THREE

Fixing the Real "World Wide Web"

Breakthroughs at the Interface of Food, Agriculture, and Large-Scale Computation

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The global food supply is humanity's only truly distributed system. Everywhere humans live, food is consumed every day, and it is concomitantly produced almost everywhere on the planet and then broadly distributed with great precision around the globe.

Over the years, many people—from Thomas Malthus in 1798 to Paul Ehrlich in the second half of the twentieth century to newspaper editors in the twenty-first—have correlated increasing global population with a strictly finite amount of arable land and predicted the whole system would come crashing down. So far, they have all been wrong; the system has shown itself to be much more resilient than one might think.

Past performance, of course, does not guarantee future success. There are major emergent trendlines that could impair the system—or even lead to its collapse over the longer term. By some estimates, agriculture contributes up to 10 percent to 25 percent of global greenhouse gas ("GHG") emissions,[1] contributes to significant biodiversity loss, and results in widespread soil degradation.[2] The impact of these trends is ecological, economic, and—because of food's primacy—political and cultural. Examples of this complex feedback loop can be

1. IPCC.
2. Montanarella, Pennock, and McKenzie.

seen in studies that have shown increased CO_2 in the atmosphere may result in less-nutritious foods.[3]

Despite the food system's ability to meet most people's caloric needs, the United Nations' Food and Agriculture Organization estimates that even in 2019, before the COVID-19 pandemic, 690 million people were chronically undernourished—which is 10 million more people than were undernourished in 2018, and 60 million more than were undernourished five years earlier.[4] Yet in the developed world, acreage under cultivation decreases every year as productivity and yield outstrip demand.[5] Today's food insecurity crises are more a consequence of the unequal distribution of current agricultural technologies and local and regional economic policy, which, in turn, have consequences for larger issues of climate change and planetary sustainability.

For example, the average acre of corn in the United States yields 160 bushels, with top farmers producing more than 600 bushels per acre.[6] Meanwhile, in Sub-Saharan Africa, the average is 30 bushels per acre.[7] However, many Sub-Saharan farms use traditional agricultural approaches, which often have lower environmental impact than the high-yielding farms of the United States and other developed nations. Most industrial farm acreage in the West is devoted to non-biodiverse monoculture, which is heavily reliant on pesticides and synthetic fertilizer. The World Resources Institute cites agricultural runoff (mainly synthetic fertilizer and animal waste) as a key cause of eutrophication of once-productive coastal waters, creating huge "dead zones," where oxygen concentration is insufficient to support most marine life.[8] Further, agriculture's GHG production contributes to warming seas,[9] upsetting the nutrient cycle in many fisheries and threatening global thermohaline circulation,[10] often called the "ocean conveyor belt." So, producing more food on land often hurts our ability to harvest more from the sea.

Meanwhile, the COVID-19 pandemic also exposed weakness at the other end of the agri-food value chain. New York City's point-of-sale outlets, for example, typically only have four to five days of food in stock.[11] While this lack of inventory minimizes food waste, even backup processors, distributors, and retailers

3. Dong, Gruda, Lam, and others.
4. Kretchmer.
5. Fisher.
6. Spiegel.
7. Nigatu and Hansen.
8. World Resources Institute.
9. IPCC.
10. Brierley and Kingsford.
11. New York City Economic Development Corporation, NYC Mayor's Office of Recovery & Resiliency.

were hard pressed to keep basic foodstuffs on hand during the recent pandemic.

By contrast, about 65 percent of Sub-Saharan Africans rely on subsistence farming.[12] Those families grow a lot of their own food, which puts them at the end of the shortest possible value chain while also making them vulnerable to fluctuating local environmental conditions. As the fastest rates of urban growth continue in many of the lowest-income countries, more of the people most at risk will also be exposed to local supply-chain vulnerabilities.

The Green Revolution of the 1950s, 1960s, and 1970s produced massive yield gains thanks to the widespread adoption of modern agrarian practices such as synthetic fertilizer, pesticides, and modern grain varietals. In the 1980s and 1990s, the Global Positioning System (GPS) and genetically modified organisms (GMOs) were new innovations rippling across the global food supply. In the early part of this millennium, the continuing digitization of agriculture—focusing on bytes, not bushels—drove further yield improvements.

For the coming decades, the grand challenge will be to achieve what Jules Pretty has called "sustainable intensification." That is to say, we must further increase yields while reducing or eliminating the harmful impacts of our current agricultural system.

In 2019, Cornell University and the journal *Nature Sustainability* convened a panel of international experts who neatly characterized this goal for the global agri-food system: It should provide everyone with a diet that is healthy, equitable, resilient, and sustainable (HERS).[13] Although this chapter acknowledges today's grand problems, including climate change, we believe that adapting and spreading already proven technologies to the developing world can help us reach that HERS goal even as the world's population is generally expected to reach a peak of about 9.7 billion by 2064 before declining to 8.8 billion by the end of this century.[14]

Over the past decade, the convergence of the plunging cost of storage, computer resources, and bandwidth has spawned a wave of innovation, unleashing the now well understood and widely written about concept of artificial intelligence (AI). While many understand the value of AI in things like smarter business applications or more intelligent home electronics, this technology has also unlocked advanced computational approaches to enormously complex real-world problems in the global agri-food system. It has concurrently accelerated advances in relevant fields such as robotics, earth observation, and bioengineering.

In this chapter, we explore "Deep Tech" innovations that promise to increase

12. Savage.
13. Barrett, Benton, Fanzo, and others.
14. Stein, Goren, Yuan, and others.

efficiency, yields, and sustainability. We define Deep Tech as the combination of the latest advances in science and technology driven by unique computing and algorithmic advantages. The current vulnerabilities in the global agri-food system do not call for individual innovations or even a single revolution, à la the Green Revolution, but rather a series of revolutions working concurrently to reshape an enormous and disparate system. Creating a more equitable and sustainable global food supply chain can be met only with a whole-planet approach where governments, regulatory agencies, and NGOs share a unified vision. Private, for-profit companies also have a substantial role and, in many cases, the greatest incentive to innovate and bring these innovations to market as quickly as possible for use across the globe.

We certainly do not claim that the innovations discussed below represent a comprehensive solution, but this chapter is more than an exercise in wishful thinking. These technologies are all proven and ready for wider adoption. They can help us understand ecological risks, reduce our dependence on dangerous chemicals, and reduce the environmental impacts of the global agri-food system, moving the needle significantly by 2030.

We focus on four areas of advancement: applied AI; microbes and bioengineering; robotics; and a collection of technologies that can reduce the impact of meat production, which is unsustainable as currently practiced. Some of the technologies we highlight will broadly influence the global agri-food system, and some will reshape specific sectors as the global population—and attendant environmental pressures—increase.

AI on a Global Scale

As the old adage goes, you can only manage what you can measure. Heretofore, much of the food-industrial complex and its inputs from the agriculture systems have been too diverse, dispersed, and complex to measure or observe in any truly comprehensive or holistic way.

Agriculture is literally a down-to-earth activity, so space is not the most obvious place to find relevant innovations. But as the "space race" among national superpowers cooled, it gave way to transformational innovation from private sector companies seeking cost-effective ways to leverage Earth's orbit for humanity's gain. This private sector space race has created unparalleled opportunity for measurement-driven insight into agricultural systems across our planet through the creation and deployment of small satellites that provide affordable weekly or even daily medium- and high-resolution Earth images.

Persistent imaging from Earth's orbit allows agronomists to identify trends and issues early and track crop health in near-real time, including the detection of in-field variation with dense vegetation analysis and vitality alerts. With daily or weekly updates and field-level detail, farmers can respond quickly to changes in crop health and optimize variable rate application of chemicals to manage costs. Private satellite companies also help clients to monitor deforestation or pollution, limiting both reputational—and, more important, environmental—harm.

One of the pioneers in this industry, Planet,[15] deploys its own constellation of satellites to survey the entire landmass of the planet at three- to five-meter resolution on a daily basis. It then uses AI and machine learning to stitch together an essentially cloud-free, field-level snapshot that gives farmers, agronomists, and agribusinesses a new level of virtually real-time insight into what is happening on the ground—everything from crop productivity to water stress. This perspective on agricultural systems is invaluable, especially in less developed nations that lack their own imaging capabilities.

Extreme complexity is one factor that has caused the global agri-food system to lag other industries when it comes to leveraging data. In almost every industry and at every level, data is now a commodity with its own inherent value as an input. In most areas, the sheer size of these data sets has grown beyond the ability of human comprehension without the use of AI algorithms to help make sense of them. Stock trading once centered around crowded trading floors and timing decisions correctly based on new information as it became unevenly available. Today, some estimates suggest that up to 80 percent of equities markets trading volume is generated by black box trading algorithms that make decisions based on complex inputs from across the globe. The rule of thumb among commodities traders is that the agriculture market is ten times larger and ten times more complex than the finance industry, with much more variegated inputs from long-term weather forecasts to consumer meat demand to the growth rate of coconut plantations.

The global food system's complexity has recently been in evidence on several occasions. In 2010, Vladimir Putin ordered Russia to stop wheat exports after a crop failure threatened to increase the price of bread. His action threw global markets into chaos.[16] In 2019, flooding in the American Midwest had the same effect on global corn and soybean prices around the world.[17] Then 2020 brought a continued series of quasi-biblical-scale plagues: drought in Central America, locusts in east Africa, and fall armyworm in China. Each devastated a region in its own way, but understanding their effects in global markets requires both granular data and a way to extract meaningful data and patterns.

15. Zachary's venture firm DCVC is an investor in Planet, as well as Gro Intelligence, Pivot Bio, Zymergen, Sabanto, and Halter, all of which are also mentioned in this chapter.

16. Parfitt.

17. Kliesen and Bokun.

The same advances that brought financial markets from the trading floor to the data center can be used to make sense of enormously complex global agriculture and food interactions. Companies like Gro Intelligence are using AI to merge tens of millions of data sets comprising literally trillions of data points, creating sophisticated production and consumption forecasts and responsive models of agricultural supply and demand at the national or global level.

A broad spectrum of companies across agribusiness and finance, seed, and fertilizer companies upstream from farms—as well as food service, wholesale, and retail stores downstream from farms—use Gro's models to make key decisions about how to run their businesses.

Gro's AI-powered insight gives agribusinesses access to dozens of forecasts for key crops and markets—everything from soybeans in the United States to sorghum in Ethiopia and sugarcane in Brazil. These forecasts allow, for example, poultry, livestock, and dairy farmers to model feed prices, and provide traders with the insight they need to both align purchasing quantities with domestic and overseas demand and mitigate price risks through hedging strategies.

Gro also fuses its AI-driven insights into the global agriculture and food system with advanced climate change models, which underlie its financial indexes for factors like drought to help customers better manage climate risk. Banks and insurers can similarly use these indices and forecasts, including yields, commodity demand, and price forecasts, to assess creditworthiness and set policy premiums. Understanding regional finance and credit conditions helps financial institutions to properly price capital.

Closer to the consumer end of the spectrum, the food and beverage industry uses commodities such as corn, wheat, cocoa, sugar, coffee, and, of course, fresh produce to make much of what the world buys and eats. The ability to better predict yields and prices is just one advantage. It is now also possible to monitor the climate in real time to identify possible supply disruptions. Again, land suitability rankings help buyers decide where to develop, diversify, and solidify their supplier bases. Wholesale and retail sectors buyers can similarly analyze price trends and monitor growing conditions at key points of origin to forecast price disruptions days, if not weeks, in advance.

Overall, thanks to private sector efforts to both gather and harness data, it is increasingly possible to monitor and model the global food supply chain in real time and understand regional markets and situations in a world context. This offers unprecedented opportunities for efficiency gains across the vast complexity of agribusiness at all scales around the world.

From the Petroleum Century to the Microbe Century

Many people think of the computer industry as the defining business of the twentieth century, but when looking at the century in its entirety, the petrochemical industry shaped it much more profoundly, for better or worse. The burning of fossil fuels has contributed the lion's share of GHGs, but if Standard Oil had not commercialized kerosene production for the nascent petroleum industry, whales most likely would have been hunted to extinction for their oil, which was previously used for lighting.

Similarly, while the invention of petroleum-derived plastics created a huge pollution problem, it reduced the demand for elephant ivory for buttons and other small parts, which were incredibly difficult to make with existing materials. That those majestic animals still walk the Earth may be due, in part, to oil.

No industrial process has had a greater impact than Fritz Haber's discovery, in 1909, of a means to convert atmospheric nitrogen into ammonia for use as fertilizer. The Haber-Bosch Process has been called "the detonator of the population explosion."[18] The synthetic fertilizer produced this way nearly doubled global agricultural output, and it is the only reason our planet can support its current population.

Haber and Bosch may have staved off a Malthusian population calamity, but synthetic nitrogen fertilizer is far from perfect. Its production uses at least 2 percent of the world's total energy and contributes a whopping 7 percent of global GHG emissions.[19] In the field, synthetic nitrogen fertilizer's effectiveness is weather-dependent; if it rains too soon after the fertilizer application, much of it runs off, harming riparian, coastal, and ocean ecosystems, creating over five hundred ocean dead zones around the world.

One of the most bedeviling unintended consequences of the widespread use of synthetic nitrogen fertilizer is that its application inhibits the nitrogen-fixing properties of symbiotic bacteria that occur naturally in the soil microbiome. Farms have now become dependent on expensive synthetic fertilizers that have barely changed since their invention more than a hundred years ago. Breaking modern agriculture's expensive addiction to synthetic fertilizer would be a significant step toward sustainability, and there are several companies seeking to identify or create microbes to sustainably produce nitrogen for crops.

One such company is Pivot Bio, based in Berkeley, California. Using cutting-edge AI, its scientists analyzed trillions of interactions across thousands of soil samples to identify, culture, and create soil microbes that can be applied in-furrow

18. Smil.
19. Walling and Vaneeckhaute.

at the time of planting. As seeds germinate and roots grow, the microbes adhere to the roots, living in a symbiotic relationship with the plant. The microbes feed off the exudates emitted by the plant's roots and deliver nitrogen daily to the plant throughout its growth cycle. The farmer benefits from lower costs and increased yield. The environment benefits from plants, which are spoon-fed only the nitrogen they need; there is no fertilizer to break down into the atmosphere or run off into our waterways.

Completely replacing synthetic nitrogen fertilizer globally is years—likely decades—away. But even a modest proliferation of microbe-based approaches throughout the agricultural systems of industrialized nations will have a material positive impact on the sustainability of our food system.

Microbes may also help us solve environmental problems associated with another global addiction: palm oil.

This remarkably versatile oil is produced from the fruit of the oil palm tree. Over the last fifty years, palm oil has become a key ingredient in an astonishing number of foods, cosmetics, industrial products, and biofuels. As many as half of the products in a typical grocery store contain it. Demand has increased exponentially, to about 75 million tons per year—roughly 18 pounds for every person on earth![20]

What began as a crop that provided cash income for small farmers in developing nations across the tropics has grown into an environmental disaster. Oil palm plantations now occupy 44 million acres, more than half of which, until recently, were covered by mature tropical forest in Indonesia and Malaysia.[21] Oil palm plantations are replacing some of the world's most diverse ecosystems with relatively inert monocultures and destroying the habitat of critically endangered species. Such tropical deforestation contributes about 10 percent of greenhouse gases.[22] It is yet another crop that is fertilizer-intensive, so it also harms aquatic ecosystems.

Consumer awareness of these environmental harms is growing. But every year, more and more consumer products are imbued with this hard-to-replace ingredient. At this point, global industry cannot kick the collective palm oil habit, so an alternative supply of palm oil is needed instead, one that does not encourage slash-and-burn agriculture.

Fortunately, it is now possible to ferment identical or even superior "palm" oils using yeast, much the way beer is made. Manufacturing oil this way does not even require palm cultivation, so it entirely avoids deforestation and poses no harm to the endangered animals of the rain forest.[23]

20. Raghu.

21. International Union for the Conservation of Nature.

22. Union of Concerned Scientists.

23. DCVC is an investor in C16 Bio, which brews a sustainable alternative to palm oil from microbes.

While palm-free palm oil will certainly benefit our planet, we should be mindful that the palm oil economy has had a tremendous economic impact on the regions where palms are grown, lifting entire communities out of poverty. To protect livelihoods, one solution would be to ramp up oil fermentation in the same regions to help replace farm income and jobs.

In another dimension of the farm technology challenge, similar to how fertilizers have dramatically boosted farm yields, the adoption of modern pesticides has significantly reduced the crop losses to pests. However, the broad application of pesticides also harms beneficial insects like honeybees. An alternative means of protecting crops is to use microbial manufacturing to create new kinds of pest-resistance and pesticides that do not require broad application or that are less toxic to beneficial insects. Such pesticides use hitherto-unexplored protein compounds that occur naturally in the environment.

Zymergen is one such "biofacturer" based in Emeryville, California. It also uses fermentation, but not to create a single product like fermented palm oil. Rather it is working at the nexus of robotics, biotechnology, and advanced AI to build many new proprietary microbes that produce a broad range of new compounds and materials with useful and superior properties. Microbial manufacturing at this level uses intracellular biosensors, parallel genome editing technologies, robotics, and software to build and screen up to billions of microorganisms, enzymatic pathways, and genetic interactions in parallel. The goal is to rapidly iterate new genomic designs to create the next generation of materials for the world. This approach produces compounds that are less harmful to the environment. It also uses as its starting point corn by-products and other sugars, rather than petroleum, which is equivalent to feedstock for many of current advanced materials reaching far across the global economy.

Robots to the Rescue

Back in the 1960s, when imagining the future, many people envisioned Rosie, the animated robot maid in *The Jetsons*. When that TV show was written, the integrated circuit was new, and the exponential power of Moore's Law was yet to be revealed. It was a common assumption that processing power would continue to be scarce and that households would have a single Rosie running the kitchen. Instead, millions of households today have a kitchen in which every appliance has a computer brain and many "micro-robots" each perform a single task, like baking bread or washing dishes.

The abundance of cheap processing power helped clarify that the actual hard problem is navigating the real world or having the flexibility to perform multiple or novel tasks. Indeed, robots like Rosie, with a human's versatile ability to manipulate objects in 3D, are still largely futuristic. In the agricultural field, the challenge of manipulating fragile crops is still daunting. So, for now, large segments of farming, like harvesting vegetables, still rely on a lot of "wetware"—humans.

That said, robots already make farming more productive. Even robots capable of only relatively simple and repetitive actions have been empowered by AI. For example, robotic sprayers can now use machine vision and neural networks to tell crop from weed and flower from leaf.

"See-and-spray" robotics platforms can spray herbicide on weeds and fertilizer on crops with precision similar to that of inkjet printers. Enabled by cutting-edge machine vision and AI, these robots evaluate billions of plants on every field. The precise targeting of see-and-spray systems improves sustainability and promises to cut chemical usage by 90 percent or more. By eliminating the need to treat entire fields with herbicides, this technology cuts farmers' costs, reduces surface runoff, and discourages the development of resistant weeds.

Some robotic breakthroughs have only indirect environmental impacts but show a lot of promise when it comes to farm economics in developed countries, where a shortage of workers is a chronic problem. Contracting out some tasks, such as seeding, to farming-as-a-service (FaaS) companies that offer robotic assistance on a per-acre basis offers a possible solution to labor shortages. Indeed, farmers' fields are excellent places to practice autonomous driving. At perhaps the peak of the autonomous vehicle hype cycle (circa 2018), John Deere executives were heard quipping, "We've been making autonomous vehicles since the 1980s," referring to the company's tractors.

A good example of an FaaS company is Sabanto, which operates autonomous tractors outfitted with GPS receivers, control boxes, and steering actuators to control the tractor and planter. Units are programmed to return to a predetermined area for seed and fuel when needed. The goal is to develop equipment that can operate with increasing autonomy, relying on only an off-site operator and one person on-site to deploy equipment, fuel tractors, and refill planters with seed. Less required labor means lower costs.

Although it is easy to see how an autonomous tractor can improve life for a farmer, it is less obvious how robotics might help a dairy farmer to herd her cows. At present, employees on horseback or all-terrain vehicles, assisted by herding dogs, can move hundreds of cattle. This is a labor-intensive process that is risky for both animals and people.

It need not be. Cows are trainable and quickly learn behaviors through the use of positive and negative reinforcement. Halter, a New Zealand–based startup, envisions a world in which every dairy cow wears a solar-powered, Wi-Fi–connected training collar that allows a single dairy farmer, working from her milking shed, to move herds from pasture to pasture or bring them to the barn without direct contact, all while avoiding watersheds and other environmentally sensitive areas.

These training collars can give farmers new insight into their herds, helping to eliminate the need for human—or herding dog—intervention in cattle management. Every cow is individually identified in an app on the farmer's smartphone, and each cow's unique location is known at all times. Farmers can "herd" animals with their phones, divide their cows into different herds, and move them around the farm by using the collar's sound and vibration to help a cow understand where it should go.

Beyond making things more efficient for farmers and protecting the local environment, this technology can also make life better for cattle. With greater insight into both the individual cow and the herd as a whole, farmers can quickly identify and support animals that may be lame or sick.

Some robotics solutions, like the ones that reduce chemical use, directly improve sustainability. But even solutions that simply improve farm efficiency and quality of life for farmers (and animals) can have an impact in an interconnected global market. For example, through 2030, small holdings of less than two hectares will continue to produce much of the food in the developing world. For those small farmers, investing in new technology is much harder, but commercial innovations may ease access to capital equipment. Hello Tractor, a company operating in Kenya and Nigeria, has been described as "Uber for tractors," allowing small farms to book a tractor for short periods through a smartphone app. This, in turn, allows farmers who could not make a return on such a capital investment from their own land to earn money from these tractors which would otherwise sit idle.

Farms in the developed world face chronic labor shortages so robotic help is often welcome. But some people fear that increased mechanization and automation will displace farmworkers in the developing world where employment is already scarce. We do not dismiss this fear, but other industries that are further along the curve have often found that AI and advanced automation do not eliminate jobs as much as change them. Repetitive, rote work is automated, leaving humans to focus on management and further innovation, which further increases farm productivity.

Despite the promise of robotics, a cautionary note beyond job markets is also warranted. Agricultural technology research and development is often understandably focused on the largest commercial crops, such as corn, wheat, and soybeans. These crops are often processed and become ingredients in foods with less-than-optimal nutritional profiles. The EAT-Lancet Commission recently published a report concluding that "a diet rich in plant-based foods and with fewer animal source foods confers both improved health and environmental benefits."[24] Following the commission's dietary recommendations would lower food costs for people in the developed world, but more than 1.5 billion people in less developed nations could not afford to replace the sugars, saturated fats, starchy vegetables, and refined grains in their current diet with healthier vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils. Technology that has the effect of further lowering the relative cost calories from less healthy ingredients may have an adverse impact on the "healthy" part of the HERS goal.

Our Meat Problem

The first step in solving a problem is admitting you have one—and the world definitely has a meat problem. Even domestic pets have a meat problem. If all of the pets in the United States were counted as a standalone country, they would be the world's fifth-largest country in terms of meat consumption![25]

Per the World Resources Institute, beef requires twenty times more land and emits twenty times more GHG emissions per gram of edible protein than common plant proteins, such as beans and other legumes.[26] The majority of the world's native grasslands are already heavily utilized for livestock production, so incremental beef demand increases pressure on forests. According to the Food and Agriculture Organization of the United Nations, livestock sector growth has been a prime driver of the massive deforestation in Brazil in recent years.[27]

The United States and other developed nations consume far more meat per capita than do less developed countries, but as urbanization continues and average living standards climb, the world's appetite for meat is increasing. Between 1965 and 2015, per capita meat consumption in developing nations tripled from about 22 pounds per year to more than 66 pounds.[28]

Thankfully, cultured meats or plant-based meat alternatives show real promise. The company Beyond Meat was a revolution for a number of reasons. Primarily, it demonstrated that a non-pharmaceutical biological product could sustain a robust public market valuation (at $1.5 billion, it was one of the most successful IPOs of 2019). Beyond Meat's revenues have nearly tripled every year since 2016, evidencing the public's willingness to vote with their pocketbooks. Additionally, it paved the way for myriad other meat alternatives, such as Impossible Foods, to gain broader adoption.

While the market for cultured or plant-based meat alternatives is growing,

24. Willett, Rockström, and others.
25. Okin.
26. Waite, Searchinger, and Ranganathan.
27. Alexandratos, Gürkan, Mielke, and others.
28. Ibid.

between now and 2030, the vast majority of meat will still come from raising and slaughtering animals. Limiting the environmental impact of raising animals, especially ruminants, now forms a global imperative. This should begin with beef production, which produces the most GHG per ounce of protein.

Methane emissions are a major contributor to the GHG intensity of beef production. Methane is relatively short-lived in the atmosphere, but it is extremely potent, trapping up to eighty times more heat than carbon dioxide over a twenty-year period. More than one-third of all the atmospheric methane resulting from human activity is produced by dairy and beef herds as a by-product of the gut bacteria that enable cattle to break down their food.[29] Because cattle are ruminants, they mostly belch that methane out.

Reducing that natural methane release presents one of the most immediate opportunities for reducing the cattle industry's GHG emissions. One solution is found, perhaps surprisingly, in seaweed. *Asparagopsis armata* is native to New Zealand and Australia, and *Asparagopsis taxiformis* grows off the coast of Hawaii, where it is an ingredient in the traditional fish preparation called *poké*. Both contain a small amount of bromoform, which is a caustic chemical in its pure form, often used as a lab reagent. (It is similar to chloroform, made famous in spy novels.)

As it turns out, bromoform at the levels found in *Asparagopsis* disrupts the enzymes of the cattle's gut microbes that produce methane gas as waste during digestion. In field trials in Australia and the United States carried out by CSIRO, University of California, Davis, and the University of Pennsylvania, an *Asparagopsis*-based feed additive reduced methane emissions by up to 99 percent in beef and dairy cattle as well as sheep, with no adverse effects to livestock, their products, or the environment.[30] The bromoform-rich diet appears to increase feed conversion, so adding bromoform actually lowers costs to farmers. (A way to think of the increased conversion efficiency is that more of the carbon goes into growing the cow's body and less escapes to the atmosphere as methane.)

Growing seaweed also offers mild environmental benefits. It reduces ocean acidification and absorbs about five times as much carbon dioxide as land plants on a per-pound basis. However, only small amounts of *Asparagopsis* are required for the feed additive process, so even at industrial scale, the GHG benefits of seaweed cultivation would be dwarfed by the impact of materially reducing the one-third of humanity's methane emissions.

29. Borunda.
30. Commonwealth Scientific and Industrial Research Organization.

Incremental Improvements for a More Equitable, Resilient, and Sustainable Future

While initially targeted at industrialized markets, many of the technologies described in this chapter will improve food security and global environmental sustainability no matter where they are implemented. Substantive reductions in GHG emissions anywhere in the world will slow the rate of climate change for everyone.

But the reality of technological advancement is that industrialized countries typically develop new technologies that are not exported to developing ones until costs decrease over time. However, the populations in the regions with the most food insecurity, especially Sub-Saharan Africa, are on track to increase at an annualized rate of greater than 2 percent for the rest of the decade.[31] To do the most good and have the biggest impact on agricultural sustainability, it is imperative for these new technologies to be made quickly accessible to farmers in the developing world. We are hopeful that many of the technologies discussed above become "leapfrog technologies" in the same way that developing economies went straight to mobile phones without first having extensive landline networks. Many of the same countries now have more sophisticated mobile money and payments systems than some industrialized countries.

Business and policy leaders have personal responsibilities, too. Companies cannot focus solely on innovation at the expense of public education and government engagement. Like other science-based innovations, these approaches offer real progress toward addressing some of the most pressing technical challenges facing food supply chains. At the same time, where food comes from is a personal and delicate subject. Without taking the important steps to educate governments and listen to the public, innovative companies risk hitting regulatory hurdles or consumer skepticism. Meanwhile, government leaders need to do their part, as well. When new agricultural technologies arrive, policymakers need to ensure adversely affected regions are able either to take advantage of the new breakthroughs or to bridge to economic opportunities in more sustainable industries.

The global agricultural and food system is remarkably complex. In many ways, it is an ecology as much as an industry. But that complexity means there are countless points where incremental improvements can produce massive positive impacts without having to remake an entire system with huge inertia. The technologies we have discussed, and many other advances, are ushering in a future of healthier nutrition that can be more equitable, resilient, and sustainable for all.

31. *Economist* Special Report.

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