CONTENTS

INTRODUCTION

World-Changers

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 pan-tropical 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 configuration, 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 climate 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.

$H_{263}O_{110}C_{106}N_{16}P_{1}$ Cyanobacteria

$H_{375}O_{132}C_{88}N_{6}Ca_{1}P_{1}$ Humans

* 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): H = hydrogen, O = oxygen, C = carbon, N = nitrogen, Ca = calcium, and P = 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—H, O, C, N, and P.

What do organisms do with these elements? Joined in water, H and 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 (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor (H_2O).* 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 CO_2 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 O_2—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—H_2O). 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 H_2O) 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 CO_2 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