Nitrogen cycle

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NITROGEN CYCLE

The nitrogen cycle is the shift between different chemical forms of nitrogen through biologic, physical, and geologic processes on Earth. Nitrogen is an essential element for all living things. It is a building block of biologic molecules such as proteins and nucleic acids. The majority of nitrogen on the planet is in the form of molecular nitrogen in the air. Only certain bacteria can convert nitrogen into biologic molecules that occur mainly inside living cells. Humans are interfering with the nitrogen cycle by making nitrogen fertilizers and by oxidizing atmospheric molecular nitrogen through the extensive burning of fossil fuels.

PRINCIPAL TERMS

- **ammonia:** a colorless and highly toxic gas with a strong odor; the odor of ammonia is frequently detected in stables or in sewage; salts of ammonia are used as fertilizer for plants
- **ammonium ion:** produced as a waste of such animals as fish, during decomposition of organic nitrogen wastes by bacteria, and by metabolism of some bacteria; forms after dilution of ammonia in water; acidic and toxic to humans because it interferes with respiration
- **biogeochemical cycle:** cycling of chemical elements such as nitrogen, carbon, and phosphorus
- **enzyme:** biologic catalyst made of proteins
- **eutrophication:** process in which water bodies (rivers, ponds, lakes, and oceans) receive excess nutrients (mainly nitrogen and phosphorus) that stimulate abundant growth of algae and plants
- **food web:** the complex web of feeding relationships in nature
- **nitrate:** the ion of nitric acid; an essential nutrient for plants
- **nitric acid:** nitrogen-containing strong acid, used by medieval alchemists to separate gold from silver; now used in the manufacturing of dyes, plastics, and drugs and in laboratories
- **nitrite:** the ion of nitrous acid; source for some microorganisms; extremely hazardous to humans, especially babies
- **nitrogen:** a key chemical element on Earth; a colorless and odorless component of air

Cycling of Nitrogen on Earth

The majority of Earth's chemical elements are circulating through biologic, physical, chemical, and geologic processes. These processes operate in circles and are called biogeochemical cycles.

Nitrogen is one of the key elements in human activities and in biologic, physical, chemical, and geologic processes. Estimates show that more than 20 million tons of nitrogen exists on every square mile of the planet. The atmosphere contains up to 78 percent molecular nitrogen (N_2), and this nitrogen is mainly cycling through biologic processes.

Four major nitrogen-transformation (biologic) processes exist in nature: nitrogen fixation, ammonification, nitrification, and denitrification. Mineralization is the only geologic process that is involved in the circulation of nitrogen. The main mineral sources of nitrogen on Earth are Bengal saltpeter (KNO_3) in India and other Asian countries and Chile saltpeter ($NaNO_3$) in South America. Natural gas also contains nitrogen.

Vast amounts of nitrogen are circulated by physical and chemical processes. Nitric oxide (NO) is formed in the air from N_2 and O_2 (molecular oxygen) during thunderstorms by lightning. Nitric oxide oxidizes further to nitrogen dioxide (NO_2) and later reacts with water to form nitric (or nitrous (HNO_3) acids. Acids fall to the ground during rain and form nitrates (NO^-_3) and nitrites (NO^-_2) in the soil (acid rain).

Living things require nitrogen as a component for proteins, nucleic acids (deoxyribonucleic acid, or DNA, and ribonucleic acid), and other organic compounds. Nitrogen is often a limiting plant nutrient. Plants take up nitrogen from soil mainly as ammonium ions, nitrate, or nitrogenous organic compounds and incorporate nitrogen into organic molecules such as proteins or nucleic acids. The nitrogen then follows food webs from plant eaters (herbivores) to decomposers (mainly microbes). Animals use only organic forms of nitrogen.

Nitrogen Fixation

The utilization of molecular nitrogen (N_2) by particular bacteria is called nitrogen fixation. Some of these bacteria (*Rhizobium*) live in symbiosis with certain legume plants and others are free-living bacteria such as cyanobacteria or *Azotobacter*. Legume plants include soybeans, clover, alfalfa, beans, and pears. Symbiotic nitrogen-fixing cyanobacteria provide nitrogen to other plant species such as the water-fern *Azolla* and liverworts and cycads.

The nitrogen fixation or reduction of N_2 to NH_3 (ammonia) is a complicated, multistep process ($N_2 + 8e^- + 8H^+ + 16ATP \rightarrow 2NH_3 + H_2 + 16ADP + 16P$). Ammonia produced by this process is further converted to proteins, nucleic acids (DNA), and other nitrogen-containing organic molecules ($NH_3 \rightarrow$ nitrogenous organic molecules: proteins, nucleic acids, and so forth).

The nitrogen fixation is catalyzed by the enzyme nitrogenase. Nitrogenase is sensitive to molecular oxygen (O_2). Nitrogen-fixing organisms possess a number of morphological and biochemical modifications designed to protect enzymes from oxygen inactivation. For example, the bacterium *Rhizobium* controls the oxygen level in cells by the protein leghemoglobin, which catches oxygen. In the case of cyanobacteria, there are specialized cells (called heterocysts) for nitrogen fixation. Heterocysts show high rates of respiration, which ultimately reduces oxygen levels in these cells.

Nitrogen fixation is an energy-consuming process, which explains why cyanobacteria normally have only 5 to 10 percent of heterocysts among their cells. To maintain nitrogen fixation, other cyanobacterial cells (vegetative cells) work to generate enough energy for heterocysts.

All life on Earth depends on nitrogen fixation because the main reservoir of nitrogen on Earth is in the air as molecular nitrogen (N_2). The main path of nitrogen from the air into biologic nitrogen-containing molecules of different organisms is through nitrogen fixation. Nitrogen fixation also is of enormous importance to agriculture because it supports the nitrogen needs of many crops. This process was discovered by Russian microbiologist Sergei Winogradsky.

Apart from natural nitrogen fixation, the industrial Haber-Bosch process converts molecular nitrogen to ammonia. In this process nitrogen fertilizers are made for agriculture. Haber-Bosch is an energy-consuming route, and the process of manufacturing nitrogenous fertilizers consumes up to 50 percent of the energy input in modern agriculture.

Ammonification

Ammonification is the process of making ammonia or ammonium ions (NH_4^+) by living things. Ammonium ions are produced as a waste of such animals as fish and during decomposition of organic nitrogen wastes by bacteria and by metabolism of some bacteria. Bacteria, for example, can convert nitrate into ammonia in soils or in the human gut.

Globally, only a small amount (15 percent) of nitrogen reaches the atmosphere as ammonia, compared with N_2 and N_2O. The majority of ammonium ions are quickly consumed in soil and water by microorganisms and plants. At different points in the food web, ammonium ions are returned to the environment.

Nitrification

Nitrification is caused by the sequential action of two separate groups of soil bacteria: the ammonia-oxidizing bacteria (the nitrosifyers) and the nitrite-oxidizing bacteria (nitrifying bacteria). These bacteria obtain energy by consuming nitrogen compounds and can feed only on inorganic compounds. The end product of nitrification is nitrate, a valuable nitrogen source for plants.

Nitrification is a two-step process. Nitrosifyers, such as the bacterium *Nitrosomonas*, convert ammonium ion into nitrite first ($NH_4^+ + O_2 \rightarrow NO^-_2 + H_2O + H^+$). Later, nitrifying bacteria, such as the bacterium *Nitrobacter*, oxidize nitrite into nitrate ($NO^-_2 + O_2 \rightarrow NO^-_3$).

Nitrosifyers and nitrifying bacteria are common in soil and water. They live especially in areas where ammonia is present in high amounts, such as sites of ammonification and in wastewater and manure. Nitrification does not contribute significantly to agriculture. Although liked by plants, nitrate is not always available for plants in soils. Nitrate is quickly consumed by microorganisms during denitrification. Additionally, one species of Archaea (microorganisms similar to bacteria) undergoes nitrification by oxidizing ammonia in the oceans.

Denitrification

The conversion of nitrate into gaseous nitrogen compounds such as N_2O, NO, and N_2 by different bacteria in soils is called denitrification, or nitrate reduction. Bacteria use nitrate as a substitute for oxygen during respiration and convert it to different nitrogenous compounds according to the following chain of reactions: $NO^-_3 \rightarrow NO^-_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2$.

Eventually, nitrogen is released into the atmosphere as N_2O and NO or as N_2. Simultaneously, bacteria decompose significant amounts of organic matter within the soil.

Denitrification has a negative effect on agriculture, as it removes nitrogen from soils. In contrast, denitrification can be useful in wastewater treatment.

Human Interference in Nitrogen Cycle

Human interference in the nitrogen cycle can be significant. Human activities are generally responsible for adding excessive amounts of inorganic nitrogen into the water or soil. Adding nitrogen into water causes a rapid cultural eutrophication of water bodies.

Most of the inorganic nitrogen in water comes from soil fertilization, industrial and domestic wastes, septic tanks, feed-lot discharges, domestic-animal wastes (including birds and fish), and discharges from car exhausts. Eutrophication occurs regularly in nature but does so slowly, often through hundreds or thousands of years.

During human eutrophication of water bodies, algae grow fast and choke waterways and consume large amounts of dissolved oxygen. Some algae also produce toxins. This rapid and uncontrollable growth of algae—a process that produces algal blooms or red tides—causes decay and, eventually, the destruction of aquatic ecosystems. Fish and other aquatic organisms die by the thousands, suffocated by oxygen depletion or killed by the action of toxins. Algae need inorganic nitrogen ions as a nitrogen source for their growth (for making proteins).

Ammonium and nitrate ions are the main human nitrogen pollutants in water. The removal of inorganic nitrogen from industrial and domestic wastewater is required to protect water quality. Inorganic nitrogen ions can be removed from water by physicochemical and biologic methods.

Human contamination of soil by inorganic nitrogen is another substantial problem that occurs through nitrogen fertilization of soil. In such cases, nitrogen derives from industrial nitrogen fixation or from using leguminous plants (soy, beans, peas, and alfalfa).

In addition, extensive burning of fossil fuels by humans converts atmospheric nitrogen (N_2) into nitrogen oxides. Nitrogen oxides react in the atmosphere with the ozone (O_3) to make nitric acid. Nitric acid is one of the components of acid rain, which damages soils and forest richness by destroying communities of organisms. Thus, the burning of fossil fuels by humans contributes to acid rain and to the destruction of the ozone layer in the atmosphere.

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Further Reading

Chang, Raymond, and Jason Overby. *General Chemistry: The Essential Concepts*. 6th ed. Columbus, Ohio: McGraw-Hill, 2010. A comprehensive book on general chemistry that includes chapters on the nitrogen cycle and nitrogenous compounds.

Graham, Linda E., and Lee W. Wilcox. *Algae*. Upper Saddle River, N.J.: Prentice Hall, 2000. A popular book on algae, including their role in the nitrogen cycle and nitrogen fixation.

Madigan, Michael T., et al. *Brock Biology of Microorganisms*. 13th ed. Boston: Benjamin Cummings, 2012. Several chapters of this classical textbook on microbiology describe in detail microbial processes such as nitrogen fixation, ammonification, nitrification, and denitrification. Also examines nitrifying and nitrogen-fixing bacteria.

Markov, Sergei A., Michael J. Bazin, and David O. Hall. "Potential of Using Cyanobacteria in Photobioreactors for Hydrogen Production." In *Advances in Biochemical Engineering/Biotechnology*, edited by A. Fiechter. Vol. 52. New York: Springer, 1995. Detailed scientific review of cyanobacteria and their role in nitrogen fixation. Process of nitrogen fixation is explained from biochemical and physiologic points of view.

Nebel, Bernard J., and Richard T. Wright. *Environmental Science: Towards a Sustainable Future*. Englewood Cliffs, N.J.: Prentice Hall, 2008. A popular textbook on ecology and environment that describes the nitrogen cycle and human interference with the cycle. Also examines the control of hazardous nitrogen chemicals.

Reece, Jane B., et al. *Campbell Biology*. 9th ed. Boston: Benjamin Cummings, 2011. A general biology textbook that explains biologic molecules that contain nitrogen and their role in the metabolism of living things. Separate chapters cover the nitrogen cycle, human interference in the cycle, and different biologic processes involving nitrogen, such as the excretion of animal-produced nitrogenous wastes.

White, David. *The Physiology and Biochemistry of Prokaryotes*. New York: Oxford University Press, 2011. Describes bacteria and explains in detail bacterial metabolism of nitrogen compounds such as

nitrogen fixation, nitrification, denitrification, and ammonification.

See also: Acid Rain and Acid Deposition; Atmospheric Properties; Carbon-Oxygen Cycle; Geochemical Cycles; Hydrologic Cycle; Lightning and Thunder; Ozone Depletion and Ozone Holes; Rainforests and the Atmosphere; Remote Sensing of the Atmosphere; Severe Storms