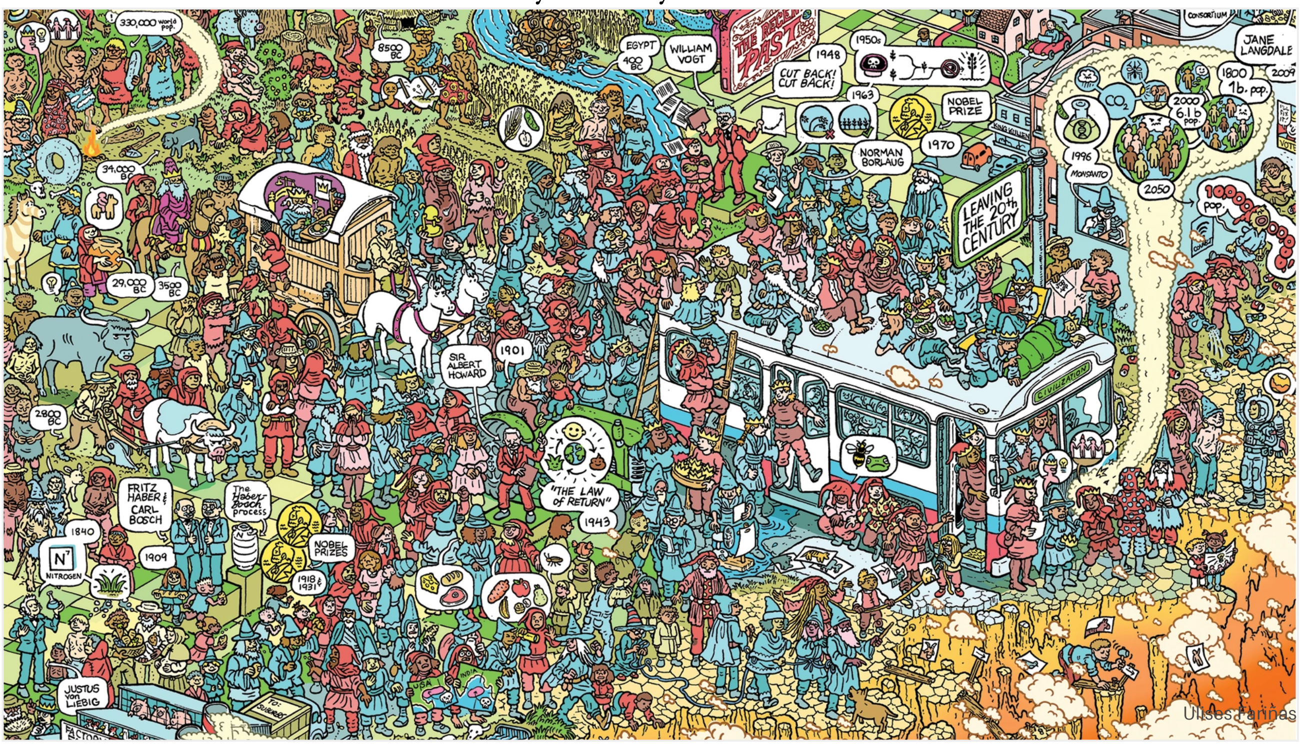
The Atlantic

Can Planet Earth Feed 10 Billion People?

Humanity has 30 years to find out.



Ulises Fariñas

Story by Charles C. Mann

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All parents remember the moment when they first held their children—the tiny crumpled face, an entire new person, emerging from the hospital blanket. I extended my hands and took my daughter in my arms. I was so overwhelmed that I could hardly think.

Afterward I wandered outside so that mother and child could rest. It was three in the morning, late February in New England. There was ice on the sidewalk and a cold drizzle in the air. As I stepped from the curb, a thought popped into my head: *When my daughter is my age, almost 10 billion people will be walking the Earth*. I stopped midstride. I thought, *How is* that *going to work?*

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In 1970, when I was in high school, about one out of every four people was hungry—"undernourished," to use the term preferred today by the United Nations. Today the proportion has fallen to roughly one out of 10. In those four-plus decades, the global average life span has, astoundingly, risen by more than 11 years; most of the increase occurred in poor places. Hundreds of millions of people in Asia, Latin America, and Africa have lifted themselves from destitution into something like the middle class. This enrichment has not occurred evenly or equitably: Millions upon millions are not prosperous. Still, nothing like this surge of well-being has ever happened before. No one knows whether the rise can continue, or whether our current affluence can be sustained.

Today the world has about 7.6 billion inhabitants. Most demographers believe that by about 2050, that number will reach 10 billion or a bit less. Around this time, our population will probably begin to level off. As a species, we will be at about "replacement level": On average, each couple will have just enough children to replace themselves. All the while, economists say, the world's development should continue, however unevenly. The implication is that when my daughter is my age, a sizable percentage of the world's 10 billion people will be middle-class.

Affluence is not our greatest achievement but our biggest problem.

Like other parents, I want my children to be comfortable in their adult lives. But in the hospital parking lot, this suddenly seemed unlikely. *Ten billion mouths*, I thought. Three billion more middle-class appetites. How can they possibly be satisfied? But that is only part of the question. The full question is: How can we provide for everyone without making the planet uninhabitable?

Bitter Rivals

WHILE MY CHILDREN WERE GROWING UP, I took advantage of journalistic assignments to speak about these questions, from time to time, with experts in Europe, Asia, and the Americas. As the conversations accumulated, the responses seemed to fall into two broad categories, each associated (at least in my mind) with one of two people, both of them Americans who lived in the 20th century. The two people were barely acquainted and had little regard for each other's work. But they were largely responsible for the creation of the basic intellectual blueprints that institutions around the world use today for understanding our environmental dilemmas. Unfortunately, their blueprints offer radically different answers to the question of survival.

The two people were William Vogt and Norman Borlaug.

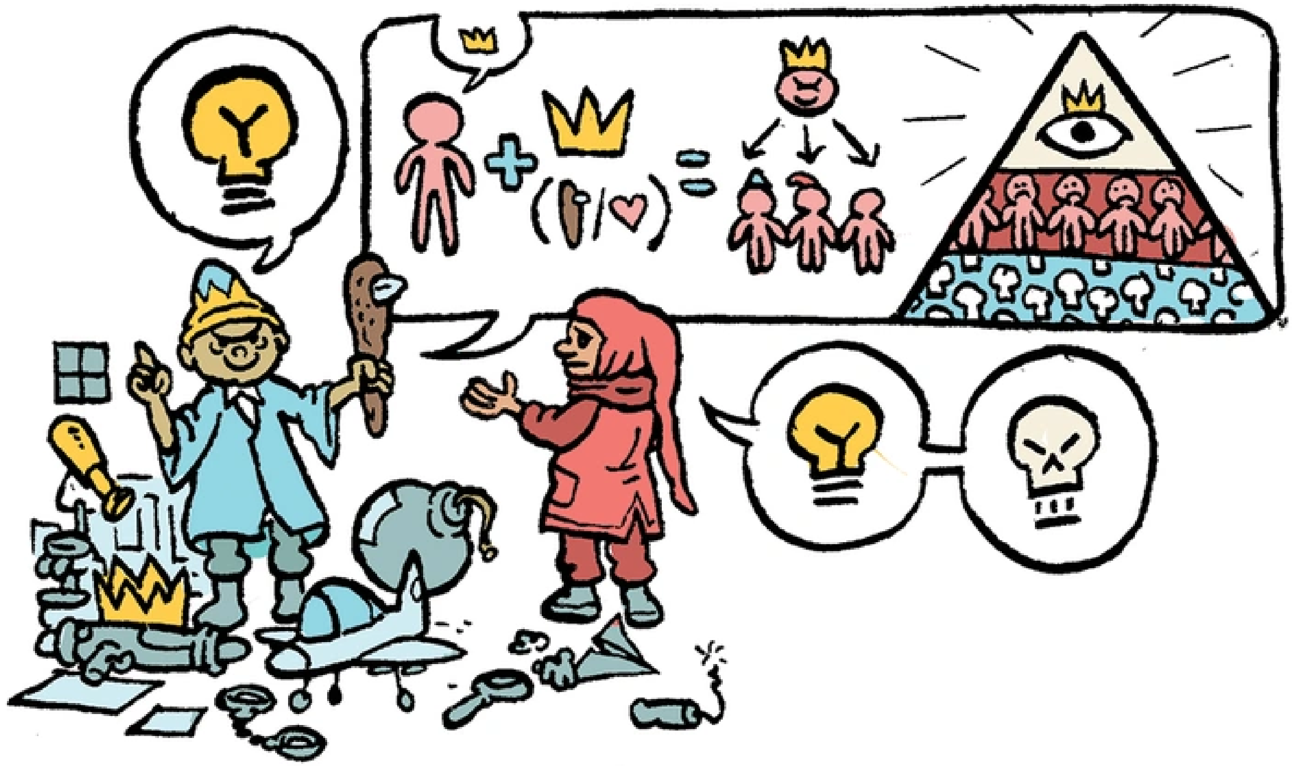
Vogt, born in 1902, laid out the basic ideas for the modern environmental movement. In particular, he founded what the Hampshire College population researcher Betsy Hartmann has called "apocalyptic environmentalism"—the belief that unless humankind drastically reduces consumption and limits population, it will ravage global ecosystems. In best-selling books and powerful speeches, Vogt argued that affluence is not our greatest achievement but our biggest problem. If we continue taking more than the Earth can give, he said, the unavoidable result will be devastation on a global scale. *Cut back! Cut back!* was his mantra.

Borlaug, born 12 years after Vogt, has become the emblem of "techno-optimism"—the view that science and technology, properly applied, will let us produce a way out of our predicament. He was the best-known figure in the research that in the 1960s created the Green Revolution, the combination of high-yielding crop varieties and agronomic techniques that increased grain harvests around the world, helping to avert tens of millions of deaths from hunger. To Borlaug, affluence was not the problem but the solution. Only by getting richer and more knowledgeable can humankind create the science that will resolve our environmental dilemmas. *Innovate! Innovate!* was his cry.

Both men thought of themselves as using new scientific knowledge to face a planetary crisis. But that is where the similarity ends. For Borlaug, human ingenuity was the solution to our problems. One example: By using the advanced methods of the Green Revolution to increase per-acre yields, he argued, farmers would not have to plant as many acres, an idea researchers now call the "Borlaug hypothesis." Vogt's views were the opposite: The solution, he said, was to use ecological knowledge to get smaller. Rather than grow more grain to produce more meat, humankind should, as his followers say, "eat lower on the food chain," to lighten the burden on Earth's ecosystems. This is where Vogt differed from his predecessor, Robert Malthus, who famously predicted that societies would inevitably run out of food because they would always have too many children. Vogt, shifting the argument, said that we may be able to grow enough food, but at the cost of wrecking the world's ecosystems.

I think of the adherents of these two perspectives as "Wizards" and "Prophets." Wizards, following Borlaug's model, unveil technological fixes; Prophets, looking to Vogt, decry the consequences of our heedlessness.

Borlaug and Vogt traveled in the same orbit for decades, but rarely acknowledged each other. Their first and only meeting, in the mid-1940s, led to disagreement —immediately afterward, Vogt tried to get Borlaug's work shut down. So far as I know, they never spoke afterward. Each referred to the other's ideas in public addresses, but never attached a name. Instead, Vogt rebuked the anonymous "deluded" scientists who were actually aggravating our problems. Borlaug branded his opponents "Luddites."



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Both men are dead now, but the dispute between their disciples has only become more vehement. Wizards view the Prophets' emphasis on cutting back as intellectually dishonest, indifferent to the poor, even racist (because most of the world's hungry are non-Caucasian). Following Vogt, they say, is a path toward regression, narrowness, poverty, and hunger—toward a world where billions live in misery despite the scientific knowledge that could free them. Prophets sneer that the Wizards' faith in human resourcefulness is unthinking, ignorant, even driven by greed (because refusing to push beyond ecological limits will cut into corporate profits). High-intensity, Borlaug-style industrial farming, Prophets say, may pay off in the short run, but in the long run will make the day of ecological reckoning hit harder. The ruination of soil and water by heedless overuse will lead to environmental collapse, which will in turn create worldwide social convulsion. Wizards reply: *That's exactly the global humanitarian crisis we're preventing!* As the finger-pointing has escalated, conversations about the environment have turned into dueling monologues, each side unwilling to engage with the other.

Which might be all right, if we weren't discussing the fate of our children.

The Roads to Hell

VOGT ENTERED HISTORY IN 1948, when he published *Road to Survival*, the first modern we're-all-going-to-hell book. It contained the foundational argument of today's environmental movement: carrying capacity. Often called by other names —"ecological limits," "planetary boundaries"—carrying capacity posits that every ecosystem has a limit to what it can produce. Exceed that limit for too long and the ecosystem will be ruined. As human numbers increase, *Road to Survival* said, our demands for food will exceed the Earth's carrying capacity. The results will be catastrophic: erosion, desertification, soil exhaustion, species extinction, and water contamination that will, sooner or later, lead to massive famines. Embraced by writers like Rachel Carson (the author of *Silent Spring* and one of Vogt's friends) and Paul Ehrlich (the author of *The Population Bomb*), Vogt's arguments about exceeding limits became the wellspring of today's globe-spanning environmental movement—the only enduring ideology to emerge from the past century.


William Vogt (Denver Public Library, Western History Photographic Collections)

When *Road to Survival* appeared, Borlaug was a young plant pathologist working in a faltering program to improve Mexican agriculture. Sponsored by the Rockefeller Foundation, the project focused on helping the nation's poor corn farmers. Borlaug was in Mexico for a small side project that involved wheat—or rather, black stem rust, a fungus that is wheat's oldest and worst predator (the Romans made sacrifices to propitiate the god of stem rust). Cold usually killed stem rust in the United States, but it was constantly present in warmer Mexico, and every spring winds drove it across the border to reinfect U.S. wheat fields.

The sole Rockefeller researcher working on wheat, Borlaug was given so little money that he had to sleep in sheds and fields for months on end. But he succeeded by the mid-'50s in breeding wheat that was resistant to many strains of rust. Not only that, he then created wheat that was much shorter than usual—what became known as "semi-dwarf" wheat. In the past, when wheat was heavily fertilized, it had grown so fast that its stalks became spindly and fell over in the wind. The plants, unable to pull themselves erect, had rotted and died. Borlaug's shorter, stouter wheat could absorb large doses of fertilizer and channel the extra growth into grain rather than roots or stalk. In early tests, farmers sometimes harvested literally 10 times as much grain from their fields. Yields climbed at such a rate that in 1968 a USAID official called the rise the Green Revolution, thus naming the phenomenon that would come to define the 20th century.

Norman Borlaug (Courtesy of Rockefeller Archive Center)

The Green Revolution had its most dramatic effects in Asia, where in 1962 the Rockefeller Foundation and the Ford Foundation opened the International Rice Research Institute (IRRI) in the Philippines. At the time, at least half of Asia lived in hunger and want; farm yields in many places were stagnant or falling. Governments that had only recently thrown off colonialism were battling communist insurgencies, most notably in Vietnam. U.S. leaders believed the appeal of communism lay in its promise of a better future. Washington wanted to demonstrate that development occurred best under capitalism. IRRI's hope was that top research teams would transform Asia by rapidly introducing modern rice agriculture—"a Manhattan Project for food," in the historian Nick Cullather's phrase.

Following Borlaug's lead, IRRI researchers developed new, high-yielding rice varieties. These swept through Asia in the '70s and '80s, nearly tripling rice harvests. More than 80 percent of the rice grown in Asia today originated at IRRI. Even though the continent's population has soared, Asian men, women, and children consume an average of 30 percent more calories than they did when IRRI was founded. Seoul and Shanghai, Jaipur and Jakarta; shining skyscrapers, pricey hotels, traffic-jammed streets ablaze with neon—all were built atop a foundation of laboratory-bred rice.

It is as if humankind were packed into a bus racing through an impenetrable fog. Somewhere ahead is a cliff: a calamitous reversal of humanity's fortune.

Were the Prophets disproved? Was carrying capacity a chimera? No. As Vogt had predicted, the enormous jump in productivity led to enormous environmental damage: drained aquifers, fertilizer runoff, aquatic dead zones, and degraded and waterlogged soils. Worse in a human sense, the rapid increase in productivity made rural land more valuable. Suddenly it was worth stealing—and rural elites in many places did just that, throwing poor farmers off their land. The Prophets argued that the Green Revolution would merely postpone the hunger crisis; it was a one-time lucky break, rather than a permanent solution. And our rising numbers and wealth mean that, just as the Prophets said, our harvests will have to jump again—a second Green Revolution, the Wizards add.

Even though the global population in 2050 will be just 25 percent higher than it is now, typical projections claim that farmers will have to boost food output by 50 to 100 percent. The main reason is that increased affluence has always multiplied the demand for animal products such as cheese, dairy, fish, and especially meat—and growing feed for animals requires much more land, water, and energy than producing food simply by growing and eating plants. Exactly how much more meat tomorrow's billions will want to consume is unpredictable, but if they are anywhere near as carnivorous as today's Westerners, the task will be huge. And, Prophets warn, so will the planetary disasters that will come of trying to satisfy the world's desire for burgers and bacon: ravaged landscapes, struggles over water, and land grabs that leave millions of farmers in poor countries with no means of survival.

What to do? Some of the strategies that were available during the first Green Revolution aren't anymore. Farmers can't plant much more land, because almost every accessible acre of arable soil is already in use. Nor can the use of fertilizer be increased; it is already being overused everywhere except some parts of Africa, and the runoff is polluting rivers, lakes, and oceans. Irrigation, too, cannot be greatly expanded—most land that can be irrigated already is. Wizards think the best course is to use genetic modification to create more-productive crops. Prophets see that as a route to further overwhelming the planet's carrying capacity. We must go in the opposite direction, they say: use less land, waste less water, stop pouring chemicals into both.

It is as if humankind were packed into a bus racing through an impenetrable fog. Somewhere ahead is a cliff: a calamitous reversal of humanity's fortunes. Nobody can see exactly where it is, but everyone knows that at some point the bus will have to turn. Problem is, Wizards and Prophets disagree about which way to yank the wheel. Each is certain that following the other's ideas will send the bus over the cliff. As they squabble, the number of passengers keeps rising.

The Story of Nitrogen

ALMOST EVERYBODY EATS EVERY DAY, but too few of us give any thought to how that happens. If agricultural history were required in schools, more people would know the name of Justus von Liebig, who in the mid-19th century established that the amount of nitrogen in the soil controls the rate of plant growth. Historians of science have charged Liebig with faking his data and stealing others' ideas—accurately, so far as I can tell. But he was also a visionary who profoundly changed the human species' relationship with nature. Smarmy but farsighted, Liebig imagined a new kind of agriculture: farming as a branch of chemistry and physics. Soil was just a base with the physical attributes necessary to hold roots. Pour in nitrogen-containing compounds—factory-made fertilizer—and gigantic harvests would automatically follow. In today's terms, Liebig was taking the first steps toward chemically regulated industrial agriculture—an early version of Wizardly thought.

But there was no obvious way to manufacture the nitrogenous substances that feed plants. That technology was provided before and during the First World War by two German chemists, Fritz Haber and Carl Bosch. Their subsequent Nobel Prizes were richly deserved: The Haber-Bosch process, as it is called, was arguably the most consequential technological innovation of the 20th century. Today the Haber-Bosch process is responsible for almost all of the world's synthetic fertilizer. A little more than 1 percent of the world's industrial energy is devoted to it. "That 1 percent," the futurist Ramez Naam has noted, "roughly doubles the amount of food the world can grow." The environmental scientist Vaclav Smil has estimated that nitrogen fertilizer from the Haber-Bosch process accounts for "the prevailing diets of nearly 45% of the world's population." More than 3 billion men, women, and children—an incomprehensibly vast cloud of hopes, fears, memories, and dreams—owe their existence to two obscure German chemists.

Hard on the heels of the gains came the losses. About 40 percent of the fertilizer applied in the past 60 years was not absorbed by plants. Instead, it washed away into rivers or seeped into the air in the form of nitrous oxides. Fertilizer flushed into water still fertilizes: It boosts the growth of algae, weeds, and other aquatic organisms. When these die, they fall to the floor of the river, lake, or ocean, where microbes consume their remains. So rapidly do the microbes grow on the manna of dead algae and weeds that their respiration drains oxygen from the lower depths, killing off most other life. Nitrogen from Midwestern farms flows down the Mississippi to the Gulf of Mexico every summer, creating an oxygen desert that in 2016 covered almost 7,000 square miles. The next year a still larger dead zone—23,000 square miles—was mapped in the Bay of Bengal, off the east coast of India.

Rising into the air, nitrous oxides from fertilizers is a major cause of pollution. High in the stratosphere, it combines with and neutralizes the planet's ozone, which guards life on the surface by blocking cancer-causing ultraviolet rays. Were it not for climate change, suggests the science writer Oliver Morton, the spread of nitrogen's empire would probably be our biggest ecological worry.

Passionate resistance to that empire sprang up even before Haber and Bosch became Nobel laureates. Its leader was an English farm boy named Albert Howard (1873–1947), who spent most of his career as British India's official imperial economic botanist. Individually and together, Howard and his wife, Gabrielle, a Cambridge-educated plant physiologist, spent their time in India breeding new varieties of wheat and tobacco, developing novel types of plows, and testing the results of providing oxen with a superhealthy diet. By the end of the First World War, they were convinced that soil was not simply a base for chemical additives. It was an intricate living system that required a wildly complex mix of nutrients in plant and animal waste: harvest leftovers, manure. The Howards summed up their ideas in what they called the Law of Return: "the faithful return to the soil of all available vegetable, animal, and human wastes." We depend on plants, plants depend on soil, and soil depends on us. Howard's 1943 *Agricultural Testament* became the founding document of the organic movement.

Wizards attacked Howard and Jerome I. Rodale—a hardscrabble New York–born entrepreneur, publisher, playwright, gardening theorist, and food experimenter who publicized Howard's ideas through books and magazines—as charlatans and crackpots. It is true that their zeal was inspired by a near-religious faith in a limit-bound natural order. But when Howard lauded the living nature of the soil, he was referring to the community of soil organisms, the dynamic relations between plant roots and the earth around them, and the physical structure of humus, which stickily binds together soil particles into airy crumbs that hold water instead of letting it run through. All of this was very real, and all of it was unknown when Liebig shaped the basic ideas behind chemical agriculture. The claim Howard made in his many books and speeches that industrial farming was depopulating the countryside and disrupting an older way of life was accurate, too, though his opponents disagreed with him about whether this was a bad thing. Nowadays the Prophets' fears about industrial agriculture's exhausting the soil seem prescient: A landmark 2011 study from the United Nations' Food and

Agriculture Organization concluded that up to a third of the world's cropland is degraded.

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At first, reconciling the two points of view might have been possible. One can imagine Borlaugian Wizards considering manure and other natural soil inputs, and Vogtian Prophets willing to use chemicals as a supplement to good soil practice. But that didn't happen. Hurling insults, the two sides moved further apart. They set in motion a battle that has continued into the 21st century—and become ever more intense with the ubiquity of genetically modified crops. That battle is not just between two philosophies, two approaches to technology, two ways of thinking how best to increase the food supply for a growing population. It is about whether the tools we choose will ensure the survival of the planet or hasten its destruction.

"Not One of Evolution's Finest Efforts"

ALL THE WHILE that Wizards were championing synthetic fertilizer and Prophets were denouncing it, they were united in ignorance: Nobody knew *why* plants were so dependent on nitrogen. Only after the Second World War did scientists discover that plants need nitrogen chiefly to make a protein called rubisco, a prima donna in the dance of interactions that is photosynthesis.

In photosynthesis, as children learn in school, plants use energy from the sun to tear apart carbon dioxide and water, blending their constituents into the compounds necessary to make roots, stems, leaves, and seeds. Rubisco is an enzyme that plays a key role in the process. Enzymes are biological catalysts. Like jaywalking pedestrians who cause automobile accidents but escape untouched, enzymes cause biochemical reactions to occur but are unchanged by those reactions. Rubisco takes carbon dioxide from the air, inserts it into the maelstrom of photosynthesis, then goes back for more. Because these movements are central to the process, photosynthesis walks at the speed of rubisco.

Alas, rubisco is, by biological standards, a sluggard, a lazybones, a couch potato. Whereas typical enzyme molecules catalyze thousands of reactions a second, rubisco molecules deign to involve themselves with just two or three a second. Worse, rubisco is inept. As many as two out of every five times, rubisco fumblingly picks up oxygen instead of carbon dioxide, causing the chain of reactions in photosynthesis to break down and have to restart, wasting energy and water. Years ago I talked with biologists about photosynthesis for a magazine article. Not one had a good word to say about rubisco. "Nearly the world's worst, most incompetent enzyme," said one researcher. "Not one of evolution's finest efforts," said another. To overcome rubisco's lassitude and maladroitness, plants make a lot of it, requiring a lot of nitrogen to do so. As much as half of the protein in many plant leaves, by weight, is rubisco—it is often said to be the world's most abundant protein. One estimate is that plants and microorganisms contain more than 11 pounds of rubisco for every person on Earth.

Evolution, one would think, should have improved rubisco. No such luck. But it did produce a work-around: C4 photosynthesis (*C4* refers to a four-carbon molecule involved in the scheme). At once a biochemical kludge and a clever mechanism for turbocharging plant growth, C4 photosynthesis consists of a wholesale reorganization of leaf anatomy.

When carbon dioxide comes into a C4 leaf, it is initially grabbed not by rubisco but by a different enzyme that uses it to form a compound that is then pumped into special, rubisco-filled cells deep in the leaf. These cells have almost no oxygen, so rubisco can't bumblingly grab the wrong molecule. The end result is exactly the same sugars, starches, and cellulose that ordinary photosynthesis produces, except much faster. C4 plants need less water and fertilizer than ordinary plants, because they don't waste water on rubisco's mistakes. In the sort of convergence that makes biologists snap to attention, C4 photosynthesis has arisen independently more than 60 times. Corn, tumbleweed, crabgrass, sugarcane, and Bermuda grass—all of these very different plants evolved C4 photosynthesis.

In the botanical equivalent of a moonshot, scientists from around the world are trying to convert rice into a C4 plant—one that would grow faster, require less water and fertilizer, and produce more grain. The scope and audacity of the project are hard to overstate. Rice is the world's most important foodstuff, the staple crop for more than half the global population, a food so embedded in Asian culture that the words *rice* and *meal* are variants of each other in both Chinese and Japanese. Nobody can predict with confidence how much more rice farmers will need to grow by 2050, but estimates range up to a 40 percent rise, driven by both increasing population numbers and increasing affluence, which permits formerly poor people to switch to rice from less prestigious staples such as millet and sweet potato. Meanwhile, the land available to plant rice is shrinking as cities expand into the countryside, thirsty people drain rivers, farmers switch to more-profitable crops, and climate change creates deserts from farmland. Running short of rice would be a human catastrophe with consequences that would ripple around the world.

Rather than tinker with individual genes, the scientists are trying to refashion photosynthesis.

The C4 Rice Consortium is an attempt to ensure that that never happens. Funded largely by the Bill & Melinda Gates Foundation, the consortium is the world's most ambitious genetic-engineering project. But the term *genetic engineering* does not capture the project's scope. The genetic engineering that appears in news reports typically involves big companies sticking individual packets of genetic material, usually from a foreign species, into a crop. The paradigmatic example is Monsanto's Roundup Ready soybean, which contains a snippet of DNA from a bacterium that was found in a Louisiana waste pond. That snippet makes the plant assemble a chemical compound in its leaves and stems that blocks the effects of Roundup, Monsanto's widely used herbicide. The foreign gene lets farmers spray Roundup on their soy fields, killing weeds but leaving the crop unharmed. Except for making a single tasteless, odorless, nontoxic protein, Roundup Ready soybeans are otherwise identical to ordinary soybeans.

What the C4 Rice Consortium is trying to do with rice bears the same resemblance to typical genetically modified crops as a Boeing 787 does to a paper airplane. Rather than tinker with individual genes in order to monetize seeds, the scientists are trying to refashion photosynthesis, one of the most fundamental processes of life. Because C4 has evolved in so many different species, scientists believe that most plants must have precursor C4 genes. The hope is that rice is one of these, and that the consortium can identify and awaken its dormant C4 genes—following a path evolution has taken many times before. Ideally, researchers would switch on sleeping chunks of genetic material already in rice (or use very similar genes from related species that are close cousins but easier to work with) to create, in effect, a new and more productive species. Common rice, *Oryza sativa*, will become something else: *Oryza nova*, say. No company will profit from the result; the International Rice Research Institute, where much of the research takes place, will give away seeds for the modified grain, as it did with Green Revolution rice.

When I visited IRRI, 35 miles southeast of downtown Manila, scores of people were doing what science does best: breaking a problem into individual pieces, then attacking the pieces. Some were sprouting rice in petri dishes. Others were trying to find chance variations in existing rice strains that might be helpful. Still others were studying a model organism, a C4 species of grass called *Setaria viridis*. Fast-growing and able to be grown in soil, not paddies, *Setaria* is easier to work with in the lab than rice. There were experiments to measure differences in photosynthetic chemicals, in the rates of growth of different varieties, in the transmission of biochemical markers. Half a dozen people in white coats were sorting seeds on a big table, grain by grain. More were in fields outside, tending experimental rice paddies. All of the appurtenances of contemporary biology were in evidence: flatscreen monitors, humming refrigerators and freezers, tables full of beakers of recombinant goo, *Dilbert* and *XKCD* cartoons taped to whiteboards, a United Nations of graduate students a-gossip in the cafeteria, air conditioners whooshing in a row outside the windows.

Directing the C4 Rice Consortium is Jane Langdale, a molecular geneticist at Oxford's Department of Plant Sciences. Initial research, she told me, suggests that about a dozen genes play a major part in leaf structure, and perhaps another 10 genes have an equivalent role in the biochemistry. All must be activated in a way that does not affect the plant's existing, desirable qualities and that allows the genes to coordinate their actions. The next, equally arduous step would be breeding rice varieties that can channel the extra growth provided by C4 photosynthesis into additional grains, rather than roots or stalk. All the while, varieties must be disease-resistant, easy to grow, and palatable for their intended audience, in Asia, Africa, and Latin America.

"I think it can all happen, but it might not," Langdale said. She was quick to point out that even if C4 rice runs into insurmountable obstacles, it is not the only biological moonshot. Self-fertilizing maize, wheat that can grow in salt water, enhanced soil-microbial ecosystems—all are being researched. The odds that any one of these projects will succeed may be small, the idea goes, but the odds that all of them will fail are equally small. The Wizardly process begun by Borlaug is, in Langdale's view, still going strong.

The Luddites' Moonshot

FOR AS LONG AS Wizards and Prophets have been arguing about feeding the world, Wizards have charged that Prophet-style agriculture simply cannot produce enough food for tomorrow. In the past 20 years, scores of research teams have appraised the relative contributions of industrial and organic agriculture. These inquiries in turn have been gathered together and assessed, a procedure that is fraught with difficulty: Researchers use different definitions of *organic*, compare different kinds of farms, and include different costs in their analyses. Nonetheless, every attempt to combine and compare data that I know of has shown that Prophet-style farms yield fewer calories per acre than do Wizard-style farms—sometimes by a little, sometimes by quite a lot. The implications are obvious, Wizards say. If farmers must grow twice as much food to feed the 10 billion, following the ecosystem-conserving rules of Sir Albert Howard ties their hands.

Prophets smite their brows at this logic. To their minds, evaluating farm systems wholly in terms of calories per acre is folly. It doesn't include the sort of costs identified by Vogt: fertilizer runoff, watershed degradation, soil erosion and compaction, and pesticide and antibiotic overuse. It doesn't account for the destruction of rural communities. It doesn't consider whether the food is tasty and nutritious.

Wizards respond that C4 rice will use less fertilizer and water to produce every calorie—it will be better for the environment than conventional crops. *That's like trying to put out fires you started by dousing them with less gasoline!* the Prophets say. *Just eat less meat!* To Wizards, the idea of making farms diverse in a way that mimics natural ecosystems is hooey: only hyperintensive, industrial-scale agriculture using superproductive genetically modified crops can feed tomorrow's world.

Productivity? the Prophets reply. *We have moonshots of our own!* And in fact, they do.

Wheat, rice, maize, oats, barley, rye, and the other common cereals are *annuals*, which need to be planted anew every year. By contrast, the wild grasses that used to fill the prairie are *perennials*: plants that come back summer after summer, for as long as a decade. Because perennial grasses build up root systems that reach deep into the ground, they hold on to soil better and are less dependent on surface rainwater and nutrients—that is, irrigation and artificial fertilizer—than annual grasses. Many of them are also more disease-resistant. Not needing to build up new roots every spring, perennials emerge from the soil earlier and faster than annuals. And because they don't die in the winter, they keep photosynthesizing in the fall, when annuals stop. Effectively, they have a longer growing season. They produce food year after year with much less plowing-caused erosion. They could be just as productive as Green Revolution–style grain, Prophets say, but without ruining land, sucking up scarce water, or requiring heavy doses of polluting, energy-intensive fertilizer.

Echoing Borlaug's program in Mexico, the Rodale Institute, the country's oldest organization that researches organic agriculture, gathered 250 samples of intermediate wheatgrass (*Thinopyrum intermedium*) in the late 1980s. A perennial cousin to bread wheat, wheatgrass was introduced to the Western Hemisphere from Asia in the 1930s as fodder for farm animals. Working with U.S. Department of Agriculture researchers, the Rodale Institute's Peggy Wagoner, a pioneering plant breeder and agricultural researcher, planted samples, measured their yields, and crossbred the best performers in an attempt to make a commercially viable perennial. Wagoner and the Rodale Institute passed the baton in 2002 to the Land Institute, in Salina, Kansas, a nonprofit agricultural-research center dedicated to replacing conventional agriculture with processes akin to those that occur in natural ecosystems. The Land Institute, collaborating with other researchers, has been developing wheatgrass ever since. It has even given its new variety of intermediate wheatgrass a trade name: Kernza.

Like C4 rice, wheatgrass may not fulfill its originators' hopes. Wheatgrass kernels are one-quarter the size of wheat kernels, sometimes smaller, and have a thicker layer of bran. Unlike wheat, wheatgrass grows into a dark, dense mass of foliage that covers the field; the thick layer of vegetation protects the soil and keeps out weeds, but it also reduces the amount of grain that the plant produces. To make wheatgrass useful to farmers, breeders will have to increase kernel size, alter the plant's architecture, and improve its bread-making qualities. The work has been slow. Because wheatgrass is a perennial, it must be evaluated over years, rather than a single season. The Land Institute hopes to have field-ready, bread-worthy wheatgrass with kernels that are twice their current size (if still half the size of wheat's) in the 2020s, though nothing is guaranteed.

Domesticating wheatgrass is the long game. Other plant breeders have been trying for a shortcut: creating a hybrid of bread wheat and wheatgrass, hoping to marry the former's large, plentiful grain and the latter's disease resistance and perennial life cycle. The two species produce viable offspring just often enough that biologists in North America, Germany, and the Soviet Union tried unsuccessfully for decades in the mid-1900s to breed useful hybrids. Bolstered by developments in biology, the Land Institute, together with researchers in the Pacific Northwest and Australia, began anew at the turn of this century. When I visited Stephen S. Jones of Washington State University, he and his colleagues had just suggested a scientific name for the newly developed and tested hybrid: *Tritipyrum aaseae* (the species name honors the pioneering cereal geneticist

Hannah Aase). Much work remains; Jones told me that he hoped bread from *T. aaseae* would be ready for my daughter's children.

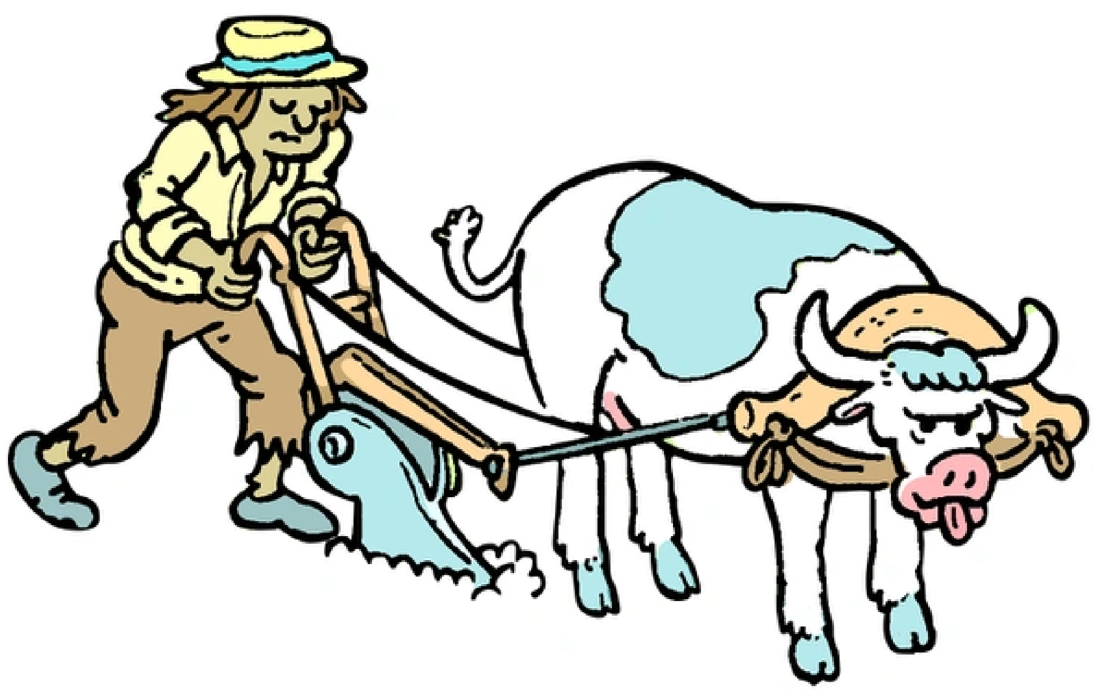
Farming is a kind of useful drudgery that should be eased and reduced as much as possible to maximize individual liberty.

African and Latin American researchers scratch their heads when they hear about these projects. Breeding perennial grains is the hard way for Prophets to raise harvests, says Edwige Botoni, a researcher at the Permanent Interstate Committee for Drought Control in the Sahel, in Burkina Faso. Botoni gave a lot of thought to the problem of feeding people from low-quality land while traveling along the edge of the Sahara. One part of the answer, she told me, would be to emulate the farms that flourish in tropical places such as Nigeria and Brazil. Whereas farmers in the temperate zones focus on cereals, tropical growers focus on tubers and trees, both of which are generally more productive than cereals.

Consider cassava, a big tuber also known as manioc, mogo, and yuca. The 11th-most-important crop in the world in terms of production, it is grown in wide swathes of Africa, Asia, and Latin America. The edible part grows underground; no matter how big the tuber, the plant will never fall over. On a per-acre basis, cassava harvests far outstrip those of wheat and other cereals. The comparison is unfair, because cassava tubers contain more water than wheat kernels. But even when this is taken into account, cassava produces many more calories per acre than wheat. (The potato is a northern equivalent. The average 2016 U.S. potato yield was 43,700 pounds per acre, more than 10 times the equivalent figure for wheat.) "I don't know why this alternative is not considered," Botoni said. Although cassava is unfamiliar to many cultures, introducing it "seems easier than breeding entirely new species."

Much the same is true for tree crops. A mature McIntosh apple tree might grow 350 to 550 pounds of apples a year. Orchard growers commonly plant 200 to 250 trees per acre. In good years this can work out to 35 to 65 tons of fruit per acre. The equivalent figure for wheat, by contrast, is about a ton and a half. As with cassava and potatoes, apples contain more water than wheat does—but the caloric yield per acre is still higher. Even papayas and bananas are more productive than wheat. So are some nuts, like chestnuts. Apples, chestnuts, and papayas cannot make crusty baguettes, crunchy tortillas, or cloud-light chiffon cakes, but most grain today is destined for highly processed substances like animal feed, breakfast cereal, sweet syrups, and ethanol—and tree and tuber crops can be readily deployed for those.

Am I arguing that farmers around the world should replace their plots of wheat, rice, and maize with fields of cassava, potato, and sweet potato and orchards of bananas, apples, and chestnuts? No. The argument is rather that Prophets have multiple ways to meet tomorrow's needs. These alternative paths are difficult, but so is the Wizards' path exemplified in C4 rice. The greatest obstacle for Prophets is something else: labor.



Ulises Fariñas

The Right Way to Live

SINCE THE END OF THE SECOND WORLD WAR, most national governments have intentionally directed labor away from agriculture (Communist China was long an exception). The goal was to consolidate and mechanize farms, which would increase harvests and reduce costs, especially for labor. Farmworkers, no longer needed, would move to the cities, where they could get better-paying jobs in factories. In the Borlaugian ideal, both the remaining farm owners and the factory workers would earn more, the former by growing more and better crops, the latter by obtaining better-paying jobs in industry. The nation as a whole would benefit: increased exports from industry and agriculture, cheaper food in the cities, a plentiful labor supply.

There were downsides: Cities in developing nations acquired entire slums full of displaced families. And in many areas, including most of the developed world, the countryside was emptied—exactly what Borlaugians intended, as part of the goal of freeing agriculture workers to pursue their dreams. In the United States, the proportion of the workforce employed in agriculture went from 21.5 percent in 1930 to 1.9 percent in 2000; the number of farms fell by almost two-thirds. The average size of the surviving farms increased to compensate for the smaller number. Meanwhile, states around the world established networks of tax incentives, loan plans, training programs, and direct subsidies to help big farmers acquire large-scale farm machinery, stock up on chemicals, and grow certain government-favored crops for export. Because these systems remain in effect, Vogtian farmers are swimming against the tide.

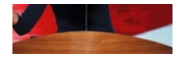
To Vogtians, the best agriculture takes care of the soil first and foremost, a goal that entails smaller patches of multiple crops—difficult to accomplish when concentrating on the mass production of a single crop. Truly extending agriculture that does this would require bringing back at least some of the people whose parents and grandparents left the countryside. Providing these workers with a decent living would drive up costs. Some labor-sparing mechanization is possible, but no small farmer I have spoken with thinks that it would be possible to shrink the labor force to the level seen in big industrial operations. The whole system can grow only with a wall-to-wall rewrite of the legal system that encourages the use of labor. Such large shifts in social arrangements are not easily accomplished.

And here is the origin of the decades-long dispute between Wizards and Prophets. Although the argument is couched in terms of calories per acre and ecosystem conservation, the disagreement at bottom is about the nature of agriculture—and, with it, the best form of society. To Borlaugians, farming is a kind of useful drudgery that should be eased and reduced as much as possible to maximize individual liberty. To Vogtians, agriculture is about maintaining a set of communities, ecological and human, that have cradled life since the first agricultural revolution, 10,000-plus years ago. It can be drudgery, but it is also work that reinforces the human connection to the Earth. The two arguments are like skew lines, not on the same plane.

My daughter is 19 now, a sophomore in college. In 2050, she will be middle-aged. It will be up to her generation to set up the institutions, laws, and customs that will provide for basic human needs in the world of 10 billion. Every generation decides the future, but the choices made by my children's generation will resonate for as long as demographers can foresee. Wizard or Prophet? The choice will be less about what this generation thinks is feasible than what it thinks is good.

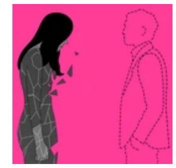
This article is adapted from Charles C. Mann's most recent book, The Wizard and the Prophet. *It appears in the March 2018 print edition with the headline "How Will We Feed the New Global Middle Class?"*

CHARLES C. MANN *is a contributing writer at* The Atlantic. *His books include* 1491, *based on his March 2002 cover story, and* The Wizard and the Prophet.



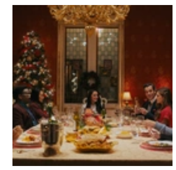
4 Dear Therapist: I Was the Other Woman

LORI GOTTLIEB



5 I’m Really Sorry, but Let’s Talk About That Chicken Movie

MEGAN GARBER



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