

C. Nutrients influence productivity.

1. **Nutrients** are elements and compounds that organisms consume and require for survival.

2. A lack of any required nutrient will limit production. In marine systems, too much nitrogen is generally limiting, and in freshwater, too much phosphorus is limiting. Several experiments have been conducted to verify this conclusion.

3. In natural ecosystems, some nutrients always run off land into oceans. This nutrient input causes high primary productivity in nearshore waters along continents.

4. When human factors, such as farming, urbanization, and industry, increase this nutrient load, then eutrophication and hypoxia often occur. This creates dead zones.

5. The number of dead zones has been rising globally. But the awareness of the problem has led to runoff reduction in some locations and improvement is evident.

D. Ecosystems interact spatially.

1. The scale of an ecosystem can vary from being tiny, such as a small puddle, to being large, like a forest or lake. In some contexts, the entire biosphere might be viewed as an ecosystem.

2. In areas where ecosystems meet and interact, the transitional zones are known as ecotones and contain elements from each ecosystem.

E. Landscape ecologists study geographic patterns.

1. **Landscape ecology** is the broad-scale study of how landscape structure affects the abundance, distribution, and interactions of organisms. These structures often encompass multiple ecosystems.

2. A landscape is made up of a spatial array of **patches** spread over the landscape in a **mosaic** and connected at ecotones.

3. The specific habitat needs of an organism will often determine its distribution across patches and possibly its division into sub-populations or **metapopulations**.

4. **Conservation biologists** are concerned about the fragmentation of habitats caused by human development pressures.

F. Remote sensing helps us apply landscape ecology.

1. A **geographic information system (GIS)** is a common tool for landscape ecology. This is computer software that integrates data from a number of sources, including satellite imagery, to provide a broad picture of landscape use.

2. By integrating different data sets such as geology, hydrology, populations, and development, GIS helps improve the planning of land use.

G. Modeling helps ecologists understand systems.

1. **Models** are simplified representations of complex natural processes.

2. **Ecological modeling** allows scientists to help explain and predict how ecological systems function.

3. Models are tested by gathering new data from natural systems; scientists use this data to refine their models.

H. Ecosystems provide vital services.

1. Healthy functioning ecosystems provide services called **ecosystem services**, which support our lives and society in profound and innumerable ways.
2. Earth systems provide natural resources and additional services, such as water and air purification, soil production, water storage, and waste disposal.
3. Ecosystems also provide recreational and educational opportunities.
4. One of the most important ecosystem services is the cycling of nutrients.

## IV. Biogeochemical Cycles

A. Nutrients circulate through ecosystems in biogeochemical cycles.

1. Nutrients move through the environment in cycles called **nutrient cycles** or **biogeochemical cycles**.
2. Most nutrients travel through the atmosphere, hydrosphere, and lithosphere, and from one organism to another, moving between **pools**, or **reservoirs**, remaining in a reservoir for a **residence time**.
3. The rate at which materials move between reservoirs is termed **flux**; the flux between reservoirs can change over time. Flux typically involves negative feedback loops that promote dynamic equilibrium.
4. A reservoir that releases more material than it accepts is called a **source**; one that accepts more than it releases is called a **sink**.
5. Human activity has changed some flux rates and generated destabilizing positive feedback loops

B. The water cycle influences all other cycles.

1. Water is the essential medium for most biochemical reactions.
2. The water cycle, or **hydrologic cycle**, summarizes how water - in liquid, gaseous, and solid forms - flows through our environment.
3. Water carries nutrients and pollutants from terrestrial sources to rivers and then to the oceans.
4. The oceans are the main reservoir, holding 97% of all water on Earth. Less than 1% of planetary water is usable by humans.
5. Water moves from the hydrosphere into the atmosphere by **evaporation**, a conversion of a liquid to a gaseous form. Its flux depends on wind speed and temperature.
6. Water also moves into the atmosphere via **transpiration**, the release of water vapor from the leaves of plants. Both processes are a natural form of distillation.
7. Water returns from the atmosphere as **precipitation** to complete the cycle

when water vapor condenses and falls as rain or snow.

8. Some of this water is taken up by plants or animals, or is captured behind dams for human use; most, however flows as **runoff** into streams, rivers, lakes, ponds, and oceans.
9. Some precipitation and surface water soaks down to recharge underground reservoirs known as **aquifers**. Aquifers are sponge-like regions of rock and soil that hold **groundwater**, water found underground beneath layers of soil.
10. The upper limit of the groundwater in an uppermost aquifer is referred to as the **water table**.
11. Aquifers can hold water for a long time; many are from periods when Earth's glaciers melted. They also can take long periods of time, hundreds or thousands of years, to recharge.

C. Our impacts on the water cycle are extensive.

1. We have dammed rivers and created reservoirs, increasing evaporation.
2. We have changed vegetation patterns, increasing runoff and erosion and decreasing recharge.
3. Atmospheric pollutants have changed the chemical nature of precipitation.
4. Irrigation, industry, and other human uses have depleted aquifers and increased evaporation, leading to water shortages in some parts of the world.
5. Water shortages are giving rise to conflicts throughout the world and are predicted to increase.

D. The carbon cycle circulates a vital organic nutrient.

1. Carbon is an ingredient in carbohydrates, fats, proteins, bones, and cartilage, as well as in the shells of all living things.
2. The **carbon cycle** describes the routes carbon atoms take through the environment.
3. Producers, including plants, algae, and cyanobacteria, pull carbon dioxide out of the atmosphere and out of surface water to use in photosynthesis.
4. During respiration, producers, consumers, and decomposers break down carbohydrates to produce carbon dioxide and water.
5. A portion of the carbon taken in by organisms is stored in tissues. The abundance of plants makes these a large reservoir of carbon and that level is being intensively studied to assess its impact on global climate change.
6. Sedimentary rock is the largest reservoir in the carbon cycle.
7. Organisms that have died can settle in sediments in oceans or wetlands and be converted by pressure to fossil fuels or rock.
8. The oceans are the second largest reservoir of carbon. They accumulate carbon from the atmosphere, runoff, and dead marine organisms.
9. Scientists are studying whether the oceans can offset the increased carbon

dioxide in the atmosphere, but the increased acidity that results may limit the uptake.

E. We are shifting carbon from the lithosphere to the atmosphere.

   1. As we mine fossil fuel deposits and cut or burn vegetation, we remove carbon from reservoirs and increase the net flux into the atmosphere.
   2. This ongoing flux of carbon into the atmosphere is a major force behind global climate change.
   3. Atmospheric scientists remain baffled by the ―missing carbon sink,‖ the roughly 1–2 billion metric tons of carbon unaccounted for (out of approximately 7) that should be in the atmosphere due to fossil fuel combustion and deforestation.

F. The phosphorus cycle involves mainly lithosphere and ocean.

   1. The element phosphorus is a key component of DNA, RNA, ATP, and cell membranes.
   2. Phosphorus is primarily found in rocks, soil, sediments, and oceans; the weathering of rocks releases phosphates into water at a very low rate of flux.
   3. The **phosphorus cycle** has no appreciable atmospheric component.
   4. Concentrations of available phosphorus in the environment are very low; this is often a limiting factor for producers.

G. We affect the phosphorus cycle.

   1. We mine rocks for phosphorus to make fertilizers, and our sewage discharge and agricultural runoff are high in phosphates.
   2. These additions of phosphorus can cause rapid increases of biomass in soil and eutrophication, leading to murkier waters and altering the structure and function of aquatic ecosystems.

H. The nitrogen cycle involves specialized bacteria.

   1. Nitrogen makes up 78% of the atmosphere and is the sixth most abundant element on Earth.
   2. The **nitrogen cycle** involves chemically inert nitrogen gas, which most living organisms cannot use. This makes the atmosphere the major reservoir for nitrogen.
   3. Lightning, highly specialized bacteria, and human technology are the only ways to fix nitrogen into compounds that living organisms can use.
   4. Nitrogen is frequently a limiting factor for producers and therefore limits populations of consumers, including humans.
   5. There are two ways that inert nitrogen gas becomes ―fixed‖ so that plants can use it—nitrogen fixation and nitrification.

      a. **Nitrogen fixation** occurs through lightning or **nitrogen-fixing bacteria** that live in mutualistic relationships with many leguminous plants.

      b. **Nitrification** occurs through specialized free-living bacteria.

c. **Denitrifying bacteria** convert nitrates in soil or water to gaseous nitrogen.

I. We have greatly influenced the nitrogen cycle.

1. Nitrogen fixation has historically been a bottleneck, limiting the flux of nitrogen out of the atmospheric reservoir.
2. The **Haber-Bosch process** allows humans to synthesize ammonia, accelerating its flux into other reservoirs within the cycle.
3. Burning forests, fields, and fossil fuels all increase the amount of atmospheric nitrogen, as does bacterial decomposition of animal wastes from feedlots.
4. Strategies to limit the amount of damage caused by excess nutrients in the waterways are not successful at this time.

J. People are searching for solutions to the dead zone.

1. In 1998, Congress passed the Harmful Algal Bloom and Hypoxia Research and Control Act, which called for an assessment of the dead zone's ecological and economic impacts.
2. A state and federal task force proposed reducing nitrogen flowing down the Mississippi River by 30% by the year 2015, in order to reduce the dead zone's average size to 5,000 $km^2$ (1,930 $mi^2$).
3. To protect farmers, in 2004, Congress reauthorized the Harmful Algal Bloom and Hypoxia Research Control Act, encouraging scientists, farmers, and policymakers to search for innovative ways to alleviate pollution while safeguarding agriculture.
4. In 2009, the Obama administration responded with $320 million for programs to fight nutrient pollution in the Mississippi River Basin.
5. The Gulf should also benefit from a separate program to protect and restore the Mississippi River's delta. It would boost the growth of marsh plants, helping to restore coastal wetlands.

## V. Conclusion

A. A systems approach to understanding Earth's dynamics is important in helping us avoid disrupting its processes. Integrating systems perspectives with scientific findings allows us to address issues like the Gulf of Mexico hypoxic zone.

B. Knowledge of the ways in which biotic and abiotic systems interact, and how energy and mass flow through the systems, is essential. An understanding of biogeochemical cycles that describe the movement of nutrients within and among ecosystems is also crucial because human activities are causing significant changes in these cycles.

C. Natural ecosystems use renewable solar energy, recycle nutrients, and are stabilized by negative feedback loops. We should take a careful look at these systems that have withstood the test of time as models of sustainability.

Key Terms

- aquifers
- atmosphere
- biogeochemical cycles
- biosphere
- carbon cycle
- conservation biologists
- denitrification
- denitrifying bacteria
- dynamic equilibrium
- ecological modeling
- ecosystem
- ecosystem services
- ecotone
- emergent properties
- eutrophication
- evaporation
- feedback loop
- flux
- geographic information systems
- gross primary production
- groundwater
- Haber-Bosch process
- homeostasis
- hydrologic cycle
- hydrosphere
- hypoxia
- landscape ecology
- lithosphere
- metapopulation
- model
- mosaic
- negative feedback loop
- net primary production
- net primary productivity
- nitrification
- nitrogen cycle
- nitrogen fixation
- nitrogen-fixing bacteria
- nutrient cycles
- nutrients
- patches
- phosphorus cycle
- pool
- positive feedback loop
- precipitation
- productivity
- reservoir
- residence time
- runoff
- sink
- source
- system
- transpiration
- water cycle
- watershed
- water table