GLOBAL NATURAL CYCLES

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Summary

Life is manufactured from a small number of elements arranged to form an immense variety of compounds. Organisms require elements in fairly constant ratios, and the rate of supply limits organic productivity. Because the ultimate sources of life-supporting elements are Earth’s crust, water, and the atmosphere, biological processes are tightly linked to the exchange of elements between these reservoirs, some of which cycle

slowly. Organic evolution has improved element supply rates through novel physiological adaptations that enhance element acquisition and nutrient use. Some scientists argue that evolution has favored life forms with characteristics that stabilize Earth's climate system, but this hypothesis may not apply to *Homo sapiens* who are presently changing climate by burning fossil fuels, deforestation and a variety of other activities.

The carbon cycle is an ideal example of how biological, chemical, and physical processes interact to influence the capacity of Earth to support life. Carbon in the atmosphere exists mostly as CO_2 and CH_4, both of which are greenhouse gases. Plants and phytoplankton consume about 30% of the CO_2 in the atmosphere annually. Much of the carbon removed from the atmosphere is returned quickly through respiration, but a portion remains stored for decades to millennia in plant biomass, soil organic matter and marine sediments. Exchange between these reservoirs and the atmosphere can explain many characteristics of the climate system. Human activity has greatly enhanced such exchanges.

Nitrogen and phosphorus are the nutrient elements that most often limit organic productivity. The atmosphere and rocks are the ultimate (long-term) sources of nutrients. Yet, most of the annual demand for nutrients is met through efficient recycling mechanisms. Life itself exercises strong control over nutrient element cycling.

Many trace elements are both nutrients and contaminants depending on their concentration. At low concentrations they may limit productivity due to their absence, while at high concentrations they suppress productivity because they are toxic. Their ecological importance is generally greater than their abundance would suggest.

1. Introduction to the Element Cycles

In December 1990, the Galileo spacecraft observed a planet in our solar system with oceans of liquid water, a ubiquitous green pigment, and an atmosphere with O_2 and methane in extreme thermodynamic disequilibrium. Of course, the planet was Earth. This experiment was conceived by Carl Sagan as an opportunity to test a key characteristic of life at the global scale – its influence on the chemical forms and distribution of elements. Yet, life is just one force shaping global element cycles. Purely physical and chemical processes generate element cycles in the absence of life. Such processes include the input of solar radiation from the sun, mixing of the oceans and tectonic cycling of the crust (**see *The Geosphere***). The study of natural element cycles has developed into the field of biogeochemistry, an area of scientific inquiry that seeks to integrate the traditional disciplines of biology, geology, and chemistry. A full appreciation of the field also requires knowledge of the physics of atmospheres, oceans, and continents.

Biogeochemistry involves the study of element sources, their transport, transformations, and sinks. Elements are constantly moving between reservoirs (e.g. soils, oceans, and atmospheres) and/or changing form (e.g., from carbon bound in CO_2 gas to carbon bound in sugar). Because most elements on Earth are neither created nor destroyed by processes operating on the planet, they pass through any given reservoir or chemical form repeatedly over time and are thereby cycled. Each process that modifies the form of an element may be considered in isolation, but in reality theses processes are coupled to an element cycle. Organisms participate in most phases of element cycles, but they are particularly strong element transformers (i.e., they change elements from one chemical form to another).

A key challenge facing biogeochemists is the need to integrate information across vast scales of time and space. Many element cycling studies are done at a scale of square meters, yet the results are most relevant when extrapolated to landscape or global scales measured in units ranging from 10 km^2 to 1 × 10^6 km^2. Scales of time and space are often linked. For example, during photosynthesis light energy is rapidly converted to chemical energy in a process that requires a pH difference across membranes in the chloroplast (Figure 1). At the other end of the spectrum, yearly rates of forest growth depend upon the number and distribution of light harvesting leaves across large tracts of forest. One approach to scaling such information is to model the essential physical and biogeochemical processes with mathematical equations. Parameters in the equations are given values derived from small-scale studies or remotely sensed data. The equations are then used to predict chemical cycling at larger scales. Biogeochemical models benefit from spatially explicit databases of important attributes such as temperature, rainfall, precipitation, vegetation, and soil texture. They are often coupled to climate models to predict future climate change.

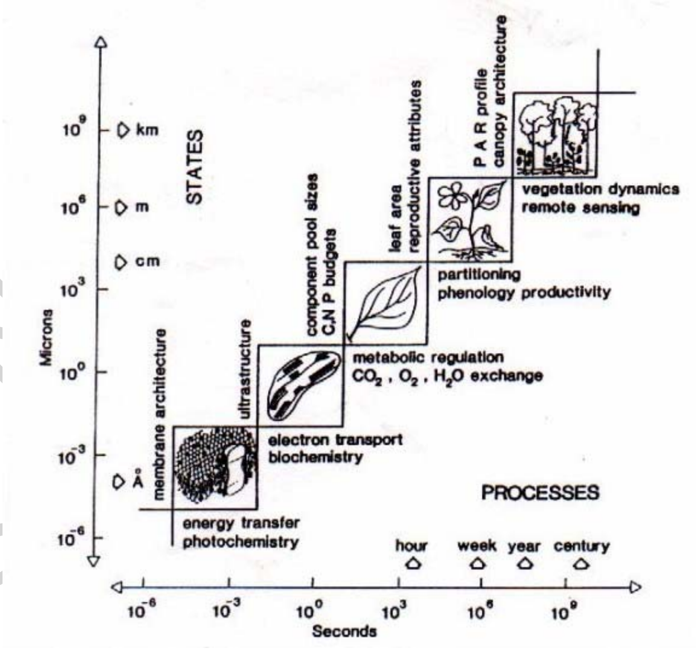

Figure 1. A framework for integrating scales of time and space ranging from the molecule to the biosphere for processes related to CO_2 uptake by vegetation
Source: Osmond C.B. and W.S. Chow (1988) Ecology of photosynthesis in the sun and shade: summary and prognostications. Australian Journal of Plant Physiology 15:1–9.

Models are also used to integrate across various scales of time ranging from years to millennia. The parameters for such models require information about past climates or distributions of plant communities. Fortunately, the history of chemical cycling on Earth is recorded in rocks, ice caps, coral reefs, tree rings, soils, aquatic sediments, and many other features. Sherlock Holmes, the fictitious English detective, would have been proud of the creative approaches that have been used to decipher and interpret these historical records.

This article briefly reviews the biological and physical forces that operate on element cycles. It focuses on carbon (C), nitrogen (N), and phosphorus (P) because of their key roles in energy acquisition and growth, and because they represent a range of possibilities for the importance of biological versus geological processes. Certain key features of the other element cycles are considered here, while more specific information is available in the articles in this section.

2. Brief History of the Elements

The pool of elements in which life exists today is largely the same as that endowed to Earth upon its formation about 4.6 × Ga (**see *Universe as Earth's Environment***). However, there have been changes in the chemical forms and distribution of elements over time. The planet can be divided into three concentric spheres on the basis of differences in chemical composition: the core, mantle, and crust (outermost). Heavy elements, especially iron (Fe), are concentrated in the core, while the crust is enriched in relatively light elements that form aluminosilicate minerals such as potassium feldspar ($KAlSi_3O_8$). Thus, the biosphere arose in a chemical mixture that was unique to the planet's surface.

The atmosphere is composed of elements that were released as gases from molten rocks while the planet was still relatively hot. This process continues today with volcanic eruptions rich in H_2O, CO_2, SO_2, H_2S, and HCl. Volatile compounds that do not readily dissolve in oceans, such as N_2 and O_2, have accumulated to high levels in the atmosphere. These gases currently account for 78% and 21% of the atmosphere, respectively. Many ocean salts were derived from the dissolution of gases with high water solubility such as CO_2, SO_2, and Cl_2.

The oceans and atmosphere remained moderately reducing until microbes evolved O_2-generating photosynthesis as early as 3.5 Ga. Only much later did O_2 began to increase in the atmosphere. It was scrubbed from seawater in oxidation reactions with Fe^{2+} (a reduced, soluble form of Fe), and from the atmosphere by reduced gases such as CH_4. The oxidation of Fe^{2+} produces $Fe(OH)_3$ and related compounds that precipitate in water. This process probably accounts for the Banded Iron Formation, a geological feature that holds major economic deposits of iron ore in the United States. Peak deposition of the Banded Iron Formation occurred 2.5–3.0 Ga. The accumulation of O_2 in the atmosphere started a process of oxidizing Fe^{2+} and other reduced minerals in continental rocks.

As the supply of reduced minerals, solutes, and gases capable of reacting with O_2 dwindled, O_2 began to accumulate to high levels in the atmosphere; Earth's surface has been a highly oxidized environment ever since. The abundance of O_2 changed element cycling in several fundamental respects. For example, elements such as Fe and Mn typically precipitate in O_2-rich environments and therefore have low concentrations in water. Microorganisms that cannot tolerate O_2 now exist only in anaerobic environments such as wetland soils or the digestive tracts of termites and cattle. Organisms that use O_2 for respiration dominate the planet because the process yields far more energy than other forms of respiration. The abundance of O_2 allowed the formation of a protective ozone layer (O_3) that presumably enhanced the stability of organic chemicals, including the organic structure of the genetic code, by shielding organisms from high-energy ultraviolet radiation. Also, high O_2 levels made fire an important biogeochemical force. Because most of the O_2 in the atmosphere is balanced by reduced compounds buried in ocean basins, no amount of burning or forest destruction could significantly lower the atmosphere's current O_2 content.

3. Mass Flow of Air, Water, and Rock

Element cycles are inextricably linked to the mass flow of the reservoirs in which they reside. The principle reservoirs are the atmosphere, ocean and crust. Each reservoir has a characteristic rate of change that influences rates of element cycling. Because all elements move between these reservoirs, their cycles may have both rapid and slow phases (**see *Mass and Energy***).

3.1. Atmospheric Circulation

The atmosphere is the most rapidly cycling reservoir with a mixing time of about three years. The portion of the atmosphere between the ground and a height of 10–15 km is the troposphere, which holds 80% of the atmosphere's mass. The stratosphere begins at the top of the troposphere and has a height of ~30 km. It has far less mass than the troposphere, but holds 90% of the atmosphere's ozone (O_3). Mixing between the two layers is generally slow. Gases and aerosols emitted at Earth's surface are likely to be removed before reaching the stratosphere due to chemical reactions and dissolution in rainfall. However, gases that are highly insoluble in water and chemically stable, such as CH_4, N_2O, and the chlorofluorocarbons (CFCs), are important exceptions to this rule. Because they are long-lived, these gases mix slowly into the stratosphere where they influence O_3 and climate (**see *Atmosphere and Climate***).

3.2. Ocean Circulation

The oceans hold >97% of the Earth's water and constitute large reservoirs of many key elements. As with the atmosphere, the oceans are composed of horizontal layers with characteristic rates and modes of element cycling. The mixed layer extends from the surface to between 75 and 200 m and is well mixed by winds. Gases, nutrients, organic matter, and heat that enter the ocean's surface will mix down to about 100 m depth in one year. Although the mixed-layer is <5% of the ocean's volume, it exchanges gases rapidly with the atmosphere and supports the productivity of phytoplankton. Below the surface lies the deep-water layer, which is 95% of the water volume and is relatively colder, saltier, denser, and nutrient rich.

Surface waters circulate about the ocean in great basin-wide circles called gyres, which are driven by winds. Because water has a high capacity for storing heat, this process transports heat from the tropics, where solar heating is intense, to the cooler poles. A well-known example is the Gulf Stream that travels from the Gulf of Mexico northeast to Europe, thereby contributing to the fact that Europe's temperature is higherthan would be expected given it’s latitude. During the winter, the density of seawater increases as it approaches the poles due to loss of heat and freshwater; freshwater freezes out onto the polar ice caps leaving behind salts. The increase in density is sufficient to cause surface water to sink into a deep-water layer of the same density. The sinking water displaces existing water, triggering a deep-water current that eventually rises back to the surface at tropical latitudes. The deepest ocean currents may take hundreds to thousands of years to reach the surface again.

The long circulation time of deep ocean currents hold an important lesson for those interested in the effects of global warming. Once the chemistry or heat content of the deep ocean changes, it will remain so much longer than a change in the atmosphere or ocean surface. Gases and heat absorbed by the ocean now will eventually be released again to the atmosphere. Thus, we cannot expect to quickly reverse the course of greenhouse warming once it begins.

3.3. Rock Circulation

The longest time-scale relevant to element cycling is the circulation of rocks. The crust and upper mantle form a relatively rigid layer at Earth's surface, called the lithosphere, that ranges from 50 to 200 km thick. The lithosphere is divided into eight major plates that fit together like a puzzle to form the patchwork of continents and ocean basins we have today. Below the lithosphere is the asthenosphere (also part of the mantle) that is relatively plastic and fluid. Convection currents in the asthenosphere cause the lithospheric plates to move about the surface, at various times sliding past one another, pulling apart or colliding.

New ocean crust is created when molten rock (magma) from the mantle rises up to fill cracks created where plates separate. The hot magma crystallizes to form igneous rocks (Figure 2). One of the most active ocean-spreading regions is the mid-Atlantic ridge, home to a unique marine ecosystem that derives energy from reduced chemicals in sea water emanating from the sea floor. Plates remelt when they are forced back down into the mantle during collisions in a process called subduction. Subduction occurs whenever the leading edge of one of the plates bears oceanic crust. If one plate bears the relatively light rocks of the continental crust, the oceanic crust is always subducted. If both plates bear oceanic crust, then one will be subducted into the mantle and the other will remain at the surface. Oceanic crust circulates through this pathway every 110×10^6 y–170×10^6 y, carrying elements along for the journey.

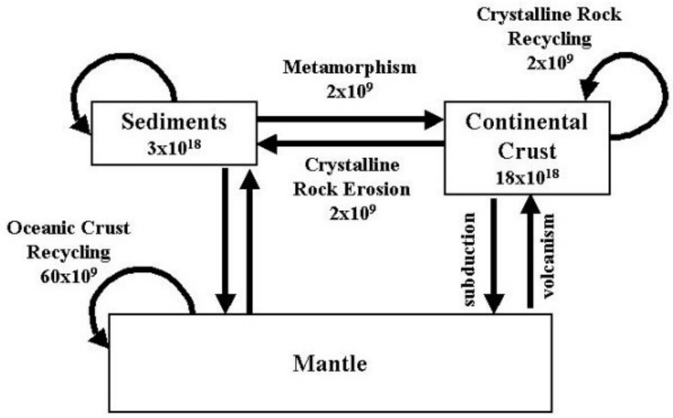

Figure 2. A generalized diagram of the steady-state rock cycle
Sediments and continental crystalline crust masses are in units of metric tons (1×10^6 g), and fluxes are metric tons per year. Total sedimentation is 9×10^9 metric tons annually. Source: Gregor C.B. (1988). Prologue, cyclic processes in geology, a historical sketch. *Chemical Cycles and the Evolution of the Earth* (ed. C.B. Gregor, R.M. Garrels, F.T. Mackenzie, and J.G. Maynard), pp. 5–16. New York: John Wiley and Sons. Copyright 1988 Wiley. Reprinted with permission by John Wiley & Sons, Inc.

A somewhat slower rock cycle begins when two plates bearing continental crust collide. Neither plate is subducted, but rather both are crushed and deformed, often folding to form new mountain ranges. Over geologic time, the mountains erode away and are carried to oceans as sediments and dissolved ions. Ocean sediments and salts undergo diagenesis to sedimentary rocks as they are buried. Under extreme pressure and heat, the crystal structure of sedimentary rocks changes creating metamorphic rocks (**see** *Internal Forces and Their Influence on the Earth's Surface*).

Elements bound into rocks are released in the process of rock weathering. In physical weathering the rock is broken into smaller and smaller pieces, but the chemical composition of the rock is largely unchanged. The primary agents of physical weathering are water and roots. Liquid water seeps into cracks in the rock then expands upon freezing; plant roots operate in a similar manner by slowly expanding during growth.

In chemical weathering the elemental composition of the rock changes as particular elements are released and others stay behind. The elements that are released can reform into secondary (clay) minerals such as kaolinite. This process is greatly enhanced by the activity of plant roots and soil microbes that produce CO_2 during respiration. The CO_2 dissolves in water forming carbonic acid.

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3 \qquad (1)$$

Carbonic acid, warm temperatures, and low pH all enhance the rate of chemical weathering. This is a key feature in the cycle of many elements for which rocks are their ultimate source, including most nutrients. The group includes phosphorus (P), calcium

(Ca), sodium (Na), potassium (K), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), and several more trace elements. Because these elements are essential nutrients, the rate of rock weathering places a long-term limit on the potential productivity of ecosystems.

A number of the environmental problems that we face today are caused by a human-induced increase in rock "weathering" through mining activity. For example, mining provides phosphorus, a key ingredient in fertilizers that greatly enhances the yield of agricultural crops. Unfortunately, phosphorus moves in water from agricultural fields to streams, lakes, and estuaries where it often overstimulates aquatic productivity. Excess phosphorus may cause changes that range from shifts in community composition, to losses of species diversity and fish mortality. Mining has also increased the abundance of lead (Pb), zinc (Zn), mercury (Hg), selenium (Se), and other metals that are toxic even at low concentrations.

3.4. Soils

An important product of the rock weathering process is soil. Soil is the biologically active layer of Earth's crust and is composed of minerals, organic matter, and biota. Roughly 50% of a soil's volume is solids (minerals and organic matter) and 50% is space (air and water). Soil solids act as both an element source for organisms and an element sink. Weathering releases elements from minerals, while decomposition (i.e., mineralization) releases elements from organic matter. Many important characteristics of soils are derived from the proportion of sand, silt, and clay minerals, which differ in size and charge. The largest particles are sand (0.05–2.0 mm diameter), followed by silt (0.002–0.05 mm), and then clay (<0.002 mm). The amount of clay is a particularly important feature of soils because clay particles carry a negative charge that forms electrostatic bonds with nutrient cations such as NH_4^+, Ca^{2+}, and K^+. Soil organic matter is also negatively charged and serves the same nutrient storage function.

The soil atmosphere is a much more dynamic environment than the free atmosphere in which people live. Soil O_2 levels vary from 21% (the same as air) under relatively dry conditions to 0% after soil pores have been saturated with water for a period of days or weeks. Wetland plants have physiological and morphological adaptations that allow them to continue aerobic respiration even when flooded, but the absence of O_2 has profound changes on microbial communities, which shift from dominantly aerobic to anaerobic species (**see *Soils***).

3.5. Element Cycles

The most important cogs in any nutrient cycle are: (1) the producers that combine inorganic elements and light (or chemical energy) into organic compounds, (2) the decomposers that convert the organically bound elements back to an inorganic form, and (3) the air and water that transports the elements within and between ecosystems. In fact, the simplest ecosystem that could theoretically exist would consist of one producer and one decomposer.

Life is a dominant factor regulating element cycles. Organisms exploit the unique properties of elements for energy and nutrients. Not surprisingly, life has evolved the biochemical machinery to enhance rates of the chemical transformations on which they depend. For example, organisms increase the supply of certain forms of nitrogen and phosphorus by accelerating nitrogen fixation, rock weathering, and detritus decomposition. Biota also influence nutrient cycles that were previously considered to be largely abiotic. For example, biota influence nutrient inputs from precipitation, dust deposition, and rock weathering; they influence nutrient exports by mineral precipitation, erosion, stream flow, flooding, and leaching to groundwater. Because organisms and chemical cycling are intimately coupled in ecosystems, neither can be understood in isolation from the other. Reciprocal interactions between organisms and their chemical environment present some of the most basic questions facing scientists:

- To what extent do element cycles regulate the distribution and abundance of organisms?
- To what extent does the distribution and abundance of organisms regulate element cycling?
- Does high biological diversity help stabilize element cycles?
- Do feedbacks exist between biota and climate that either dampen or amplify climate change?

4. The Carbon Cycle

The carbon cycle is an ideal example of how biological, chemical, and physical processes interact to influence the capacity of Earth to support life. Carbon is a versatile element. It has the unusual property of bonding to itself (i.e., C–C bonds) to form short chains, long chains, branching chains, and rings. This versatility in structure begets versatility in function, which ranges from light capture to information storage. The role of carbon in energy storage and transformation is due to its ability to exist in several oxidation states. As gases, most carbon compounds adsorb strongly in the infrared region of the electromagnetic spectrum, which makes them powerful heat-trapping (greenhouse) gases. These features are all absent in silica, another abundant element and a neighbor of carbon in group IVA of the periodic chart. Carbon accounts for about 50% of all biomass and seems particularly suited to support life.

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Bibliography

Butcher S.S., Charlson R.J., Orians G.H., and Wolfe G.V., ed. (1992). *Global Biogeochemical Cycles*, 379 pp. San Diego, California: Academic Press. [This is an introduction to biogeochemical cycles with an emphasis on geochemistry.]

Fenchel T., King G.M., and Blackburn T.H. (1998). *Bacterial Biogeochemistry: The Ecophysiology of Mineral Cycling*, 307 pp. San Diego: Academic Press. [This focuses on the important links between biogeochemical phenomena, microbial metabolism and ecology.]

Mackenzie F.T. (1998). *Our Changing Planet: An Introduction to Earth System Science and Global Environmental Change*, 486 pp. Upper Saddle River, New Jersey, USA: Prentice Hall. [This is a balanced introduction to biogeochemical cycles. It includes study questions but few citations.]

Schlesinger W.H. (1997). *Biogeochemistry: An Analysis of Global Change*, 443 pp. San Diego: Academic Press. [This is an introduction to biogeochemical cycles with an especially lucid treatment of biological processes. The text has a wealth of literature citations.]

Biographical Sketch

J. Patrick Megonigal is a Senior Research Scientist at the Smithsonian Environmental Research Center in Edgewater, Maryland, USA. His research is focused on the carbon cycle as a means of understanding the responses of ecosystems to stressors such as flooding and climate change. Element cycling interactions between plants and microorganisms, particularly in wetland ecosystems, is a common theme in his field and laboratory research projects. Dr. Megonigal is a member of the Ecological Society of America, the American Geophysical Union, and the Society of Wetland Scientists. He holds an MS in biology from Old Dominion University, Virginia and a PhD in biogeochemistry from Duke University, North Carolina.