Cycles of Life

Civilization and the Biosphere

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CHAPTER 1

The Biosphere: Realm of Life

On November 25, 1889, as the British ship *Golconda* was steaming off the Great Hanish Islands in the Red Sea, its passengers saw a huge swarm of locusts flying at a high altitude on a northeastern course. The magnitude of this migration so impressed G. T. Carruthers, an English naturalist on board, that he timed its duration and estimated the total number of insects and their mass. His calculations appeared less than a month later in *Nature:* he had arrived at a figure of more than 24 quadrillion locusts weighing some 43 billion tons.

A few months later Vladimir Ivanovich Vernadsky, a young privat-docent of mineralogy at Moscow University, read that brief description, turned the

Vladimir Ivanovich Vernadsky (1863–1945), a pioneer in geochemistry and the founder of systematic studies of the biosphere.

page, returned to it, and made a few notes on a card. It made no sense to file the bit about swarming locusts either with his mineralogical notes or with his extensive excerpts regarding the history of science. He took out a new folder and inscribed it *zhivoye veshchestvo*, living matter.

More than thirty years later Vernadsky, then a visiting professor at the Sorbonne, went back to the note. "That swarm of locusts," he wrote in his book *La Geochimie*, "expressed in terms of chemical elements and in metric tons, may be seen as analogical to a rock formation, or, more precisely; to a moving rock formation endowed with free energy." Analogical because the elements embodied in the locusts had to come, via plants devoured by the swarm, from rocks in the Earth's crust and from air and water, the ubiquitous agents of rock transformation.

But to Vernadsky the swarming locusts also exemplified life's ability to accelerate the rate of planetary change. The migrating swarm transports its embodied elements much faster and much farther than even the most rapid weathering and denudation of a rock of equal mass. And the accumulation of complex organic compounds during the swarm's propagation, and the generation of simple gases and mineral substances during its demise, are typical of how life performs its dynamic role as a processor of mass and energy: living organisms remove compounds from the environment, transform them, and then return them to soils, waters, and the atmosphere.

The numbers in Carruthers's letter to *Nature* were cited for decades as facts, but because he made an absurd assumption about the density of the swarm (more than 1500 insects per cubic meter, while the real number was most likely lower than one locust per cubic meter) his total was off by several orders of magnitude. Modern students of insect migrations believe that the swarm had perhaps 40 billion rather than 24 quadrillion insects.

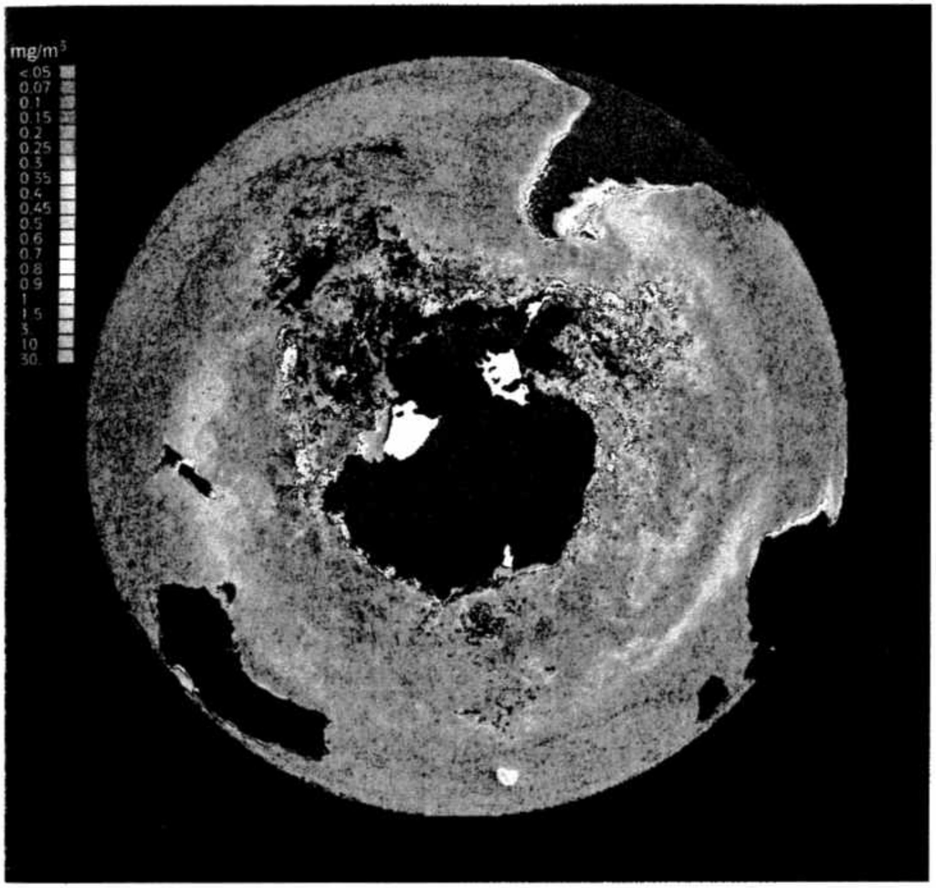
Carruthers's figures were wrong—but Vernadsky's reasoning was correct. He was aware of the possible errors inherent in such estimates, but the graphic description of the huge high-flying swarm led him to a great scientific synthesis. What many thinkers and scientists before him sensed, and even expressed in sometimes poetic ways, he set down in clear scientific terms. Earth's life, whose complex evolution is so obviously dependent on a host of environmental factors, is itself an enormously important agent of planetary change, often influencing, or even determining, the course and the outcome of the grand processes that shape the Earth's surface, ocean and soil chemistry, atmospheric composition, and climate.

Unlike such spectacular natural phenomena as volcanic eruptions, floods, or hurricanes, these processes are mostly inconspicuous—but unceasing.

An excellent example can be found hidden in cold Antarctic waters where tiny, single-celled organisms—the phytoplankton—photosynthesize for more than 20 hours a day during austral summers. This photosynthesis withdraws huge volumes of carbon dioxide (CO_2) from the surface waters and transfers the molecule's carbon into new phytoplankton mass. That mass is eagerly consumed by enormous swarms of zooplankton, including tiny crustaceans, that float in the surface waters. Zooplankton, in turn, are eaten by fish, squid, birds, and sea mammals.

If the dead remains of these organisms were simply to accumulate at the ocean's floor, this circumpolar photosynthesis would eventually exhaust the atmosphere's huge CO_2 stores and, everything else being equal, bring a much cooler climate to the planet by depleting its most important greenhouse gas. In reality, respiration by zooplankton, and by other oceanic herbivores and carnivores, returns at least 90 percent of the assimilated carbon to the near-surface waters. From there the gas can either escape to the atmosphere or be reused by phytoplankton.

The remaining dead organic matter settles to the deeper ocean, where most of this detrital rain is either eaten by zooplankton and the fishes of the deep or is colonized by bacteria and slowly



Concentrations of phytoplankton are especially high in Antarctic waters. This map shows the average levels of phytoplankton pigment recorded by the Nimbus-7 satellite between November 1978 and June 1986. Yellow to red hues indicate the highest concentrations, blue to purple the lowest.

Diatoms, single-celled algae with intricately patterned, hard cell walls, are among the most common phytoplanktonic species in both ocean and fresh waters. (Magnified about 200 times.)

decomposed. This settling removes carbon from the near-surface ocean and transfers the element into deep waters, from where it can return to the atmosphere by upwelling only after years, decades, or even centuries. Finally, a tiny part of the assimilated carbon is deposited at the ocean's bottom, and it will only resurface when geotectonic forces raise the sediments above the sea level, often tens of millions of years in the future.

Carbon's fate thus depends on its being cycled from inorganic compounds—be they in cold circumpolar waters or in air, soils, or streams—to living matter and back again. In this intricate interplay of living organisms and their environment the element is involved not just in simple physical transfers but also in complex sequences of chemical reactions. A single compound adjective sums it up best: carbon, and other elements of life, participate in *biogeochemical* cycles.

The element's assimilation provides the foundation of life, but the process also has a profound effect on atmospheric concentrations of CO_2, and consequently on the ocean's chemistry and the Earth's climate. By constantly consuming carbon in the near-surface layer and by transferring part of it into deeper waters, phytoplankton reduce atmospheric CO_2 levels. Should these continuous transfers ever cease, atmospheric CO_2 concentrations would eventually rise to levels nearly twice as high as their natural, pre-nineteenth-century, mean, and temperatures would rise with them. A lifeless ocean would lead to even higher CO_2 concentrations—and thus an even warmer climate.

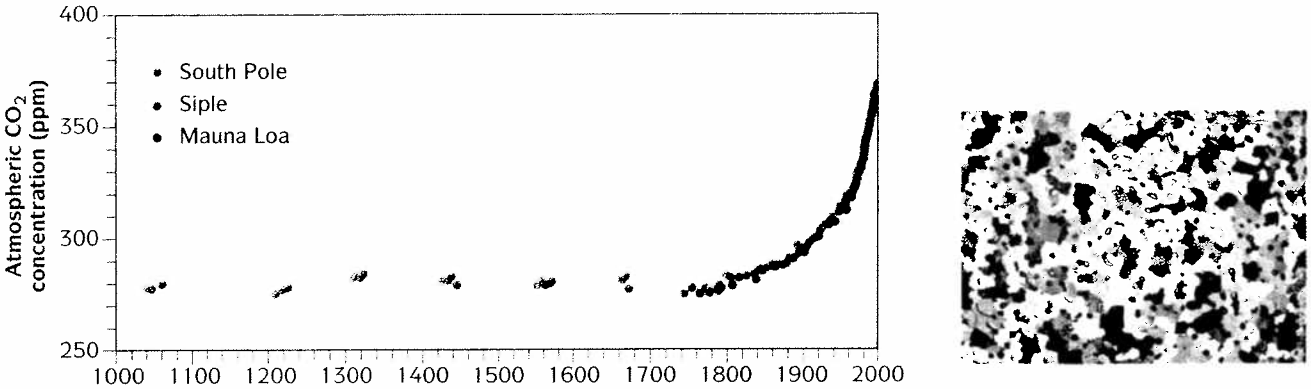
The cycling of elements like carbon is imperative because—except for a steady infall of cosmic debris, an occasional encounter with a comet or an asteroid, and small losses of hydrogen and helium from the top of the atmosphere—the planet is a closed processor of matter. Elements needed to build the structures of life and to maintain their intricate metabolism must come from the Earth's crust, air, and waters, to where they will eventually return.

Yet as massive as the natural cycling processes are, they are not beyond human interference.

Since the middle of the nineteenth century man-made (anthropogenic) emissions of CO_2—arising from combustion of fossil fuels and the conversion of natural ecosystems to farmland and built-up areas—have increased the atmospheric concentrations of the gas by about 30 percent. This rise has been faster than any natural increase during the past 420,000 years (the period for which we can reliably reconstruct the atmospheric CO_2 record from air bubbles trapped in polar ice). Together with rising levels of other greenhouse gases this increase could, by raising atmospheric temperatures, eventually alter the global environment.

The possible consequences of this global change are many. They could range from appreciable shifts in the worldwide distribution of precipitation and northward displacement of great boreal forests to new threats from insect-borne diseases and, ultimately, even to a shift in the global circulation of ocean waters. Obviously, such changes—and the many feedbacks they would inevitably generate—would have profound impacts on the future course of civilization.

The possibility of a relatively rapid global warming may be the most worrisome example of an unintended consequence arising from human interventions in grand elemental cycles—but it is far from being the only one. We are, for example, also injecting massive amounts of nitrogen into the environment. The element is being lost from synthetic fertilizers applied to croplands and given off in reactive compounds generated during the combustion of fossil fuels. Given the addition of at least 2–3 billion people before the year 2050, we can expect a substantial increase in both of these sources of nitrogen. Although nitrogen is essential for plant growth, a surfeit of its reactive compounds in soils, waters, and the atmosphere leads to many undesirable, even outright harmful, environmental changes. This is an interference whose consequences may become increasingly worrisome during the next two generations.



Continuous sampling of the air at the Mauna Loa observatory in Hawai'i has provided accurate measurements of atmospheric CO_2 since 1958, but the best record of historic and ancient CO_2 levels has been preserved in air bubbles trapped in polar ice in Antarctica (South Pole and Siple Station) and in Greenland. Left: Atmospheric concentrations of carbon dioxide had been remarkably stable during the several thousand years preceding the industrial era. Since that time they have risen by about 30 percent, a change with potentially enormous consequences for the Earth's climate. Right: This image shows a thin (half millimeter) slice of Antarctic ice viewed in polarized light; in this light the trapped air bubbles appear amber colored.

The Biosphere and Material Cycling

Scientists have acknowledged the critical roles played by organisms, including humans, by recognizing the existence of a realm of life that they call the biosphere superimposed on the three obvious terrestrial spheres of air, water, and rocks. Vernadsky elaborated the idea of biosphere in *Biosfera*, his second book, begun in Paris, finished in Prague, and published first in Russian in 1926. This is how he summarized the basic concepts a few years before his death in 1945:

> Living matter exists only in the *biosphere*. This includes the whole atmospheric troposphere, the oceans, and a thin layer in the continental regions. . . . The biosphere is distinguished as the domain of life, but also, and more fundamentally, as the region where changes due to incoming solar radiation can occur. . . . Within the biosphere . . . the inert matter greatly predominates in mass or volume. There is a continual migration of atoms from the inert matter to living matter and back again. . . .
>
> *Biogeochemical phenomena* are the basis of the biosphere.

Vernadsky's terse summation offers a rich collection of ideas from which to start our inquiry, beginning with the biosphere itself.

According to Vernadsky, the biosphere embraces the entirety of the atmosphere's lowermost layer, the troposphere. Warmed primarily from below by heat rising from the Earth's surface, the troposphere becomes steadily colder as altitude increases. Turbulent mixing and convection distribute the heat, making the troposphere thicker in the tropics, where it reaches up to about 15 kilometers (km), and thinner above the polar regions, where it extends upward about 10 km. The troposphere is the domain of weather—of changing pressures, shifting winds, clouds, and precipitation—and even its higher reaches contain windborne microbes, spores, and insects, and, occasionally, flocks of migrating birds.

But no organisms can live permanently 10 km above sea level. At those altitudes temperatures are too low to keep water liquid, and oxygen is too

Tufts of small plants mark the highest boundary of the permanent biosphere in the Kharta area, on the east side of Mount Everest.

scarce to sustain animal metabolism. Consequently, the highest reaches of actively inhabited biosphere extend between 6 and 7 km above sea level, where the hardiest ground-hugging plants photosynthesize, and tiny insects feed on organic debris deposited by strong winds.

As for the biosphere's oceanic reach, the sinking of dead organic matter carries it far beyond the thin and variable uppermost layer penetrated by sunlight, the ocean's euphotic zone extending from millimeters in muddy waters to a few hundred meters in the clearest tropical seas. As this dead organic matter descends through the water, it becomes food for a variety of consumers, ranging from microorganisms (tiny herbivorous zooplankton and scavengers of detritus) to large and sleek carnivorous fishes, and including bizarre bioluminescent creatures dwelling in the perpetual twilight of the ocean's midwaters.

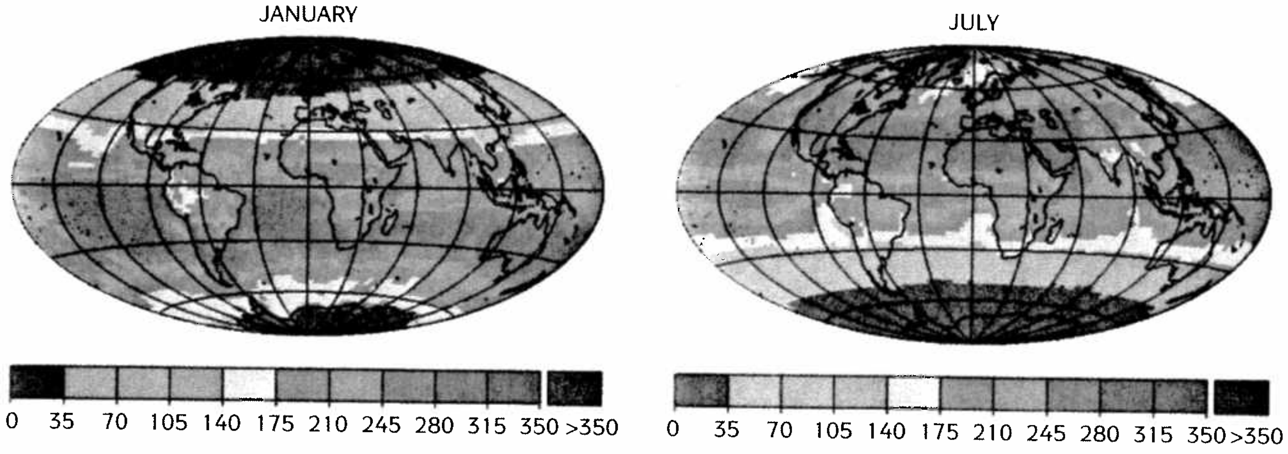
Even at the very bottom of deep seas we can find organisms synthesizing new living matter from inorganic materials. Dives by research submersibles—the first one in 1977 by ALVIN at the Galapagos rift to a depth of 2550 meters (m)—revealed hydrothermal vents spewing warm water laden with hydrogen sulfide (H_2S). At these vents live several species of chemoautotrophic bacteria, organisms that do not need any sunlight to synthesize living tissue, but instead derive their energy from the oxidation of H_2S. So productive are these bacteria that their output supports surprisingly rich communities including crabs, mussels, clams, and giant tube worms.

Back on land, the biosphere extends deeper than the dens and tunnels of burrowing insects and animals, and exceeds even the reach of bacteria, fungi, and invertebrates in the deepest organic soils. During the late 1980s drilling tests at the Savannah River Plant in South Carolina, carefully designed to avoid any contamination, uncovered rich communities of underground bacteria in pristine boreholes at depths exceeding 500 m. These unusual and diverse communities varied markedly among individual strata and showed little significant decline with progressive depth.

The deepest reach of the biosphere: giant tube worms (they can be up to one meter long), bivalves, and a white crab photographed near a hydrothermal vent at the bottom of the Pacific Ocean, not far from the Galapagos Islands.

Subsequent drillings found sulfate-reducing bacteria living 1670 m below the surface in a petroleum reservoir in the East Paris Basin, in marine sediments more than 500 m below the Pacific sea floor—and even in water samples collected at the depth of 3900–4000 m in Gravberg 1 borehole drilled to nearly 7 km in the granitic rock of the interior of the Siljan Ring, an ancient meteorite impact site in central Sweden.

Living organisms are made up of carbon-based macromolecules organized in wet tissues. Their elemental composition is thus dominated by hydrogen (H), oxygen (O), and carbon (C). Indeed, no other elements enter the biosphere's most abundant stores of living matter, the long chainlike molecules of cellulose and cross-linked molecules of lignin that make up the woody tissues of trees and shrubs. About nine-tenths of the biosphere's aboveground plant tissues are in the form of living and dead woody biomass.



The global distribution of incoming solar radiation in January and July, measured in watts per square meter (W/m^2). Incoming solar radiation is not evenly distributed, by either region or season. First, the tilt of the Earth's axis causes seasonal averages to shift according to latitude. Then, regional departures from these broad patterns arise from differences in cloud cover. The rainy Amazon region in January and monsoonal Southeast Asia in July receive much less radiation than expected for their latitude. In contrast, the cloud-free South Atlantic in January, and the Middle East in July, receive the highest energy input.

Other tissues incorporate a number of different elements, or need them to perform critical biochemical reactions. Silicon stiffens planktonic cells and cereal straws carrying heavy ears of grain; intricate layers of calcium form mollusc shells; and phosphorus joins calcium in a compound that makes up some three-fifths of vertebrate bones. Within cells, phosphorus is essential for the transfer of energy. Nitrogen is present in all the amino acids making up the structural and metabolic proteins necessary for life, and all proteins must contain sulfur. To date we know of about 30 elements essential for life.

Living organisms provide a relatively short-lived resting place for assimilated elements. They release them—in compounds generated during their metabolism and decomposition—into a number of environmental sinks, or storages. The most important are the atmosphere, the soil, and the ocean. To move among sinks, elements have to be carried by water or wind, and the energy needed to move them comes from two distinct sources. Geotectonic processes are energized by the Earth's internal heat, but by far the largest energy source is the fusion of hydrogen nuclei in the Sun. Reactions in the star's core consume 4.3 million tonnes (Mt) of matter every second and liberate nuclear energy, which is rapidly transformed into the radiation suffusing our planetary system.

The Earth is, of course, an open energy system: its clouds and light surfaces reflect almost a third of the incoming radiation back to space, leaving the rest to be absorbed by the atmosphere, waters, land, and living organisms, and then reradiated back to space as heat. In supplying the energy needed for photosynthesis, solar radiation powers a key step in biospheric cycling. Yet on the average, photosynthesizing plants and bacteria convert less than half a percent of the absorbed radiation into new living matter. But all other biospheric radiation flows are critical for creating and maintaining the conditions that make photosynthesis possible. They heat the ground and oceans, ensuring the existence of liquid water and maintaining the proper soil and plant temperatures necessary for biochemical reactions. And they provide the energy for moving water and air, the media that carry compounds involved in biospheric cycling.

Given the billions of years that life has existed on Earth, given the vast number of organisms, and the finite supply of accessible matter, evolution could not have been sustained without the recycling of critical elements. And these cycles—embracing the synthesis of new biomass, the death of tissues and organisms, their decomposition, and the return of elements to inorganic stores—must be relatively rapid. Without such replenishment, even relatively slow withdrawals would exhaust the largest planetary stores over an evolutionary timescale of nearly 4 billion years.

Minerals, Water, and Oxygen

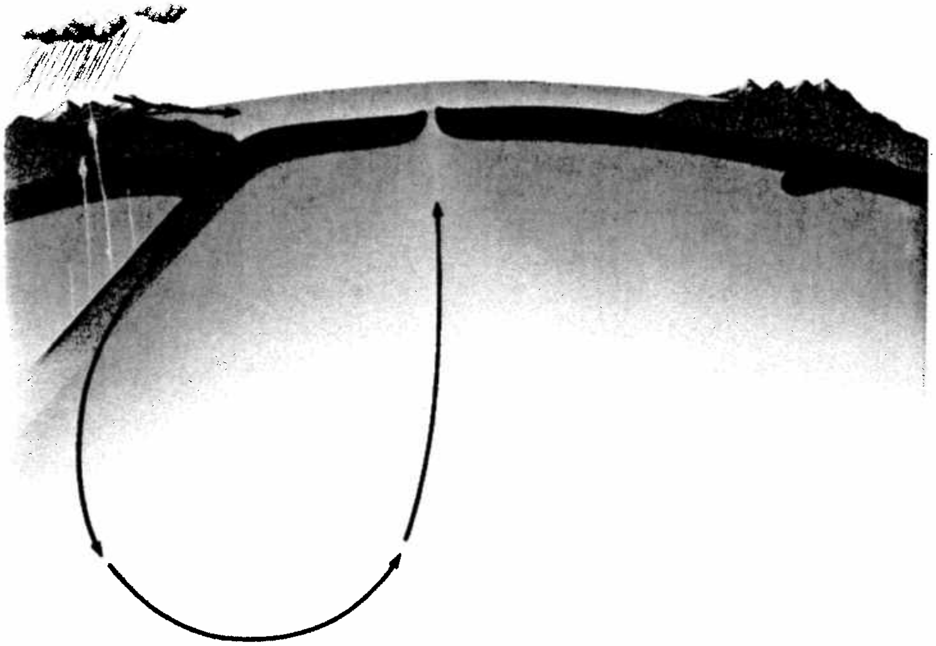
Earth's life depends on the cycling of elements, but not all of these cycles involve critical interventions by living organisms. Biospheric flows of minerals—including such essential plant micronutrients as phosphorus, potassium, or silicon—are components of the grand natural sedimentary cycle. After their deposition on the ocean floor, the elements are returned to the biosphere only millions of years later by geotectonic processes creating new crust. Obviously, living organisms cannot influence the gargantuan geotectonic forces, predating the emergence of life, that ultimately control mineral cycling—but they do play a secondary role in mineral cycles, for they help to accelerate the weathering of rocks.

Unless they are embodied in migrating organisms, be it as swarming locusts or as salmons swimming upstream to breed and die, elements cycling within the biosphere can be carried over longer distances only by water, wind, and ice. The last possibility is relatively unimportant during extended interglacial periods, and since the last glaciation ice has been only a minor factor in mineral cycling, its influence restricted to the margins of the biosphere, in circumpolar regions and on the highest mountains.

Winds, though, can carry fine particles of loose sediments, weathered rocks, or topsoil (including organic matter) over very long distances. Any crustal or oceanic compound, solid or liquid, can become passively airborne. Strong winds lift large volumes of dust and sand in arid regions, and may carry them even to a distant continent. Saharan dust shows up repeatedly on Alpine glaciers and Caribbean beaches. In one of the most spectacular episodes of the 1990s, about 50,000 t of dust mixed with pollen, mostly from Algeria, were carried on March 10, 1991, some 7000 km northward to northern Scandinavia.

Windborne chlorides and sulfates in droplets of sea spray, released by pounding surf or separated from storm waves, can affect rain composition far inland. Similarly, major volcanic eruptions can inject enormous masses of compounds even into the stratosphere, ensuring their gradual spread across the globe. Although these atmospheric dispersions can transport episodically large amounts of mineral elements over long distances, and can alter climates for months or even years, the overwhelming proportion of minerals are cycled through the biosphere not by air, but by water.

Weathering strips a thin layer of matter, less than 0.1 mm on average, from the Earth's crust every year, liberating minerals from rocks. Rain and ice move these compounds into streams that eventually reach the ocean. There the elements join the bottom sediments and are removed once again from the biosphere. Only a tiny fraction of waterborne minerals become incorporated into living tissues, and are thereby temporarily delayed on their oceanward journey, but the quantity is usually sufficient to support a high rate of photosynthesis.



Mineral cycles are driven by grand geotectonic movements: after deposition in sediments, the elements are returned either through tectonic uplift or, after the subduction of oceanic plates in deep trenches, through the upwelling of magma along midocean ridges.

Even the thousand-year span of a civilization is far too short a period in which to complete global mineral cycles: we just glimpse the elements liberated by weathering as they piggyback on water's flow to the ocean. These compounds will return to the biosphere only when ocean-floor deposits are either lifted above sea level during new mountain-building periods coming at intervals of 400 to 500 million years or when the deposits reemerge from a long journey through the Earth's mantle. In the latter case, they pass first through a subducting trench, sink into the mantle, and then well up as hot, liquid magma through ridges or hot spots in the ocean floor.

In contrast to minerals that must piggyback on water flows in the brief intervals between their extended sedimentary pauses dictated by the Earth's geotectonics, there are five elements that circulate through the biosphere rather rapidly. Not by accident, these five elements—hydrogen, oxygen, carbon, nitrogen, and sulfur—are indispensable for life.

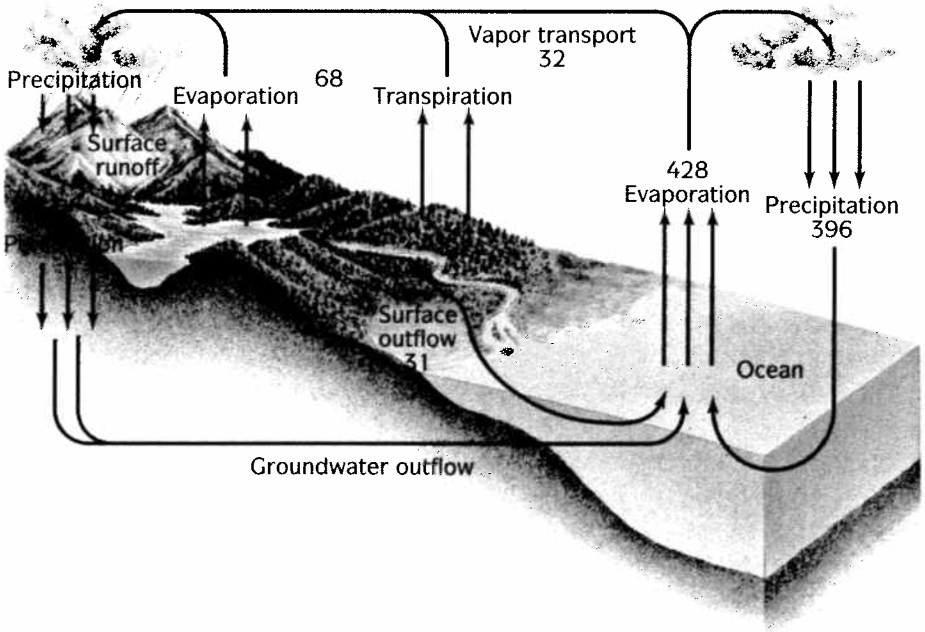
The first two of these elements, of course, form water, and the last three, like minerals, may be transported in water to the ocean and endure prolonged burials. But unlike minerals, which can become only passively airborne, these five elements form stable gaseous compounds and hence may also be cycled continuously through the atmosphere, making them "doubly mobile." But the cycles of these doubly mobile elements are not subject to identical biospheric controls—and are not equally sensitive to worrisome human interventions.

The water cycle, carrying hydrogen and oxygen, is the most rapid circulation within the biosphere, and it is also the most massive. The well-known cycle of evaporation, transport through the atmosphere, precipitation, and flow to the ocean is dominated by the ocean's huge water stores. More than 97 percent of the Earth's water is in the ocean, and almost 90 percent of all water evaporated comes from its surfaces. About half of all the solar energy absorbed at the Earth's surface is transferred to the atmosphere through the evaporation and condensation of water. The evaporating water absorbs heat as it changes from liquid to gas, then releases heat into the atmosphere when it condenses into droplets.

Water's constant biospheric cycling, then, is overwhelmingly a matter of straightforward physical processes. As such, water cycling worked on the Earth 4 billion years ago, and it would work on any planet where the temperature and pressure ranges allow the compound to exist in both liquid and gaseous states. Indeed, the river channels and erosional landforms observed on Mars are clear signs that liquid water once flowed on that planet.

Water is indispensable for living organisms: it typically makes up 60 to 80 percent of living tissues; it is by far the most important donor of hydrogen in photosynthesis; and as the carrier of nutrients and metabolic products water is irreplaceable. Moreover, water has a unique combination of thermodynamic advantages that make it an ideal global temperature regulator.

Water has a high specific heat capacity, which means that it must absorb a relatively large amount of heat before its temperature rises. Water's specific heat capacity is the highest of all common liquids, and it is four to five times higher than that of common rocks. Consequently, the Earth's solid surfaces heat and cool rapidly, producing a large range of temperature extremes—while water bodies gain and lose heat much more slowly and store much more energy per unit volume for a given rise in temperature. These properties make water an excellent heat regulator and prevent wide temperature



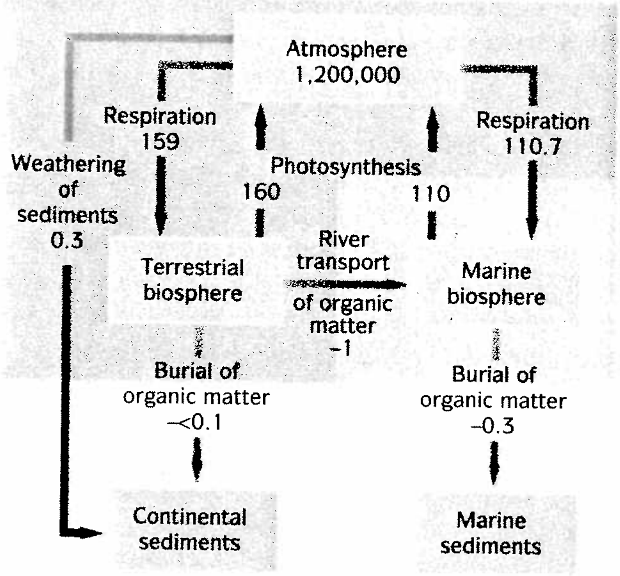
The Earth's water cycle is driven primarily by the liquid's continuous evaporation from oceans. Rivers return most of the water precipitated on the continents, but some recent investigations have shown that the groundwater outflow may be more substantial than thought previously. The volumes of major flows are labeled relative to the volume of continental precipitation, whose total amount is assigned the value of 100.

swings in bodies of water as small as ponds or as vast as the ocean.

Water has also a very high heat of vaporization: it must absorb a relatively large amount of energy to complete the transformation to the vapor state. That property makes water a good medium for transporting latent heat in vapor and for energizing wind flow and other atmospheric processes. Its high thermal conductivity (second only to mercury among liquids) ensures that the absorbed heat is fairly rapidly distributed through its mass; and its relatively low viscosity makes it an outstanding distributor of heat in ocean eddies and currents. Without water's biospheric abundance, ambient temperatures would not be well above freezing over such large portions of the Earth.

On a global scale, life itself has only a marginal role to play in water cycling. Living organisms store no more than 0.00004 percent of all water, and plants evapotranspire only about 10 percent of all water entering the atmosphere. While human actions can severely disrupt local, even regional, water flows, it has been beyond our capability to alter the key fluxes of the global water cycle. This reality may change through our interference in the carbon cycle: appreciable global warming, induced largely through rising CO_2 levels, would intensify mean rates of evaporation worldwide and alter precipitation patterns in many regions.

The cycling of oxygen presents a peculiar case: the element's biospheric presence was undoubtedly created mostly by life, yet its long-term stability appears to be controlled by the geotectonic cycle. The atmosphere's oxygen is in the form of molecules made of two oxygen atoms (O_2). The bulk of atmospheric oxygen originated in the profuse photosynthesis carried out by ancient bacteria, and bacteria and plants continue playing indispensable roles in both the generation and consumption of biospheric O_2. Photosynthesis produces O_2 by breaking apart water molecules; plants, animals, and numerous bacteria consume O_2 in respiration (in the process organic compounds release the energy stored by photosynthesis).



Oxygen production and consumption in the biosphere, as reconstructed by Heinrich Holland (atmospheric O_2 is in billions of tonnes, and fluxes are in billions of tonnes a year). Every year the burial of organic matter removes about 300 Mt of oxygen that was produced during its photosynthesis—but the atmospheric oxygen level remains stable because the oxidation of carbon, sulfur, and iron during rock weathering, as well as the oxidation of volcanic gases (H_2, CO, and SO_2), balance the cycle.

About 60 percent of all O_2 generation and consumption is due to photosynthesis and respiration, two flows in the carbon cycle. In the short run the two fluxes are in virtual balance. A tiny fraction of new phytomass, on the order of 0.2 to 0.3 percent, eludes oxidation by burial in, mostly marine, sediments—and thus life produces more O_2 than it consumes. Nevertheless, the O_2 content of the atmosphere is not rising, for the "extra" gas is used up in the weathering of sedimentary rocks and in the oxidation of volcanic gases.

Some 30 percent of all biospheric O_2 production and consumption are linked to an analogous action of the sulfur cycle. Specialized bacteria transform sulfate ions (SO_4^{2-}) to H_2S, releasing O_2. The H_2S reacts with iron minerals to produce pyrite (FeS_2), and the burial of FeS_2 in sediments removes sulfur to where it cannot be oxidized. The process can be reversed, and oxygen consumed, only when these sediments are eventually exposed to oxidative weathering.

The element's atmospheric level is thus maintained primarily by a sedimentary-tectonic cycle—by the burial of biomass counterbalanced by mineral weathering and the oxidation of volcanic gases. It could not be changed substantially by even an implausibly intense human intervention. Even the combustion of all known reserves of fossil fuels, a feat made most unlikely by its unbearable economic costs, would reduce the concentration of atmospheric O_2 by only about one percent.

And so we are left with three doubly mobile elements—carbon, nitrogen, and sulfur—whose recycling is critically dependent on the ubiquitous and intricate participation of living organisms. The three cycles indispensable for life are also the creations of life—and they are particularly vulnerable to human interference.

The Doubly Mobile Elements and Their Cycles

Inevitably, the double mobility of carbon, nitrogen, and sulfur—in soluble waterborne compounds as well as in gases—makes their cycling much speedier than the cycling of mineral elements. Atmospheric pathways are usually much faster than waterborne flows—but not always. CO_2 molecules that are released when bacteria decompose a rotting apple may be recaptured almost instantly by photosynthesizing leaves in a tree canopy. If the molecules escape above the canopy, vertical mixing can lift them high into the troposphere, and prevailing winds carry them repeatedly around the planet. They can stay aloft for more than a century before returning to a leaf.

In contrast, nitrogenous and sulfurous gases usually reside in the atmosphere only briefly. Dimethylsulfide escaping from decomposing seaweeds may return to the ocean, after atmospheric reactions convert it to sulfate, in less than a day, and hydrogen sulfide released by bacteria in coastal muds can be rapidly reoxidized even before it can escape into water. Or nitrogen oxide may be transformed into airborne nitrates that will be incorporated into rain droplets, or settle in dry form, just a few days later.

While the sequence of evaporation, precipitation, and runoff that forms the water cycle involves only changes of state, the three doubly mobile elements necessarily undergo chemical transformations in the course of their recycling. They combine with other elements, either losing electrons in the process of oxidation, or gaining them in the process of reduction. And unlike what happens in a multitude of mineral cycles, the chemical transformations involving carbon, nitrogen, and sulfur are performed largely by living organisms. In terms of total material throughput, plants and bacteria dominate these transformations; animals make a secondary contribution; and the largest animals hardly matter.

The high mobility of the three elements and the versatility of their compounds ensure their constant availability despite their relative scarcity in the biosphere. This is true on every spatial scale, from microcirculations in soils to global turnovers, and simple calculations demonstrate the need for such rapid cycling.

Photosynthesizing bacteria and plants withdraw well over 100 billion tonnes (Gt) of carbon, as carbon dioxide (CO_2), from the atmosphere every year. Without the return of the gas, through plant respiration and the decomposition of organic matter, the atmosphere's CO_2 stores would be exhausted in about six years. The top 15 centimeters (cm) of

The dense canopy of rain forest near the Amazon River's estuary exemplifies the biosphere's capacity to incorporate carbon from CO_2 into densely growing and highly productive ecosystems.

Iowa's fertile farm soils contain between 600 and 700 kilograms of sulfur per hectare (kg/ha), while good crops of corn remove about 10 kg/ha annually; without recycling, continuous farming would exhaust a soil's sulfur supplies in less than a century. And although nitrogen makes up four-fifths of the atmosphere, without recycling bacteria that convert nitrogen from the air (N_2) into ammonia (NH_3) would deplete even this huge mass of nearly 4 quadrillion tonnes in less than 20 million years.

There are two key reasons why carbon must be cycled rapidly: it is the quintessential element of life—yet it is very rare outside living matter. Its share in the Earth's crust is less than 0.05 percent (compared to silicon's nearly 28 percent), and relatively speaking, it is even rarer in the atmosphere, where its share is less than 0.02 percent of the total mass, or roughly two orders of magnitude less than the rare gas argon. And yet the element, taken up from this atmospheric trace, makes up nearly half of all dry biomass.

In a story in *The Periodic Table,* the late Italian chemist and writer Primo Levi marvels at this disparity:

> This, on the human scale, is ironic acrobatics, a juggler's trick, an incomprehensible display of omnipotence-arrogance, since from this ever renewed impurity of the air we come, we animals and we plants, and we the human species, with our . . . discordant opinions, our millenniums of history, our wars and shames, nobility and pride.

Carbon's dominance in biomass is no accident. The element stands in the central group of the periodic table, able to form covalent bonds (the strongest interatomic links) with most nonmetals, and it joins readily with many radicals (atoms or molecules with unpaired electrons). Carbon compounds combine, in a felicitous analogy suggested by the English biochemist Arthur Needham, momentum with inertia:

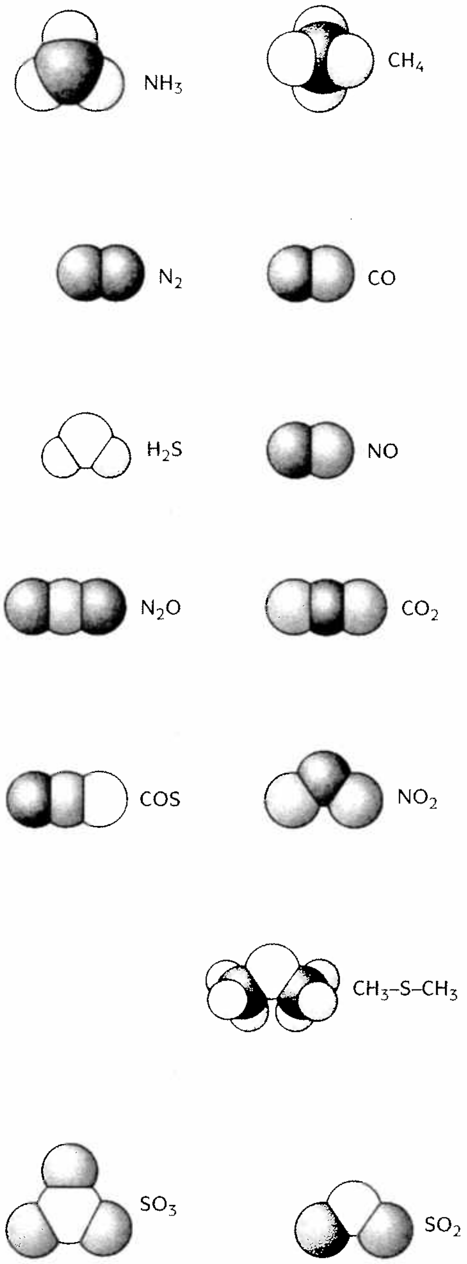
formed rather easily, they tend to be fairly stable, yet they are far from being unreactive.

Carbon's physical diversity is no less remarkable. Pure carbon takes forms as varied as amorphous carbon black, stacked sheets of planar hexagonal graphite, crystalline arrangements of diamonds, and, a discovery of the 1980s, the pentagonal and hexagonal casings of hollow fullerenes. United with other elements, carbon forms an enormous variety of biospheric compounds; these include light gases as well as numerous solids that provide integrity to such different structures as tree trunks, ungulate hooves, and bird feathers.

But the carbon in living organisms is only a tiny fraction of the carbon that exists in the planet's stores of organic matter—that is, in any material that is now or once was part of living tissue. More than 99 percent of organic carbon is locked in kerogens, the transformed remains of ancient planktonic biomass that long ago enriched fine muds preserved in oil shales. These kerogens can be (expensively) distilled to produce petroleum-like compounds, and their aggregate mass is three orders of magnitude greater than the mass of all the world's coals, the most abundant of the conventional fossil fuels, and four orders of magnitude greater than the biomass of all living organisms.

Nitrogen is an even rarer constituent of the crust (averaging about 25 ppm), and in ocean waters its concentration is a mere 80 parts per trillion (ppt). Almost all the nitrogen in the atmosphere is present in the form of unreactive N_2, an odorless, colorless, nonflammable, and nontoxic gas that cannot be used in plant or animal metabolism. Compared to carbon, reactive nitrogen is a minor constituent of the biosphere, but one of decisive importance. The element is present in the molecules of DNA and RNA that store and transfer all genetic information needed for the building of proteins.

None of this was known when the great French chemist Antoine Lavoisier, while engaged in sorting



Space-filling models of the major gaseous carbon, nitrogen, and sulfur compounds in the Earth's atmosphere, arranged according to their molecular weight. The atoms in these models are colored according to a standard system: black for carbon, white for hydrogen, red for oxygen, blue for nitrogen, and yellow for sulfur.

out the composition of air during the 1770s, labeled the element *azote*, without life. The scientific name that prevailed, Jean Antoine Chaptal's "nitrogen," does not reflect the element's essential role in life either; it refers to the element's presence in *nitre*, the salt potassium nitrate (KNO_3) used in gunpowder and meat preservation. But Lavoisier's choice is understandable: unlike O_2, N_2 is highly unreactive, easily seen as the "nonvital air."

This inertness has its source in the strength of the triple bond uniting the two atoms of N_2. Among common gases the energy required to dissociate N_2 is surpassed only by that needed to break apart carbon monoxide (CO), by about 14 percent. But CO is much easier to oxidize, while no oxidizing agent reacts with N_2 at ambient temperature and normal atmospheric pressure. Once the bond is broken, however, the individual atoms react readily.

Sulfur is not rare in the ocean—it exists most commonly in combination with oxygen atoms as the negatively charged sulfate ion (SO_4^{2-}), called an anion to denote the extra electrons that it carries. Sulfate is the second most abundant anion in present-day seawater, after chloride (Cl^-)—but it is uncommon in the Earth's crust. In living matter, sulfur ranks in abundance an order of magnitude below nitrogen and three orders of magnitude below carbon. But its scarcity, which makes sulfur hardly more than a marginal contaminant of living matter, belies the element's vital role in life: no proteins can be built without it. Its role as a crucial component of proteins paradoxically explains sulfur's biospheric scarcity. As already noted, the bulk of the Earth's living biomass exists as the woody tissues of trees and shrubs, which contain no proteins. In contrast, animal life is protein-rich, but its biomass amounts to only a tiny fraction (less than one percent) of all living matter.

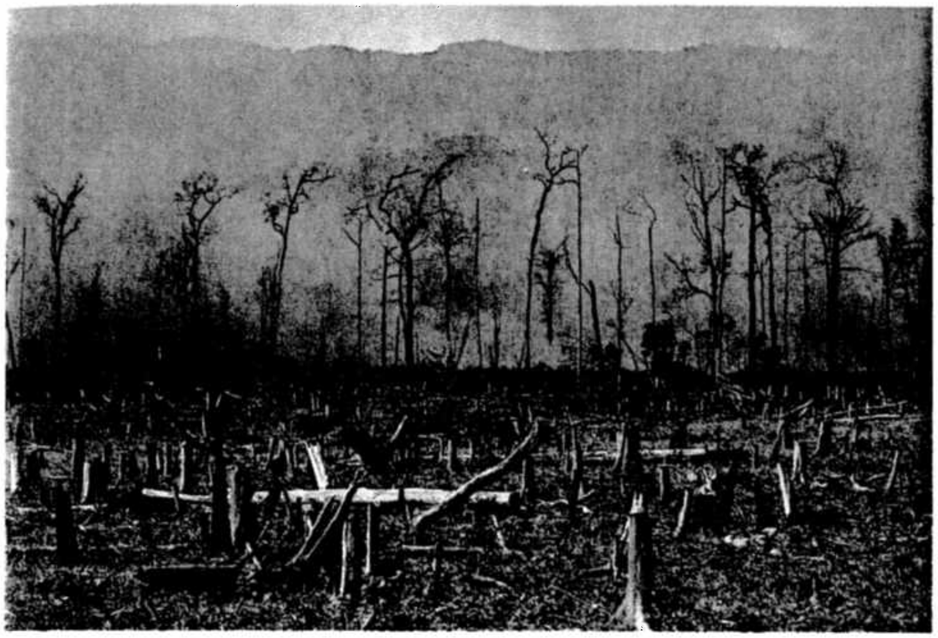
Sulfur's critical role is to keep proteins three-dimensional. The building blocks of proteins are 20 different amino acids, of which only two, methionine and cysteine, have sulfur embedded in them. When amino acids form the long chains, called polypeptides, that compose a protein, sulfur bridges link the chains together and allow the protein to maintain the complex folded structure necessary for engaging in countless biochemical reactions. Proteins without disulfide bridges would collapse in a heap of polypeptide chains.

Only since the middle of the twentieth century have we come to appreciate the many subtleties of biospheric cycles. With this new understanding has come a new concern about the many environmental, and hence also economic and social, consequences of human interventions in these flows. These interventions are ancient, but until recently they have been restricted in extent and intensity. As their scope has escalated with the rise of our fossil-fueled civilization, humankind has become a major agent of biogeochemical change.

In many parts of the world and for many generations, our activities have been overwhelming the natural biospheric flows of carbon, nitrogen, and sulfur on a local level. Shifting cultivators who repeatedly burn vegetation, settled farmers who plant legumes and apply organic wastes, and traditional metallurgists who smelt ores with wood-derived charcoal can temporarily increase or decrease some local fluxes by up to an order of magnitude. Many of these traditional processes still continue, but the interferences have increased dramatically with the rise of high-energy civilization.

Since the 1950s some anthropogenic flows have come to rival the largest biospheric fluxes even on a global scale. For example, emissions of sulfur from fossil fuel combustion and metal smelting now surpass the combined global production by bacteria and volcanoes. Their growth has brought extensive acidification of sensitive soils and lakes and accelerated corrosion of materials to eastern North America, most of Europe and parts of East Asia, and it has also affected the climate of these densely populated regions.

The quantity of nitrogen oxides we generate is more than five times larger than all preindustrial



A tropical rain forest burns in Petén, Guatemala. The conversion of tropical forests to new pastures and croplands is a major cause of rising carbon dioxide levels in the atmosphere.

flows of these compounds. Once converted to nitrates, these oxides contribute to regional or semicontinental acidification. And, all this reactive nitrogen is now providing surprisingly high levels of fertilization to natural ecosystems, a development, as we will see, with both welcome and worrisome consequences.

And although CO_2 emissions from biomass and fossil fuel combustion amount to only a fraction of the global photosynthetic flux, they are now surpassing the rate with which oceans and plants can remove all of this additional input from the atmosphere. The result is a steady increase in the atmospheric concentration of this most important anthropogenic greenhouse gas—and the possibility of global climatic change.

Technical fixes can solve many of these man-made problems, but they may have unintended consequences that exacerbate other forms of environmental degradation. One of the best examples of such a counterintuitive effect is the large-scale acidification of lakes and soils taking place in eastern North America, which, as I will show in some detail, had its origins in an impressive air pollution clean-up.

Before evaluating the impacts, existing and potential, of human interferences, I will detail the structure and the dynamics of the three cycles. But first, in the next chapter, I trace the history of how we came to understand life's role in their workings. The progression of knowledge described therein has made it possible to establish the irreplaceable roles that biospheric cycles play in the maintenance of Earth's life, and hence in the well-being of civilizations.