Biogeochemical Cycles: Carbon and Phosphorus

Inquire: Biogeochemical Cycles

Overview

Mineral nutrients are cycled through ecosystems and their environment. Of particular importance are water, carbon, nitrogen, phosphorus, and sulfur. All of these cycles have major impacts on ecosystem structure and function. As human activities have caused major disturbances to these cycles, their study and modeling is especially important. Ecosystems have been damaged by a variety of human activities that alter the natural biogeochemical cycles due to pollution, oil spills, and events causing global climate change. The health of the biosphere depends on understanding these cycles and how to protect the environment from irreversible damage.

Big Question: What are the processes in the biogeochemical cycles of carbon and phosphorus?

Watch: Chesapeake Bay: An Ecosystem Affected by Phosphate and Runoff

The Chesapeake Bay is one of the most scenic areas on Earth; however, it is now in distress and is recognized as a case study of a declining ecosystem. In the 1970s, the Chesapeake Bay was one of the first aquatic ecosystems to have identified dead zones, which continue to kill many fish and bottom-dwelling species such as clams, oysters, and worms. Several species have declined in the Chesapeake Bay because surface water runoff contains excess nutrients from artificial fertilizer use on land. The source of the fertilizers (with high nitrogen and phosphate content) is not limited to agricultural practices. Many nearby urban areas and more than 150 rivers and streams empty into the bay, 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 individual homeowners.

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 caused not only by fertilizer runoff and dead zones, but also because of overharvesting. 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, thus greatly disrupting the ecosystem.

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 by Virginia and Delaware to clean and restore the bay have been hampered because much of the pollution entering the bay comes from other states, which emphasizes the need for interstate 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.

Read: Biogeochemical Cycles

Overview

Energy flows directionally through ecosystems, entering as sunlight and leaving as heat during the transfers between trophic levels, or the different levels in the food chain. Rather than flowing through an ecosystem, the matter that makes up living organisms is conserved and recycled. The six most common elements associated with organic molecules are carbon, nitrogen, hydrogen, oxygen, phosphorus, and sulfur. These elements take a variety of chemical forms and may exist for long periods in the atmosphere, on land, in water, or beneath Earth’s surface. Geologic processes, such as weathering, erosion, water drainage, and the subduction of the continental plates, all play a role in the cycling of elements on Earth. Because geology and chemistry have major roles in the study of this process, the recycling of inorganic matter between living organisms and their nonliving environment is called a biogeochemical cycle.

The cycling of these elements is interconnected. For example, the movement of water is critical for the draining away of nitrogen and phosphate into rivers, lakes, and oceans. The ocean is also a major reservoir for carbon. Thus, mineral nutrients are cycled, either rapidly or slowly, through the entire biosphere between the biotic (living) and abiotic (non-living) world and from one living organism to another.

The Carbon Cycle

Carbon is the fourth most abundant element in living organisms. Carbon is present in all organic molecules, and its role in the structure of macromolecules is of primary importance to living organisms. Carbon compounds contain energy, and many of these compounds from plants and algae have remained stored as fossilized carbon, which humans use as fuel. Since the 1800s, the use of fossil fuels has accelerated. As global demand for Earth’s limited fossil fuel supplies have risen since the beginning of the Industrial Revolution, the amount of carbon dioxide in our atmosphere has increased as the fuels are burned. This increase in carbon dioxide has been associated with climate change and is a major environmental concern worldwide.

The carbon cycle is most easily studied as two interconnected subcycles: one dealing with rapid carbon exchange among living organisms and the other dealing with the long-term cycling of carbon through geologic processes.

The Biogeochemical Carbon Cycle

The movement of carbon through land, water, and air is complex, and in many cases, it occurs much more slowly — geologically-speaking — than the movement between living organisms. Carbon is stored for long periods in what are known as carbon reservoirs, which include the atmosphere, bodies of liquid water (mostly oceans), ocean sediment, soil, rocks (including fossil fuels), and the Earth’s interior.
As stated, the atmosphere is a major reservoir of carbon in the form of carbon dioxide, which is essential to the process of photosynthesis. 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, and so each one affects the other reciprocally. Carbon dioxide (CO$_2$) from the atmosphere dissolves in water and, unlike oxygen and nitrogen gas, reacts with water molecules to form ionic compounds. 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 form sediments on the ocean floor. Over geologic time, the calcium carbonate forms limestone, which comprises the largest carbon reservoir on Earth.

On land, carbon is stored in soil as organic carbon as a result of the decomposition of living organisms or from weathering of terrestrial rock and minerals. Deeper under the ground, at land and at sea, are fossil fuels, the anaerobically decomposed remains of plants that take millions of years to form. Fossil fuels are considered a non-renewable resource because their use far exceeds their rate of formation. A non-renewable resource is either regenerated very slowly or not at all. Another way for carbon to enter the atmosphere is from land (including land beneath the surface of the ocean) during the eruption of volcanoes and other geothermal systems. Carbon sediments from the ocean floor are taken deep within Earth by the process of subduction: the movement of one tectonic plate beneath another. Carbon is released as carbon dioxide when a volcano erupts or from volcanic hydrothermal vents.

Carbon dioxide is also added to the atmosphere by the human practice of animal husbandry. The large number of land animals raised to feed Earth’s growing human population results in increased carbon-dioxide levels in the atmosphere caused by their respiration. This is another example of how human activity indirectly affects biogeochemical cycles in a significant way.
Although much of the debate about future effects of increasing atmospheric carbon on climate change focuses on fossils fuels, scientists take natural processes such as volcanoes, plant growth, soil carbon levels, and respiration into account as they model and predict the future impact of this increase.

The Biological Carbon Cycle

Living organisms are connected in many ways, even between ecosystems. A good example of this connection is the exchange of carbon between heterotrophs and autotrophs within and between ecosystems by way of atmospheric carbon dioxide. Carbon dioxide is the basic building block that autotrophs use to build multi-carbon, high-energy compounds, such as glucose. The energy harnessed from the sun is used by these organisms to form the covalent bonds that link carbon atoms together. These chemical bonds store this energy for later use in the process of respiration. Most terrestrial autotrophs obtain their carbon dioxide directly from the atmosphere, while marine autotrophs acquire it in the dissolved form (carbonic acid, HCO₃⁻). However the carbon dioxide is acquired, oxygen is a byproduct of fixing carbon in organic compounds. Photosynthetic organisms are responsible for maintaining approximately 21 percent of the oxygen content of the atmosphere that we observe today.
there is excess available for the respiration of other aerobic organisms. Gas exchange through the atmosphere and water is one way that the carbon cycle connects all living organisms on Earth.

Reflect Poll: Altering the Biogeochemical Cycles

Ecosystems have been damaged by a variety of human activities that alter the natural biogeochemical cycles. What do you think most alters the natural biogeochemical cycles?

- pollution
- oil spills
- events causing global climate changes

Expand: The Phosphorus Cycle

Overview

Phosphorus is an essential nutrient for living processes; it is a major component of nucleic acids and phospholipids, and, as calcium phosphate, makes up the supportive components of our bones. Phosphorus is often the limiting nutrient (necessary for growth) in aquatic, particularly freshwater, ecosystems.

In nature, phosphorus exists as the phosphate ion (PO₄³⁻). Weathering of rocks and volcanic activity releases phosphate into the soil, water, and air, where it becomes available to terrestrial food webs. Phosphate enters the oceans in surface runoff, groundwater flow, and river flow. Phosphate dissolved in ocean water cycles into marine food webs. Some phosphate from the marine food webs falls to the ocean floor, where it forms sediment. (credit: modification of work by John M. Evans and Howard Perlman, USGS)
The Impact of Phosphorus

Phosphorus occurs in nature as the phosphate ion (PO$_4^{3-}$). In addition to phosphate runoff as a result of human activity, natural surface runoff occurs when it is leached from phosphate-containing rock by weathering, thus sending phosphates into rivers, lakes, and oceans. This rock has its 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 is then moved to land over geologic time by the uplifting of Earth’s surface.

Phosphorus is also reciprocally exchanged between phosphate dissolved in the ocean and marine organisms. The movement of phosphate from ocean to 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.

Excess phosphorus and nitrogen that enter these ecosystems from fertilizer runoff and from sewage cause excessive growth of algae. The subsequent death and decay of these organisms depletes dissolved oxygen, which leads to the death of aquatic organisms, such as shellfish and finfish. This process is responsible for dead zones in lakes and at the mouths of many major rivers, and for massive fish kills, which often occur during the summer months.

A dead zone is an area in lakes and oceans near the mouths of rivers where large areas are periodically depleted of their normal flora and fauna. These zones can be caused by eutrophication, oil spills, dumping toxic chemicals, and other human activities. The number of dead zones has increased for several years, and more than 400 of these zones were present as of 2008. 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 of over 8,463 square miles. Phosphate and nitrate runoff from fertilizers also negatively affect several lake and bay ecosystems, including the Chesapeake Bay in the eastern United States.
Lesson Toolbox

Additional Resources and Readings

An Amoeba Sisters video covering the carbon cycle
- Link to resource: https://www.youtube.com/watch?v=NHqEthRCqQ4

A Crash Course video covering the phosphorus cycle
- Link to resource: https://www.youtube.com/watch?v=leHy-Y_8nRs

An interactive carbon cycle game
- Link to resource: https://www.windows2universe.org/earth/climate/carbon_cycle.html

A video showing the dead zone in the Gulf of Mexico
- Link to resource: https://oceantoday.noaa.gov/happnowdeadzone/

Lesson Glossary

biogeochemical cycle: the cycling of minerals and nutrients through the biotic and abiotic world

dead zone: an area in a lake and ocean near the mouths of rivers where large areas are depleted of their
normal flora and fauna; these zones can be caused by eutrophication, oil spills, dumping of toxic
chemicals, and other human activities

eutrophication: the process whereby nutrient runoff causes the excess growth of microorganisms and
plants in aquatic systems

non-renewable resource: a resource, such as a fossil fuel, that is either regenerated very slowly or not
at all

subduction: the movement of one tectonic plate beneath another

Check Your Knowledge

1. Carbon dioxide (CO₂) from the atmosphere dissolves in phosphorus and reacts with water
   molecules to form ionic compounds.
   a. True
   b. False

2. Natural surface runoff occurs when it is leached from phosphate-containing rock by weathering,
   thus sending phosphates into rivers, lakes, and the ocean.
   a. True
   b. False

3. Carbon is present in all organic molecules.
   a. True
   b. False

Answer Key: