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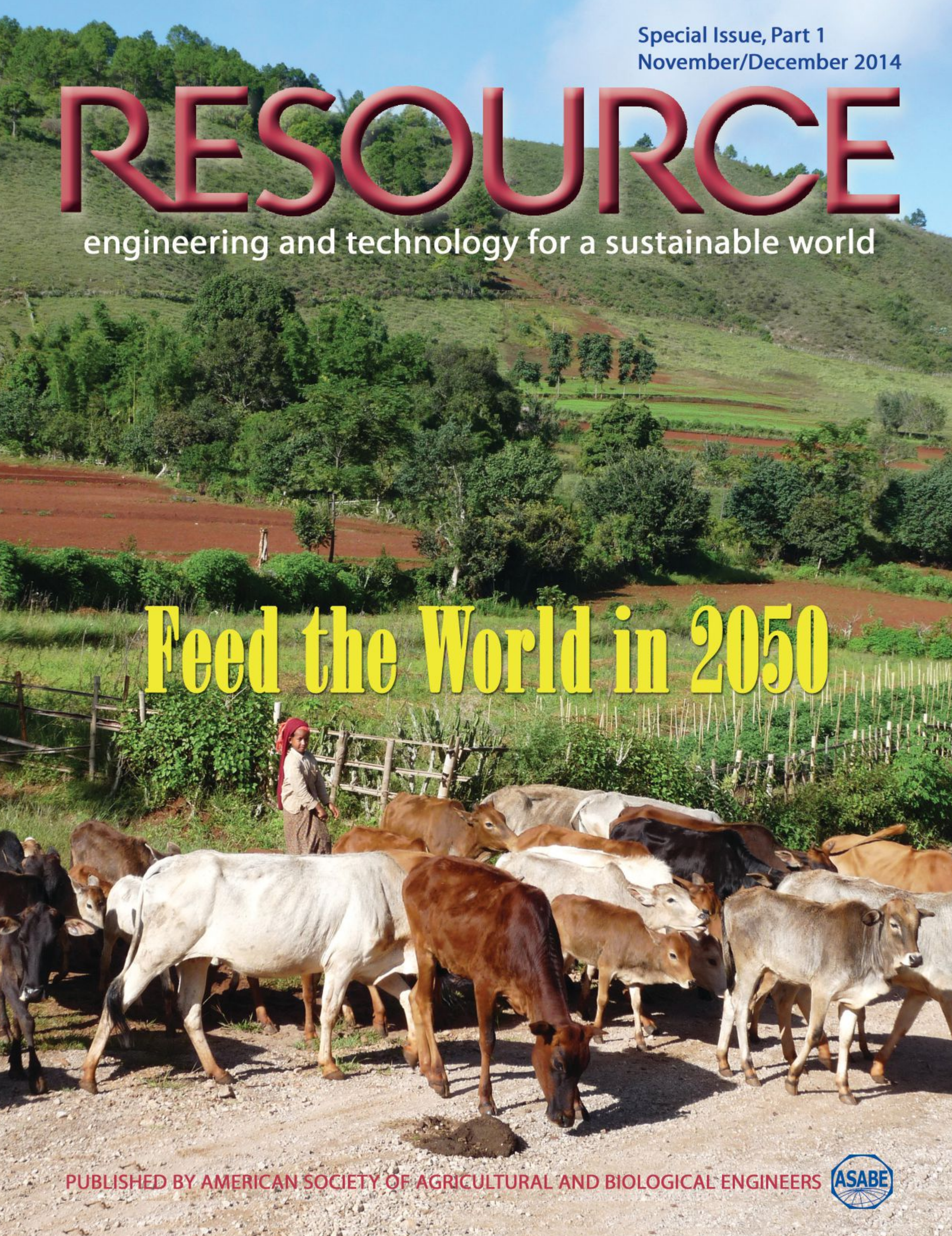
November/December 2014

RESOURCE

engineering and technology for a sustainable world



Feed the World in 2050

PUBLISHED BY AMERICAN SOCIETY OF AGRICULTURAL AND BIOLOGICAL ENGINEERS

from the President

Engage!

Engage—my simple challenge to you this year is to make a mark where you are. ASABE is comprised of outstanding engineers and scientists who are helping the world with their work. Whether you are designing a part to make precision agriculture more effective, evaluating the kinetics of cell growth to better understand a biological process, exploring ways to extend knowledge on grain storage to partners around the world, or working in another of the many areas that ASABE represents on equally important tasks, you are making an impact. As an ASABE member, you also have an opportunity to help make your Society as strong as it can be.

I would like you to consider how to **engage** ASABE in a variety of ways. It could include striving to make your Section more relevant and attractive to fellow members. It could include reaching out to partner societies to identify ways to share our influence. It could be as small as inviting an old classmate or two to renew their membership if you haven't seen them in a while. Whatever it is, be intentional about making ASABE better this year.

Providing the world of 2050 with ample safe and nutritious food under the ever-increasing pressures of climate change, water limitations, and population growth will be a monumental challenge that requires **engagement** of ASABE members with their colleagues and thought leaders from around the world. Inside this issue, you will find perspectives on the topic by contributors ranging from farmers to futurists. The challenges of food security are daunting, but I can think of no other profession that's better equipped or better qualified to tackle them. I hope you are as inspired as I am by these articles.

As I close, I would like to thank Donna Hull, ASABE's recently retired Director of Publications. For 34 years, Donna worked to enhance our publications, from *Resource* to our refereed journals. These publications are a key part of our communication to the world, and their quality reflects the efforts of our members and Donna's vision to share our stories and research. In particular, her efforts to digitize our Technical Library were invaluable. Join me in wishing her all the best in retirement.

I am energized and excited to serve as your 2014-2015 President. I look forward to seeing you at Society functions, and I welcome any ideas you have to make this a great year for ASABE.

Terry Howell Jr.
Terry.Howell@mckee.com

events calendar

ASABE CONFERENCES AND INTERNATIONAL MEETINGS

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2015

Feb. 9-11	**Agricultural Equipment Technology Conference.** Louisville, Kentucky, USA.
May 3-5	**ASABE 1st Climate Change Symposium — Adaptation and Mitigation.** Chicago, Illinois, USA.
July 26-29	**ASABE Annual International Meeting.** New Orleans, Louisiana, USA.
Nov. 10-12	**Irrigation Symposium.** Long Beach, California, USA.

2016

July 17-20	**ASABE Annual International Meeting.** Orlando, Florida, USA.

ASABE ENDORSED EVENTS

2014

Nov. 1-7	**2014 21st Century Watershed Technology Conference and Workshop.** University of Waikato, Hamilton, New Zealand.
Nov. 2-7	**2014 World Engineering Conference on Sustainable Infrastructure.** Abuja, Nigeria.

2015

May 31-June 5	**2015 18th International Soil Conservation Organization (ISCO).** El Paso, Texas, USA.
July 5-8	**CSBE Conference & Annual General Meeting.** Edmonton, Alberta, Canada.

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ON THE COVER

Multifunctional landscape in Myanmar, courtesy of INBAR.

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FEATURES

DEPARTMENTS

first word

Greatest Challenge Ever Faced ...

In 2011, *Resource* published a special issue on the "Farm of the Future." That issue gave us the opportunity to ponder what agriculture would look like in the future—it was all optimism and fun. The current issue, titled "Feed the World in 2050," has a more pressing purpose and a more serious tone.

Feeding the predicted global population of nine billion in 2050 and beyond will be the greatest challenge humanity has ever faced, dwarfing both the Manhattan Project and Project Apollo. Here's why: so far, humanity has solved virtually all its problems by throwing more resources at them—a good example is the Green Revolution—but the era of massive resources and simple solutions is coming to an end.

Most readers of *Resource* are well aware that the main problems we face are climate change, water wars, nutrient depletion, and soil degradation. I agree that these are tenacious problems, but we could, as Stephen Colbert suggested, keep moving north until we are plowing the Arctic Circle. In my view, the biggest threat to our survival is energy. It doesn't take a PhD in macroeconomics to predict that finite resources are, well, finite. And yet we have no plan for what to do when the energy runs out. We have developed the technology to look back in time to the beginning of the universe, but when it comes to looking a century ahead, we're rather uninterested. Or maybe we don't like what we see.

At the birth of the United States in 1776, the main source of energy was wood. That continued until 1885, when coal surpassed wood. The Coal Age lasted until 1950, when coal was overtaken by oil, which continues to be our main source of energy. When the oil is finally depleted, which energy source will replace it? Will we have a Renewables Age, or maybe a Fusion Age? Will it be back to coal and wood? Anyone?

In the 1950s, Dr. M. King Hubbert famously predicted that U.S. oil production would peak in 1971. He was spot on. His idea boils down to a Gaussian discovery curve followed by a similar Gaussian production curve that trails discovery by about 20 years. This curve can now be applied to world oil production. It is clear that world oil production has peaked, and fracking and tar sands only delay the inevitable. I would also like to add the "Grift coupling" here (since I stole the idea from Hubbert), stating that any activity that is highly correlated with oil production will follow the same curve. If we don't somehow decouple food production from oil, then the End of Oil will drag us down to widespread poverty and hunger.

What about solar, wind, and water power? All of these alternatives can be debunked on the back of an envelope; they simply can't replace oil. In addition, a large percentage of the population does not understand that electricity is not an energy source, but only a carrier. The same goes for the "hydrogen economy." Hydrogen is another energy carrier, and it has serious storage issues. We can generate electricity from coal, too, but during the eight hours it takes to fill the electron tank of your $100,000 Tesla, about 65% of that energy has been lost. What's more disturbing is that this is really not so bad, considering that the energy efficiency of the transportation sector is just 21%!

Tony Grift
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Meanwhile, bioenergy currently makes up 4.5% of the U.S. energy budget, which is negligible, especially considering the increasing demand for energy in the future.

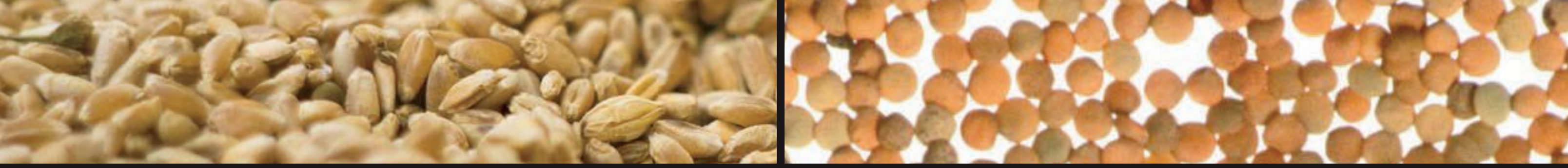
The problem is a matter of scale: humanity consumes 86 million barrels of oil per day (mbpd), or about 1,000 barrels each second. The U.S. alone, with just 5% of the world's population, uses 20 mbpd. Try replacing that with an equivalent amount of any alternative. And most of the oil is contained in the Middle East—not exactly the friendliest of environments.

We count on politicians to make the major decisions, but they never look beyond the next election cycle. And any politician who implements strategies that hurt people in the short term will not be re-elected. So, although the problem of feeding the world in 2050 can be explained with a spreadsheet, solving it is a very different matter. It was easier to put a man on the Moon. President Obama acknowledged the problem in a speech he gave back in 2012:

> *"We've seen how spikes in food prices can plunge millions into poverty, which in turn can cause riots that cost lives and can lead to instability. And this danger will only grow if a surging global population isn't matched by surging food production."*

I would like to remind Mr. Obama that surging food production will not happen unless we develop long-term solutions to our looming energy problems. Forget about hope, let's change!

If there is a positive side to feeding the world in 2050, it's that this topic is near to the hearts of ASABE members and their colleagues around the world. In fact, when we solicited contributions, we received so many useful and intelligent responses that ASABE will publish a second collection in *Resource* next year! Lastly, great issues like this would not happen if it weren't for the unwavering support and creativity of the *Resource* staff. Kudos to them, and my thanks.



... Feed the World in 2050

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Six months ago, while mulling over their morning coffee in the café at the University of Illinois Center for Genomic Biology, an agricultural engineer and a plant geneticist envisioned a cross-society magazine on the theme "Feed the World in 2050." This special publication would combine ASABE's *Resource* with *CSA News*, the member magazine for the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Letters went out ("You have been selected as a potential contributor..."), and the response was gratifying.

But back to the coffee. The brew is good, the pastries are tasty, but more importantly, the exchanges between the Dutch-born engineer (my colleague Tony Grift) and the German-born plant breeder (me) are always engaging. I look forward to this part of my daily routine. Tony and I delve into the news of the day, discuss scientific problems, and ask ourselves why others haven't thought of the brilliant solutions that we are coming up with! Our views often differ, but it's those differences that make our conversations so thought-provoking for me.

Germans, like me, are not known for our optimism, but I trust human ingenuity to solve the challenges we face. Science constantly extends the boundaries of the known universe, and we increasingly understand how life on this planet is organized and how it functions. We might not be able to feed the population of 2050 using the tools of today, but we will make discoveries that pave the way to future food security.

Tony isn't convinced. His confidence in scientific progress is not strong enough, given the enormity of the problem. "It will be impossible to produce enough food to feed nine billion people by 2050," he tells me. As he writes in his accompanying foreword, the world economy is hooked on oil, a finite resource that humans have already exploited beyond its peak. We know that the oil is running out, but we ignore it. Given the projected population increase and the rising demand for food, the coming End of Oil will have severe consequences.

To gain more understanding about the problem of feeding the world in 2050, we asked scientists, engineers, economists, architects, and journalists—people at the forefront of research and reporting on this issue—for their ideas and advice. As the responses came in, they revealed the real complexity of this challenge, and I wondered whether the world has ever successfully addressed such a pressing need on such a huge scale.

In 2000, the United Nations defined eight Millennium Development Goals (MDGs), which include eradicating extreme poverty and hunger, promoting gender equality, empowering women, and developing a global partnership for development, among other goals. The non-binding Millennium Declaration was signed by 189 UN member states, who expressed their intention to aggressively work toward these goals using measurable targets within a timeframe of 15 years.

The recently released 2014 progress report notes that several of the MDG targets have been met. These include the reduction of extreme poverty by 50%; saving millions of lives by successfully fighting HIV/AIDS, malaria, and tuberculosis; providing improved drinking water for more than 2.3 billion people; and promoting gender equality by eliminating disparities between boys and girls in primary school enrollment. However, critics question the success of the MDG program, as progress toward many other targets has been insufficient. In particular, sub-Saharan Africa seems to be disconnected from any positive development.

The problems we face are significant: too many people live in poverty, global climate change is really happening, and the world's population is steadily increasing. It may seem that the size of the solution must match the size of the challenge, but that isn't entirely true. Global problems can have local solutions.

Here is an uplifting example: Neema Urassa, a village-based agricultural advisor in the Kiteto district of Tanzania, has improved the lives of hundreds of local farmers by supplying them with improved maize seed and new information on crop management (www.feedthefuture.gov/country/tanzania). It's simple!—better seed and a few changes to the way maize is traditionally grown in the region have had a dramatic impact.

Truphosa Losioki, one of the local farmers, was skeptical about harvesting more maize with the new farming practices. But she tested the system on a small plot and, based on the results, decided to make the investment of buying the improved seed. She planted the seed on 10 acres and harvested 138 bags—a record yield, considering that the previous average yield was just 30 bags on the same 10 acres. She sold 100 bags on the market and commented, "I intend to grow maize this way on many more acres of land, in order to complete my house and send my children to Dodoma University."

Good seed, and some good information about how best to use it, changed this family's future, empowered a woman, and led the way to educating her children. Imagine what great things can be accomplished if we put into action all the ideas from our contributors in these special issues of *Resource* and *CSA News*.

Maybe I'm an optimist after all.

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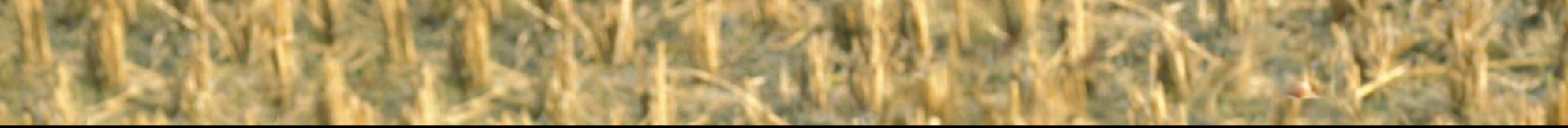


When I Think About Poverty

Robert S. Zeigler

When I think about poverty, I think back to the 1990s when I was traveling in Bangladesh. Driving through the countryside after the rice harvest, I saw some piles of dirt out in a field. I stopped to investigate. The accompanying photo shows what I found. A farmer squats in front of a hole he has just dug out. He's holding rice panicles.

What's going on here? The hole was a rat's nest. After the harvest, the landless poor of Bangladesh go out into the fields to find these nests. They excavate them to take back the rice that the rats have stolen. To me, that's poverty.

Poverty is more than not having money in your pocket—it's not having food to feed your children, not having enough to provide them a decent education or health care. **When we talk about dealing with food shortages, we're also talking about poverty.** That's something we need to be more cognizant of as we discuss food security.

The world continues to have huge concentrations of poverty, and most of these concentrations are in areas where rice is grown. **If we want to overcome the problems of hunger—and poverty—then rice must be part of the solution.**

Global demand for rice will continue to grow. Every past prediction that demand for rice will taper off has been proven incorrect. Current population trends suggest an additional billion people every 12 to 15 years. In the rice-consuming world, another billion people means 100 million tons of additional paddy needed to feed them. That's an additional 65 million tons of milled rice every decade and a half.

Where will this additional rice come from? Ideally, it will come from existing crop land, primarily in Asia. But land is moving out of agriculture, especially in Asia, where rice fields are being steadily converted to other uses. Labor is also moving out of agriculture. When I visit a rice-growing region, I always ask the farmers: What do you want your kids to be when they grow up? Rice farmers never, ever want their own children to be rice farmers!

Innovations in production practices, driven by research, will help balance these forces and help us stay where we are. However, "where we are" is not good enough. The challenges of climate change are also going to affect agriculture, especially rice cultivation. We need rice varieties that can tolerate higher temperatures and withstand floods. We also need rice varieties that can tolerate drought and saline soils, particularly in coastal areas. And we need production practices that are more efficient, that demand less water and other inputs, and that produce consistently good yields.

We can now address these challenges in ways that we never could before. Ten million years ago, rice species started to evolve. They diversified in some very difficult environments, some droughty, some stony, and some shady. That genetic diversity, in combination with advances in molecular biology and computational power, allow us to tap into incredible wealth from diverse environments. We now have the ability to cross wild relatives with domesticated rice to bring in traits separated by millions of years of natural selection and evolution.

To help achieve this, the International Rice Research Institute (IRRI) maintains the world's largest collection of rice germplasm—more than 120,000 rice accessions and wild relatives. The IRRI genebank also contains wild relatives of rice, vital additional resources to help us meet tomorrow's challenges.

We also need to understand how a rice crop behaves, and new technology will help with that. Satellite imagery and cloud-penetrating radar will show us where rice is planted, when it is planted, and how much area is planted. Combining this information with plant growth models, we can improve food security in the rice-consuming world. Add this to the decades of experiments on crop nutrient management that we've conducted across Asia, and we have the tools that will enable farmers to make real-time decisions about managing their crop.

All that being said, the ultimate question is: how do new rice varieties actually perform in farmers' fields? On 31 July 2008 at 1:17 in the afternoon, Mr. Asha Ram Pal stood in his rice field after two successive floods and considered his options. His neighbors laughed and told him to plow it up because "you're not going to get any crop out of that field." He didn't plow it up, and in October of that year he had a good harvest.

I asked Mr. Pal how the rice tasted. He said he didn't know because he sold the entire crop as seed to his neighbors—the same neighbors who told him to plow up his field in July.

The moral here is "always listen when people laugh at you, and then do the opposite of what they say." Seriously, Mr. Pal's flood-tolerant rice is already in the hands of more than 5 million farmers in Asia. I would like to suggest that a second Green Revolution in rice started at 1:17 in the afternoon on 31 July 2008, when Mr. Pal decided not to plow up his field.

Food security in 2050 requires that two Green Revolutions succeed: the first revolution, started in the 1960s, to continually increase yield to meet ever-rising demand, and a second revolution to help the poorest farmers who have no choice but to plant in the most unfavorable environments.

In addition to our research efforts, we must help people prepare for catastrophic times. Even under ideal conditions, rice farmers have a tough job. And under no circumstance should farmers have to steal back their harvest from rats.

Robert S. Zeigler, Director General, International Rice Research Institute, Los Baños, The Philippines, r.zeigler@irri.org.

Mid-page photo © Thanamat|Dreamstime.
Photo on facing page by the author.

A Futurist's View

Richard Worzel

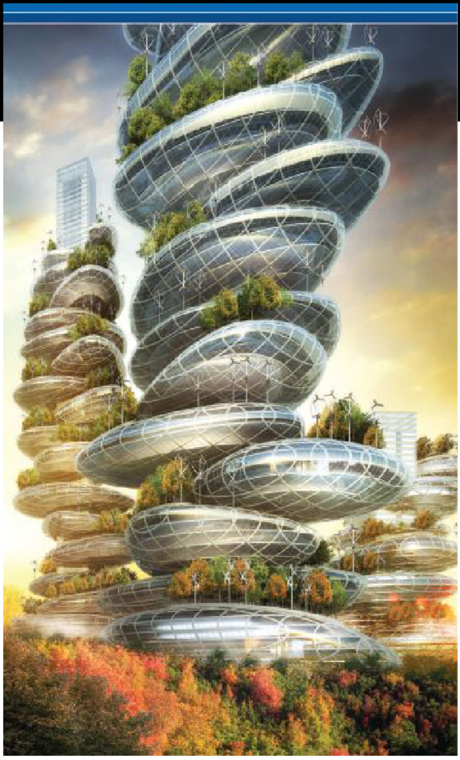
Feeding the world's population in 2050 may well be one of the most difficult things humanity has ever done, and for many reasons.

First, the global population is projected to grow by roughly 30%, from 7.26 billion today to 9.6 billion by 2050, according to the United Nations. As developing countries continue to move into the middle class, and as more people move into cities, more people will eat more expensive calories, notably meat and dairy products. This is the pattern that China exhibited during its period of greatest growth, from 1960 to 2000. The population doubled, but food consumption tripled because calories consumed per person increased from 1600 to 2600 per day. Similarly, the FAO projects that while the global population may grow by 30%, global food consumption may grow by 50% to 70%.

How can this be supported? Well, one way would be if prices rose enough to stifle the move by developing countries into the middle class, and by having hundreds of millions of poor people starve. And that would not be out of the question, because farming is going to become more difficult in the decades ahead.

While yields grew dramatically from 1960 to 2000, averaging about 3% a year, they are now growing at rates closer to 1%. Indeed, they may fall, perhaps dramatically, because of climate change. The International Maize and Wheat Improvement Center (CIMMYT) has projected that if average global temperatures rise by 2°C, then wheat yields may fall by 20%. Climate change will certainly disrupt normal growing patterns. Spring floods can damage or delay planting, as happened in the Canadian Prairies in 2011 and 2012, while droughts devastate yields, as happened in the U.S. this year. Climate change will also mean fewer pests killed off by harsh winters and more pests moving from equatorial regions into temperate zones.

Even more critically, we are running short of water. The growth of any ecosystem is limited by its scarcest necessity, and in a growing number of regions, that's water. Not only are we overdrawn at the river bank, using more water for farming than we receive in annual precipitation, we are also drawing down major aquifers faster than they can be replenished, using up reserves of fossil water that took centuries to form. Meanwhile, the continuing growth of cities means that city dwellers will demand more water, forcing politicians to divert water from agriculture.



So problems in feeding the world in 2050 abound. But if we want to ask: What would have to happen for us to be able to feed 9.6 billion people by 2050 instead of starve them, then the answers become even more complicated, in large part because they require new technologies—and the widespread application of common sense, which is always in short supply.

First, the use of GMOs in farming has to spread much more widely around the world. Europe in particular has been squeamish about allowing GMOs and has blackmailed large parts of the developing world, notably in Africa, into banning them, even though there is no credible scientific evidence indicating that they cause health problems. And the food fashionistas of North America, who are trying to force a return to small-scale, organic, and local farming, will have to realize that, if they get their way, the result will be that billions of people will starve.

Next, we have to get serious about reducing greenhouse gases. Climate change will cause problems for everyone, but it will inflict serious pain on farmers. Farms are also major contributors of GHGs. According to the IPCC, "farming accounts for 13.5% of greenhouse-gas emissions, and land-use changes (often cutting down jungle for fields) are responsible for a further 17.4%. That adds up to almost one-third [of all GHGs]." Farming is also the leading producer of methane and nitrous oxide, and runoff of nitrogen fertilizers contributes indirectly by causing toxic algae blooms. Ironically, decreasing GHGs largely means decreasing waste by increasing efficiency, which, done properly, increases profits. Being responsible may actually be lucrative.

Third, we have to start using water responsibly, and here farmers can take the lead. Normal, gravity-fed irrigation is estimated to waste about a third of the water involved, whereas Israeli-type drip-feed irrigation wastes only about a tenth. And no-till farming retains more groundwater—but encourages weeds, which GMOs would help contain.

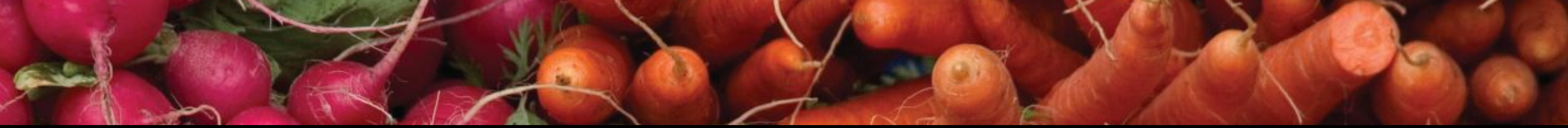
Perhaps the ultimate way we will feed 9.6 billion won't involve traditional farming at all but completely new ways of doing things. There are already plans for vertical farms, in glass-walled skyscrapers, with racks of plants growing hydroponically in revolving trays, spreading the sunlight around. This would also reduce water use and transportation costs, provide more protection against adverse weather, and make it easier to contain pests.

Or we might produce food directly by using emerging techniques, like 3D printing, to print foods to order from base ingredients. Human organs are already being printed in this way, and some food proteins have been produced as well, including fish and beef. This could lead to steaks without steers, and food without farms. It's too early to tell how expensive this would be, or whether it would be scalable, but it has the potential to shake up one of the world's most fundamental industries.

While there is a lot of uncertainty about how we can feed the world in 2050, one thing is absolutely certain: We cannot just do more of what we're doing now. Farming—and the general public's attitudes toward farming—will have to change, and change radically.

Richard Worzel, a leading futurist, consultant, Chartered Financial Analyst™, and author of *Who Owns Tomorrow?*, Toronto, Canada, www.futuresearch.com.

Architectural renderings courtesy of Asian Cairns, Sustainable Farmscrapers for Rural Urbanity, Shenzhen, China. Courtesy of © Vincent Callebaut Architecte, Paris.



A Glimpse of Our Future Food System

Freija van Duijne

We all know that there are huge challenges in feeding nine billion people, and eradicating hunger and malnutrition, in a world plagued by climate change and water shortages. Fortunately, people aren't just sitting and waiting for things to happen. Instead, the global food system is undergoing deep, transformational changes on all levels. Here are six of the main developments that we see right now that will pave the way to our future food system in 2050:

Awareness of the need to reduce waste

Based on the shocking statistics, such as global food wastage of 1.6 gigatons in 2007, it is clear that one of the solutions to global food shortages is preventing loss and waste throughout the food chain. It all starts with awareness in every part of the food chain. Sophisticated logistics for matching supply and demand, along with improved technologies for storing fresh produce and other perishables, are priority topics for R&D in agriculture and food science. The biggest waste of food, in terms of energy use, is the food that we leave on our plates and discard in our kitchens. Smaller portions, innovative doggy bags, food sharing, and tips and tricks for cooking with leftovers are simple ways to improve our wasteful lifestyles.

The emergence of the bio-economy

The throwaway economy will come to an end. We are starting to see the value of resources that were previously considered waste streams. Valuable components in plant-based materials have great potential for use as bioplastics and biofuels, and they may hold components that are useful in pharmaceuticals, food ingredients, and other high-value applications.

Climate-smart agriculture

In recent years, climate-smart agriculture has become an established term in sustainable farm management and in integrated solutions to global food security, environmental quality, and economic welfare. Climate-smart interventions focus on optimizing energy efficiency, soil quality, water productivity, and fertilizer inputs. All of these factors contribute to climate-resilient agricultural systems in economies all over the world.

The Vegetarian Butcher, purveyor of a new generation of meat substitutes, in The Hague.

Alternative plant-based proteins

The ecological footprint of meat production is much larger than that of protein-rich plants. A large proportion of our food crops is used as animal feed for meat production. This realization, together with recurrent infectious diseases, animal welfare issues, waste disposal issues, and the obesity epidemic and other human health concerns, is leading many people to adopt diets in which meat has a less prominent place. Meatless Mondays, veggie Thursdays, and flexitarianism (part meat, part vegetarian) have become common concepts, all of which are opening up opportunities for plant-based protein-rich foods. Meanwhile, the era of the bland veggie burger has passed. There are now many tasty meat alternatives, even for hardcore meat lovers.

The sustainable food movement

Seeking out sustainably produced food has become a means by which people show that they care about the world, the ecosystem, and the farmer. Sustainable food is about healthy eating, ecological responsibility, fair production (preferably local), with little or no waste and pollution. Sustainable food is also about being connected to the food system, and getting to know the people who work to grow and prepare the food we eat. It's a positive movement that helps us maintain a healthy relationship with food and build awareness about the need for a sustainable future.

Urban food production systems

Part of the sustainable food movement is about bringing food closer to the cities. Neighborhood farms and gardening projects have popped up everywhere. Most of them are artisanal and low tech, but they are all about the joy of working the soil and celebrating food production. With the emergence of affordable sensors, LED lighting, and other technologies, high-tech vertical indoor farming is also on the rise. It is not hard to imagine that many of our empty buildings and urban rooftops will be used for food production in the near future.

Looking at these trends collectively, we can see the contours of a future food system. With clever solutions to prevent waste and boost productivity in an ecologically sound way, the world population can have greater access to healthy, nutritious foods. Balanced plant-based diets can lessen the demand for animal protein in affluent societies. Sustainable foods are already becoming mainstream.

One thing is clear: everyone has a role to play. Farmers, the food industry, governments, scientists, and consumers are all bringing new perspectives, new technologies, and new practices to the global food system—and thereby taking steps toward feeding the world in 2050. That's how progress happens, and that's how the future will be built.

Freija van Duijne, foresight practitioner, Ministry of Economic Affairs (DG Agriculture), on temporary assignment based at The Hague Centre for Strategic Studies in The Netherlands: freijavanduijne@gmail.com, www.futuremotions.nl.

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Mid-page photo courtesy of The Vegetarian Butcher, www.vegetarianbutcher.com.

Toward Food Security in 2050

Judith D. Schwartz

As a journalist, I've devoted the last couple of years to looking at soil as a hub for our many global challenges—and for solutions. So when it comes to the growing of food, I take a soils'-eye view. Ultimately, food can only be as good as the soil on which it was grown. Moreover, the biological processes that drive crop production depend on the workings of numerous cycles—the carbon, energy, water, and nutrient cycles—each of which moves through the soil. If, based on my research and on-the-ground reporting, I were to offer up a prescription as to how we, collectively, can keep our population fed, it would be this simple: **our practices, actions, and policies should be assessed according to whether or not they are good for the soil.**

I see this as particularly relevant at a time of impending climate instability. For while it's not often discussed as such, soil health is a lever for climate change adaptation and mitigation. Soil—that fine, living layer that cloaks the earth—is where food, farming, and climate meet. To a large degree, our capacity to feed the world in the coming decades depends on how we treat the soil. If we approach food production from the standpoint of extracting from the soil, we risk depleting this resource. If, however, we seek agricultural practices that regenerate the soil, we not only promote food security but also ameliorate other environmental problems looming over us. Soil, you see, is the connector.

Let's zero in on some current challenges to food security. Right now, in food-producing areas around the world, the best-laid plans are haunted by the specter of weather abnormalities, notably floods and droughts. But once we bring land function—the ability of land to sustain plant and animal life—into the picture, we open up new possibilities for building security into the food supply. An emphasis on floods and droughts—whether there's not enough rain or too much all at once—leaves the impression that we're at the mercy of the elements. By contrast, a focus on land function creates a sense of agency. Specifically, it draws our attention to the many ways we can enhance soil's ability to retain water, organic matter, and microbial life, thereby offering resilience in the face of flooding and dry skies.

Land management approaches that integrate animals and crops are often used to build soil health.

Although largely invisible to the general U.S. public, land degradation due to human impact is a huge problem across the globe. According to the United Nations Convention to Combat Desertification, each year upwards of twelve million hectares (thirty million acres) of productive land is lost to desertification. This means an area the size of South Africa is slipping away every decade. Some 1.5 billion people, primarily in dryland regions, rely on land categorized as degraded for their food and livelihood. What's important to keep in mind about desertification, and, more generally, land degradation, is that it's not something that simply "happens." Rather, it's caused by such soil-harming actions as overcultivation, deforestation, poor irrigation design, poor livestock management, and the use of technology ill-suited to the landscape.

Many of the problems we attribute to climate change are in fact the direct result of soil loss and degradation. Exposed soil loses carbon. Low-carbon soil retains less water, so rainfall evaporates or flows away. Without moisture, the ground becomes a hot plate, and microorganisms die. This dynamic sets up the scenario for flooding (when rains arrive) or drought (when it doesn't)—the type of situation that's led to famine in, say, the Horn of Africa, widespread food insecurity, and global financial losses in the tens of billions of dollars annually. Functioning land has soil carbon, plant cover, and the capacity to hold moisture. In the event of heavy rain, water is absorbed by the soil and filters into aquifers. With more moisture in the "bank," such land can support plant and microbial life when rain is sparse.

An appreciation of land function sheds new light on strategies to bolster food security. For example, **the best genetics in the world won't increase yields if we attempt to grow crops on depleted soil.** While heavy nitrogen fertilizer can temporarily mask soil depletion, it ultimately alters the soil's microbial balance and pH in a way that reduces fertility, leaving farmers on a costly and counterproductive agro-chemical treadmill.

The stresses to food security are daunting, and the prospect of changing weather patterns adds to the collective alarm. However, there is good news: a shift toward considering land function introduces proven restorative practices that boost resilience to weather extremes while minimizing the cost of inputs. It's all a matter of starting with the soil.

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Top photo © Roman Milert|Dreamstime.
Bottom photo, Cold Moon Farm, Jamaica, Vermont, USA, by Tony Eprila.

A Long Way to Go

John Schueller

The author's first crop map, drawn when he was nine years old.

Knowing the back-breaking tedium of growing up on a family dairy, grain, and vegetable farm, I have spent most of my career trying to improve the design, manufacturing, control, and use of agricultural equipment, or teaching others to do so. Improved equipment makes farming better for the farmer, as well as for the crops and soils that produce the food, fiber, feed, and fuel that our modern consumer society requires. Improved equipment should maximize the productivity and efficiency of a farming operation in a way that is economically, environmentally, and socially sustainable.

Good dairy farmers treat every cow in the barn as an individual to maximize her production and health. But as for the feed for those cows, farmers may treat all their fields the same, no matter what the differences are between or within fields. It would be better if farmers could respond to field variability the way they respond to differences in their cows, and that response should be an integrated optimum response to spatial variability, combined with temporal variability and the weather.

Just as computer technology has allowed mass customization in manufacturing, it has the potential to treat each square meter of soil and each plant in the best way possible. Therefore, **my goal for 2050 is that plant agriculture will be optimized for maximum sustainability at small spatial and temporal scales.** That, rather than fancy technologies, is what precision agriculture is all about. For example, precision agriculture can mean applying the right rate of the right fertilizer at the right location to maximize production without contributing to nutrient runoff. Or it can mean applying herbicides only to weeds and at the moment of peak herbicidal efficacy.

The overpopulated world of 2050 is not going to be fed by the United States alone. Accordingly, I will continue to share information during my half-dozen international trips yearly, as well as through a variety of media for technical and farmer audiences. I intend especially to encourage the adoption of yields maps and maps of other crop and soil properties, leading to increased production while protecting the environment.

Farmers should first be encouraged to respond to these maps with intelligent analyses leading to appropriate strategic decisions, such as changing field boundaries, removing areas from production for economic or environmental reasons, adding drainage or irrigation, or changing agronomic practices. They should then be encouraged to make appropriate tactical decisions, such as controlling water, fertilizer, or pesticide applications in a spatially and temporally variable manner as the season progresses. This requires better technologies in such areas as sensors, computer algorithms, and dynamically accurate variable-rate applicators. More importantly and more difficult, it requires the agricultural knowledge of how to utilize these tools in an optimal way.

Although the agricultural research community has made strides in the right direction, it has a long way to go. Engineers need to provide better tools that can accurately respond to temporal and spatial variability and the complex biological, chemical, and physical nature of crop production. Soil scientists, crop scientists, and agronomists need to better characterize the variability of soils and crops, and determine the responses that farmers should make to that variability to maximize sustainability and profit.

To maximize our progress toward solving the needs of 2050, **significant changes are needed in the agricultural public sector.** State and federal departments of agriculture, extension services, and land-grant universities have a long history of contributing to the advancement of agricultural practices. However, inertia and administrative demands are hindering our progress toward meeting the needs of 2050. For example, despite much rhetoric and many feel-good proclamations about support for interdisciplinary and multidisciplinary approaches, the current reporting, staffing, financing, and other administrative structures, regulations, and procedures effectively discourage work between disciplines.

Dealing with these constraints is time-consuming and distracting when one discipline is involved, but the detrimental effects are multiplied when multiple disciplines are involved. **Something must be done to remove the common perception that interdisciplinary and multidisciplinary work is painful—and detrimental to one's career—so that the gaps in knowledge between disciplines can be removed.** One reason for the creation of research centers was to solve this problem, but it seems to have led instead to more administrative burdens. And those research centers have siphoned potential funds from smaller activities that are generally more efficient in generating significant outcomes.

Another needed reform in the public sector is the removal of matching fund requirements. Truly innovative and revolutionary projects of the type needed to make disruptive changes in crop production to feed the world in 2050 will not result from approaches that are "business as usual." Unfortunately, those approaches are comfortingly familiar, and therefore receive widespread support.

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The Importance of Chemical Inputs

Paul Miller

The use of agricultural chemicals to provide crop protection and nutrition is fundamental to maintaining and improving the yields for almost all food-related crops throughout the world. However, the use of such chemicals presents important challenges for both human and environmental safety. The engineering associated with the application of these chemicals is fundamental to achieving the optimum balance between promoting and protecting crop growth and managing the risks associated with off-target exposure and residues in harvested crops. This engineering challenge has been the subject of my research and development interests for more than 30 years.

Most crop protection chemicals are applied as water-based sprays from hand-held, vehicle-mounted, or aerial platforms. The delivery system needs to ensure that:

- The correct dose is applied to the target area, this dose being the minimum required to achieve the required biological outcome.
- The dose reaches the target where it will be most effective in such a way that all of the target sites receive the required dose. This may involve treating a crop area as uniformly as possible or targeting particular weed plants within a crop area.
- The losses from the treated area, either as airborne drift or leaching through the soil profile, are minimized.
- The applications are made in a timely manner with respect to crop growth stage, weed/disease/insect development, and application conditions, since timing has a major influence on the effectiveness of most chemical treatments. Where substantial areas need to be treated, the work rate is therefore a key performance parameter for many systems.

Engineering developments over the past two decades have made important contributions toward addressing the above issues, with examples relating to:

- The size of equipment and the speed at which it can operate. Ground-based machines are now larger and able to operate effectively at higher speeds and with greater boom widths, mainly because of improved vehicle and boom suspension systems.

A water-based spray hitting a plant leaf.

- Improved control of the delivered dose by using better spray rate controllers, GPS-controlled auto-section switching, and pressure management valves on hand-held equipment.
- Reduction of spray drift by using air-induction nozzles, improved control of boom height, and an improved understanding of the mechanisms that lead to spray drift as explored in computer simulation models.

The chemicals required for crop nutrition have mainly been applied as solids (prills, granules, and dusts), although there is an increasing trend for these materials to be applied as liquids to achieve high levels of accuracy in delivery. Many of the requirements for effective application of these materials, and the engineering advances needed to address them, mirror those related to pesticide sprays, with the same basic principles applying to both.

While significant progress has been achieved in the way agricultural chemicals are applied, much remains to be achieved. In Europe, the registration of useful pesticides is being lost because the chemicals are being detected at unacceptable levels in ground and surface waters. **It is becoming increasing difficult, both technically and economically, to register new chemicals, and the result is that the chemical options for controlling pests and diseases are decreasing.** The use of a relatively small number of crop protection agents creates problems of resistance; hence, those chemicals that are still available become much less effective. The use of nutrient chemicals is also restricted in Europe to manage losses to ground and surface water sources.

Because of herbicide resistance, large areas of arable land in the U.K. are now being cultivated to control grass weeds in cereal crops, resulting in high energy inputs and soil conditions that are not optimum or sustainable for crop production. New ways of applying chemicals will be needed as we move toward 2050. While the use of robots, for example, to apply mechanical treatments to control weeds has potential for some small-area specialty crops, other solutions are required for crops grown on large areas. Key components of these new systems are likely to be:

- Sensing systems that define target requirements with greater precision.
- Delivery systems with high levels of spatial and temporal resolution.
- The ability to match the physical form of the delivered agent (chemical and/or biological) with the target requirements and minimize off-target losses.
- A scale of operation that ensures the overall timeliness of the application.

Researchers in other disciplines will be needed to work with agricultural engineers to achieve improved chemical use to deliver the higher crop yields needed to feed the world in 2050. The most important of these disciplines will be those that develop the new chemical and biological agents required to modify and control crop growth. In addition, plant breeders have a key role to play by providing resistant varieties and crop traits that can aid the early detection of weeds, diseases, and pests. Chemical use will need to be an integral part of future production systems, with agricultural engineers working closely with agronomists to deliver high yields of high-quality crops.

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Mid-page photo courtesy of the author.

Playing Politics with the Future

Charles Merfield

I have been involved in food production since studying commercial horticulture in the U.K. in the late 1980s and then managing organic vegetable farms in the U.K. and New Zealand for six years. From there, I alternated between working on organic farms and post-graduate study researching organic vegetable seed production, followed by a postdoc at Teagasc in Ireland, and then setting up the Future Farming Centre in New Zealand. I have therefore been involved in all aspects of sustainable food production, and I consider my real-world farming experience critical to informing my research and my political and ethical views of agriculture.

Herbicide alternative: Interrow hoe guided by computer vision.

In particular, I am focused on using science to find practical (i.e., will work in real-world farming), permanent, and sustainable solutions to optimize (not maximize) agricultural production while minimizing the externalities of farming, especially those that degrade the biophysical and ecological systems that make agriculture and civilization possible in the first place. This process includes packaging the research results in a form that's optimal for farmers and growers to implement, i.e., good old-fashioned extension, but brought into the 21st century by being based on sociology and psychology, and treating the farmers as equals.

In a nutshell, **we need much more funding for agricultural research and extension, and for attracting the best brains to agriculture—for both science and farming.** I agree with Professor Iain Young's comments at the 2014 "Soil Change Matters" symposium that developed countries are spending very large amounts of money on projects such as the Mars Rover and the Square Kilometer Array that, while great science, are also rather frivolous considering that many fundamental biophysical processes of the Earth (climate change, soil degradation, the nitrogen deluge, etc.) are now known to be in such a perilous state that the continued existence of civilization is in the balance, and some are worried that *Homo sapiens* may join the sixth mass extinction event. If we want to be able to undertake frontier science in the future, we must first direct our efforts to sorting out the mess we have made of our home, the Earth.

Having said that, we know what is fundamentally required to create a sustainable food production system: close the lithospheric nutrient cycles; use only renewable energy; ensure that soil degradation rates are lower than pedogenesis; vastly expand physical, biological, and ecological management to replace failing agrichemicals; and treat agriculture as the foundation of civilization that it is, not just a collection of market commodities. What is therefore really required is the will to implement these changes and to complete the third agricultural revolution—from industrial agriculture to ecological agriculture.

However, **the elephant in the room of the "feeding the world" debate, in my humble opinion, is the flip side of food production—that is, food consumption.** High-school physics and ecology show that the population of any apex predator is solely determined by its prey's population. Decrease the predator's food supply, and its population will decline; increase the food supply, and the predator population grows. Humans are clearly Earth's apex predator. Therefore, increasing our food supply to "feed the world" not only feeds the current population but also increases future populations. The Green Revolution is therefore a double failure: it has failed to achieve its fundamental aim of feeding the world, after half a century of trying, and it has also doubled the human population, thus doubling the size of the problem.

Unfortunately, human population management has a rather bad name, from Malthus' solutions, which are utterly reprehensible to today's ethics, to China's "one child" policy. Fortunately, we have population management tools that are not only compatible with current moral norms but are, in fact, considered highly positive—education, empowerment of women, accessible healthcare, and an effective social safety net, especially for retirement—all of which are reliably successful at halting population increase. **What's lacking is the political courage to discuss population management as we discuss food production, and to ensure that the large proportion of the human population without education, empowerment, and security can participate in these benefits.**

In the end, the solution is fundamentally political, and every part of society—private citizens, government, business, and the professions of science, engineering, law, and medicine—have a responsibility and a role to play.

Let's approach the problem of feeding the world from a different perspective, 180° from the standard perspective of matching food production to current populations. Instead of just producing more food, by whatever means, we need to design agricultural systems that are stable at geological time scales, and then match the human population to the level of food that such sustainable systems can provide. To do otherwise simply won't solve the problem of feeding the world; it will just delay the inevitable crash.

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Photos by the author.

Combatting the Pollinator Crisis with Genomic Biology

Claudia C. Lutz, Christina M. Grozinger, Gene E. Robinson

In our struggle to achieve sustainable food production, humankind has enjoyed the benefits of a silent cadre of allies that, in the past, has been taken for granted. Modern agriculture relies on the pollinating activities of diverse animal species including bees, flies, wasps, butterflies, moths, bats, and many others. Pollinators, especially bees, play a crucial role in the production of three quarters of our major global food crops, including the vegetables, fruits, and nuts that provide the majority of our vitamins, minerals, plant-based fats, and micronutrients. Pollination is also required to produce seed for crops such as sugar beets and other root vegetables, as well as hay crops used to feed meat and dairy animals. All told, nearly 90% of flowering plant species use animal-mediated pollination, and thus pollinators play a vital role in the heath and productivity of both natural and agricultural landscapes.

Events of the past few years have forced us to confront the possibility of a world without this nutritional abundance. **The health of our pollinators is at risk.** In the U.S. and worldwide, there is evidence for long-term decline in populations of pollinating species, including honeybees, bumblebees, hummingbirds, and bats. Many other species, for which there are no long-term data, face similar ecological challenges. Pollinators are threatened by multiple factors, including pathogens, parasites, pesticides, and inadequate nutrition due to reduced abundance and diversity of flowering plants species. These and other stressors have been accumulating, largely unheeded, for years. Many of them originate from modern agricultural practices.

Perhaps the most publicly recognized example of this problem is colony collapse disorder (CCD), a phenomenon characterized by dramatic loss of honeybee colonies that was first observed in 2007. CCD is a call to action for a larger challenge: we must find novel ways to reduce the environmental burden that pollinators are forced to bear and support the health of managed and wild species.

Combatting these factors to halt or reverse pollinator loss will require an integrated approach spanning basic research, applied research, and information dissemination created by a large-scale coordinated effort between scientists, extension educators, stakeholders, policymakers, and the public. A free flow of information among these groups will ensure the effective and rapid application of research results and newly developed strategies and, equally important, provide scientists with critical insights into the key questions and problems that need to be addressed.

We need a wide array of research efforts to devise the best ways to rescue pollinator populations. Finding solutions will require a combination of many approaches—spanning genomics, disease ecology, toxicology, behavior, ecological modeling, and economic analyses. To develop effective management and conservation practices that protect pollinators, we need to understand the mode of action of stressors such as exposure to pesticides, parasites, and nutritional deficits, as well as how those stressors enhance each other's harmful effects. Furthermore, to ensure effective pollination of all crops, we must greatly expand our understanding of the basic biology of a broad number of pollinator species, beyond honeybees.

Genomic biology can play an important role in advancing our understanding of pollinator health. Genomic resources have been developed for several pollinator species, including honeybees, native bees, butterflies, and moths, as well as for some of their pathogens and parasites. Harnessing these tools and resources has significantly accelerated our studies of pollinator biology and health. Genomic studies have been used to identify the pathogens and stressors associated with CCD, demonstrate that pathogens flow readily from managed honeybee colonies to other pollinator species, and improve our understanding of the complex micriobiota, both parasitic and beneficial, found in pollinators. Genomics has also been used to examine the effect of pathogens, parasites, pesticides, and nutritional deficits on honeybee health and wellness.

We must extend this research strategy to other key pollinators and use the findings to develop diagnostics for monitoring stressors in the field, predictive models of responses to stressors, and management approaches to mitigate these stressors. It also should be possible to use genomic tools to breed more resilient pollinator populations and develop methods to combat the effects of pathogens and parasites in an ecologically sound manner.

Global food security, human health, and healthy ecosystems all depend on robust pollinator populations. By building bridges between communities of scientists from a multitude of disciplines, extension educators, stakeholder groups, policymakers, and the public, we can develop a strong network that effectively combats pollinator decline with a unified strategy that reaches from genomes to ecosystems.

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Photos courtesy of Zachary Huang, ww2.beetography.com.

Adapting Industrialized Farming to Ecosystem Realities

James Lowe

Growing up in the heart of the U.S. corn and soybean belt, son of a vocational ag teacher, and around farms and farmers from a very young age, I have always been fascinated with all aspects of how we provide food to the world. Professionally, I have explored that fascination as a food animal veterinarian, pork producer, row crop farmer, scientist, and teacher—sharing ideas across the entire spectrum of food production, processing, and distribution. Over the last 20 years, I have observed a mind-boggling improvement in the output and efficiency of agriculture as a result of applying industrial processes and techniques. While our current level of operational efficiency in animal agriculture is impressive, updating our "fence row to fence row" approach to livestock production will be necessary to meet the world's food needs over the next 35 years in a sustainable way.

We normally use the term "fence row to fence row" when talking about corn and other commodity crops, but animal production involves the same approach. We have focused on short-term maximization of economic returns by maximizing the density of a single livestock species of a very limited range of genotypes in narrow geographic regions. This approach has led to huge leaps in operational efficiency, but it has also created an ever-increasing list of epidemic diseases, which create huge economic losses, massive reductions in operational efficiency, and a high degree of variability in our food supply. Porcine epidemic diarrhea virus (PEDv) is only the latest example.

This vulnerability is the result of massive populations in close proximity that are highly interconnected and that have a low degree of resistance to new diseases and changes in existing diseases. This means that any infectious agent can quickly spread through the entire population. In ecosystem-speak, new or changed disease agents are exotic species with little pressure in their new ecosystem to keep them in check.

As a scientist and clinician, I have a broad perspective on the constraints that we face in addressing disease challenges while maintaining production. As a pork producer, I am in awe of the technologies used in crop production to quickly and accurately address these challenges. However, **while GMO technology and precision chemicals, for example, have been very effective for crop producers, animal ag needs a different approach to disease management.** The genetic complexity of animals, the lack of consumer tolerance for GMOs, and the slow rate of genetic change in even the most technologically advanced breeding programs limit our ability to use genetic approaches to reduce the impact of disease. In addition, the rapid emergence and change of pathogens makes the development of new vaccines and antibiotics difficult. Many novel pathogens are not suitable candidates for immuno-prophylaxis because they are immuno-evasive. Increased societal pressure to limit antibiotic use, with the aim of prolonging antibiotic effectiveness in humans, also limits our ability to use antibiotics against bacterial agents.

Fortunately, we are at the forefront of several new technologies that will allow us to understand animal production systems in deeper and more meaningful ways. Advanced high-throughput genomics is one of these new technologies that will improve our ability to control animal disease. When these advanced genomics techniques are used on both the microbiome and the host and coupled with cellular biology to understand gene expression and metabolism, a holistic assessment of disease can begin. By using these holistic approaches, we can begin to understand how our animal management systems affect disease resistance at the host and population level, allowing us to adapt our management strategies to optimize production efficiency and prevent disease over the long run.

These technologies can be revolutionary, and implementing them will require a new model of collaboration across a wide diversity of disciplines. This type of collaboration is happening, but traditional academic practices and funding sources do not yet fully support this new research model. However, it's heartening that researchers are generally excited about building diverse teams among academics, clinicians, and industry. Non-traditional sources of funding, while limited in scale, have also become involved in these novel teams.

So what am I going to do to help feed the world by 2050? I am going to **focus on building cross-functional teams to address the complex problems of animal production**. In particular, we will design and develop animal management systems that are more resistant to disease and that provide a low-cost, safe supply of meat in a way that preserves that planet we live on by using fewer resources per kilogram produced. I realize that's a very specific goal, but it's achievable, and it's a good start.

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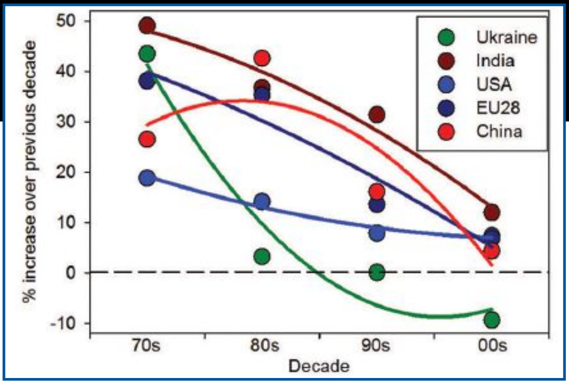
Photos by Keith Weller, courtesy of USDA-ARS.

Photosynthesis: The Final Frontier

Stephen Long and Xin-Guang Zhu



Improvement in wheat yield per unit land area is declining.

Yield potential is the yield per unit land area that a genotype can achieve at a given location in the absence of abiotic and biotic stresses. To a first approximation, it is the product of the amount of solar energy available at a location during the growing season and the efficiencies with which the crop intercepts that energy, converts it into biomass, and partitions that biomass into the harvested product, such as grain. This last efficiency is commonly known as the harvest index.

The Green Revolution achieved large increases in the yields of our major food crops by both genetic improvement of yield potential and improved agronomy. Yield potential was increased by improving energy interception efficiency and almost doubling the harvest index. Examination of modern cultivars growing under optimal conditions shows interception efficiencies of almost 90% and harvest indices of 60%. These two efficiencies are therefore close to their biological limits, since there will always be a period between planting and leaf canopy closure when the crop cannot intercept all of the incoming energy, and some biomass must remain in the stems, leaves, and roots.

Approaching these biological limits is a key factor explaining why the rate of improvement in yield per unit land area is declining, as has been shown for wheat (see graph) and for rice—our two most important crop sources of dietary calories.

In contrast to interception efficiency and harvest index, conversion efficiency has changed very little. Conversion efficiency is determined by crop photosynthesis integrated over the growing season, minus respiratory losses. Typical net conversion efficiencies of intercepted solar energy into biomass energy for modern crops, averaged over the growing season, are around 0.5%, yet the biological limits are between 4.5% for C_3 crops and 6% for C_4 crops (i.e., plants in which the first products of CO_2 assimilation are three-carbon and four-carbon compounds, respectively).

Why has selective breeding failed to improve conversion efficiency? Three reasons. First, as practical means to measure leaf photosynthetic rates became available in the 1960s and 1970s, little or no correlation was found between leaf photosynthetic rate and yield. Second, the major food crops appeared to be limited in their genetic potential to set and fill seed or grain. Third, it was reasoned that if photosynthesis is the key to yield, then selection by breeders would have resulted in increased photosynthesis. So what has changed our thinking? Ironically, the answer lies in global climate change.

Global climate change is dominated by rising CO_2 levels, and this realization encouraged many field experiments investigating the direct effects of elevated CO_2 on crops. CO_2 is a limiting substrate for photosynthesis in C_3 crops, which include wheat and rice. The primary effect of CO_2 elevation is increased photosynthesis. An overwhelming body of data now shows that crops grown with elevated CO_2 in field conditions have increased photosynthesis and invariably result in increased yields.

So can photosynthetic efficiency be improved through genetics? Unlike leaf growth and harvest index, there is little genotypic variability in photosynthesis among C_3 crops. There is also little variation between species; the mechanism in soy is identical to that in wheat and rice, so there is little to select from. However, synthetic and systems approaches through bioengineering offer new opportunities to achieve variation and thereby increase efficiency.

Over the past 50 years, the mechanism of photosynthesis has been studied to the extent that it is now the best understood of all plant processes. All the discrete steps have been described, and the relevant genes, proteins, and metabolites are well described. As a result of this knowledge, and with the availability of high-performance computers, the entire process has been represented as a complete dynamic model, allowing millions of permutations to be tested to find optimal approaches to increasing efficiency. At the same time, bioengineering has become routine for our major crops, allowing practical testing of computer-based designs.

New areas of research are emerging from these new techniques. For example, cyanobacteria, from which crop chloroplasts evolved, have their own CO_2 concentrating mechanism that was lost in the evolution of land plants, which occurred at a time when Earth's atmosphere contained many times the CO_2 concentration of today. Re-introducing this mechanism to crop chloroplasts could, in theory, increase photosynthetic efficiency by 60%.

Computer-based design can also be applied at the level of the leaf canopy. A recent analysis has shown that altering the distribution, angles, and albedo of leaves within a canopy substantial increases the photosynthetic efficiency of solar energy, water, and nitrogen use. In total, combined improvements at the cell, leaf, and canopy level could more than double the conversion efficiency of today's major C_3 crops, which is no longer possible with interception efficiency and harvest index, the other two efficiencies that govern yield potential.

Although we are far from achieving these improvements in practice, **bioengineering of model species, including tobacco, has shown significant and reproducible improvements in conversion efficiency in controlled environments. It now remains to be seen if these improvements can be replicated in realistic field conditions with major food crops.** Recent analyses show that, given current improvement trajectories, future global yields of the four largest food crops will fall far short of projected 2050 demand, possibly by as much as one-third. Genetic improvement of photosynthetic efficiency is an unexplored opportunity to deliver significant yield increases before that happens.

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Small Changes Have Big Effects

Nicholas Kiggundu

Smallholder irrigation of cabbage.

I am a soil and water engineer by profession. I live in Uganda, and my outreach activities involve helping rural communities gain access to water for domestic use, livestock, and irrigation. In the past three years, I have been working with farmers in the drylands of Uganda—specifically, the cattle corridor in the districts of Rakai and Nakasongola—on a project funded by the Austrian Government. In addition to helping the local cattle farmers, my job has been to design appropriate technologies that can supply water for domestic use and small-scale irrigation of vegetables to boost household nutrition.

The nutrition status of African children is poor due to widespread poverty, which prevents parents from feeding their children a well balanced diet. The children also contribute to the labor required to fetch water from distant water sources, which are often polluted. This daily labor could be devoted to other, more useful activities. **Fortunately, ready access to clean water can be achieved with simple technology, and it can have huge positive effects.**

Here's an example of how simple technology can make a big difference. Recently, I designed a livestock watering tank for a community in Nakasongola that includes a pump to deliver water to a watering trough that provides access for 50 head of cattle at once, many more than the traditional, inefficient earth-lined watering holes. The tank has a capacity of 3,200 m^3, which is large enough for 1,350 head of cattle during the dry season and also provides some of the community's domestic water needs. In addition, I trained a group of farmers in Rakai on irrigation-saving technologies, and these farmers have been able to diversify their production and increase their income by growing vegetables in the dry season.

These simple improvements have empowered the community. For the first time in over 20 years, the people no longer need to migrate to the lake, 20 km away, to water their livestock during the dry season. In addition, the children look healthier, and their parents say that the children are doing better at school. The children's better performance at school can probably be attributed to the children having time to do their homework—since they no longer need to fetch water from distant sources—as well as to their better nutrition.

However, while such simple technologies are useful, **developing countries are facing increased pressure from population growth**. The population of Uganda is currently estimated at 34 million people. At a growth rate of 3.3% per year, Uganda will have 94 million people by 2050. Some scholars claim that Uganda's high fertility rate, coupled with the government's lack of commitment to family planning, may cause the population to explode to 130 million by 2050. The population is bound to increase in many other African countries as well.

This increasing population calls for urgent investment to revamp the agricultural sector in Africa and in the developing world. In particular, irrigation schemes are needed to make maximum use of precious water resources and mitigate the impacts of climate change. Better water management techniques will increase water use efficiency, as seen in the irrigation schemes in the developed world. Other water management strategies, such rainwater harvesting, can also be adopted with simple technology and minimal training.

These efforts will improve the current crop water productivity of many cereal crops in developing countries, which is currently in the range of 0.3 to 0.8 kg m^{-3}, to about 1.5 kg m^{-3}. Use of fertilizers in crop production also has to be supported by providing access to fertilizers in rural areas, and better marketing strategies for farm produce are needed. In Africa, rural farmers have limited access to markets. Too often, these farmers are cheated by middlemen who fix the prices for their produce.

The short-term strategy for feeding the world in 2050 should be based on polices that support agricultural development and improving crop water productivity in the various farming systems of the developing world, including proper management of irrigation, establishment of farmer training centers, appropriate use of fertilizers according to crop needs, rainwater harvesting, and improvements in postharvest handling.

In the long term, the global focus should be on policies that benefit rural people. Farmers can be trained in crop husbandry, access to markets, and post-harvest handling techniques. Politicians can provide more funding for agricultural development. The scientific community can develop drought-tolerant, early-maturing varieties, with better water use efficiencies, that are acceptable to local cultures. Funding agencies can invest in projects that have tangible benefits on communities and that contribute to improved livelihoods. Simple projects can have an enormous positive impact on people's lives. And this approach doesn't have to cost much because we already know how to do it.

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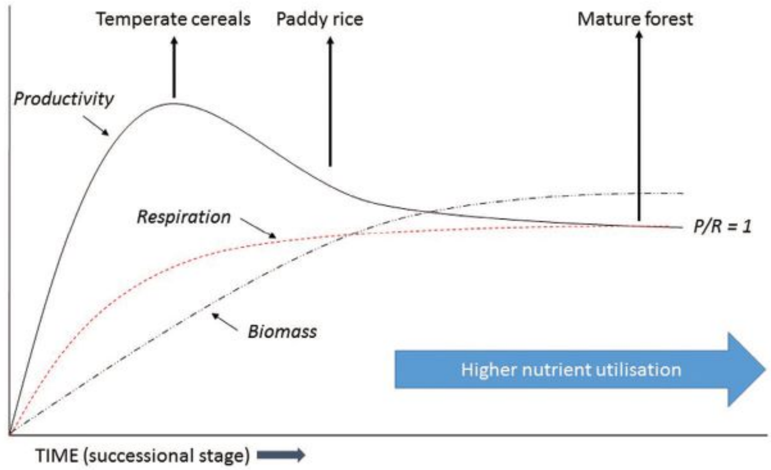
Mid-page photo by the author.

Re-Imagining Agriculture

Mark Kibblewhite



Early succession ecosystems give higher net yields, but later ones use nutrients more efficiently. Which stage is the optimum for future agriculture?

These are challenging times, and there is an urgent need for more radical thinking about agricultural productivity. Current agro-ecosystems may not be enough to close the much-discussed gap between future demand and current production. We need to re-imagine agriculture and explore options for entirely new agro-ecosystems that are intrinsically more productive and that have less environmental impact, especially to secure staple protein and carbohydrate sources.

A warning has been sounded in Europe as yields are slowing to a plateau, after a long run of steady increases, in spite of a continuing large investment in R&D and a sophisticated farming community. The reasons for this stasis are not certain. Two possibilities are that the natural limits, set by weather variability, are being approached, or that social resistance to the current technological trajectory is preventing its implementation. In any case, **the existing systems are at risk from existential threats, including those presented by climate change, because of their reliance on a limited portfolio of crops and animals, their leakage of byproducts, especially nitrogen, to the air and water, and their huge dependence on fossil fuels.**

Of course, we must not abandon efforts to increase the performance of existing systems, but we need to expand our horizons and options. As the current U.K. strategy for agricultural technologies says "[More productive agriculture] will need multiple approaches: adapting existing farming techniques, developing entirely new production systems, [and] innovative engineering." Two divergent approaches may offer ways to imagine and then engineer new agro-ecosystems. These approaches can be called the ecological approach and the artificial approach.

The ecological approach starts by observing the natural succession of ecosystems and their progressive shift from simple systems with high net productivity to more complex systems in which maintenance uses most of the energy captured by photosynthesis and nutrient utilization is highly efficient. The existing agro-ecosystems that produce staple commodities are mainly "early stage" annual crops. These systems are highly responsive to nutrient additions, but they are also intrinsically leaky and more prone to infestation than later-stage systems, such as mature grassland and forest. Interestingly, paddy rice has some characteristics of a later successional stage, while silvoarable systems are also later stage.

Can we develop novel later-stage systems that are highly efficient at capturing radiant energy and using nutrients to provide enhanced yields and environmental performance? What new insights can ecological science offer? And how can we engineer tools and processes to make candidate systems feasible and commercially viable? For example, how might we design a field that maximizes ecological performance via mixed cropping? Might it be better to establish small areas in a within-field patchwork of different crops rather than uniform fields of one crop in non-uniform landscapes?

The artificial approach posits that an entirely artificial environment offers the best means to convert radiant energy to food and to control environmental impacts, i.e., an environment in which the constraints of soil and weather and the exposure of an open system to pests and disease are avoided. Such "manufacturing" of food in built environments may appear radical, but it is already happening, for example, with controlled-environment production systems. However, to date, the artificial approach has not been applied to commodity crops. Might new sources of protein and carbohydrate be based, for example, on large-scale production of algae and its processing for human food? Are we overlooking the real potential of vertical agriculture, as envisioned by some architects and agriculturalists?

Society is realizing that increasing demand for agricultural products makes increased production imperative. And this increase must be based on higher productivity, rather than more planted area, because of competing demands for finite land and water resources. Furthermore, according to the World Bank, "Time is running out for agriculture to contribute to meeting global climate targets." The 2014 IPCC reports predict that climate change, without adaptation, will reduce yields of the world's major crops (wheat, rice, and maize) by as much as 25% by 2050. Society is looking to the scientific and engineering communities to deliver a technological solution to these problems.

It's dangerous to assume that doing more of the same, only better, is going to get the job done. Instead, it's time for more radical thinking across the whole community of researchers, advisors, and farmers—backed up by investment in higher-risk but ultimately better solutions—to closing the yield gap. A highly encouraging development is the emphasis on innovative agricultural technology in the European Union's Horizon 2020 research and development program (http://ec.europa.eu/programmes/horizon2020/en). To make the most of this opportunity, agricultural scientists and engineers have a duty to fully engage their imaginations and creativity, and to think and work more adventurously.

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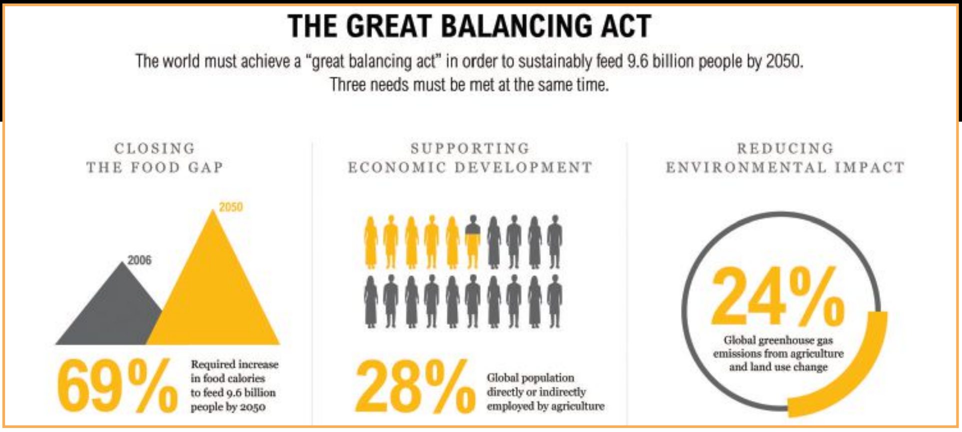
Top photo by David Nance courtesy of USDA-ARS.

A Menu of Solutions

Craig Hanson



How can the world feed more than 9 billion people by 2050 in a manner that provides economic opportunities to alleviate poverty and reduces pressure on the environment? This is the paramount question the world faces over the next four decades. Answering it requires a great balancing act of solutions to three needs. **First, the world needs to close the gap between the food available today and that needed by 2050. Second, the world needs agriculture to contribute to inclusive economic and social development. And third, the world needs to reduce agriculture's impact on the environment.**

Achieving this great balancing act will require a menu of solutions that address both food demand and food supply. The World Resources Institute's 2013-2014 World Resources Report, "Creating a Sustainable Food Future" (www.wri.org/wrr), identifies several menu items that would reduce growth in food demand, namely:

- Reduce the loss and waste between the farm and the fork of food intended for human consumption.
- Shift diets: Reduce the consumption of calories among people who are overweight or obese. Reduce the share of animal-based foods in daily diets in wealthy countries. And among animal-based foods, reduce the amount of beef consumed and substitute it with fish or poultry.
- Help every region of the planet in their efforts to achieve replacement-level fertility (roughly 2.1 children per woman) by 2050.
- Reduce the diversion of edible crops into biofuel production.

The World Resources Report also identifies menu items that would sustainably increase the supply of food, including:

- Increase yields on existing agricultural land through the annual selection and adoption of higher-yielding seeds, accelerated by marker-assisted and genomics-assisted conventional breeding and increased attention to orphan crops.
- Increase crop yields on existing agricultural land by implementing improved soil and water management practices, such as agroforestry and water harvesting.
- Limit any crop or livestock expansion to land that is currently not used to produce food, not biologically diverse, and neither stores nor is likely to sequester significant amounts of carbon.
- Increase yields of milk and meat per hectare on existing pasture and grazing lands through sustainable intensification of grazing management and related practices.
- Ensure long-term supplies of wild fish by reducing catch levels until fish populations rebound.
- Increase aquaculture production while simultaneously increasing its resource efficiency in terms of feed, land, water, and energy.

These menu items would help close the food gap, advance economic development, and reduce agriculture's impact on ecosystems, climate, and water. Of course, **no single solution can achieve a sustainable food future by itself, and the relevance of individual menu items will vary between countries and food supply chains. But all are necessary.**

Fortunately, there are signs of progress. Here are three examples from Niger, Brazil, and the U.K.:

Farmers in Niger have managed the natural regeneration of native trees growing in farm fields across five million hectares. Trees such as *Faidherbia albida* fix nitrogen in the soil, protect fields from wind and water erosion, and drop their leaves, contributing organic matter to soils. Yields of maize in such agroforestry systems can be double those of conventional farms in the country.

Brazil is exploring approaches to increase the productivity of existing grazing lands to both meet beef production needs and avoid conversion of forests into pastures. Increasing cattle grazing intensity across the country to just one-half of the sustainable carrying capacity would enable Brazil to meet its beef production needs through 2040 without converting another hectare.

In the U.K., the Waste and Resources Action Programme (WRAP) and major food retailers have been providing tips on food storage, adjusting promotions from "buy one get one free" to "buy one get one later," and changing package labeling so that households will not confuse "sell by" dates with "consume by" dates. As a result of these and other activities, household food waste in the U.K. declined by 21% from 2007 to 2012.

At the global scale, a partnership has formed to develop a Food Loss and Waste Protocol, which will become the global standard and guidance for measuring food loss and waste. It will enable countries and companies to quantify in a consistent manner how much food is lost and wasted and identify where the loss and waste occur. Partners include the World Resources Institute, the FAO, the United Nations Environment Programme (UNEP), the Consumer Goods Forum, EU FUSIONS, the World Business Council for Sustainable Development, and WRAP.

Despite these developments, there is a long way to go. The food gap is significant. Consumption patterns are difficult to change, and diffusion of new food production methods can take time. And climate change will increasingly hamper food production if left unchecked. Consequently, governments, the private sector, and civil society will need to act quickly and with conviction to implement this menu of solutions. If they do, the world just might be able to achieve a sustainable food future.

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Fish: A Must for Global Food Security

Stephen Hall

In the developing world, more than one billion people obtain most of their animal protein from fish, and 250 million depend on fisheries and aquaculture for their livelihoods. Fish represents an important and low-cost source of high-quality protein, essential fatty acids, and micronutrients.

The 2013 World Bank report "Fish to 2030: Prospects for Fisheries and Aquaculture" (www.fao.org/docrep/019/i3640e/i3640e.pdf) projects that **aquaculture will provide close to two-thirds of global food fish by 2030.** This will happen as catches from wild-capture fisheries level off and demand from an emerging global middle class, especially in China, increases. Along with the increasing demand for fish, the global fish food system faces other challenges, including overfishing, climate change, pollution, and ocean acidification.

These challenges demand a change in our approach to fisheries management and farmed fish production.

Although it's been around for centuries, **aquaculture is, in many respects, the new frontier for farming.** Between 1980 and 2010, the annual average production growth rate was about 8.8%. Aquaculture now provides about as much fish for direct human consumption as wild-capture fisheries.

This rapid growth of aquaculture has raised inevitable questions concerning its environmental sustainability. Central to these concerns are the demands that aquaculture places on resources, and the environmental consequences of the waste it generates.

It is almost certain that continued increases in production will lead to increases in aquaculture's global environmental footprint. Yet there are a variety of actions that producers can take to improve environmental efficiencies to minimize impacts and encourage sustainable growth. Among these solutions are greater investment in technological innovation and transfer, specifically breeding and hatchery technology, disease control, feeds and nutrition, and the development of low-impact production systems.

It's also important to recognize, however, that while there is an environmental cost for farmed fish, it is generally less than for other types of livestock. **Where resources are stretched, policies that promote fish farming over other types of production should be considered.**

Such promotion can also have very positive impacts on the poor in developing countries. A recent journal article (DOI: 10.1016/j.worlddev.2014.06.035), co-authored by WorldFish and the Bangladesh Institute of Development Studies, provides further proof of the need to bolster policies that create an enabling environment for aquaculture. The report shows that increases in small-scale aquaculture productivity can increase food security. More importantly, it stresses the need to support wild-capture fisheries in parallel with the development of the aquaculture sector. Many rural households rely on this common resource, so the development of policies that support both sectors is desirable.

Woman slicing raw fish in Satkhira, Bangladesh.

Yet while aquaculture might be said to represent the new frontier, there remains a continuing desire to address the challenge of maintaining wild-capture fisheries. At two summits this year, the Global Oceans Action Summit for Food Security and Blue Growth in the Netherlands (www.globaloceansactionsummit.com) and the Our Ocean Summit hosted by U.S. Secretary of State John Kerry (www.state.gov/r/pa/prs/ps/2014/06/227797.htm), announcements and strong commitments were made by governments and other stakeholders.

Thinking about aquaculture and fisheries together, what is clear is that a business-as-usual scenario, no change to the status quo, will likely mean that we will be unable to ensure a sustainable fish food system to support the predicted global demand for fish. Fisheries management requires greater global focus to maintain global wild fish stocks, and aquaculture growth needs to be managed to minimize environmental impacts.

Recently, experts from the business, policy, non-governmental, and philanthropic sectors met to discuss the challenges and potential solutions for the world's fish food system as part of the Rockefeller-funded Fishing for a Future initiative (www.fishingfuture.org). They concluded that there is currently a fragmented approach to dealing with these issues and that **a clear set of high-level goals that stimulate better coordination and collective action among stakeholders is needed.**

WorldFish, a member of the CGIAR Consortium, is an international, nonprofit research organization committed to reducing poverty and hunger through fisheries and aquaculture. We will continue to work at the local, national, and international levels to support such efforts and to help meet the challenges of sustaining the world's fisheries and promoting sustainable aquaculture so that we will be able to meet global food security needs.

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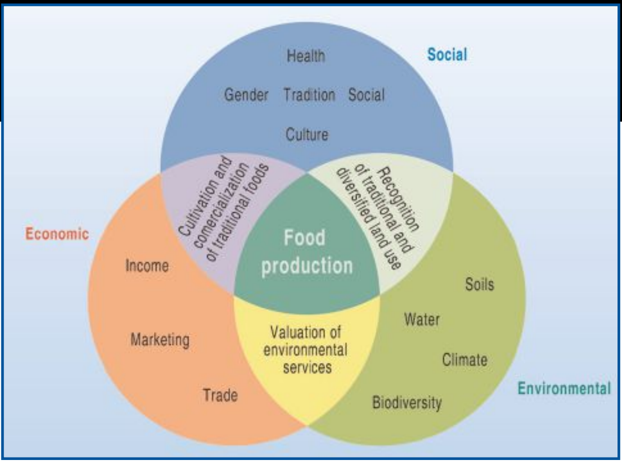
Top photo by Stephen Ausmus, courtesy of USDA-ARS. Bottom photo by M. Yousuf Tushar.

The Social Science Perspective

Stephen Gasteyer and Craig Harris



The inescapable interconnectedness of agriculture's different roles and functions. Source: IAASTD: Global Summary for Decision Maker http://www.agassessment-watch.org/.

We are both professors of sociology with AgBioResearch appointments at Michigan State University. Our work involves the community dynamics of food, water, and energy development in the United States, the Middle East, and Africa (Gasteyer), and the political ecology of food—especially livestock, fisheries, and local food—in the United States, Africa, Asia, and Latin America (Harris). Based on our experience, we've identified eight goals that must be addressed to achieve sustainable agricultural production by 2050:

1. Agricultural production must be expanded to incorporate the various parts of the entire agrifood system (we use the term "agrifood" here to mean food, feed, fiber, and fuel). This includes research and development across the agrifood value chain (e.g., attention to inputs, production, processing, distribution, and waste) as well as other systems that supply food, fiber, shelter, and energy for humans, such as fisheries, forestry, and foraging systems. In short, sustainable agrifood production requires nesting production within what political economist Elinor Ostrom referred to as "socioecological systems."

2. Agrifood systems exist at several scales, which are characterized by the geography of their production and consumption. Roughly half of the households in the world produce food to be consumed by the members of the household. Many of these households also produce food for exchange within the community or local region, thus producing the "civic agriculture" that sociologist Thomas Lyson discussed. Smaller percentages of households produce food that goes to national markets, contributing to food security, and food that is traded internationally, earning foreign exchange for less developed countries and balancing the payments of more developed countries. **Achieving sustainable food production requires balancing among these scales, so that none of them displaces the benefits that are generated by the others.**

3. There must be greater democracy in the identification of research priorities. At all levels of the research and development process, local voices must be included in the decision-making. For instance, in developing their research priorities, governments and intergovernmental organizations must include non-governmental organizations that speak for under-represented populations. Researchers must use participatory approaches that engage actors across the agrifood system in "doing science together," to paraphrase sociologist Louise Fortmann. Agrifood researchers must also work with under-represented farmers and producers, such as those who are small scale, female, minority, youth, entry level, and represent diverse racial and ethnic groups.

4. Participatory democracy must also be applied to the allocation of resources associated with agrifood systems. Sociologist Philip McMichael and others have noted with alarm the increasingly undemocratic nature of international investments in resources, such as land and water, as well as in the value chain from producer to consumer. Governments, funding organizations, and researchers must pay greater attention to who benefits, who loses, and how decisions are made about the investment and sale of resources. Together, they must develop mechanisms to better allocate access to the means and the benefits of agrifood development.

5. Sustainable production requires that agriculture is healthy for humans and animals. Breeding and development programs must balance the quantity produced with the quality produced. Further, the techniques used to produce food must not diminish or endanger health. This includes the exposure of producers and consumers to toxic chemicals and pollutants, as well as deleterious techniques of animal production.

6. It will be much easier to achieve sustainable food production in 2050 if food waste is reduced. While it is unrealistic to expect zero waste, opportunities exist for substantial reductions in waste throughout the production, processing, distribution, marketing, and consumption stages. This will generate large benefits with little expenditure of effort and resources. Research opportunities include improved food preservation and storage techniques.

7. Sustainable food production in 2050 requires equitable access to food across all social groups. Equitable access means affordable food, food security, and the right to food, as well as a voice in the production and distribution of food, or food sovereignty. Equitable access also means access to food for both human and animal consumption, and access to the resources (land, water, and seeds) needed to produce food for consumption and exchange. Good food provides both nutrition and social values in ways that are culturally appropriate. History offers many examples of social disruption caused by unequal access to food.

8. Finally, sustainable agrifood production must improve the environment. Agrifood production must minimize the negative impacts and foster positive impacts on what agroecologist Stephen Gliessman calls the "ecological foundation." This will require a commitment by governments and funding organizations to develop programs that reward contributions to ecosystem integrity and that provide disincentives for damaging the environment, by agrifood and by other economic systems (e.g., energy, mining, and construction).

Pursuing these eight goals requires that we adapt the agrifood system to a constantly changing global socioecological system. However, if we fail to adapt, the planet will change without us. Scientific research will play a critical role in illuminating the interactions, identifying the risks, developing the monitoring protocols, and developing the tools that decision-makers need.

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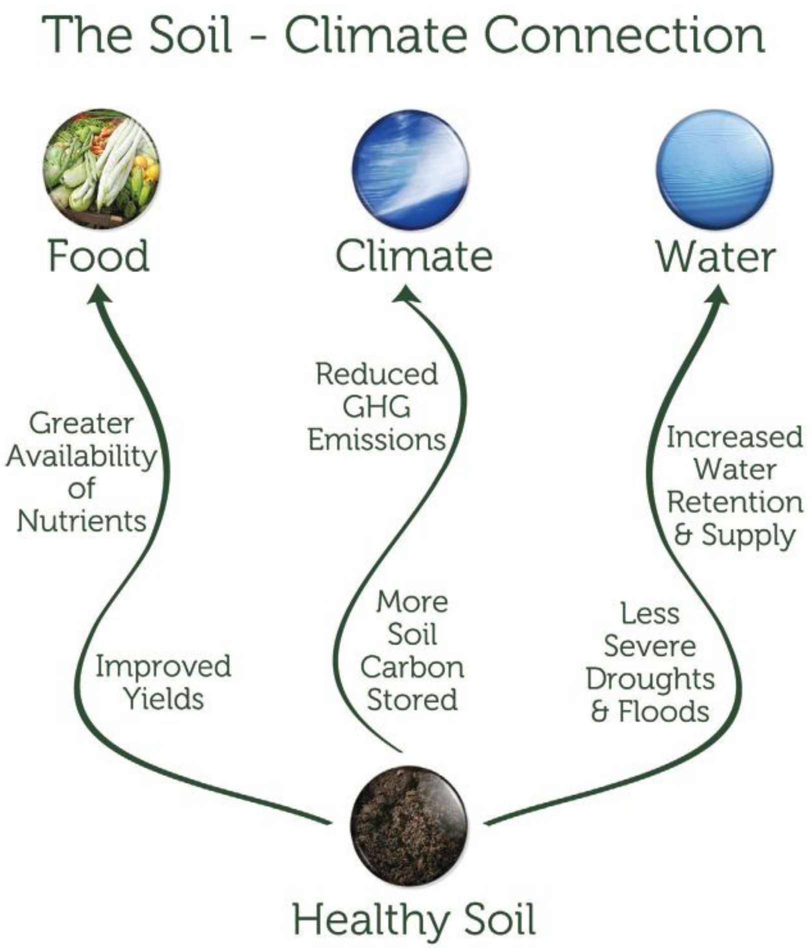
The Soil-Carbon Opportunity

Diana Donlon

Demographers project that the global population will reach nine billion by 2050. While a very large number, nine billion is something we can only more or less imagine, given that the global population currently stands at 7.2 billion. Harder to picture is what living on Earth will be like in 36 years, and this makes it hard to anticipate the conditions under which we'll be producing food.

Let's start by looking at what we know is happening to the ecosystems that support life.

Our species has caused a staggering amount of destruction: We're spewing far too much carbon dioxide into the atmosphere and heating the planet. Indeed, scientists tell us that the safe upper limit of atmospheric CO_2 is 350 parts per million, yet we crossed a very scary threshold, 400 ppm, in 2013. Extreme heat is accelerating moisture loss, reducing crop yields, and shifting growing regions. Additionally, excess CO_2 is dissolving into the oceans, causing acidification and harming fish—a vital source of protein for one billion of the world's most vulnerable people.



Is there anything we can do to lessen climate volatility and create a more food-secure future?

There is. Unlike the atmosphere and the oceans, there is one place in the global ecosystem that is actually suffering from a lack of carbon—the soil. **Carbon in soil is essential for life, and storing it there doesn't cause global problems; it solves them.**

Through photosynthesis, plants capture carbon dioxide from the atmosphere using solar energy. That carbon dioxide is converted into carbohydrates that build plant matter as well as attract and feed beneficial microorganisms around the plant's roots. While some of this plant matter eventually decomposes, releasing CO_2 back into the atmosphere, a portion of it is stored in the soil as organic matter, keeping the carbon in a stable form. In short, plants act as carbon pumps, sucking up atmospheric CO_2 and pumping it into the soil as stable carbon, where it can potentially remain for thousands of years!

However, through activities such as clearing forests, draining wetlands, plowing, overgrazing, and leaving ground bare, the world's cultivated soils have lost between 50% and 70% of their original carbon stock. Upon exposure to air, carbon in soils oxidizes and becomes CO_2.

This means **we have an opportunity, at a global scale, to address this colossal deficit by feeding our carbon-hungry soils.** Storing, or sequestering, carbon in the ground provides multiple benefits for climate stability, fresh water availability, biodiversity, and food security. It is a zero-risk, low-cost proposition that has the potential to move the earth's carbon cycle back into balance. It also has universal application. Most importantly, we already know how to do it.

We can rebuild soil carbon by adopting regenerative agriculture, which includes poly-culture, cover cropping, agro-forestry, and nutrient recycling through organic soil amendments like compost and biochar. All that stands in our way is political will.

The Center for Food Safety's Cool Foods Campaign is working at the nexus of food and climate to communicate soil solutions to climate problems. We offer a fresh and empowering approach to potentially overwhelming challenges. We use a variety of platforms to disseminate critical and inspiring messages through easy-to-share infographics, straightforward articles, short videos, and accessible reports. We are also working with thought-leaders and policy-makers to add soil carbon sequestration to the toolkit of climate mitigation strategies.

I recently had the honor of speaking with Rattan Lal, considered by many to be one of the world's preeminent soil scientists. I asked Professor Lal what he would tell people about the importance of restoring soil carbon. His answer was as simple and as elegant as the solution at hand: **"We can meet world food demand only if we can restore soil quality through improving organic carbon stocks."**

If we feed our soils, they'll feed us, and so much more.

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Top photo, "Well-Husbanded Soil," courtesy of Charles Merfield. Infographic courtesy of the Center for Food Safety.

A Truly Wicked Problem

Otto Doering

My role is often that of the lone economist in the room, something like the proverbial elephant. I provide non-advocacy economic analysis of alternative approaches for solving resource, environment, and agricultural policy problems. My career began with the Ford Foundation in Malaysia when Ford was deeply committed to overseas development and institution building. I was involved in the introduction of the early "miracle" rice varieties, starting with trials of IR3, 4, 5, 6, and finally IR8. We were assessing the economic and social impact of these new rice varieties on a large irrigation project in Malaysia, but we did not fully understand the broader ramifications of what we were doing. Returning home to the United States, as a policy economist, I assessed alternative farm programs, and today I am increasingly involved in assessing water issues, resource use questions, and climate change impacts.

Achieving adequate sustainable food production in the future is what I call a truly wicked problem because it is not amenable to the traditional scientific method of problem solving. There is no universal agreement on the definition of the problem, alternative solutions are infused with strongly held values, and there is not even agreement on what a correct goal or solution might look like. In fact, for a truly wicked problem, there is no single solution, and there is no stopping point. There is also a higher degree of outcome uncertainty with wicked problems.

Consistent with the nature of wicked problems, we lack synthesis of the diverse pieces of information essential to tackling the critical components of sustainable food production. Even a small piece of the problem requires bringing together multiple skill sets and values. Seemingly specific food security problems typically involve issues beyond any single expertise. Something that looks like an agronomic production problem may require involvement from different disciplines to create alternatives that can meet the challenge. Integrating technical and human factors is increasingly necessary in identifying the questions, let alone identifying alternative solutions. Traditional scientific solutions for the world food problem may be ineffective without considering how people behave, how institutions can engage, and how climate change might play out for multiple generations.

Can it carry us?

Although there is much talk about these kinds of broadly based, integrated approaches to problem-solving, we still don't walk the walk. Meanwhile, since my involvement in the Green Revolution, the earth's population has doubled.

My overriding concerns are two-fold: one concern is the earth's carrying capacity (a physical and biological dimension), and the other concern is the inability of markets and prices to adequately signal scarcity by taking the needs of future generations into account. Both of these concerns present a challenge to institutions and individuals around the world. In addition, the increasingly complex question of sustainable carrying capacity is more than a question of when will non-renewable resources run out. Carrying capacity also includes the earth's ability to absorb waste, such as excess carbon dioxide, as well as sustain soil fertility and adequate fresh water.

As an economist, I have to point out that markets are an important part of feeding the world. For starters, markets induce technical innovation. Because land was scarce in Japan, Japanese agriculture developed on the basis of land-saving technology—improved varieties, fertilizer, irrigation, etc. In the U.S., where land was abundant but labor was scarce, labor-saving technology was developed—cotton gins, seeders, harvesters, etc. The scarce (and therefore expensive) resource became the one worth inventing for, but is induced technological innovation, by itself, strong enough to meet the challenges of the future? I am also nagged by the fact that markets can fail.

In the short term, markets help with the allocation of goods and the development of technology. They promote innovation and efficiency, but they are not prescient about long-term future demands for exhaustible resources, nor for sustaining resources that are being degraded through overuse. The high discount rate in our current cost-benefit analysis may cause us to ignore critical benefits for future generations. Just as the physical and biological sciences have difficulty grappling with earth's carrying capacity, so economists have difficulty dealing with valuation issues for future generations. However, **today's economic decisions will shortchange future generations if we do not integrate their future needs.** Feeding the world sustainably, now and in the future, is a truly wicked problem.

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Top galaxy design © Ruslana Stovner|Dreamstime. Mid-page photo is a true-color image that shows North and South America as they would appear from space 35,000 km (22,000 miles) above the Earth. The image is a combination of data from two satellites and was created by Reto Stöckli, Nazmi El Saleous, and Marit Jentoft-Nilsen, courtesy of NASA GSFC.

Sustainability at the Landscape Scale

Marita Dieling and Dyno Keatinge

The formation of the Association of International Research and Development Centers for Agriculture (AIRCA, www.airca.org) in 2012 was stimulated by the need for integrated action to deliver sustainable agricultural intensification at the landscape scale. AIRCA is a nine-member alliance of international research and development institutes committed to increasing food security by supporting smallholder agriculture and rural enterprises within healthy, sustainable, and climate-smart landscapes.

Supported by more than 60 member countries that comprise more than 70% of the world's population, AIRCA members have activities in all major geographic regions. All have a proven record of research, development, and implementation, working closely with farmers, extension systems, national research institutes, non-governmental organizations, and the private sector across a wide range of crops and ecosystems. The following organizations are the founding members of AIRCA:

AVRDC—The World Vegetable Center: Alleviates poverty and malnutrition in the developing world through increased production and consumption of nutritious and health-promoting vegetables.

CAB International (CABI): Improves people's lives by providing information and applying scientific expertise to solve problems in agriculture and the environment.

Tropical Agricultural Research and Higher Education Center (CATIE): Specializes in tropical agriculture and natural resources, combining research, education, and outreach to provide innovative solutions for sustainable development.

Crops for the Future (CFF): Contributes to sustainable agriculture and food systems by enabling greater use of underutilized crops through research, capacity development, and policy advocacy.

International Center for Biosaline Agriculture (ICBA): Works in partnerships to deliver agricultural and water-scarcity solutions in marginal environments.

International Centre for Integrated Mountain Development (ICIMOD): Enables sustainable and resilient development through knowledge transfer and regional cooperation to support equitable livelihoods and improved well-being for the people of the greater Himalayas.

African Insect Science for Food and Health (ICIPE): Helps alleviate poverty, ensure food security, and improve the overall health status of people in the tropics by developing and extending management tools for harmful and useful arthropods while preserving the natural resource base through research and capacity building.

Indigenous vegetables in Africa.

International Fertilizer Development Center (IFDC): Helps smallholder farmers in developing countries increase their agricultural productivity, generate economic growth, and practice environmental stewardship by enhancing their ability to manage mineral and organic fertilizers and participate profitably in input and output markets.

International Network for Bamboo and Rattan (INBAR): Improves the well-being of the producers and users of bamboo and rattan within the context of a sustainable resource base.

AIRCA's vision is to put research into practice through sustainable improvements to incomes, nutrition, and food security. In particular, the intended outcomes of joint AIRCA initiatives are healthy landscapes—meaning healthy plants, enterprises, people, and animals living in a healthy and sustainable environment. By sharing our collective knowledge and experience in creating healthy landscapes, awareness of the benefits of the landscape approach will increase among potential stakeholders in the agricultural and environmental sectors. AIRCA's work is characterized by the following principles:

- Delivering impact at the agriculture-environment nexus.
- A concerted effort with a common vision.
- A holistic approach to smallholder agriculture and ecosystems.
- Ensuring sustainability of agricultural systems.

In October 2013, AIRCA released a white paper offering recommendations for transforming rural livelihoods in the developing world at the landscape level. This approach takes into account the diversity of interactions among people and the environment, agricultural and non-agricultural systems, and other factors that represent the entire context of agriculture.

To achieve these recommendations, AIRCA encourages the creation of innovative funding mechanisms that will facilitate the formation of partnerships between research and development organizations, countries, and regional networks to deliver practical solutions at the necessary scale, including the capacity to sustain these interventions over time and the development of sound policy to protect them.

The world will not achieve food security unless the needs of smallholder and family farms are adequately addressed. We believe that a greater commitment to knowledge transfer among rural farmers and more effective uses of information technology are needed. Technologies must also be suited to the scale of these operations. Sustainable intensification involves trade-offs at many levels, from individual farms and communities to regional, national, and landscape scales. These trade-offs require difficult choices and should be the subject of more research, along with greater integration of development efforts.

Donor agencies and national governments need to invest their research and development funds in a more holistic manner so that development can occur across landscapes. The present piecemeal investment model has not been effective, and the partial failure to achieve the Millennium Development Goals concerning hunger and poverty will attest to that in 2015.

Marita Dieling, Executive Secretary, Association of International Research and Development Centers for Agriculture (AIRCA), Nairobi, Kenya, mdieling@airca.org; Dyno Keatinge, Director General AVRDC - The World Vegetable Center, Shanhua, Taiwan, Dyno.Keatinge@worldveg.org.

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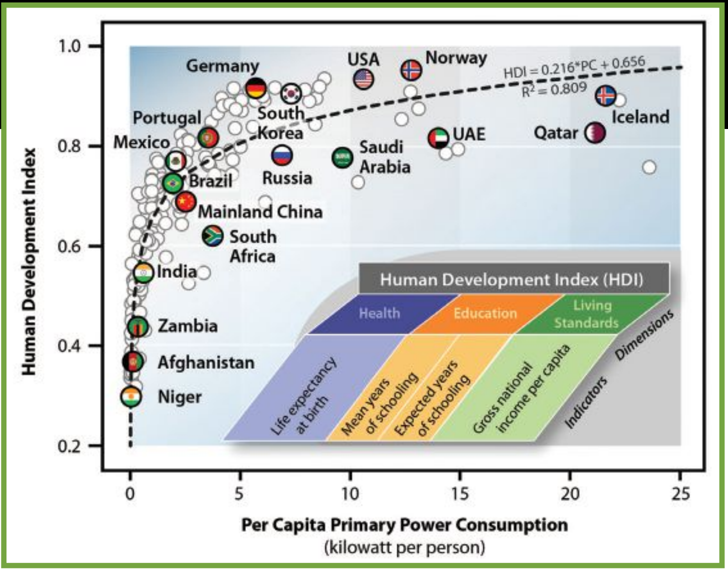
Mid-page photo courtesy of AVRDC.

Sobering Numbers

Bruce Dale



Human development by country vs. per capita power consumption in 2010.

As a chemical engineer, I have worked to produce sustainable biofuels—liquid fuels from plant matter—during my entire career. Because of the strong link between biofuels and agriculture, I am necessarily concerned about food production and all the links between energy and agriculture.

We take the modern world for granted. However, the amenities (wealth, education, healthcare, mobility, etc.) enjoyed by people in the developed nations depend absolutely on consuming huge amounts of energy, about 85% of it from fossil resources: oil, coal, and natural gas. Take away that abundant energy, and the modern world disappears. **Take away petroleum-based fuels, abundant electricity, and natural gas for fertilizers, and modern agriculture also disappears.**

The figure above highlights the link between energy consumption and general human well-being, which I will call "prosperity." This is a plot of the Human Development Index (HDI) versus the per capita rate of energy consumption (power consumption) for over 150 countries. The HDI is a composite measure of prosperity, including health (life expectancy at birth), education (mean years of schooling and expected years of schooling), and living standards (gross national income per capita). Obviously, overall prosperity is strongly and positively correlated with power consumption. The HDI is a reasonable, measurable surrogate for prosperity. It rises very rapidly as power consumption increases and then levels off or "saturates" at a power consumption of about 2 to 4 kW per capita. These are sobering numbers. Total world power consumption is currently about 16 terawatts (TW). We will soon have 8 billion people on planet Earth. If all 8 billion people were to consume a modest 2 kW, that would total 16 TW. If everyone were to consume a more comfortable 4 kW, the world would require 32 TW of power, twice the current world total. Obviously, the developed world consumes much more than 2 kW per capita, while the underdeveloped world consumes much less. This should be unacceptable to all of us—a relative few enjoying abundant power and the resulting prosperity, while many experience energy poverty.

It is deeply irresponsible to think that fossil fuels can provide twice as much power as they currently do. A society built on non-renewable power is simply unsustainable, and it will become increasingly fragile and perilous as the non-renewable sources are depleted. We must have renewable power, many terawatts of it, if we are to enjoy the prosperity that abundant energy provides—heating, cooling, lighting, and mobility. Renewable power is therefore not an option; it is essential if more people, now and in the future, are to achieve their potential as human beings.

There are many renewable sources of electricity (e.g., solar, wind, and hydro) that can provide heating, cooling, and lighting. However, only liquid biofuels, due to their high energy density, offer a complete renewable replacement for petroleum in all mobility applications, including agriculture.

Since we must have renewable energy, and we must have food, it is essential that we find ways to integrate food production with renewable energy production, including biofuels—not in competition with each other but to their mutual benefit. And we must do so in ways that are environmentally, economically, and socially sustainable. This is an enormous challenge, but especially for the profession of agricultural and biological engineers. It is the primary technical challenge around which my research and thinking are oriented.

Furthermore, this era of increased food production and increased renewable energy production must occur in a time of declining per capita resources—land, water, and conventional energy sources, especially petroleum. Conventional (cheap) oil production peaked in about 2005. We may dislike this fact, but it is undeniably true.

So we need to work harder and smarter. Increasingly, we must work with nature and with ecological principles—not against them or in ignorance of them. **Access to abundant energy, especially petroleum and natural gas, has often permitted engineers to ignore or to work against natural processes and ecological principles. We cannot afford to do so any longer.** We can change. We must change.

What should we do? Of all the things that are hard to change, changing our minds is the most difficult. Institutions change only when enough individuals change their minds. Thus, I am not too focused on changing institutions. My invitation (or challenge) to you, reading this article, is to find out for yourself if the following statements are true:

- High levels of human prosperity depend on consuming a lot of energy.
- Our society and its agricultural systems are based on non-renewable fossil energy.
- These fossil energy sources are rapidly depleting and will disappear in this century.
- Prosperity based on fossil energy will likewise disappear in this century.
- Therefore, we must quickly develop and deploy large-scale renewable energy systems, including biofuels.

If these statements are true—and I strongly assert that they are—then we have a lot to do, and we have no time to waste.

ASABE Member Bruce Dale, University Distinguished Professor, Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, USA, and Editor in Chief, *Biofuels, Bioproducts, and Biorefining,* bdale@egr.msu.edu, www.everythingbiomass.org.

Top photo © Shannon Matteson|Dreamstime.
Figure: Design, implementation, and evaluation of sustainable bioenergy production systems, *Bruce Dale and Rebecca Ong, Michigan State University and DOE Great Lakes Bioenergy Research Center, East Lansing, USA.*

New Roots for Ecological Intensification

Timothy Crews, Thomas Cox, Lee DeHaan, Sivaramakrishna Damaraju, Wes Jackson, Pheonah Nabukalu, David Van Tassel, and Shuwen Wang

To meet the global food challenge of 2050, and well beyond, there is a growing consensus that farmers will need to produce more food using fewer and fewer chemical, energy, and machine inputs. In order to achieve this, numerous researchers have called for a transition from input intensification to ecological (or sustainable) intensification. Agroecosystem characteristics that have been targeted for improvement through ecological intensification include fertilizer and water uptake efficiencies, greenhouse gas emissions, soil quality including nutrient stocks and organic matter, and crop loss to insects and pathogens.

For ecological intensification to deliver on the high hopes and expectations that have been identified by agronomists and ecologists, it will be necessary to address the very nature of our annual crop ecosystems. Low nutrient retention, loss of soil organic carbon, inefficient use of water, and high prevalence of pest organisms are inherent attributes of low-diversity ecosystems held at early stages of succession or ecosystem development—i.e., annual single-genotype monocultures. In contrast, landscapes that are further along in succession or ecosystem development—i.e., landscapes with perennial vegetation and greater interspecies and intraspecies diversity—are generally superior with respect to their numerous regulating, supporting, and provisioning ecosystem services relevant to agriculture, including nutrient and carbon retention and water uptake efficiency, regulation of pest populations, and net primary productivity.

The goal of shifting agriculture toward a higher functional stage of ecosystem development is limited by the availability of perennial crops. The Land Institute (www.landinstitute.org) and collaborating researchers from numerous institutions around the world are working to develop unique genetics that allow high grain yields from herbaceous perennial plants. Breeding approaches include (1) wide hybrid crosses between annual grains and related perennial species in order to introgress the perennial habit into the annual grain, and (2) rapid domestication—i.e., cycles of selection and inter-mating to fix and improve on traits such as nonshattering, free threshing, increased seed size, and reduced dormancy.

Perennial rice, wheat, and sorghum are examples of the wide-hybridization efforts, while Kernza^{TM} wheatgrass and *Silphium* oilseed crops are examples of rapid domestication. These perennial crops are unlike any ever seen in wild ecosystems or in agricultural fields, and thus we anticipate unique challenges in developing a new set of management practices for them. As perennial grains are planted at larger scales, they must be studied carefully to document the expected benefits and identify additional challenges. Watershed-scale advantages of perennial grains will need to be documented to inform policy.

Soil profile showing roots of the new domesticated perennial grain Kernza^{TM} on the left and annual winter wheat on the right. The soil profile has a depth of ~2.5 m. Kernza^{TM} has been domesticated from intermediate wheat grass (*Thinopyrum intermedium*). It can be milled into flour and then blended with or substituted for wheat flour.

Over the next ten years, we must lay the groundwork for additional perennial grain, pulse, fiber, and oilseed crops. New domestication efforts directed at current wild perennials require many years to select promising domesticates. Similarly, establishing wide-hybrid populations that would be useful to conventional breeding programs requires numerous generations. **In order to achieve ecological intensification with perennials by 2050, a long-term global effort will be essential.**

In August 2013, the UN's Food and Agriculture Organization hosted an expert workshop on perennial crops for food security. Attendees included almost every researcher from around the world who is doing genetics, breeding, agronomic, ecological, or socioeconomic work related to perennial grains. That meeting made three things clear: (1) the need for cropping systems based on combinations of perennial species is widely recognized; (2) that need is not being filled, largely because most (but not all) of the people doing research on perennial grains are doing it as a supplement to their larger research programs on annual crops; and (3) with sufficient funding, many more programs focused full-time on development of perennial grains could be initiated.

For several years, we have been urging public and private funding institutions, both national and international, to help fill that gap, making it possible for the informal worldwide network of perennial-grain researchers to strengthen and expand. With such support, **we envision a network of research "clusters" in as many as a dozen agriculturally strategic locations distributed across all continents.** Each cluster would include breeders, geneticists, crop ecologists, and others with a clearly defined research agenda for developing and deploying a set of perennial cereals, grain legumes, and other species appropriate for the region where that cluster is located.

The most important benefit that perennials confer is protection of the soil. In addition, farmers in more developed economies are expected to benefit from significantly lower input and energy costs. In less developed economies, ecological intensification can become accessible to subsistence farmers and growers who have limited access to capital since the beneficial ecosystem services are derivatives of the crop ecosystem itself.

Timothy Crews, Research Director, and Thomas Cox, Lee DeHaan, Sivaramakrishna Damaraju, Wes Jackson, Pheonah Nabukalu, David Van Tassel, and Shuwen Wang, Research Scientists, The Land Institute, Salina, Kansas, USA, crews@landinstitute.org.

Photos courtesy of Jim Richardson and Jerry Glover.

Genetic Engineering Will Drive Food Security

Mary-Dell Chilton

During the late 1970s and early 1980s, my research team worked out how a plant bacterium can be adapted as a tool to insert genes from another organism into plant cells. This helped open the door to new crop varieties with innovative traits. In 1982, we harnessed the gene-transfer mechanism of the bacterium *Agrobacterium* in order to produce a transgenic plant. That discovery has led to the development of new precision tools to protect plants from the environment and enhance yields.

In 2013, I was one of three scientists honored as World Food Prize Laureates for our contributions to this technology. The World Food Prize is the most important award that I have received in my career. More important, however, is the fact that agricultural biotechnologists were chosen to win the 2013 Prize, as it speaks to the importance of this new technology in addressing the food needs of future generations.

I have seen this technology develop from its infancy to fruition in the crops we see in the field today. It has been an amazingly rewarding journey to see what started out as a fundamental scientific and curiosity-driven study evolve into such wide application in the field. It is clear from the statistics, which show the many millions of acres of biotech-modified crops being harvested around the world, that the technology has taken off with remarkable speed.

None of it could have happened without high-performing, collaborative teams. This is the most interdisciplinary research you can imagine. Our field is one in which people with highly specialized expertise have to come together to achieve the genetic engineering of a plant. I could not have accomplished what I have without the people who have worked with me all these years, and I thank them for that.

The only sustainable approach to food security in 2050 and beyond is to unlock the potential of plants through innovation. Growers are rapidly adopting combined-trait crops for insect control, water optimization, yield improvement, oil and protein quality, and improved bioprocessing. Ultimately, these technologies help reduce chemical applications and provide simpler, more environmentally friendly farming practices (e.g., no till). Agricultural biotechnology will be a key driver of sustainable food production in the future, something to which my company is dedicated through the Good Growth Plan (www.goodgrowthplan.com).

In a real sense, the process that we use for genetically engineering a plant is a natural one.

We learned how *Agrobacterium* manages to put genes into plant cells, and then we copied that process. We borrowed from a natural process in order to put genes into plant cells—genes of our choice—that will benefit the farmer and end user. In short, we can now do by choice what nature only does by chance.

With genetic engineering, we have a wide choice of genes to introduce into a plant cell, and we can precisely choose the genetic regions where we want to insert them, without any unintended consequences. In traditional cross-breeding, extra genes that you don't want also find their way into the plant. It is impossible to avoid. As I see it, a genetically engineered plant is a much more defined and precise product.

Currently, multiple traits are available within a given product, but the traits are sprinkled throughout the plant genome, which makes it difficult for plant breeders to track their activity and replicate the results. The plant of the future will have stacks of desired genes precisely inserted into specific locations in the plant's genome. This is not how things are now, but it is what we are working on. The plant will have not one transgene, but a series of them.

There are two approaches for stacking genes within a plant's genome: combining GM traits through traditional breeding (breeding stacks) and transformation with a multi-gene cassette (molecular stacks). The molecular stack method, which complements breeding stacks, presents several design challenges. It is not going to be easy, but that just makes our work more interesting!

What should be done by governing bodies, international organizations, funding agencies, and the scientific community to help feed the world in 2050? **The single most important contribution that others can make is to provide accurate information about the food security challenge we are facing and the solutions that can meet the challenge.** For too long, there has been misunderstanding and misinformation about modern agriculture technologies, especially GMOs. This has led to a state of public confusion and unnecessary concern over what this process is and how safe it is. I find this very unfortunate because it did not need to happen.

We have spent far too much time trying to correct false impressions rather than focusing on all the benefits that these technologies can provide. Let us focus on their potential for the future. The world will become a hungry place in one more generation. We will need this wonderful technology to improve the seeds of the future.

Mary-Dell Chilton, Distinguished Science Fellow and Founder, Syngenta Biotechnology, Research Triangle Park, North Carolina, USA.

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Feeding the World Sustainably

Michael Chaplinsky

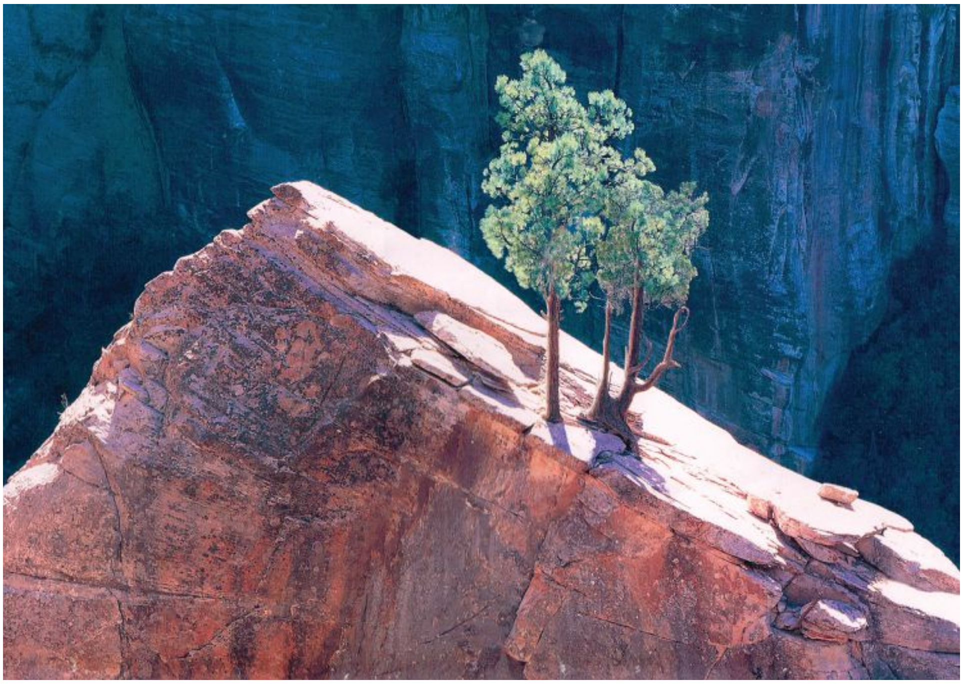
You can argue about the impacts of global warming, and you can argue about when we will run out of petroleum, but no informed person denies that global warming is real, nor that the world's oil will eventually run out. However, another crisis is also looming, and almost no one is talking about it: we are running out of the fertilizers and other chemicals needed to grow food.

My work started over 30 years ago, manufacturing fertilizer injection systems (fertigation) for crop production). Today, our company produces fertigation systems for agriculture, horticulture, landscapes, and resorts worldwide. Fertigation is the most efficient way to irrigate plants and feed the soil. **Our goal is to make every drop of water count.** Recently, we have become concerned about the long-term health of our soil and plant systems, and we have been working to implement sustainable agriculture to improve soil and plant health.

Sadly, modern agriculture is controlled by the fertilizer and chemical industries, and they don't seem to care about soil health. Their goal is high-volume crop production. That approach has been hugely successful over the last 100 years, but at a cost, and it's created an unsustainable dependence on chemical fertilizers and pesticides. This artificial control of plant biology is a lot like how the pharmaceutical industry takes care of human health—there's a pill for everything. However, many human health problems are lifestyle-related. Instead of taking yet another pill, why not adopt healthier habits? Wouldn't that be simpler, safer, and cheaper in the long run?

All plants are part of a highly evolved life cycle. Soil is the result of bacteria, protozoa, and fungi converting organic matter into minerals and nutrients, which plants use to create biomass. Soil biologists know that plants and soil have a symbiotic relationship, supplying each other with nutrients and organic matter. Sustainable agriculture applies this natural cycle to crop production, treating the soil and the plants holistically. This improves the soil and plant health and increases water efficiency while reducing the need for chemical inputs. Increased soil and plant health creates more efficient crops with deeper denser roots that are more resistant to insects and diseases.

The photo below of a tree growing on a rock in Zion National Park shows how little a plant really needs to survive when the plant and soil are in balance. Yes, it's a real tree, living on a bare rock. How is that possible? The rock has a deep crack lined with moss and lichen. Leaves and other windblown plant matter fall into the crack and gradually decompose. At some point, a seed fell into the rich moist compost and germinated. As the tree grew, its roots probed deeper into the crack, forcing the crack to open wider and retain more organic matter and moisture, which provided more nutrients for the tree. The Zion National Park area in the southwestern United States near Springdale, Utah receives less than ten inches of precipitation a year, but this tree has found a way to thrive.



Few people realize that less than 45% of the dry fertilizer applied to a crop ever gets to the plant. Most is lost below the roots. Fertigation delivers up to 95% of the nutrients to the plant through both root and foliar uptake. In addition, sustainable agriculture can reduce water use by up to 50%. It also reduces fertilizer and chemical use by up to 60%, as well as labor and energy requirements, while increasing crop quality and production by up to 50%.

Note that sustainable agriculture does not completely eliminate fertilizer or chemical use. Instead, it increases plant and soil health to produce more while using less. This is done by feeding the soil by adding enzymes, humates, and other food sources to increase the biological population so that microorganisms can convert the organic matter into plant-available nutrients.

The International Fund of Agricultural Development has heralded 2014 as the International Year of Family Farming (www.ifad.org/events/iyff/). Worldwide, rural farmers need help, and sustainable agricultural can be part of that help. By bringing nature, soil health, plant health, and water efficiency together, sustainable agriculture can double their farm production, increase their income, and improve their livelihood. We need to change agriculture by bringing the efficiency of nature back into the science of growing food. Let's do it now, while we still have the choice.

Michael Chaplinsky, Founder and President, Turf Feeding Systems, Inc., Houston, Texas, USA, mc@turffeeding.com.

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A Tribute to Norman Borlaug

Kenneth Quinn

On October 16, United Nations World Food Day, more than 1,200 people from more than 60 countries gathered at the World Food Prize in Des Moines, Iowa, to celebrate the conclusion of the Norman Borlaug Centennial Year.

They attended the Laureate Award Ceremony in the magnificent Iowa State Capitol, where the World Food Prize was presented to Dr. Sanjaya Rajaram, a native of India who has spent most of his professional life in Mexico building on Borlaug's legacy by developing hundreds of new varieties of wheat—which have increased world wheat production by more than 200 million tons.

They also participated in the three-day Borlaug Dialogue international symposium, the theme of which was "The greatest challenge in human history: Can we sustainably feed the nine billion people who will be on our planet by the year 2050?" This theme was chosen because it was the central question that animated Borlaug's professional life from the time he received the Nobel Peace Prize in 1970 until his death on September 12, 2009.

When Borlaug created the World Food Prize in 1986, his goal was to establish an award that would be the equivalent of a Nobel Prize for food and agriculture, and that would recognize and inspire exceptional breakthrough achievements in increasing the quality, quantity, and availability of food in the world.

Borlaug saw, even then, that the ability to provide sufficient nutritious food for everyone on our planet would be the central challenge facing humanity well into the 21st century. He was fond of saying that, over the past 5,000 years, the human race had cumulatively produced sufficient staple crops to feed almost all of the people who had lived on our planet. The problem was, he added, that we had to replicate all that was grown during those five millennia in the next 50 years.

Norm often spoke of the specter of population growth in terms of his home state of Iowa, where he was born on March 25, 1914. He knew that when the Iowa territory was opened for settlement in 1830, the total population on earth was approximately 1 billion people. When he was born 84 years later, the earth's population had increased to 1.7 billion. However, when he died in 2009, the population of our planet was approaching 7 billion, an increase of 5.3 billion people during the 95 years of his life, compared to an increase of just 700 million in the 84 years before he was born. In 2046, when Iowa celebrates its bicentennial, the global population will surpass 9 billion.

Norm saw the crisis of global food production coming, and he despaired that international leaders did not recognize the urgency of this problem. At times, he even wondered whether the success of the Green Revolution that he had ignited perhaps caused governments to believe that the food problem was solved forever, causing them to drop their guard and cut back on essential research.

When Norm welcomed me to head up the World Food Prize in 1999, he told me that he often felt that he was a lone voice calling attention to this urgent need. And so, together he and I worked for more than a decade to build the World Food Prize annual events into an occasion that would bring attention to these issues. That effort has paid off.

The renowned economist Jeffrey Sachs said that some of "the key issues that were part of the United Nations Millennium Development Goals were first discussed at the World Food Prize." Sir Gordon Conway, agricultural ecologist and former president of the Royal Geographical Society, has called our annual Borlaug Dialogue "the premier conference in the world on global agriculture," as it brings together ministers of agriculture, CEOs, and the president of the World Bank with smallholder farmers from Africa, research scientists, and NGO leaders.

During the last months of his life, Norm took heart from the announcement of the principles that would undergird President Obama's Feed the Future Initiative, which were first articulated by Secretary of State Hillary Clinton at the World Food Prize Laureate Announcement Ceremony at the State Department on June 12, 2009.

A few months later, Bill Gates gave his first-ever speech on global agriculture and bringing the Green Revolution to Africa at the Borlaug Dialogue symposium in Des Moines, just one month after Norm passed away. At the conclusion of his presentation, I told Mr. Gates that his initiative and call to action, which would be launched at the forum that Norm himself had created, gave Norm great hope for the future during the last months of his life.

This past year has seen events all around the world as part of the Centennial Observance of Norm's birth, calling attention to the epic challenge we face. The centerpiece of the year was the unveiling of a statue of Norman Borlaug in the U.S. Capitol in Washington, D.C., on March 25—Norm's birthday. The statue was placed by his home state of Iowa, reflecting his status as the state's greatest hero and America's greatest agricultural scientist.

A weeklong tribute to Norm was organized by CIMMYT in Obregon, Mexico (where a statue of Norm was erected by the local farmers), in addition to ceremonies at the University of Minnesota, where Norm obtained his PhD in plant pathology; the USDA, where he had his first job with the U.S. Forest Service, and the World Food Prize Hall of Laureates in Des Moines.

Other Borlaug Centennial events during the year included a special Borlaug Global Rust Initiative celebration in Pakistan, the Sasakawa Africa Association commemoration in Uganda, a seminar in his honor at the M.S. Swaminathan Research Center in Chennai, India, and a conference in Karaj, Iran, organized by the Agricultural Biotechnology Institute of Iran.

Secretary of State John Kerry paid tribute to Norm in his opening address at the U.S.-Africa Summit in Washington, D.C. In addition, I was pleased to be able to honor Norm in the keynote I delivered at the FAO World Food Day Commemoration in New York and in my remarks at the global meeting of the World Farmers Organization in Argentina.

I often tell people that Norm's dream was to bring the Green Revolution to Africa. His passion was for inspiring the next generation, and his last words were: "Take it to the farmer."

The World Food Prize, through its Borlaug Centennial Observance and our annual programs, endeavors to carry forward that legacy and to ensure that Norman Borlaug's inspiration is with us as we confront the single greatest challenge in human history.

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Photo illustration by Trayveon Lewis, World Food Prize intern.

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