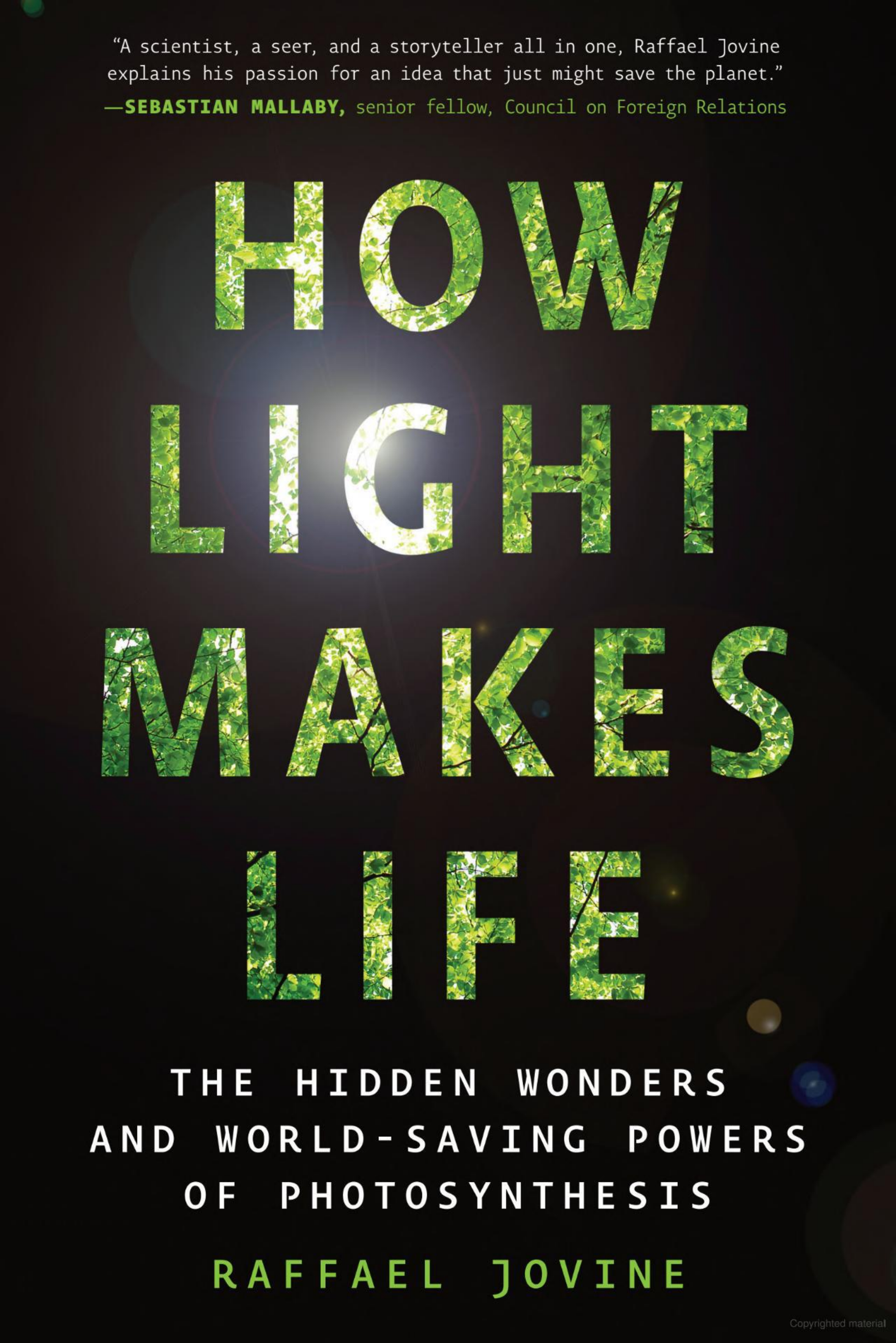

“A scientist, a seer, and a storyteller all in one, Raffael Jovine explains his passion for an idea that just might save the planet.”
—**SEBASTIAN MALLABY,** senior fellow, Council on Foreign Relations

HOW LIGHT MAKES LIFE

THE HIDDEN WONDERS AND WORLD-SAVING POWERS OF PHOTOSYNTHESIS

RAFFAEL JOVINE

HOW LIGHT MAKES LIFE: *The Hidden Wonders and World-Saving Powers of Photosynthesis*

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PROLOGUE

"I remember in college another guy and I had an idea that—mind if I talk about myself?"

"If you don't, I will."

"Well, this guy and I had this idea. We wanted to find out what made the grass grow green. That sounds silly and everything but the biggest research problem in the world is there. I tell you why. Because there is a tiny little green engine in the green of this grass and in the green of the trees that has a mysterious gift of being able to take energy from the rays of the sun and store it up. You see that's how the heat and power in coal and oil and wood is stored up. We thought that if we could find the secret of all those millions of little engines in this green stuff, we can make big ones. And then, we can take all the power we can ever need right from the sunrays, you see . . ."

"That's wonderful, I never knew that."

"We worked on that, worked on, day and night, we got so excited we forgot to sleep. If we

made just one little discovery, we would walk on air for days . . ."

"Yes? And then what?"

"Well, then we left school. Now he is selling automobiles and I'm in some strange thing called banking."

—Jean Arthur and James Stewart, *You Can't Take It with You* (1938), Columbia Pictures

My long relationship with photosynthesis began with this 1938 black-and-white romantic comedy, in which a love-struck banker's son convinces a brilliantly eccentric academic's daughter to marry him. The pivotal moment is when the banker's son finally reveals his abandoned passion for research into the hidden power of plants.

Until I saw this movie, I had been a sickly kid who worked as a child actor instead of attending school. I was mesmerized. "That green engine thing makes so much sense!" I shouted in my head. I concluded if that is what it takes to get the girl, I needed to know everything about this enigmatic thing called photosynthesis.

I stopped skipping school and, with the help of an inspired teacher, I learned how to build a greenhouse. My acting career was over, and I became the first conventional high-school graduate in my bohemian family. Studying photosynthesis took me from being an actor to completing post-doctorate studies in molecular biophysics and biochemistry.

You Can't Take It with You is not really a film about plants and science. Most people watching it would say it explores whether material wealth provides emotional satisfaction. Fortunately, in the eighty-two years since it was made, much more progress has been made in photosynthesis research than in answering questions about what makes us happy.

I still want to store the power of sunrays. Unfortunately, studying photosynthesis does not always get you the girl. Fortunately, I did not know that at the time.

Why write about photosynthesis?

Photosynthesis is the conversion of sunlight into chemical energy, which involves an indescribably intricate collection of biological processes. This book does not explore this beautiful and complex machinery. Instead, it looks at what the value and the impact of this "green stuff" is, for people and for the planet. This book is not intended for teaching purposes. It definitely will not suffice as reference material and it will skip over vast bodies of brilliant research. But it can, I hope, communicate at least some of that tingle of glee and wonderment scientists feel when we get the chance to reveal a tiny facet of the magic of nature.

It is a process that, as so often with biology, is described as if it was merely reacting to survive chemical, geological, or cosmic pressures. Such a view obscures how turning light into life has shaped our planet and continues to do so. Photosynthesis does not happen in spite of the foundational and powerful forces of nature; photosynthesis itself is one of these forces.

Almost from the beginning of life on Earth, photosynthesis has generally increased living spaces and vital resources. It has transformed our oceans, created our atmosphere, sculpted our mountains and continents. It has turned our once hyper-hostile young planet into a vibrant, elegant, and abundant world into which it is still pumping more life energy and usable energy than anything else does. At the same time, it has managed to be gorgeous, colorful, and surprising.

Our own species, one that shares about 40 percent of our genes with apples, is very much a direct product of this process. The deliberate manipulation of photosynthesis has largely been responsible for the mind-boggling success of *Homo sapiens*. Today, amid all the challenges we face, photosynthesis remains a dominant force large enough, fast enough, and powerful enough to rebalance our complicated world, even after hundreds of years of human mismanagement. It is the most affordable and attainable way to repair our exhausted ecosystems before we run out of time. And it will do all this while feeding us, providing us with new jobs, and improving habitats for all creatures great and small.

But only if we let it.

The exploitation of our natural environment in ugly and counterproductive ways is continuing to accelerate. The developed world wants to protect the enormous gains it has created in health and wealth by gobbling up the last remaining resources. Developing nations want to use more energy and consume even more of the same resources to catch up.

Across the world, policy makers and business, community and spiritual leaders are beginning to experiment with carbon taxes or similar disincentives to reduce carbon emissions. We are constantly reminded that too much carbon dioxide is destabilizing our weather and responsible for everything from floods to famine.

Such efforts to reduce carbon use are clearly necessary but they are also insufficient. Without the natural removal of emissions from the environment, emissions will continue to accumulate. We need to not only reduce emissions but also increase the planetary capacity to regenerate and refresh the atmosphere. In practice, there is only one way to do this.

Amid all the noisy and bitter arguments over weather, photosynthesis has spent four billion years quietly broadcasting a constructive, consistent, and positive message every day on every continent and across every ocean. You can taste, smell, touch, and see the benefits of photosynthesis every time you eat and with every breath you take.

Photosynthesis is the original, largest, and most powerful "Net Negative" technology ever, and it is at our fingertips right now. Increasing photosynthesis is something that every one of us can do, no matter where we live or what our income bracket. It works everywhere in the world and, compared to any other carbon reduction measures, it is extremely affordable.

In this book, I hope to show that we have everything we need to stop global degradation while continuing to succeed as a species and develop our economies. Rebuilding our world is surprisingly easy to do and good for our health as well. Every seed carries the instructions to save our world.

The book is structured in seven chapters.

The first tells the story of how photosynthesis was discovered. It is stranger than you might expect because, for a long time, we did not understand what was staring us in the face. Gradually, over the course of four hundred years, human ingenuity deciphered the riddle of how sunlight turns inorganic matter into food. In doing so, we transformed our limited and pessimistic relationship with nature to one where we can feed the world, even with an enormous population.

Chapter 2 outlines our planet's relationship with photosynthesis. It shows how sun-fueled biological processes have made the world we know today and why biology is more than powerful enough to transform it again, several times over.

Chapter 3 asks who—or what—is actually responsible for this magic. The answer to this is full of surprises, with new organisms that have global impact still being discovered today. The richest resources and environments on our planet are created by a collaboration of photosynthesizing plants and animals, including ourselves.

Chapter 4 looks at different forms of photosynthesis across oceans and on land. It challenges preconceptions about how best we can absorb carbon and rebalance our planet's fragile systems. There are enormous opportunities, on every continent, in every environment.

In chapter 5, I posit reasons to be both alarmed and hopeful. The "good news" emphasizes the immense hurdles our species has overcome before and shows why we can yet find sustainable solutions to the huge challenges ahead. The "bad news" sets out just how far and how fast our excesses are unraveling hundreds of millions of years of biological progress.

Chapter 6 seeks to put a value on photosynthesis. Almost everything worth anything in our economies is either directly or indirectly made possible because of the process of harnessing sunlight energy, which is provided to us absolutely free. And, if we can show how valuable it is, perhaps people might appreciate it more.

And finally, in chapter 7, I ask where we can go from here. We have a choice. We can actively grow our planet again. We can produce more food, sustain more life, and create a fairer world. And, yes, we can do this while making more money, too. Best of all, each one of us, no matter our circumstances, can make a constructive, life-affirming contribution.

Scientists are humans and, as such, are sometimes driven by the desire to get rich or squeeze more profit from nature. More often we are simply inspired by our love for the weird, wonderful, dazzling organisms that we study. And all of us hope that we may have the chance to make the world a bit better.

I know this to be true because those same motivations have driven me. I started out by building and planting a greenhouse in secondary school because I loved watching things grow. Even then I wanted to be a research biologist mostly because it was the most exotic work I could imagine, so much more interesting than the boring films my family made. Those were the days when the new discipline of genetic engineering was all over the news and I wanted to tailor organisms like Eldon Tyrell did in

Blade Runner; I wanted to grow new eyes for my blind brother.

In college, I learned the first DNA sequencing methods and how to manipulate genes in yeast, and how to crystallize proteins. After graduating in molecular biochemistry and biophysics, I took a job in a research lab at a time when chemical photosynthesis was all the rage, and I tried to help decode how light energy is converted into chemical energy so that we could make biologically inspired solar-electricity-generating cells.

But my first piece of fieldwork, looking at marine photosynthesis, made me realize that months in laser laboratories had not prepared me sufficiently to learn about its true potential. Organisms in the real world are more sophisticated and resilient than I had ever imagined. Watching the response of the algae that lived under the ice in Antarctica to the Ozone Hole demonstrated that natural communities were flexible, responsive, and tougher than I would have believed as a molecular biologist. When the conditions are just right for them, many algae can quickly acclimatize to their environment and divide so fast that they outgrow everything around them. I began studying what triggered algal "blooms" so that we might be able to prevent and better manage so-called red tides, which can disrupt ecological systems.

Then life interfered again in the form of a growing family and a recession. I became a management consultant and, just as interest in algal biofuels began to intensify, found myself working on balance sheets to help merge pharmaceutical companies.

Stuck in the office, I dreamed of field work. I missed algae. When my biologist friends complained it was too expensive to grow algae and told me that the US Navy was paying $700 per gallon of biofuel, I was puzzled. Algae had been growing on a truly enormous scale for free, like clockwork, every spring and autumn, for three and a half billion years. Puddles automatically fill with algae. Which made me ask, "Exactly what is so difficult about growing algae?"

Using my newfound consultant skills, I evaluated what made growing them so expensive. Brilliant engineers had attempted to grow known laboratory strains of algae to an industrial scale in artificial conditions. The results were clever but the systems were complex and brittle with enormous costs. At every stage, the objective was to control the organisms both inside and outside the reactors, whereas in nature, the organisms control their environment. In an effort to copy nature, I started looking at how to apply the "bloom" formation process found offshore to growing algae in man-made ponds. I designed and patented a process that replaced the expensive heavily engineered methods with low-cost natural ones.

Given population and environmental trends, I knew we would need more food. I hoped I could address an imbalance and started a company. Soon we were testing the idea at an abalone farm in South Africa. Next was a research project in Oman that was 260 times larger, followed by a site 15 times larger than that in the Sahara Desert in Morocco. Unsurprisingly, working with nature is challenging, but we are now growing microalgae to produce animal feed, human food, high-value chemicals, pigments, and pharmaceuticals. We are creating a new very valuable food out of desert, seawater, and sunlight. We are increasing the size of our production system and, in our small way, doing a bit to help rebalance the planet—by using the oldest growth system on Earth.

Although we live in a troubled world, we can all explore new opportunities to make a better and richer one.

Time and time again our species has overcome seemingly impossible challenges. We can do so again. And, best of all, every one of us can contribute in a practical way—without having to go to the desert to grow algae—while having a lot of fun.

CHAPTER 1

WHAT IS PHOTOSYNTHESIS?

When my wife wants to get my attention with an urgent email, she writes "Algae, Algae, Algae" in the subject line. Embarrassingly, I fall for this trick every time. However, I will reluctantly concede that not everyone is as fascinated by single-celled organisms as I am.

And I will also recognize that many readers may be forgivably hazy as to what this weird fourteen-letter word "photosynthesis" means. Some may even have bad childhood memories of trying to learn the following formula:

$$6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$$

So, at the outset of this book, let me try to describe this miraculous energy machine.

1. Photosynthesis is the process by which biological organisms capture light energy to combine simple environmental chemicals like water and gases and convert them into useful and more complex compounds that fuel growth, reproduction, movement, and almost all life on this planet.

2. Organisms that use such external energy sources are called primary producers. These form the base for all food chains, including our own.

3. Photosynthesizing organisms are not just green land plants. There are many others that are very important for balancing global nutrient, energy, and chemical cycles.

Discovery

Until four hundred years ago, the conventional wisdom was that plants "ate" dirt. Yes, we believed those green rascals chomped on the soil. People held this view despite tens of thousands of years in which they had tended, observed, selected, named, classified, and processed plants with the greatest care and sensitivity.

We had discovered that fruit, grains, nuts, and berries make highly nutritious food, and storing it for lean times obviously made sense even to stone-age hunter-gatherers.

Planting crops enabled people in lush and meteorologically benign places to settle. Producing, trading, and preparing food became—as it still is today—a major source of wealth and employment across the world. Our clothing, housing, and very survival depended on growing plants.

Throughout all this time, humans—the smartest creature on the planet—had prospered by learning from their environment and noticing the smallest of details. And still, somehow, for several millennia, people did not spot that plants need light. Instead, the prevailing dogma was that plants consume the soil that they grow on. I suppose it is possible to see how such a misconception could have started. Fallow fields, which have had a season to recuperate after a harvest, do better than those that are continuously farmed. Spent soils are spent. That is still true today, so maybe the misconception that plants eat soil was related to our understanding of the need to recharge the land.

Even so, it is still pretty remarkable that we did not make a connection with light. The sprout on a potato that has been stored over winter in a light-tight basket is yellow. If you then take it out and expose it to light, the same sprout turns green within a day. Surely people observed such changes in coloration? You would have thought that farmers would have made the connection between light and the satisfying green look of plants; that Peruvian potato cultivators, who cherished their beautiful flowers, would have worked out how much light their favorite spuds needed. What about sunflowers that turn their faces to the sun? It seems improbable that nobody made the connection between growth and the sun, and yet it was not documented.

Mystics, priests, and physicians

It was not until the seventeenth century that a better understanding began to emerge but, frankly, even then it was faltering progress.

The first breakthrough came from a Flemish alchemist whose medical experiments, apparently inspired by dreams of the archangel Raphael, had to be hidden from the Spanish Inquisition. Jan Baptist van Helmont was a physician primarily focused on the study of human physiology. He introduced the mystical term "gas" into medical literature. He discovered that the "fermenting must"—carbon dioxide in today's language—made the air in wine cellars unbreathable and was carried in blood running through veins and expelled by the lungs.

In the 1620s, van Helmont turned his attention to testing the dogma that soil was consumed by plants. He cultivated a willow tree sapling in a covered pot, filled it with two hundred pounds of carefully weighed and dehydrated soil, then watched the tree grow. Five years later, he found the tree had gained 169 pounds in weight, while the soil weighed only two ounces less. He concluded, partially correctly, that plants consume water instead of soil. One can quibble with the exact methods, but this was the first modern reference to a structured and often repeated experiment that tested what plants need to grow.

Like so many discoveries in science, the idea for it had probably been around a lot longer. Leonardo da Vinci had conducted a similar experiment with pumpkin seeds that was later discovered in his unpublished notebooks.[1] Da Vinci, in turn, may have been inspired by Nicholas of Cusa, who suggested the experiment in his book *De staticis experimentalis* in 1450.[2] And Nicholas of Cusa himself may have been inspired by a Greek text dated between 200 and 400 CE called *Recognitions*. Ideas can hang around for thousands of years before someone actually tests them.

Van Helmont got us halfway there by proving that plants don't eat soil. Ironically for someone who had studied the biological function of carbon dioxide, he completely missed the fact that his tree was consuming gases and light. Perhaps, had the Spanish Inquisition not placed him under house arrest for blasphemy, his findings might have been debated and repeated sooner. Instead, they remained unnoticed until 1648, when his book *Ortus Medicinae*[3] was published posthumously by his son.

A further advance in human knowledge almost happened in 1679 when a French physicist and priest, Edme Mariotte, developed a theory that plants might acquire part of their nourishment from the air. He was a gifted man who was present at the foundation of the French L'Académie des Sciences, but unfortunately he failed to publish his findings. Indeed, *Discours de la nature de l'air, de la végétation des plantes. Nouvelle découverte touchant la vue* only made it into print 250 years later, in 1923.[4] Note to young scientists: Please publish, disseminate, test, repeat, and discuss your findings—do not expect your ideas to emerge by magic. And, even then, sometimes ideas have to circulate for a long time before they are accepted.

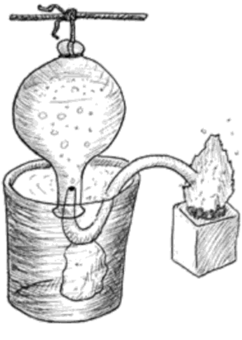

Figure 1: In 1727, Stephen Hales built his own equipment to trap gases, which could then be fed to plants. Image of combustion gas trap redrawn from Vegetable Staticks [*sic*].

Instead, we had to wait until the eighteenth century for the next landmark on this slow journey of scientific discovery. Stephen Hales, an English clergyman whose many achievements included the first measure of blood pressure, began studying a process called transpiration—or the loss of water from leaves. He surmised that "plants very probably draw through their leaves some part of their nourishment from the air."

Huffing and puffing through his lung-powered homemade bellows and strange "re-breathing" machines, he experimented with inverted bottles, and observed that the volume of air above the water surface decreased when a plant was grown in a closed atmosphere. He concluded that air was "being imbibed into the substance of the plant." In his 1727 book, *Vegetable Staticks,*[5] he even conjectured that light might be an energy source for plants.

These ideas began to percolate through Europe. In 1779, a Dutch physician called Jan Ingenhousz decided to test the idea that plants exchange air by submerging leaves under water in sealed bottles and then waiting for bubbles to form. Bottle after bottle of drowned leaves testified to the failure of these early experiments until a shaft of sunlight accidentally illuminated one of his bottles. Within minutes, he was watching the formation of the long-awaited bubbles.

Ingenhousz, anchored in the scientific tradition of the day, was surprised that light had anything to do with it. He repeated the experiment with many different plants in dark and light bottles. He even tested whether it was thermal heating from his fireplace or the visible light of the sun that caused the bubbles to form. Eventually, he deduced that light was necessary for bubble formation and concluded the released gas was "fire air," soon to be called oxygen. He went on to test which gases were emitted in the dark and described these as "damaging the air" in contrast to those emitted during the day, which "purified" the air. Today we know that the plants removed carbon dioxide from spent air during the day.

By the end of the Enlightenment, we were really making progress, and scientific understanding of photosynthesis was about to take a giant step forward, thanks to Erasmus Darwin. He was a polymath physician, pathologist, and botanist, as well as the grandfather of the rather more famous Charles Darwin. He was also a slave-trade abolitionist, a supporter of women's education (especially for his illegitimate daughters), and the writer of bizarre poems such as "The Loves of the Plants."[6] It was in this poem in 1789 that he first touched on heavily concealed concepts of biological evolution.

This poem, found in Part II of Darwin's book *The Botanic Garden,* is prefaced with an "Apology" that outlines how it presents theories and scientific information through the deployment of mythic beings—gnomes, sylphs, nymphs, and salamanders, as well as deities of Egypt, Rome, and Greece—in the hope of making them more accessible. Without an index or any discernible structure, the poem merrily jumps from topic to topic. For example, the first canto contains the following order of subjects: "Hesperian Dragon, Electric Kiss. Halo around the heads of Saints, Electric Shock, Lightning from Clouds. Cupid snatches the Thunder-bolt from Jupiter, Phosphoric Acid and Vital Heat produced in the Blood. The Great Egg of Night. Western Wind unfettered." *The Botanic Garden* is made up of two books, each with four cantos, and the whole thing is a wild muddle, interspersed with additions, arguments, footnotes, and lists of scientific findings and data.

Yet, in "Note 5" on Sun Rays, Erasmus Darwin adds the following to Canto 1.I.136:

> Some modern philosophers are of opinion that the sun is the great fountain from which the Earth and other planets derive all the phlogiston [burnable material] which they possess; and that this is formed by the combination of the solar rays with all opake [sic] bodies, but particularly with the leaves of vegetables, which they supposed to be organs adapted to absorb them. And that animals receive their nourishment from vegetables they also obtain in a

> secondary manner their phlogiston from the sun. And lastly as great masses of the mineral kingdom, which have been found in the thin crust of the earth which human labour has penetrated, have evidently been formed from the recrements of animal and vegetable bodies, these are also supposed thus to have derived their phlogiston from the sun.

The additional notes added to the poem continue with some wildly improbable theories about how the sun works. Yet, in his obscure way, Darwin had stumbled on exactly what happens with photosynthesis and plant growth.

Emerging from this melange of archangels, alchemy, sylphs, and experiments with homebuilt apparatuses was a new understanding that plants absorbed air and water to produce usable energy. Crucially, this early biology had also enabled people to see that sunlight was necessary for the process of turning water and gases into food and oxygen. This is the core tenet of photosynthesis. Although this new idea took hundreds of years to develop, it eventually removed the misapprehension under which human beings had labored for millennia: that plants ate soil.

There is another lesson in these stories. Even at a time when communications were desperately slow and books were being published posthumously by quirky investigators, ideas could still migrate across countries, grow, and trigger structured experimentation. Sure, the equipment was crude, messages were concealed in obscure analogies, and progress was painfully slow. Of course, many other scientists confounded the debate, with learned repetition of the status quo. Yet the lessons from these experiments were reproducible and demonstrable, and slowly they began to transform our understanding of nature.

Think for a moment about the danger of the old belief that land was being consumed by hungry green creatures called plants. This view made the world a finite, declining, and pessimistic place. In contrast, by learning that plants turn sunlight, water, and air into food, we discovered that the world was not finite—that there was "new" production. And that this plant-mediated production complemented our animal-based consumption: They inhale what we exhale. Instead of a world in which plants and animals were both eating up a limited amount of food and land on the planet, we were understanding that expansion and growth were possible. And, at the dawn of the nineteenth century, that was very necessary.

Feeding the masses, fueling the revolution

The sporadic scientific progress being made by alchemists, priests, poets, and physicians was about to accelerate. Revolutions—political, agricultural, and industrial—were creating modern nation-states with educated, organized, and potentially rebellious populations that demanded ever-greater quantities of food.

Three scientists, all of them very much products of their tumultuous century, and often a degree of personal torment, deserve credit for advancing our knowledge at this crucial time.

The first of them was Justus Liebig. Growing up in Darmstadt in the Rhineland, he experienced the famine of 1816—the "year without a summer"—when food crops were destroyed under the darkened skies caused by the explosion of the Tambora volcano in Indonesia. The experience is said to have shaped his later work as the founder of agrochemistry, a branch of science that would harness the power of plants to feed the world like never before.

His first experience of chemistry was helping his father mix paints and pigments for sale while experimenting with "fulminating mercury." Then bad things began happening to him. He was expelled from his pharmaceutical apprenticeship after burning down the attic of his mentor. Later he was forced to flee university because of his sympathies for nascent German nationalism. But Liebig got a second—and even a third—chance, possibly because he was a particularly beautiful young man. His sonnet-writing friend August Platen described him as a "lean figure, with an earnest friendliness in his symmetric face and large brown eyes with shadowy eyebrows, [which] arrest you in first seeing him."[7] He secured a grant to study at the Sorbonne in Paris with many of chemistry's greatest minds, including Alexander von Humboldt, who, impressed with Liebig's explosive mercury experiments, recommended him for a professorship at the University of Giessen. Some of the faculty there did not appreciate having a young professor with dodgy revolutionary ideas foisted on them and, initially, to make things worse, his fertilizer experiments failed. Ridiculed by his colleagues, struggling with funding, and sometimes paying for his staff and laboratory out of his own salary, he updated his book *Agrikulturchemie* seven times before it was published in its final form in 1856.

Finally, while struggling through multiple episodes of exhaustion, he succeeded in creating new nitrogen-based chemical fertilizers that would increase yields at reduced cost. He also demonstrated how depleted soils must be replenished with organic matter to support their health. He thus established for the first time a method and the tools by which farm yields could be improved on exhausted soils, without farmers having to leave the fields fallow while they regenerated naturally.

In the meantime, Liebig also co-discovered chloroform, found less toxic ways to make mirrors, revolutionized analytical chemistry, invented baking powder, created a meat extract to treat cholera patients