3

How the Biosphere Works

Tyler Volk

The Earth's surface is a special system worthy of a name. As I will elaborate in this chapter, all life and the three environmental matrices of atmosphere, soil, and oceans form a closely integrated network that can be called the *biosphere*. Its upper boundary is clearly the top of the atmosphere. Its lower boundary is admittedly fuzzier. Groundwater reaches kilometers down into pores of rock, and bacteria have been found kilometers down as well. But for practical purposes, both in terms of providing a rationale for our concepts and for technical modeling of the impacts of organisms on the chemistry of the global environment on relatively short timescales, we can exclude from the definition of the biosphere the minerals in rocks underneath the soil because the elements in those rocks have been out of active circulation for millions or hundreds of millions of years.

Defining the Biosphere within the Gaia Perspective

Some Gaia theorists, like James Lovelock (2006) and Tim Lenton and David Wilkinson (2003), use the word Gaia to be closely equivalent to this chapter's definition of the biosphere. But within Gaia they usually include the surface rocks that have been affected by organisms in Earth's geologic past, such as carbonate rocks (limestone) that were laid down from the accumulated shells of creatures many millions of years ago. A Gaia that is larger than the biosphere as defined above does help us grasp the fact that the effects of life stretch beyond any present slices of time. But the point remains that those carbonate rock minerals have been absent from active circulation for vast ages; as far as the organisms living today are concerned, it is almost as if the carbonate rock minerals did not exist. As will be shown, what is in or out of circulation is key to characterizing the biosphere as a unique system worthy of a name.

The air circulates globally in about a year. Such rapid mixing is evident from the fact that although most of the human-generated fossil-fuel injections of CO_2 into the atmosphere take place from nations in the Northern Hemisphere, the CO_2 at the South Pole has been rising at levels and rates that are almost identical to those at sites in the Northern Hemisphere—for example, at Mauna Loa, Hawaii, as is clear from nearly fifty years of data (figure 3.1).

From studies of deep ocean currents[1] the ocean is known to turn over and mix in about one thousand years. Soil, the third environmental matrix in the biosphere, is stirred by creatures and the chemical circuits of decomposition. Most of the matter in the soil is cycled over at timescales of tens to hundreds of years (for the most part). Organisms themselves "turn over" on the intervals that bound their lives: from days to hundreds of years—though we should give a nod of honor to the much longer-lived Methuselah trees, such as Bristlecone pines.

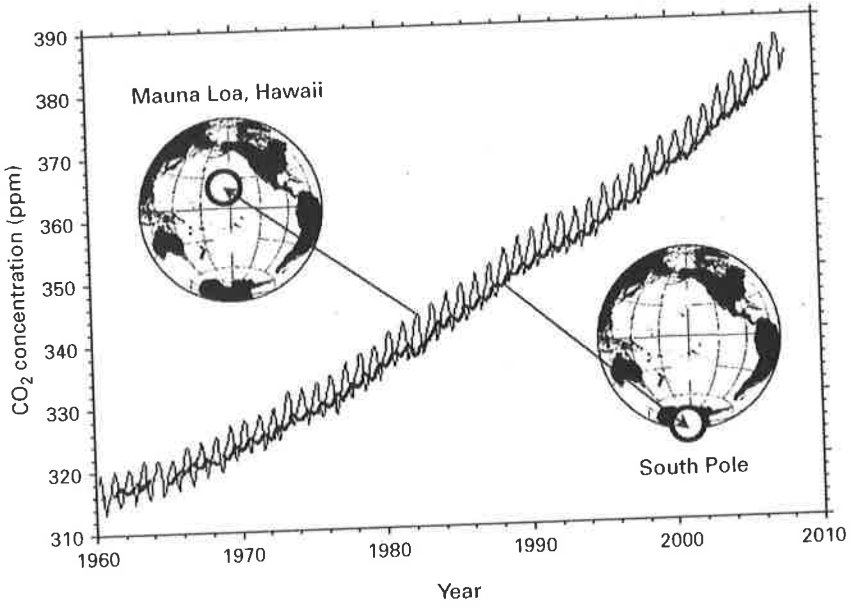

Figure 3.1
Atmospheric CO_2 data from the South Pole Observatory (90°S, dark line), compared with data from Mauna Loa, Hawaii (19°N, oscillating light line). Data from the Carbon Dioxide Information Analysis Center.

So what should we conclude from this survey of the timescales? Because the air, ocean, and soil interconnect, the entire system—including the organisms within these three largest environmental matrices—circulates on about the same timescale as that of the ocean, namely, about one thousand years. This is short with respect to the timescales of evolution, during which species come and go across millions of years, so the components inside the biosphere are interlinked like a single biochemical stew, synchronized in what are virtually evolutionary instants by their chemical connections to each other.

Sometimes, and I must emphasize the need to be wary about this point, the word "biosphere" is taken to mean all of life. For example, a discussion on how the atmosphere, hydrosphere, and biosphere interact would make no sense in my terminology, in which the atmosphere and oceans are internal parts of the greater biosphere. There is a perfectly good, unambiguous word for the sum of all life: the biota. In a second alternative meaning, which I suggest is also infelicitous, sometimes "biosphere" is used to refer to the zone where life is found, from the ocean sediments to the tops of mountains. But this is highly abstract and without physical meaning. The entire atmosphere is mixed both horizontally and vertically and so the chemical impacts of life are not confined to the air only up to the tops of mountains.

Sometimes both of these renegade meanings of "biosphere" are used in nearby sentences without even pointing out the incongruity to the reader. One geologist has recommended the term "ecosphere" (Huggett 1999), but that term has not taken off in the competition for word dominance, and so I will stick with "biosphere" as the integrated system of air, oceans, soil, and life. It has often been used in this way, and there are good reasons for wanting to think more about this united, well-mixed, and amazingly complex thin shell of a system—within which we and all other creatures live sandwiched between hard rock and black space.

Fluxes of Bio-essential Elements inside the Biosphere

With a definition in place, a good place to start inquiring into how the biosphere works is to look at the magnitudes of fluxes of matter. Carbon is a great choice for that because carbon is the core of the organic molecules of life, whether terrestrial or marine. Carbon is in a key atmospheric greenhouse gas (CO_2). It is in a major ion in the ocean (bicarbonate, HCO_3^-, as well as in other marine forms). It is crucial to the structure of soil, as humus, which provides nutrients, ion exchange, and moisture retention. The carbon cycle has been well studied, especially because of rising concentrations of CO_2 from the global combustion of fossil fuels, releasing new carbon atoms now circulating in the biosphere (figure 3.1). The cycle of carbon has received a lot of attention in field studies and global inventories.

The interconnectedness of all the biosphere's parts via the cycling of elements can be illustrated by considering the fate of one carbon atom that we exhale. We end up putting most of the carbon in the food we eat into the atmosphere as CO_2 metabolic waste gas. An airborne carbon atom from one of those waste molecules may end up in a couple years in a bicarbonate ion in ocean water, next in the body of a green phytoplankton, then expelled as organic waste from a crab-like tiny zooplankton that eats the algae, then consumed by bacteria and expelled as inorganic waste and thus passed into bicarbonate again; from there, it could be shunted back into the air as CO_2 in the process of air–sea gas exchange (perhaps all within a half dozen years), and then it might be placed by photosynthesis into the cellulose structure in the leaf of an oak tree in China.

Within this vast circuitry—which gets as convoluted as the paint strands in a Jackson Pollack—the tiny sizes of the molecules almost defy imagination. The waste molecules of CO_2 that we exhale mix globally throughout the atmosphere in about a year, across all those lands that we have ever traveled and those we have not yet seen. I have calculated that *every* green leaf that grows anywhere on the planet (e.g., in about a year from now, to allow for the complete mixing of the atmosphere) will contain a few dozen atoms of carbon from the 500 million trillion new CO_2 molecules that we released from each and every one of our exhalations.

The annual total release of CO_2 from all humans is relatively small, compared with the CO_2 that comes out of the soil each year, generated by soil organisms that feed on the organic carbon in the soil, which in turn comes mostly from dead plants, their leaves, branches, and roots. The respired CO_2 from those soil organisms enters the soil's air and then percolates up into the atmosphere. It comes from worms and millipedes, fungi and beetle larvae, but mostly from soil bacteria—a respired flux that totals about 60 billion tons of carbon in the form of CO_2 each year.

That number is only about half of the flux of carbon that enters terrestrial green plants each year (120 billion tons) because about half the CO_2 that the plants take in for photosynthesis is respired back into the air as the plants burn their own newly formed sugar molecules as a source of energy to drive the subsequent chemical reactions they need to form their proteins, lipids, and nucleic acids for maintenance and growth. Another huge number comes from the exchange of carbon in the form of CO_2 between ocean and air (100 billion tons per year, the air-sea gas exchange referred to earlier). Figure 3.2 shows these numbers as fluxes within circuits in the biosphere. In this simplified big picture, I have ignored several levels of detail, such as the 80 billion tons of carbon photosynthesized within the ocean's surface by phytoplankton, the 40

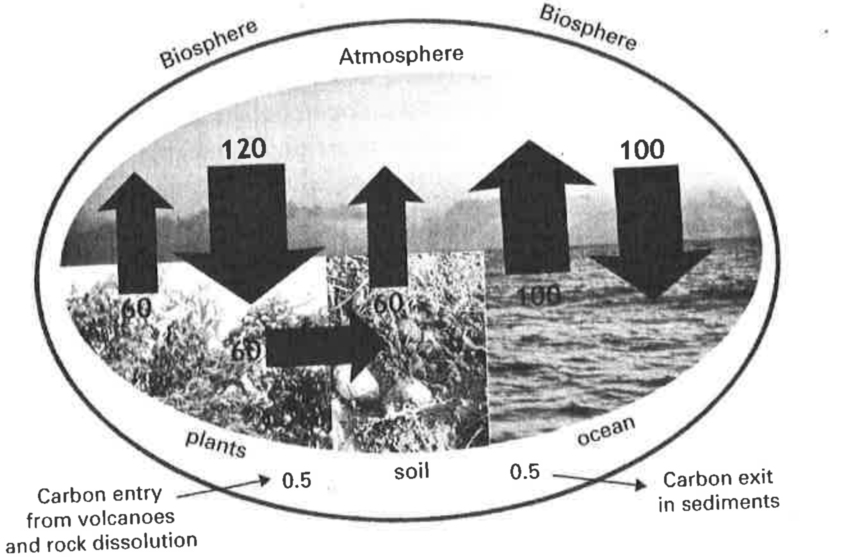

Figure 3.2
Massive fluxes of carbon in the cycle of nature: Air–ocean gas exchange of CO_2 (100 billion tons of carbon each way per year), photosynthesis by terrestrial plants that turns CO_2 into organic molecules of life (120 billion tons of carbon per year), respiration by plants to build more complex molecules inside their bodies and release of CO_2 (60 billion tons of carbon per year), transfer of carbon primarily by plants but also by animals as detritus into the soil (60 billion tons of carbon per year), respiration by soil organisms, mostly bacteria, releasing CO_2 into the soil and then up into the air (60 billion tons of carbon per year; for simplicity this includes respiration by land animals from insects to mammals of about 5 billion tons of carbon per year). The entry and exit fluxes to and from the biosphere are much smaller, as shown. Not shown is the cycle of photosynthesis and respiration in the ocean (see the text).

billion tons they respire, the 40 billion tons consumed by zooplankton and the other consumers in the ocean's food webs, and the several billion tons consumed by animals on land. There are also the other circuits of carbon in the oceans associated with water currents and regeneration by bacteria in deep water, in the details of how carbon circulates in ocean sediments and in different kinds of terrestrial soils, and in a relatively small flux that rivers carry to the ocean.

The simplified big picture allows me to get to a point that holds even if more detail is considered. In figure 3.2, I have added the fluxes of carbon that enter and leave the biosphere. These border fluxes are small compared to the major fluxes of carbon shown within the biosphere. Specifically, geologists estimate that half a billion tons of carbon enter the biosphere as CO_2 from volcanoes and as carbonate ions (CO_3^{2-}) released when rocks such as limestone dissolve and pass their chemicals into groundwater. About the same amount (which must be true on long enough timescales) leaves the biosphere during what geologists call carbon burial. Almost all burial takes place in ocean sediments, as carbon exits the biosphere in the form of carbonate shells from organisms, as well as in a smaller amount in unrecycled organic matter.

The amount of carbon the global hordes of photosynthesizers require each year to live and grow is much larger than the half billion tons of new carbon that enters the biosphere. Summing the net terrestrial plant photosynthesis of 60 billion tons and the net marine photosynthesis of 40 billion tons yields 100 billion tons a year required for the current biosphere's annual growth of green living things, and all other creatures are fully dependent for their livelihood on that primary amount that infiltrates the various food webs. That amount of 100 billion tons per year is a factor of 200 times larger than the fresh rate of carbon supply into the biosphere. The flow of carbon into global photosynthesis is therefore dependent on the cycles of carbon *within* the biosphere. We have already seen the source of this supply: it comes from the respiration of heterotrophs such as zooplankton, whales, fungi, centipedes, eagles, people, and many other creatures, including the all important marine and soil bacteria.

In considering the fluxes in the global carbon cycle, I have emphasized the unity of the biosphere—that it is truly a system somewhat isolated from the rocks below by its large internal system of fluxes compared to the small fluxes back and forth across its lower boundary. I do not want to make more of a tempting organic analogy than just what I will say here, but the biosphere's large internal fluxes and small border fluxes might be compared to the human body, with its large flows of blood around the internal organs and relatively small fluxes of food and water that go in and out each day. In addition to deriving a message about the unity of the biosphere, we can see a second point from the big picture: the workings of the biosphere are intricately tied to the fact that the wastes from certain groups of creatures become nutrients to other groups of creatures.

Waste Networks of Biochemical Guilds

I have previously suggested the name "biochemical guilds" for groups of organisms that perform what are virtually equivalent metabolic transformations of certain elements in the biogeochemical cycles of the biosphere (Volk 2003a). For example, in the discussion about the magnitudes of fluxes, I lumped all photosynthesizers to get a global number. I can do this because they all take carbon from CO_2 and turn it into carbon chemically bound in organic molecules. Most heterotrophs, on the other hand, are members of the biochemical guild of respirers. Members of this guild take the carbon from organic matter and turn it into CO_2 waste, deriving material for their bodies and, crucially, energy for their metabolisms. Admittedly, denoting lines between groups can get complicated. For example, photosynthesizers perform some respiration as well. Different categories can be generated, depending on who is doing the analysis and for what purpose. The reality goes beyond any analysis, say of an ecosystem, biome, or globe. There really are common metabolisms out there. Furthermore in the cycles of the elements that are key to living things the biochemical guilds can link up to each other because wastes from one are nutrients to another.

The year 1958 marked the first real-time data for atmospheric CO_2 at Mauna Loa. That year also premiered a television program called *The Naked City* about police work in New York City. Each episode had a concluding epilogue which always began, "There are eight million stories in the naked city, this has been one of them...." If we were to look at each carbon atom, for example, in a place called The Naked Biosphere, then our narrator, in conclusion to any one story of those atoms would have to say, "There are two million billion trillion quadrillion stories in the global carbon cycle, this has been one of them...." (That is not a random big number, see note 1 in the appendix for the calculation.) But because the atoms follow certain statistics, we, as audience, might be more interested in how the life of an average atom of carbon compares, say, to one of nitrogen or phosphorus. Those different elements have substantially unique stories worth individual episodes. Furthermore, because there are only a couple dozen bio-essential elements, following an episode of big events in the biogeochemical cycle of carbon, the narrator might say: "There are twenty stories in The Naked Biosphere, this has been one of the them. . . ."

So what about a second story? What gives with nitrogen? Here's a summary of several main steps. Nitrogen-fixing bacteria (and lightning, to a smaller extent) convert nitrogen gas (N_2) into ammonium (NH_4^+). Bacteria called nitrifiers change ammonium (NH_4^+) into nitrate (NO_3^-). Ammonium assimilation is performed by plants and algae that can alter ammonium (NH_4^+) into nitrogen-containing organic compounds, such as proteins (call it N_{org}). In ammonification, decomposers in the soil and oceans break down those organic compounds in wastes (N_{org}, e.g., proteins in decaying leaves of plants) into ammonium (NH_4^+). Bacteria called denitrifiers take in nitrate (NO_3^-) and excrete nitrogen gas (N_2). Finally, within the categories of nitrifiers and denitrification are groups of bacteria that create intermediate forms of nitrogen, such as nitrite (NO_2^-) and nitrous oxide (N_2O).

In the stories of the bio-essential elements in The Naked Biosphere, sometimes the elements join together, while at other times they travel separately. When carbon enters the leaf of a green plant as CO_2, that carbon atom might well get hooked up with an atom of nitrogen as a bonded neighbor in an amino acid inside what will become a protein molecule. The nitrogen atom came up into the plant through the roots, dissolved as an ion of ammonium or nitrate in the water from the soil. Then, after the decaying leaf (now on the soil litter) passes through the guts of an earthworm, the carbon atom could exit the earthworm as CO_2 and the nitrogen atom might go into the ammonium-salt waste. The paths part of the once-joined atoms.

There is a second main point to the stories of the bio-essential elements. In one crucial way, broadly speaking, the stories of carbon and nitrogen are similar. As already alluded to, the wastes from creatures in one biochemical guild can be nutrients to those in another guild. CO_2 is waste we expel, but it is airborne food to green plants. The nitrogen gas N_2 is waste from the denitrifying bacteria but a nutrient to the nitrogen-fixing bacteria. If you look at the parts of the nitrogen cycle outlined above, you can find several other pairings (or more complicated networks) in which a chemical form of an element is waste from one but nutrient to another: ammonium as waste to ammoniaficators, but nutrient to ammonium assimilators and nitrifiers; nitrate as waste from nitrifiers, but nutrient to denitrifiers.

Similar stories are found in the cycles of carbon with methanogens, which produce methane as waste, and methanotrophs, which feed on methane. Comparable stories are also in the cycle of sulfur, and more. It all seems so amazing, as if there is some superdesign in the workings of the biosphere knitting everything together.

The designer, of course, is none other than the blind watchmaker of evolution. A waste in the environment that was ejected from an organism was always, at minimum, a potential source of raw material for another type of organism that had (or could evolve) the metabolism to use that waste, either as a source of matter or energy (when coupled with other substances). Many details of when and how evolution played a role in forging the biogeochemical cycles are still under scientific scrutiny (e.g., there is no clear consensus about when oxygen-generating photosynthesis began). But without doubt the resulting biosphere is truly phenomenal. The waste–nutrient networking gives us pause to think anew about the mundane, elementary school story of the CO_2 photosynthesis and respiration cycle, since the message therein is so much more expansive—a systemic pattern.

The Term "Gaia" Can Personalize a Relationship with the Biosphere

We all have a personal relationship with the biosphere whether or not we like it. With our breaths, our food intake, and our waste ejection, we participate in food webs and in the great life-supporting, global biogeochemical cycles that link us to the upper reaches of the atmosphere, to the deepest cold reaches of the ocean, to the dark, pungent places in the soil, as well as to every creature with which we cohabit all the corners of the biosphere. Our links reach back in time, too. Every one of us is a product of a 100 percent successful series of reproductive acts that go all the way back without break to the beginnings of life and the earliest cells. And all this continuous evolutionary unfolding took place within a biosphere that was (as it had to be by definition) hospitable to life, even if the conditions for the first two billion years, at least, were deadly inhospitable with respect to *today's* life, because of lack of oxygen and other "problems."

I have tried to provide some scientific facts about our togetherness with all other species and environmental matrices in the biosphere. How do Gaia and Gaia theory, according to the renowned British scientist James Lovelock, fit into the picture I have drawn?

Terms that trigger our bonding instincts aid the creation of ties with large entities that otherwise would be perceived as too abstract (Pinker 2002). Unions can be called brotherhoods, a nation might be hearkened as the motherland, and corporations are sometimes blatantly termed families. It seems clear that by labeling the biogeochemical entity that we share with other creatures with the name of an ancient Greek Earth goddess, Gaia, one evokes a greater sense of belonging than would be possible with technical biogeochemical terminology.

Without doubt Lovelock has helped foster feelings of togetherness with the bacteria and with the water of the oceans, to mention just a couple members of the biosphere. And his writings and technical papers have helped further a scientific focus on feedback loops within the biosphere. Knowledge about such loops, as a general principle of global biogeochemistry, were firmly in discussions of the global carbon cycle, for instance, for years preceding Lovelock's Gaia hypothesis in the 1970s. But his own approach has helped focus attention on properties at the biosphere scale.

Let's look in more detail at what Lovelock is currently saying about Gaia, using the definition of Gaia theory from his recent book (2006: 162), *The Revenge of Gaia*: "A view of the Earth that sees it as a self-regulating system made up from the totality of organisms, the surface rocks, the ocean, and the atmosphere tightly coupled as an evolving system. The theory sees this system as having a goal—the regulation of surface conditions so as always to be as favorable as possible for contemporary life. It is based on observations and theoretical models; it is fruitful and has made ten successful predictions."

I have no major squabbles with the first sentence. One could debate the meaning of "self-regulation," and I have found it to be a term that Gaia theorists like to use without careful definition. But one could take it to mean approximately what complexity theorists mean when they say "self-organization," which could be applied, for instance, to the formation of a hurricane. I have argued that any perceived stability in the biogeochemical system of the biosphere is simply the result of the way that any complex, dynamical chemical system would settle into zones of limited behaviors (see note 2 in the appendix).

I am less happy about calling Gaia "an evolving system." Richard Dawkins (1982) pointed out that Gaia is a population of one, and therefore by definition cannot evolve. Evolution requires a population of variants that can be selected based on their reproductive contributions to the next generations. So when I introduce Gaia in a classroom at New York University to nonscience students on a course about the biosphere, and compare the biosphere to an organism, I quickly follow up with a denial of similarity because organisms evolve but Gaia does not. I admit that I sometimes like to foster in the students a sense of togetherness and concern by employing the personalized term Gaia. However, I also want it known that Gaia does not evolve. Of course, in a loose sense, such language is acceptable. Astronomers speak of the evolution of galaxies, as they change from blobs to spirals.

My problems change from annoying nits I want to pick to issues more serious in Lovelock's second sentence. I reject as inherently problematic Lovelock's use of the word "goal." A goal is a term that is usually reserved for human-engineered cybernetic systems (computers, cars) that are designed to perform in certain ways and, more generally, for the representations that humans carry around in their minds about their future states. The concept of goal can be appropriate for living creatures, particularly those with nervous systems that change their behavior in the face of environmental conditions. Granted, abstract concepts in language can spread out like oil on the surface of a still lake and lead us to extended uses for a word such as "goal." But I wouldn't want to say, for example, that the water vapor in the sky has the goal of becoming a cloud, even though most of it will end up in clouds. I also wouldn't want to say that clouds have the goal of removing water from the sky. So what is the goal of Gaia? Is Gaia like a hungry fox chasing a rabbit or a cloud generating raindrops?

Lovelock maintains that the goal is "the regulation of surface conditions so as always to be as favorable as possible for contemporary life." Yet Stephen Schneider (1986) pointed out two decades ago the problem with positing a metric like "as favorable as possible." What does that mean? Paraphrasing Schneider, favorable for penguins or for tropical butterflies? Following my own analysis, environmental conditions in the biosphere could be a lot more favorable, if we consider the metric of global terrestrial photosynthesis (Volk 2003b). It is now about 60 billion tons of carbon from CO_2 fixed into organic tissue annually. But most plants would be more productive under higher CO_2 levels. That would provide more organic carbon for the food webs of animals, fungi, and bacteria. More rain might be helpful too, as would a more favorable supply of soil nutrients. Considering just these environmental constraints on current productivity and maintaining biochemical machinery of photosynthesis, the lands today are only about one-tenth as productive as they could be, were the conditions "more favorable." Speaking in the language of "as favorable as possible" makes it sound that we are under the care of a nurturing super-parent. Why hasn't Gaia delivered on that need for more rain? Or more nutrients?

A Gaia theorist might respond by saying "as favorable as possible" does not mean in any possible world. The theorist might say that it is not perfect, but only as good as it could be. But what does that mean? All in all, I do not see Lovelock's language as scientifically helpful. At the same time Lovelock's language has contributed to inculcating a personal relationship. His idea that we are part of a larger entity that has a goal of creating favorable conditions reminds me of many traditional religious viewpoints on the cosmos.

The biosphere has nurtured us in the sense that it consists of an integrated network of biochemical cycles. Crucial parts of those cycles are produced by guilds of organisms in which wastes from one become nutrients to another. These wastes are goals in the sense that organisms need to rid themselves of their wastes to detoxify—an important process of living metabolisms. The wastes, however, are not produced at cost to give to other creatures. (I just want to be clear, I am not hinting that Gaia theorists say this.) The wastes are simply by-products. The biosphere is a stupendous network of waste by-products that are also nutrients. For me, this view connects the daily ins and outs of my breaths to the hard-won knowledge about the global biogeochemical cycles in a way that is both rationally and emotionally fulfilling.

All, I hope, will soon know these basic principles about how the biosphere works. Engineers, politicians, agronomists, voters, gardeners, wilderness preservationists, and any global citizen who desires to seize responsibilities and joys of life in the biosphere will be led to contemplate and help collectively decide on courses of action in the specter of potentially huge climate change. Knowledge about the working of the biosphere is pragmatic knowledge for a shifting and uncertain future, and the root cause of these changes is the perturbation of the global carbon cycle.

The increase in the concentration of atmospheric CO_2 shown in figure 3.1 is only about half the amount of CO_2 that was released from the combustion of fossil fuels. The rest of the CO_2 went elsewhere. Indeed much more than half went elsewhere, but then some came back directly or came back as replacement fluxes from the oceans and land carbon subsystems of vegetation and soils. The dynamics of the whole cycle are shifting, resulting in such carbon-caused phenomena as ocean acidification and crop and forest fertilization, in addition to the raw physics of climate change. Issues such as carbon capture and storage for artificial sequestration, the possible carbon neutrality of bioenergy crops, reforestation as natural sequestration, and the multitude of promising energy systems that do not emit CO_2—all are intimately bound up with the carbon cycle, its present disruption, and potential solutions to the resulting climate change and other perturbations (see Volk 2008).

Appendix

1. Calculation of number of carbon atoms in the biosphere: about 40,000 billion metric tons of carbon in the biosphere (mostly in the ocean) = $40{,}000 \times 10^9 \times 10^6\,\text{g/t} = 40 \times 10^{18}\,\text{gC}$. At 12 gC/mole and 6.02×10^{23} atoms/mole (Avogadro's number), the biosphere then contains 2×10^{42} atoms of carbon. Partitioning the exponent 42, that's 6 + 9 + 12 + 15, thus about 2 million billion trillion quadrillion atoms of carbon.
2. To delve into more depth about some of the issues I raise here regarding how the networks of biochemical by-products work, see my book (Volk 2003a). I also recommend the recent book by Wilkinson (2006) that explores the inevitability of chemical cycles and other fundamental processes of the biosphere. Stephen Schneider, the editor of the journal *Climatic Change*, wrote a prescient editorial (1986) about the conceptual problems in formulating Gaia theory, and has recently sponsored the publication of views and debates about Gaia theory. See, for example, Kleidon (2002, 2004), Lenton and Wilkinson (2003), Kirchner (2002, 2003), Lenton (2002), Lovelock (2003), and Volk (2002, 2003b, 2003c, 2007).

Note

1. But primarily from the estimated age of marine radiocarbon (carbon-14), which diffuses into the ocean as part of the carbon cycle after its formation in the upper atmosphere.

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4

Water Gaia: 3.5 Thousand Million Years of Wetness on Planet Earth

Stephan Harding and Lynn Margulis

Without continuous flows of carbon, hydrogen, nitrogen, sulfur, phosphorus, and other essential elements, primarily as compounds in watery solution, no known life form continues to thrive. The purpose of life, much like other thermodynamic systems open to the flow of matter and energy, is to dissipate chemical and thermal gradients (differences across distances) as elegantly detailed by Schneider and Sagan (2006). The assurance of energy and matter flows in appropriate amounts, rates, and useable chemical form is a sine qua non of the living state. All living beings tend to overgrow their bounds and are invariably limited by appropriate availability of energy and matter. The many limitations to life's intrinsic capacity for growth and diversification is the process Charles Darwin (1809–1882) recognized as "natural selection."

Our Thesis: Life Retained Planetary Water

We champion the poorly developed Gaian view that life has vigorously helped maintain abundant water on the Earth's surface over the last three and a half thousand million years. We defend the idea that life's populations persist and continue to expand on Earth not because a "lucky accident" has situated our moist planet at an optimal distance from the sun; rather communities of living organisms have actively maintained wet local surroundings. The result has been the retention of moist habitability over geological time. We suggest that without life's involvement in complex geological, atmospheric, and metabolic processes, Earth would long ago have lost its water, becoming a dry and barren world much like Mars and Venus. Theoretical interpolation of a lifeless planet Earth between that of Mars and Venus shows that our planet now would be a dry, carbon dioxide-rich world