# CONTENTS

Introduction: World-Changers 1

## PART I. LESSONS FROM THE PAST

1. The Biggest Environmental Change of All 15
2. Plants Colonize the Continents 36

## PART II. ARE WE SO DIFFERENT?

3. Life’s Battery and Earth’s Blanket 57
4. How We Know What We Know about Climate Change 79
5. The Goldilocks Element 100
6. White Gold, Finite and Irreplaceable 116
7. Water, the Key to Life on Land 140

## PART III. A WAY FORWARD?

8. Biogeochemical Luck 163
9 Some Remaining Puzzles 185

Acknowledgments 211
Works Cited 215
Index 217
WHAT DOES it take to change the world? Not change in some transient political way, nor even with a revolutionary invention like the wheel, nor the mastery of fire. I mean change in a way that shapes the course of all life on Earth over geologic and evolutionary time. Change like the meteor impact sixty-five million years ago that shrouded the planet in so much dust that it blocked out the sun, wiped out the dinosaurs, and paved the way for the rise of mammals. Such catastrophic, world-changing events don’t happen very often. When they do, they shape the tree of life forever.

This book is not about meteor impacts but about different, equally dramatic, world-changing events—events precipitated by life itself. These are rarer than meteor impacts and don’t inspire big-budget Hollywood thrillers, but their effects are profound and long-lasting. They arise when evolution produces a new kind of organism, one that can gather certain resources better than any that has come before it. In so doing, such organisms can rework the chemistry of the planet in extraordinary ways.

Such evolutionary leaps are so rare that they are typically separated by hundreds of millions, or even billions, of years. Fascinatingly, a common thread connects these organisms and the
changes they precipitate across these unimaginable depths of time. This book explores this connection, tracing the life-driven global change from an anoxic Earth under a faint sun to the industrial world we inhabit today. We’ll dive into some of the biggest changes our planet has experienced, the organisms that have caused them, and the lessons we can learn from the past that may help us prepare for the future.

The first and biggest of these changes occurred in a world without animals, plants, or fungi—when no organism was bigger than a single cell. Thus we will start, roughly two and a half billion years ago, with the proliferation of a new kind of single-celled organism called cyanobacteria. These ocean-dwelling microbes created a global environmental catastrophe while setting the stage for the emergence of multicellular life. We’ll then jump two billion years forward, to about four hundred million years ago, when the second world-changing kind of organism in our story, land plants, emerged from the water. Their proliferation across the continents took a pantropical world and plunged it into an ice age. Lastly, we’ll come to the present. As different as humans may seem from cyanobacteria and plants, we have become a third great world-changing organism, and we share much more with our predecessors than meets the eye.

The thread that links these organisms and the changes they precipitate across the unimaginable depths of geologic time is woven from five elements that together make up over 99 percent of every living cell: hydrogen (H), oxygen (O), carbon (C), nitrogen (N), and phosphorus (P). They make up what I’ll call “Life’s Formula”: HOCNP. All organisms great and small engage in a relentless search for these elemental ingredients, gathering them from the environment to build their bodies. Those that succeed—survive. Those that don’t—don’t. When evolution produces an organism that can gather these elements in a
novel, more efficient, and more successful way, it sets the stage
for that organism to change the world.

How can the evolution of a single type of organism change
the entire world? The answer lies in Life’s Formula. In one con-
figuration, these elements are the building blocks of all living
matter. In another, they combine to make the gases in the air that
keep Earth warm for life to persist (save phosphorus, whose very
different role I’ll devote a whole chapter to later on). Thus, if
evolution produces an organism that can pull unprecedented
amounts of one or more of these elements from the environment,
the concentration of heat-trapping gases in the air will change,
and thus the climate. The more outsized success an organism
has in gathering the ingredients of life, the more dramatic cli-
mate change will become. In this way these elements link life and
climate—in the past, present, and future.

The three world-changing organisms in this story sit on
very different branches of the tree of life: microbial, plant, and
animal. In part I, we’ll dive deep into the geologic past to tell
the story of the first two world-changers: cyanobacteria and
land plants. We’ll explore how the single-celled cyanobacteria
evolved new ways to gather the constituents of Life’s Formula,
particularly carbon and nitrogen, and precipitated the biggest
environmental change of all time: the Great Oxidation Event.
Then we’ll fast-forward almost two billion years and introduce
the second world-changing class of organisms—land plants.
Their evolutionary innovations in gathering hydrogen, oxygen,
and phosphorus allowed them to spread across the previously
barren continents. But plants’ proliferation inexorably sent
the then-tropical planet, with bathtub-temperature oceans at
the North Pole, into an ice age that froze many of the world’s
first forests out of existence. In both cases, we can understand
these changes through the elements in Life’s Formula, which
connect us all to the planet we inhabit. The history of cyanobacteria and land plants also sets the stage for the story of humans—the third great world-changer.

In part II, we’ll focus on how human industry, innovation, and proliferation has precipitated a new geologic era called the Anthropocene. Despite all the obvious differences between us and our plant and bacterial predecessors, we are linked by a common elemental thread: HOCNP. Indeed, this link is the key to unraveling the complex web of global environmental woes wrought by modern society. Understanding that is the key to part III, where we’ll look to the future. Like our predecessors, our remarkable access to these five elements has brought enormous benefits while pushing us inadvertently toward environmental catastrophe. Mitigating the unintended consequences of our remarkable innovation depends on our management of the elements we are using to change the world. If we want a more sustainable future, we have a lot to learn from those who came before us.

Now that I’ve briefly introduced our three organisms, let’s take a look at the five atoms that make up Life’s Formula and shape our climate. Here are two chemical “formulae”* representing two of the world-changing organisms in our story.

\[ \text{Cyanobacteria} \quad H_{263}O_{110}C_{106}N_{16}P_{1} \]

\[ \text{Humans} \quad H_{375}O_{132}C_{88}N_{6}Ca_{1}P_{1} \]

* I put “formulae” in quotes because cells aren’t single chemicals; they are mixes of thousands. However, this is the approximate “formula” you would get if you analyzed a whole organism.
For those of you who are a bit rusty with high school chemistry: the letters represent the five elements I’ve already introduced (plus a sixth, calcium): \( \text{H} = \text{hydrogen}, \ \text{O} = \text{oxygen}, \ \text{C} = \text{carbon}, \ \text{N} = \text{nitrogen}, \ \text{Ca} = \text{calcium}, \ \text{and P} = \text{phosphorus} \). The subscripts represent their relative abundance in our respective bodies. For example, in a cyanobacterial cell (the first “formula”), there are slightly more than twice as many hydrogen atoms as oxygen ones (263 to 110), and 263 times as many hydrogen atoms as there are phosphorus atoms. Humans (the second “formula”) have a remarkably similar makeup, both in terms of the kinds of elements in our bodies and their relative abundance. Indeed, I could write a “formula” for any living creature, and it would look very similar to these. Of the more than one hundred known elements, these five (plus or minus calcium, for those with bones or shells) are the most abundant in every organism on Earth, in the same order of abundance and with roughly the same ratio. “Life’s Formula” is remarkably consistent from bacteria to plants to humans. This shared chemistry puts all organisms in the same boat. All living things need to wring these crucial elements from our environment. To proliferate, life must have access not to one, but to all five—\( \text{H}, \ \text{O}, \ \text{C}, \ \text{N}, \ \text{and P} \).

What do organisms do with these elements? Joined in water, \( \text{H} \) and \( \text{O} \) make up the vast majority of all cells, and astrobiologists (people who think about and look for life beyond Earth) are convinced that life is impossible without water. To name just a couple of its myriad roles: water is used in photosynthesis, which is the base of almost all food chains (much more on that later), and in the reactions that power all animal cells. Water is easy to get in the oceans, but on dry land staying hydrated is the most pressing need of any living thing. This challenge will play a prominent role when we talk about the evolution of land plants in chapter 2. Carbon, life’s third-most abundant element,
forms the backbone of all biological molecules: DNA, RNA, protein, fats, carbohydrates, sugars, and many more. Directly or indirectly, most organisms depend on photosynthesis to gather carbon. Photosynthetic organisms (like plants) use the energy of sunlight (“photo”) to capture carbon dioxide from the air and synthesize it into biological molecules that store that energy in their chemical bonds. Other organisms (like us and the animals we eat) consume those molecules and break them down to release that energy and fuel our activities, and return carbon dioxide to the air. Thus, photosynthesis directly links life to the most important gas keeping the planet warm—carbon dioxide. I’ll explore this link in much more detail in the following chapters. Finally, all living things, photosynthetic or not, need nitrogen and phosphorus to make DNA (and many other key biological molecules). These two elements are embedded in the genetic code of all life on Earth, but as we’ll see, they are often in short supply relative to the amount that organisms need to survive.

The abundance of these irreplaceable elements varies enormously across Earth’s surface, and this variation dictates where and how much life exists. Little lives in the Atacama Desert in the high Andes of Chile, where it can go centuries without rain. Little lives across vast swaths of Antarctica, where temperatures are too cold for photosynthesis to capture carbon from the air. Perhaps more surprisingly, little lives in the warm, sunlit waters of the central equatorial Pacific Ocean, where a paucity of nitrogen creates a watery “desert.” But in the eastern Pacific, where ocean currents enrich the sunlit waters with nitrogen and other nutrients, the sea teems with life. Similarly, on land, in the Sierra Nevada of California, regions underlain by particularly phosphorus-poor rocks host no trees or soil forms, and bare rock abounds. Nearby, where geologic happenstance provides
more phosphorus in the rock, giant spruce trees tower above soil-mantled slopes.

The constraints placed on life by the relative abundance or scarcity of these elements are, by themselves, a fascinating story of the world’s ecosystems. It is a story explored by my field of science, biogeochemistry, which focuses on how energy and atoms move between organisms and their environments. I’ve worked for decades in this field, and I’ll share some of what I’ve learned in this book. But as I suggested earlier, these constraints are only half of the story here. These elements are important not just for living things but for the environment in which those things live. They are the constituents of the so-called greenhouse gases that keep our planet warm enough for life to exist. So, let’s turn briefly away from the biology of life to the chemistry of Earth.

The main greenhouse gases keeping our planet habitable are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and water vapor (H₂O).* As you can see from their formulae, they consist of four of the five elements that make up all living things. But when these elements are configured in the form of these greenhouse gases rather than living molecules, the building blocks of life create an invisible blanket that traps heat in our atmosphere. As early as the 1850s, scientists had figured out that higher concentrations of greenhouse gas in the air led to a warmer planet. Like glass in a greenhouse or the windows in your car, greenhouse gases allow sunlight to hit Earth’s surface, but also trap some of the heat that would otherwise radiate back into space. Glass’s transparency to sunlight and capacity for heat retention are why the inside of your car is

---

* I’ll try to keep the chemical formulae to a minimum, but I’m going to use CO₂ for carbon dioxide from here onward.
so hot on a sunny summer day. Greenhouse gases’ transparency to sunlight and ability to retain heat make the whole planet warmer. In fact, Earth would be a permanently frozen world without them. Greenhouse gases make Earth a Goldilocks Planet—not too hot and not too cold. And the abundance of greenhouse gases in the air is linked, through shared elements, to the activities of living things.

Despite loving science classes in high school, taking lots of science in college (though I was a history major), and even getting a master’s degree in geology, I didn’t realize that scientists thought about the way biology, geology, and chemistry intersect to shape our living planet until I started my PhD program. Perhaps this is because of the way we teach science, particularly in the United States, where each discipline is taught separately from the others. These silos make it easy to miss the idea that life exists at the intersection of these fields, with biological machinery struggling to overcome the chemical challenge of eking out a living on a rocky planet. Because of these silos, I didn’t fully understand what it meant to inhabit a “living planet.” Of course, it meant that there is life on Earth. But, just as importantly, it describes a planet shaped by life itself, particularly by organisms that can influence the flow of the elements in Life’s Formula. I hope that by the end of this book you’ll agree that understanding our era of rapid, multifaceted human changes to the planet through this elemental lens offers an illuminating window into those changes and a connection with changes in the past. Perhaps more importantly, I want to show that we can use this way of viewing the world to help navigate toward a more sustainable future.

To set the stage a bit further, I’ll return to our three world-changers. Let’s start with the cyanobacteria. A little more than two billion years ago, they evolved to combine two very effective ways of gathering and using carbon, nitrogen, hydrogen, and
oxygen. First, they used the photosynthetic reaction still used by plants today, which is a very efficient way to use the sun’s energy to power biological reactions. Second, they used a process called nitrogen fixation, which allowed them to capture nitrogen from a virtually unlimited supply in the air. As far as we know, no previous organism had combined these two hugely beneficial biochemical processes. This combination gave the cyanobacteria unprecedented access to elements in Life’s Formula, which in turn allowed them to increase dramatically in number. We find fossil evidence of their remains billions of years later. However, for those of us who succeeded them on our living planet, their chemical legacy was far more important than their fossils. Their evolutionary innovations increased the total amount of photosynthesis on Earth. And photosynthesis had an unwanted byproduct—oxygen (the molecule O₂—the gas that we need in order to breathe). For two billion years there had been no oxygen in the environment; oxygen was always bound to some other atom (as in water—H₂O). Over time, cyanobacteria pumped out so much oxygen that it overwhelmed the environment’s ability to absorb it. This ended the continuous anoxia (lack of oxygen) that marked the first two billion years of Earth’s history. Ours became the only known planet in the universe with an oxygen-rich atmosphere, the kind all multicellular organisms (like us) need to breathe. But for the then denizens of the planet, who had been shaped by over a billion years of evolution in anoxic conditions, the transition from no oxygen to oxygen was probably the biggest environmental catastrophe of all time. It fundamentally changed Earth’s chemistry, plunged Earth into what was probably its first ice age (more on that in chapter 1), and determined which organisms dominated and which were relegated to the sidelines. All because an evolutionary innovation produced a new way of gathering
the elements that shape our living planet and produced a by-product that changed the world.

Two billion years later, an admittedly unimaginable expanse of time, our story’s second world-changers evolved: the land plants. They emerged from the water onto the continents around four hundred million years ago and took advantage of a whole new habitat, the 30 percent of Earth’s surface that rises above sea level. In order to spread across the land, plants had to evolve ways of gathering three of the five elements in “Life’s Formula” that were particularly hard to get in this new habitat: hydrogen and oxygen (in water) and phosphorus. It is no small feat for an immobile plant to stay hydrated (that is, gather H₂O) on dry land. The land plants solved this puzzle by rooting into the underlying rock, creating the world’s first soils. These roots pried phosphorus, the fifth element in Life’s Formula, from its ultimate source, rocks. Access to unprecedented levels of phosphorus allowed plants to grow as nothing had grown before, creating towering forests on once-unvegetated continents that then spanned from the equator to the South Pole.

The movement of plants from water to land created a host of incidental consequences. The most important aspect of this story is that plants’ relentless photosynthesis eventually pulled so much CO₂ out of the air that the blanket keeping Earth warm “thinned” enough to plunge the once-tropical world into a deep freeze. Another near-global ice age ensued. The first tropical forests were frozen by their own success. Once again, evolutionary innovation in gathering the atoms in Life’s Formula had catastrophic environmental consequences.

At first blush, the changes wrought by humans seem very different from those driven by our world-changing predecessors.
We are sentient, have remarkable technology, and seem so different from cyanobacteria and plants that the thread connecting us with them is not immediately apparent. But if we look a little deeper, as we will here, it turns out that we three world-changers have a lot in common. Human successes and challenges, like theirs, stem from the elements embedded in Life’s Formula.

Let me briefly foreshadow human impacts. Every year we burn through hundreds of years of stored photosynthetic energy, the geologically altered cells of our world-changing predecessors, now exploited as fossil fuels: oil, coal, and natural gas. This energy has lifted billions out of poverty, helped increase human lifespans, and (most would argue) improved our quality of life. But releasing this energy has also spewed CO$_2$ into the atmosphere at a rate that is unprecedented in the last several hundred thousand years, and may well be unprecedented in the history of the world. By the mid-twenty-first century we will likely double the amount of greenhouse gases in the atmosphere relative to the start of the Industrial Revolution in the mid-nineteenth century. And our success is not founded on fossil fuels alone. In less than a century, humans have also doubled the amount of nitrogen in circulation, quadrupled the amount of phosphorus, and captured five times more water in human-made reservoirs than is contained in all the rivers on Earth. These innovations allow us to fertilize and irrigate enough crops to feed our swelling ranks, which as I write is about to exceed eight billion. Even as we reap the fruits of these efforts, the changing stocks and flows of the elements that underlie our success have profound consequences for its longevity. Like our world-changing predecessors, we cannot avoid the elemental links between the living and unliving world. We share the same needs, and as we’ll cover in some detail, we share methods to
fulfill them with our bacterial and plant predecessors. We should beware of similar consequences.

Despite this rather grim historical perspective, it is critically important to understand that we have two unique advantages when it comes to avoiding catastrophe. Unlike our world-changing predecessors, we can see what is coming. Perhaps even more importantly, we have options for moving away from the way we’ve done things in the past. We can use this knowledge to inform a transition—one to a society that considers how to manage the elements in Life’s Formula in a way that minimizes unintended consequences and maximizes human well-being. We don’t know how to do this perfectly, but we know enough to start the transition from managing Earth by neglect to managing it with purpose. For some, the idea of human management of the Earth system is so full of hubris that it’s not worth discussing. To this I counter: we are already doing it. Humans are now a dominant geologic force for the global cycles of the elements that change the world. I don’t know whether we will act on what we can learn from our predecessors and avoid the worst consequences that come with changing the world. As Yogi Berra is purported to have said, “it’s tough to make predictions, especially about the future” [28]. But the only way that we can exit the twenty-first century more sustainably than we entered it is if we act on what we have learned. There is no way back—but there is a way forward.
INDEX

Adams, Addie, 103
adenosine diphosphate (ADP), 118
adenosine triphosphate (ATP), 118
ADP. See adenosine diphosphate
agriculture: in Amazon region, 126–27;
biogeochemistry and, 155; in Central Valley, California, 147–48; corn
production, rates of, 110; fertilizer
use in, 111–12; food production and,
111; Green Revolution, 111; irrigation
systems, 152–53; nitrogen fertilizers,
108–14; Ogallala Aquifer in U.S.,
149–51; phosphorus fertilizers and,
127–29; regenerative, 204–5; rivers
as water source for, 147; salty soils
and, 153–55
air conditioners, 174–76
air pollution, 160; in U.S., increases in,
134
algae, in oceans, 22. See also dead
zones
alternative stable states concept, 138
Amazon Rainforest, 22; deforestation
of, 124–25; fungi in, 125; in lowland
regions, 122; nutrient-poor soils in,
188–89
Amazon region: agricultural produc-
tion in, 126–27; dams in, 146
amine group, 101
amino acids, 101–2
ammonia (NH₃), 102, 108
anoxia: early development of Earth
and, 9; planets and, 16. See also
“dead zones”
Antarctica, 6; measurement of carbon
dioxide in ice cores from, 75, 85
Anthropocene: 4
aquifers: GRACE satellites, 151–52;
Ogallala Aquifer, 149–51; under
Sahara Desert, 149; wells and,
150
archaea, 22
Archaeopteris, 44, 47–48
Arrhenius, Svante, 84–92
astrobiology, 5
Atacama Desert, 6
atmosphere, of early Earth, 16; carbon
dioxide removed from, 51; oxygen-
ation of, 48–49; oxygen percentages
in, 16
ATP. See adenosine triphosphate
bacteria: carbon and, 103–4, 108; land
plants and, 106; nitrogen and, 106;
nitrogen-fixing, 106; in oceans, 22;
purple sulfur, 25. See also cyanobac-
teria; soil bacteria
Barry, Jim, 75
bell jar experiment, 17–19, 24; Earth as, 58
Berra, Yogi, 12
biodiversity, 160
biogeochemical cycles, 34
biogeochemistry, 7; in modern agriculture, 155, in tropical forests, 186–89
biological nitrogen fixation, 30, 35
biology, 8
Brown, Patrick, 199
Brown University, 79

C. See carbon
cacti, 144, 190
Canfield, Donald, 31
carbohydrates, carbon in, 6
carbon (C): capture of, 31; in carbohydrates, 6; in cyanobacteria, 8–9, 39; in DNA, 6; in fast carbon cycle, 59–62, 65–67, 69; in fats, 6; in fossil fuels, 77, 117, 158–59; in soil, 50; in limestone, 51, 58; in living cells, 2–3, 5–6; in marble, 58; in modern photosynthesis, 31; in oceans, 27; in photosynthesis, 38–39; in proteins, 6; in RNA, 6; slow carbon cycle, 59, 62, 65–66, 69; in sugars, 6
carbon cycle: climate change and, 138; cyanobacteria as influence on, 183; human impact on, 11, 65–66, 67–68, 164; land plants as influence on, 183; fast carbon cycle, 59–60, 66; glaciation from, 59; slow carbon cycle, 59, 62. See also fast carbon cycle; slow carbon cycle
cement production, 182
carbon dioxide (CO₂): acidification of water, 47, 50–51; in Antarctica ice cores, 75, 85; climate change influenced by, 69–74; concentrations in atmosphere, 192; dissolving in oceans, 23; effects of land plants on, 44–45; from fossil fuels, 66–68; geologic rates of change for, 68; as greenhouse gas, 7, 32; heat trapping properties, 87; from human respiration, 67–68; in land plants, 53, 143–44; in pan-tropical world, 49–50; in photosynthesis, 19, 53–54; recent emissions of, 109; removal from atmosphere, 51; seasonally dependent concentration of, 69; stability of, 32; stomata and, 142–43

CH₄. See methane
carbon dioxide (CO₂): acidification of water, 47, 50–51; in Antarctica ice cores, 75, 85; climate change influenced by, 69–74; concentrations in atmosphere, 192; dissolving in oceans, 23; effects of land plants on, 44–45; from fossil fuels, 66–68; geologic rates of change for, 68; as greenhouse gas, 7, 32; heat trapping properties, 87; from human respiration, 67–68; in land plants, 53, 143–44; in pan-tropical world, 49–50; in photosynthesis, 19, 53–54; recent emissions of, 109; removal from atmosphere, 51; seasonally dependent concentration of, 69; stability of, 32; stomata and, 142–43

climatic: alternative stable states concept, 138; attribution of, 80; attribution experiments, 83–99; carbon cycle and, 138; carbon dioxide production and, 69–74; causation evidence for, 82–83; definition of, 80–81; detection of, 80; El Niño/ La Niña, 84; from fossil fuel use, 80, 98, 156; future predictions for, 94–96; from greenhouse gas emissions, 76, 82–83, 96–97; human impacts on, 73–76, 80, 159–60; increases in average global temperatures from, 70–73; from natural variation, 97; ocean levels influenced by, 98; planetary boundaries concept and, 138; water access influenced by, 155

Clinton, Bill, 207
CO₂. See carbon dioxide
carbon dioxide release from combustion of, 64; commercial
production of, 63; early use of, 62–63; fossil plants and, 64–65
Coleridge, Samuel, 27–28
Colorado River, 146, 156–57; watershed temperature changes, 157
Congo region, rainforests in, 122
coral, 51
corn production, 110, 202
Costa Rica, 190; rainforests in, 20–22; La Selva Biological Station, 185–86
cotton, 145
cryptic crusts, 41
cyanobacteria: carbon and, 8–9, 39; chemical formula of, 4; energy storage by, 30–31; evolution of, 2–3, 8–9, 23–24, 57; hydrogen and, 8–9; modern photosynthesis and, 31–32; nitrogen and, 8–9, 38–39; nitrogen fixation and, 9; in oceans, 38; oxygen in, 9, 32–33, 164; phosphorus in, 39; as single-celled organism, 2
dams, rivers and: in Amazon region, 146; on Colorado River, 156–57; Three Gorges Dam, 146
dead zones, 137; algae blooms from phosphorus fertilizer use, 135–36; decomposition, 65; oxygen’s role in, 52; as reverse reaction to photosynthesis, 137
deforestation: of Amazon Rainforest, 124–25; importance for climate change, 182; desalinated water, 145–46; deserts. See Atacama Desert; Gobi Desert; Sahara Desert
diatoms, 22
dinosaurs, extinction of, 61
DNA: composition of, 6, 118
earth, development as planet: anoxia and, 9; as a bell jar, 58; early greenhouse effects, 32; as “living planet,” 35; oxygen production on, 9–10; solar energy inputs to, 77; transition to oxygenated planet, 35; water and, 10
ecosystems, 192–93
Einstein, Albert, 90–94
El Niño/La Niña climatic shifts, 84
endosymbiosis, 41–42
energy: cyanobacteria and, 30–31; photosynthetic, 11. See also coal; fossil fuels; hydropower; natural gas; oil; solar energy; wind energy
energy use: by air conditioners, 174–76; in metabolism, 165; of electricity, 168–73; by heat pumps, 174–76; from fossil fuels, 165, 167; in home heating, 174–75; home renovations and, 177–78; in North America, 166; in private homes, 173–78; reduction strategies, 171–84; in U.S., 167; in wealthy nations, 166–67, 183
Environmental Protection Agency, 169
erosion, of soil: in Iowa, 203; Natural Conservation Service, 203; regenerative agriculture and, 204–5
experiments, for climate change attribution, 83–99
Experiments and Observations on Different Kinds of Air (Priestly), 17
extinction events: for dinosaurs, 61; Great Oxidation Event, 33–34
Fabaceae family, 103–4. See also legumes
fast carbon cycle, 59–60, 66–69
fats, carbon in, 6
Fe. See iron
feedbacks, greenhouse gases and, 88
fertilizers: in modern agriculture, 111–12; NPK, 19–20; role in food production, 158–59; waste-derived, 207. See also nitrogen fertilizers; phosphorus fertilizers
food chains, in oceans, 37
food production: irrigation systems and, 152–53, 158–59; of legumes, 141; Life’s Formula and, 142; modern agriculture and, 111; modified grasses, 141; Ogallala Aquifer and, 149–51; role of fertilizers in, 158–59; of root vegetables, 141; salty soils and, 153–55
foods: chemical energy from, 76–77; nitrogen-rich, 159; phosphorus-rich, 159
food sustainability, strategies for, 193–206; genetic modification and, 201; land requirements, 197–98; livestock reduction, 196–97; meat-heavy diets and, 195–99; meat-replacement products, 199; personal choices, 194–95; plant-based and vegetarian diets and, 198–200
Foote, Eunice, 74
forests: Archaeopteris in, 47–48; in Hawai’i, 121–22; Life’s Formula and, 22. See also deforestation; rain forests
fossil fuels, 11; carbon-based energy in, 77, 117, 158–59; carbon dioxide from, 66–68; climate change from use of, 80, 98, 156; fast carbon cycle and, 62; as finite source, 101; nitrogen fixation and, 191; replaceability of, 77–78. See also coal; natural gas and oil
fossil plants, 43–44; Archaeopteris, 44, 47–48; coal and, 64–65
fuel sources. See coal; fossil fuels; nuclear fuels
fungi, 44, 47; in Amazon Rainforest, 125; phosphorus uptake by, 124; recycling of nutrients by, 188; water retention by, 52
Galloway, James, 27
gasoline combustion, 63, 65
genetically modified foods (GMO foods), 201; soybeans, 129
glacial meltwater, 157–58
glaciation, 33; from carbon dioxide removal, 59
GMO foods. See genetically modified foods
Gobi Desert, 122
Gould, Stephen Jay, 105
GRACE satellites. See Gravity Recovery and Climate Experiment satellites
Grand Canyon, 15, 146
Gravity Recovery and Climate Experiment satellites (GRACE satellites), 151–52
Great Barrier Reef, 81–82, 160
Great Oxidation Event, 31–34; biogeochemical cycles, 34; environmental changes from, 3; as extinction event, 33–34; global greenhouse gases and, 33–34; nitrogenase and, 105
greenhouse gases: carbon dioxide, 7, 32, 49; climate change from, 76, 82–83; feedbacks and, 88; Great Oxidation Event and, 33–34; heat
trapped by, 74; human impact on, 11, 69–70, 74–78, 80–81, 82–83, 89, 92–93, 96–99; methane, 7, 32; nitrous oxide, 7, 32, 102; transparency to visible light, 8; water and, 7, 32; emissions from wealthy nations, 166–67, 183

Ice Ages, 10, 54; Arrhenius on, 85–86; continental ice sheets and, 70; land plants and, 3–4

Industrial Revolution: carbon dioxide emissions during, 59, 66–67; global temperatures changes after, 98

infrared radiation, 86–87

International Energy Agency, 180

Iowa, soil in, 202–6; erosion of, 203

iron (Fe), 16, 33, 39–40, 43, 137–138

iron oxides, 126, 130; in soils, 123

irrigation systems, 191; food production and, 152–53, 158–59; with groundwater, 150

Kramer, Sasha, 206–8

land plants: bacteria and, 106; cacti, 144, 190; carbon cycle influenced by, 183; carbon dioxide use by, 53, 143–44; carbon storage in, 164; colonization of continents, 44; evolutionary impact of, 19; evolution from ocean dwellers, 37; evolution of, 10, 37, 48; Fabaceae family, 103–4; fast carbon cycle and, 60–61; fossil remains in, 43–44, 47; fungi, 44, 47; causing Ice Ages, 3–4; leaf waxes, 45; leaves, 45–46, 52, 143; Life’s Formula and, 19; liverworts, 42; mosses, 42; phosphorus and, 117; photosynthesis by, 42; oxygen production by, 19; reactive nitrogen and, 102; root systems in, 44, 46–47; seeds and, 43, 47–48; stomata on, 142–43; succulents, 144, 190; sunlight and, 43; water retention strategies, 45–46, 52; weathering influenced by, 67–68
La Niña climatic shifts. See El Niño/
La Niña climatic shifts
la
va
flows: chlorine gas and, 36; in
Hawai‘i, 37, 46; soils derived from,
120; nitrogen availability in, 122
Lawes, John Bennet, 131
law of gravity models: by Einstein,
91–92; by Newton, 91
leaves, in land plants, 45–46, 52; nutri-
ents in, 188–89; stomata, 142–43
leghemoglobin, 200
legumes: bacteria carbon and, 103–4,
108; leghemoglobin, 200; phospho-
rus fertilizers and, 127; root nodules
in, 103–4; as source of protein, 107.
See also soybeans
Life’s Formula: evolution and, 2–3;
food production and, 142; land
plants and, 19; phosphorus in, 10,
116–17; rock-derived elements in, 40
limestone, 51, 58; cement production
and, 182
liverworts, 42
Manhattan Project, 50
marble, 58
Margulis, Lynn, 42
Mars, 16
Matson, Pamela, 119
Vitousek, Peter, 119
meat-heavy diets, food sustainability
strategies and, 195–99
meat-replacement products, 199
meltwater. See glacial meltwater
methane (CH₄): as greenhouse gas, 7,
32; from natural gas use, 169; stability
of, 7, 32
microbial organisms, 3. See also specific
organisms
mitochondria, 41–42
Mo. See molybdenum
modern photosynthesis: carbon in, 31;
cyanobacteria and, 31–32; evolution
of, 26
molybdenum (Mo), 39
Monument Valley, 15
Moore, Lisa Schulte, 202–6
mosses, 42
Mount Tambora, 71
N. See nitrogen
N₂O. See nitrous oxide
Naeem, Shahid, 18
National Academy of Sciences, 207
Natural Conservation Service, 203
natural gas, 11; electricity from, 169–
70; methane leaks from, 169
Newton, Isaac, 90–93; law of gravity,
91
NH₃. See ammonia
nitrate (NO₃⁻), 102
nitric acid (HNO₃), 114
nitric oxides (NO/NO₂), 102
nitrogen (N): absence from lava flows,
122; bacteria and, 106; biologically
unavailable, 29; carbon compared
to, 101–2; in cyanobacteria, 8–9,
38–39; distribution of, 27–29; in
DNA, 6; environmental loss of, 114;
German military uses of, 107–9; in
Haber-Bosch Process, 108–9, 113,
205–6; human production of, 11; as
inert gas, 29; as infinite source, 101;
irreplaceability of, 101, 117–18; in
soil, 106–7; in living cells, 2–3;
ocean deserts and, 6; in oceans,
27–29; photosynthesis limited by,
141; in rainforests, 21; reactive, 102;
recycling of, 208; triple-bonded, 29. See also nitrogenase; nitrogen fertilizers; nitrogen fixation.

nitrogenase, 30, 104–6; Great Oxidation Event and, 105; as promiscuous enzyme, 105

nitrogen fertilizers: development of, 108–9; fossil fuels and, 191; Haber-Bosch Process and, 110–13; increase in use of, 108–9, 192–93; inefficiency of, 113; non-fossil based, 209; soil bacteria and, 114

nitrogen fixation, 9, 106–7, 110–11, 199; biological, 30; evolution of, 35; in oceans, 37

nitrogen-rich foods, 159

nitrous oxide (N₂O): production of, 114; as greenhouse gas, 7, 32

NO₃⁻: See nitrate

non-fossil-based nitrogen fertilizers, 209

NO/NO₂. See nitric oxides

North America, energy use in, 166. See also United States

NPK fertilizer, 19–20

nuclear fuels, 77; electricity from, 169, 180

O. See oxygen

ocean “deserts”: 6, 22

sea level: climate change as influence on, 98

oceans: algae in, 22; anoxic, 24; archaea in, 22; bacteria in, 22; carbon in, 27; coral in, 51; cyanobacteria in, 38; desalinated water from, 145–46; distribution of life in, 22; food chains in, 37; greenness of, 23; hydrogen in, 27; nitrogen fixation in, 37; nitrogen in, 27–29; oxygen in, 27; photosynthetic organisms in, 38, 142; photosynthetic process in, 26–27. See also ocean deserts; Pacific Ocean

Ogallala Aquifer, 149–51

oil, 11. See also gasoline combustion

“On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground” (Arrhenius), 84–85

osmosis, water and, 154

Oxygen (Canfield), 31

oxygen (O): anoxia and, 9; in cyanobacteria, 9, 32–33, 164; during development of Earth, 9–10; free oxygen, 16, 35; in living cells, 2–3, 5; in oceans, 27; percentage of Earth’s atmosphere, 16; reactive, 17; role in decomposition, 52; as waste product, 35. See also Great Oxidation Event; water

P. See phosphorus

Pacific Ocean, 83–84; El Niño/La Niña climatic shifts, 84

pan-tropical climate, carbon dioxide causing, 49–50; cooling of, 54

phosphate ore, 128–29

phosphorus (P): in adenosine diphosphate, 118; in adenosine triphosphate, 118; commercial mining of, 132, 191; cost benefits of, 130; in cyanobacteria, 39; in DNA, 6, 118; as finite source, 118, 132; in fungi, 124; geologic rejuvenation of, 133–34; global distribution of ore, 132–33; human mining of, 11; land plants and, 117; leaching of, 137; in Life’s Formula, 10, 116–17; in living cells, 2–3;
phosphorus (P) (continued)
  long-term risks of pollution from, 133–35; photosynthesis limited by, 141; recycling of, 208–10; as a rock-derived element, 40; deposits, 132; in tropical rainforests, 21, 123–24, 187–90
  phosphorus fertilizers: algae growth from, 135–36; guano-based, 131; legumes and, 127; soybeans and, 127–30
  phosphorus-rich foods, 159
  photosynthesis: in cacti, 190; carbon dioxide capture in, 19, 38–39, 53–54; components of, 6; energy production through, 24–25; fast carbon cycle and, 59–60; in land plants, 42; modern, 26, 31, 38–39; nitrogen limitation to, 141; in ocean deserts, 22; in ocean forests, 22; in oceans, 26–27, 38, 142; oxygen as byproduct of, 9; phosphorus limitation to, 141; primitive, 25–26; respiration and, 60–61; stored energy from, 11; sunlight in, 20; water in, 5, 25, 143–44
  photosynthetic energy, 11
  Pioneer Valley, 15
  planetary boundaries concept, 138
  plant-based diets, 198–200
  plants: chloroplasts in, 41; evolution of, 3; nitrate, 102; water as constraint for, 20. See also land plants; ocean plants; specific plants
  pollution. See air pollution; water pollution
  population booms, 68–69, 100, 110
  poverty, 159
  Priestly, Joseph, 30; bell jar experiment, 17–19, 24, 58; putrefaction of air, 17–19, 24
  primitive photosynthesis, 25–26
  private homes, energy use in, 173–78
  promiscuous enzyme, 105
  proteins: amine group, 101; amino acids, 101–2; ammonia and, 102; carbon in, 6; legumes as source of, 107
  purple sulfur bacteria, 25
  putrefaction: of air, 17–19, 24; in bell jar experiment, 17–19, 24, 58; land plants and, 19
  rainfall, in future climate models, 156
  rainforests, tropical: in Amazon Rainforest, 22, 122, 124–25; biochemistry experiments in, 186, 188–89; in Congo region, 122; in Costa Rica, 20–22; dry seasons in, 190; nitrogen in, 21; phosphorus in, 21, 123–24, 187–90; root mats in, 123–24; variability of soils in, 21–22, 186–87. See also deforestation
  reactive nitrogen, 102
  recycling: in fungi, 188; as natural process, 38; of nitrogen, 208; of nutrients, 188; of phosphorus, 208–10; by root systems, 188; of sewage sludge, 205–6, 208–9
  regenerative agriculture, 204–5
  respiration: carbon dioxide from, in humans, 67–68; energy production through, 64; fast carbon cycle and, 60; photosynthesis and, 60–61; sugars and, 63
  “The Rime of the Ancient Mariner” (Coleridge), 27–28
  Riskin, Shelby, 124–27
rivers, as water source: for agricultural production, 147; damming of, 146
RNA, carbon in, 6
rock-derived elements, 39–40;
through dissolving of rocks, 53; in Life’s Formula, 40
root systems: in land plants, 44, 46–47;
recycling of nutrients by, 188

Sahara Desert, 23; aquifers under, 149
soil salinization, 153–55
Saskatchewan, 142
Saudi Arabia, 142, 209
Schindler, David, 135
Scott, Sheldon, 57–58, 63, 65
sedimentary rocks, 16
seeds, of land plants, 43, 47–48
La Selva Biological Station, 185–86
sewage sludge, recycling of, 205–6, 208–9
sewage treatment, in Haiti, 206–7
Sierra Nevada region, 6
simulations, in climate change models, 84
slow carbon cycle, 59, 62, 69; humans and, 65–66
Smil, Vaclav, 110
soil. See soils
SOIL. See Sustainable Organic Integrated Livelihoods
soil bacteria, nitrogen fertilizer transformations by, 114
soils: in Amazon Rainforest, 188–89;
carbon storage in, 50; on Hawaiian Islands, 121–22, 125–26; in Iowa, 202–6; iron oxides in, 123; from lava flows, 120; nutrient-poor, 188–89;
salty, 153–55; in tropical rainforests, 21–22, 186, 188–89
solar energy: incident on Earth, 77;
electricity from, 169, 180–82
soybeans, 126–30, 202; GMO, 129;
non-GMO, 129; phosphorus fertilizers and, 127–30
stomata, 142–43
succulents, 144, 190
sugars: carbon in, 6; respiration and, 63
sunlight: land plants and, 43; in photosynthesis, 20
super phosphates, 131
surface water, 145–46
Sustainable Organic Integrated Livelihoods (SOIL), 207
Sweden, 208
tectonic plates, 52, 61–62
temperatures, global: climate change as influence on, 70–73; after Industrial Revolution, changes in, 98.
See also climate change
thermodynamic laws, in climate change models, 95
tropical rainforests. See rainforests
United States (U.S.): air pollution in, 134; energy use in, 167; Environmental Protection Agency, 169;
Natural Conservation Service, 203;
Ogallala Aquifer, 149–51; phosphorus ore deposits in, 132; water pollution in, 134
University of Montana, 140
Urey, Harold, 50
U.S. See United States
vegetarian diets, 198–200
Venus, 16
Index

Vitousek, Peter, 36–37
volcanoes: carbon escape through, 59; in Hawaiian Islands, 120–21; Mount Tambora, 71

waste-derived fertilizer, 207
water (H\textsubscript{2}O): acidification of, 47, 50–51; carbon dioxide and, 47, 50–51; climate change and, 155; changes in access to, 155; use for growing crops, 145; desalinated, 145–46; as finite source, 151; from glacial meltwater, 157–58; as greenhouse gas, 7, 32; groundwater, 145–46, 148; human use of, 144–46, 151–52; irrigation systems, 152–53; osmotic processes, 154; in photosynthesis, 5, 25, 32, 143–44; plants constrained by, 20; movement of, 144–45; from rivers, 147–48; surface, 145–46
water pollution, 134
water retention, in land plants, 45–46, 52
wells, aquifers and, 150
wind energy, electricity from, 169, 181–82
World Health Organization, 112
World War I, nitrogen use during, by German army, 107–9