The Challenge of Feeding the World Sustainably: Summary of the US-UK Scientific Forum on Sustainable Agriculture (2021)

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THE CHALLENGE OF FEEDING THE WORLD SUSTAINABLY

Summary of the US-UK Scientific Forum on Sustainable Agriculture

NATIONAL ACADEMY OF SCIENCES

THE ROYAL SOCIETY

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PREFACE

The need for sustainable agriculture is becoming ever more significant. The world's population is still increasing, requiring more from our agricultural systems. Malnutrition and diet-related illnesses are present in nearly all societies. At the same time, agriculture plays a significant role in some of the biggest environmental challenges that humanity is facing, including the climate crisis, biodiversity loss, deforestation, and the pollution of our soil, water, and air. The need to balance the growing demand for nutritious food with these environmental threats is a complex issue, and ensuring sustainable food systems will require a collaborative effort from many different communities.

These issues were addressed during the US-UK Scientific Forum on Sustainable Agriculture that was held in Washington, DC, on March 5–6, 2020. Organized by the National Academy of Sciences and the United Kingdom's Royal Society, the forum brought together leading scientists, researchers, policy makers, and practitioners in agricultural sciences, food policy, biodiversity, and environmental science (among other specialties). The forum provided an opportunity for members of these research communities to build multidisciplinary and international collaborations that can inform solutions to a broad set of problems.

The forum highlighted current approaches to sustainable agriculture such as precision farming, crop resilience, biodiversity retention, waste reduction, and dietary diversity. Over the course of the forum, there were moments of both optimism and pessimism, with overarching recognition that business as usual cannot continue. For some participants, the solutions are evident, and effective implementation is the barrier to change. For others, the challenge of balancing measures to ensure positive outcomes for all is yet to be overcome. Overall, the forum attendees recognized that sustainable solutions to the challenges of our food systems will be context-specific, depending on, for example, resource availability, location, and community priorities. Further global collaboration and communication will be needed to meet current and future needs.

It was demonstrated at the forum that, while there is a need for further research on sustainable agricultural methods, action can be taken now. The forum highlighted the scientific and technological developments that have been made, not only in identifying problems but also in finding solutions. Moreover, the insightful and productive conversations that took place over the course of the forum emphasized the willingness of participants to promote and discuss their work with the aim of informing political and societal decisions.

The world changed dramatically in the weeks and months following the forum. The COVID-19 pandemic has focused attention on the fragility and strength of humanity and has emphasized the need for international collaboration in overcoming interconnected, global issues. Although creating and maintaining sustainable agricultural systems is a different kind of problem, it also transcends borders and requires wide-ranging global action. As we seek to create a more resilient post-pandemic world and consider fundamental changes in our approaches to health, safety, and security of life on Earth, sustainable agriculture cannot be overlooked.

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NATIONAL ACADEMY OF SCIENCES

The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research.

THE ROYAL SOCIETY

The Royal Society is a self-governing Fellowship of many of the world's most distinguished scientists. Its members are drawn from all areas of science, engineering, and medicine. It is the national academy of science in the United Kingdom. The Society's fundamental purpose, reflected in its founding Charters of the 1660s, is to recognize, promote, and support excellence in science and to encourage the development of use of science for the benefit of humanity.

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The surface of the Earth has been transformed by agriculture. Cropland and pastureland cover more than one-third of the Earth's ice-free surface. Of the water withdrawn from rivers, lakes, and aquifers, 70 percent goes to agriculture. The global food system feeds a world population of nearly 8 billion people, which is a remarkable achievement. Yet, more than 800 million people worldwide remain malnourished, and more than 2 billion adults and children are overweight or obese, in part because of a worldwide trend toward eating more processed foods and higher quantities of salt, sugar, and fat.

Agriculture's extensive use of the Earth's land and water has already had many deleterious effects on the environment and on biodiversity. Inputs to agriculture in the form of fertilizers, pesticides, and the mechanization of farming have produced higher yields but also have polluted the air, water, and soil. The expansion of agriculture has placed pressures on wild habitats and fisheries. Greenhouse gases from agriculture are contributing to higher temperatures and changing precipitation patterns, which have further stressed many plant and animal species.

Under a business-as-usual scenario, the deleterious effects of agriculture on the environment and on biodiversity will continue to increase. Higher levels of food production will require more fertilizer, pesticides, and irrigation and more extensive resource extraction from the land and sea. Growing populations and increased demand will exert pressures to convert more wildland to cropland. Such an approach would bring more air and water pollution, increases in greenhouse gas emissions, greater degradation and erosion of soils, greater threats to biodiversity, and intensified competition for land and other resource inputs. Given the already substantial effects of agriculture on biodiversity and the environment, such a future is not sustainable.

Many deliberative levers of change are available to transition agriculture to sustainability, including increased agricultural efficiency and yields, smarter land use, better use of markets and trade, reduction of waste, and shifts in diets. These levers of change often have multiple benefits. For example, many of the foods associated with a higher risk of chronic diseases like diabetes and heart disease, such as red meat and highly processed foods, also have the highest environmental impacts. Eating less of these foods and more locally produced fruits, vegetables, legumes, and nuts would reduce greenhouse gas emissions while also reducing the number of years of life lost to diet-related diseases. Similarly, reduction of the 25 to 30 percent of all food produced that is lost or wasted would mitigate environmental harms while enhancing food security and health.

Many ongoing and potential developments in science and technology could contribute to sustainability. An approach known as precision agriculture based on extensive data gathering, analysis, and use offers great potential to improve yields, reduce costs, and minimize environmental damage. Genetic technologies and other advanced biotechnologies could yield crops and livestock resistant to high temperatures and drought, protect against new and emerging pests and disease, increase efficiency in water use, improve nutritional value in foods, and reduce fertilizer use. Technologies such as robotics, artificial intelligence, process engineering, and synthetic biology could come together to shift the paradigm from “food produced by agriculture” to “food produced by manufacturing.” The social sciences could also foster sustainability—for example, through interdisciplinary assessments of incentives and preferences.

Policy actions will be needed to move the world not only toward sustainable agriculture but also toward a much broader sustainable global food system. A wide range of policy levers exists to overcome barriers to change, including incentives, regulation, and the establishment of new governance frameworks. At the same time, researchers will continue to investigate the food system and sustainability and how best to implement new knowledge in policy. Incremental steps may not be enough to produce the needed change. When dramatic change becomes possible, researchers and policy makers will need to be prepared with solutions that can be implemented quickly.

Sustainable agriculture will be characterized by healthy ecosystems and healthy diets that ensure resilience to climate change, economic security, social inclusion, and human well-being. A clear, long-term strategy for what needs to be achieved would provide policy actors and food systems with both direction and coherence. A coalition of national and international organizations, perhaps through an ongoing forum on sustainable agriculture, could promote both the research that is needed and the translation of this research into evidence-based policies.

1 The Challenge of Sustainable Agriculture

Agriculture has had a greater influence on the surface of the Earth than any other human activity (see Figure 1-1). More than one-third of the Earth's ice-free surface is devoted to agriculture, and the portion is increasing as more land is converted to crop and livestock production.[1] Of the water withdrawn from rivers, lakes, and aquifers, 70 percent goes to agriculture,[2] and 20 percent of aquifers are already overexploited.[3] As the global population and per capita income continue to increase, the pressure on land and water to provide food will grow.

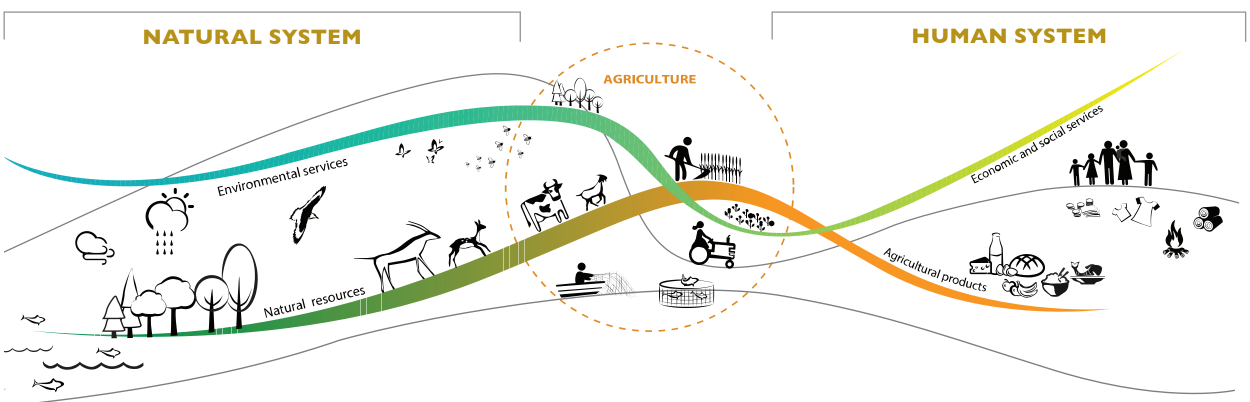


FIGURE 1-1
Agriculture is the link between the natural world and the products and services that have made the modern world possible.

SOURCE: Food and Agriculture Organization of the United Nations. 2014. *Guiding a Common Vision for Sustainable Food and Agriculture: Principles and Approaches*, pp. 14–15, Figure 1. Rome, Italy: Food and Agriculture Organization of the United Nations. Reproduced with permission.

[1] Ramankutty, N., Z. Mehrabi, K. Waha, L. Jarvis, C. Kremen, M. Herrero, and L. H. Rieseberg. 2018. Trends in global agricultural land use: Implications for environmental health and food security. *Annual Review of Plant Biology* 69(1):789–815.

[2] UNESCO (United Nations Educational, Scientific and Cultural Organization). 2020. *United Nations World Water Development Report 2020: Water and Climate Change*. Paris, France: UNESCO.

[3] Gleeson, T., Y. Wada, M. F. P. Bierkens, and L. P. H. van Beek. 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature* 488:197–200.

This extensive use of the Earth's land and water has already had many deleterious effects on natural habitats and human health. Land use change for agriculture is the biggest threat to biodiversity globally.[4] Somewhere between 21 and 37 percent of total global greenhouse gas emissions can be attributed to food systems, including agriculture and other land use, storage, transport, packaging, processing, retail, and consumption.[5] Pollution from fertilizer and pesticide use runs off into rivers, lakes, and ultimately the ocean, threatening aquatic and marine ecosystems and the people who rely on those ecosystems for food, water, and jobs.[6] Intensive agriculture has contributed to soil degradation, the spread of zoonotic diseases and antibiotic resistance, and the loss of traditional skills, knowledge, institutions, and farming practices.

The global food system feeds a world population of nearly 8 billion people, which is a remarkable accomplishment. Yet, more than 800 million people worldwide remain undernourished, nearly 150 million children are stunted (too short for their age), and nearly 50 million children are wasted (too thin for their height).[7] At the same time, more than 2 billion adults and children are overweight or obese, in part because of a worldwide trend toward eating more processed foods and higher quantities of salt, sugar, and fat.[8] Increasing rates of obesity have in turn boosted the number of diet-related chronic diseases, including diabetes, cardiovascular disease, and some kinds of cancers.

The US-UK Scientific Forum on Sustainable Agriculture

It was against this backdrop that the National Academy of Sciences and the United Kingdom's Royal Society convened leading scientists and practitioners in the fields of agricultural sciences, food policy, biodiversity, and environmental science (among others) at the US-UK Scientific Forum on Sustainable Agriculture, which was held in Washington, DC, on March 5–6, 2020. Participants at

[4] Tilman, D., M. Clark, D. R. Williams, K. Kimmel, S. Polasky, and C. Packer. 2017. Future threats to biodiversity and pathways to their prevention. *Nature* 546:73–81.

[5] IPCC (Intergovernmental Panel on Climate Change). 2019. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, eds. Geneva, Switzerland: IPCC.

[6] Onyango, J. 2018. Agricultural nutrients and pesticide pollution in aquatic ecosystems, with policy implications. *Research & Reviews: Journal of Ecology and Environmental Sciences* 6(4).

[7] Development Initiatives. 2018. *The 2018 Global Nutrition Report: Shining a Light to Spur Action on Nutrition*. Bristol, UK: Development Initiatives.

[8] The GBD 2015 Obesity Collaborators. 2017. Health effects of overweight and obesity in 195 countries over 25 years. *The New England Journal of Medicine* 377(1):13–27.

the forum included researchers who study a range of topics from soil health and crop sciences to food security and population health—communities that do not commonly have opportunities to collaborate. The US-UK Scientific Forums provide opportunities for leading scientists, primarily from the United States and the United Kingdom, to identify research opportunities, build multidisciplinary and international collaborations, and discuss how science can provide or inform solutions to pressing international problems.

Sessions at the forum were organized into four themes: enhancing food security in a rapidly changing climate, agriculture's positive and negative effects on biodiversity and environmental health, agroecosystem productivity and agro-food system efficiency, and consumption behaviors, nutrition, and policy. This summary of the forum draws on three sources: the presentations by participants, the discussions following the presentations, and the plenary reports from small groups that met for 1 hour on the second day of the forum to discuss the future of sustainable agriculture. This summary should not be seen as representing conclusions of the National Academy of Sciences or the Royal Society. Rather, it consists of observations and suggestions for future action made by forum participants.

Organization of the Summary

Chapter 2 of this summary of the US-UK Scientific Forum on Sustainable Agriculture examines agriculture's impacts on biodiversity and the environment. Agriculture is just one part of a much larger global food system, but it is the indispensable core of that system and inevitably shapes and modifies the system's other components.

Chapter 3 considers the links among agriculture, diets, nutrition, and health. These links extend to the environment, because healthier diets tend to place less stress on the environment and biodiversity, which creates additional incentives and levers for change.

Chapter 4 looks at developments in science and technology that could enhance the sustainability of agriculture, including precision farming, biotechnologies, and research in the social sciences.

Finally, **Chapter 5** discusses some of the policy actions that could move the world not only toward sustainable agriculture but also toward a much broader sustainable global food system.

2 Agriculture's Impacts on Biodiversity, the Environment, and Climate

Agriculture has had major impacts on biodiversity and the environment. Inputs to agriculture in the form of fertilizers, pesticides, and the mechanization of farming have grown, which has produced higher yields but also has increased pollution of the air, water, and soil. The expansion of agriculture to previously wildland and the more intense harvesting of seafoods have placed new pressures on wild habitats and fisheries. Greenhouse gases from agriculture are contributing to higher temperatures and changing precipitation patterns, which have further stressed many plant and animal species.

Biodiversity and the state of the environment also have had major impacts on agriculture. Changes in climate are already affecting which crops can be grown where and the productivity of farmlands and pasturelands. Declining biodiversity is reducing the numbers and variety of pollinators, loosening natural checks on pests, and eliminating species that could have benefited humans in the future.

These and other interconnections among agriculture, biodiversity, and the environment add complexity to efforts to change food systems. However, these interactions also increase the number of ways in which agricultural production, biodiversity, and environmental resilience can be enhanced. For example, improving agricultural production while reducing the environmental impacts of agriculture requires considering broader ecological processes and ecosystem services as well as the wider social and cultural consequences of farmers' knowledge and actions.

Agriculture and Climate Change

According to the Intergovernmental Panel on Climate Change, reflecting a consensus of both scientists and governments, higher temperatures, changing precipitation patterns, and greater frequency of extreme events are already affecting food security.[1] For example, fruit and vegetable production, a key component of healthy diets, is particularly vulnerable to climate change. Livestock is also vulnerable, with increasing atmospheric carbon dioxide and temperature expected to degrade the productivity, species composition, biogeochemistry, and the quantity and the quality of forage available to herbivores in pastoral systems.

Agriculture is already a major contributor to greenhouse gas emissions, and it is likely to become a proportionately greater contributor as other sectors engage in mitigation. Agriculture's contributions

[1] IPCC (Intergovernmental Panel on Climate Change). 2019. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.* P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, eds. Geneva, Switzerland: IPCC.

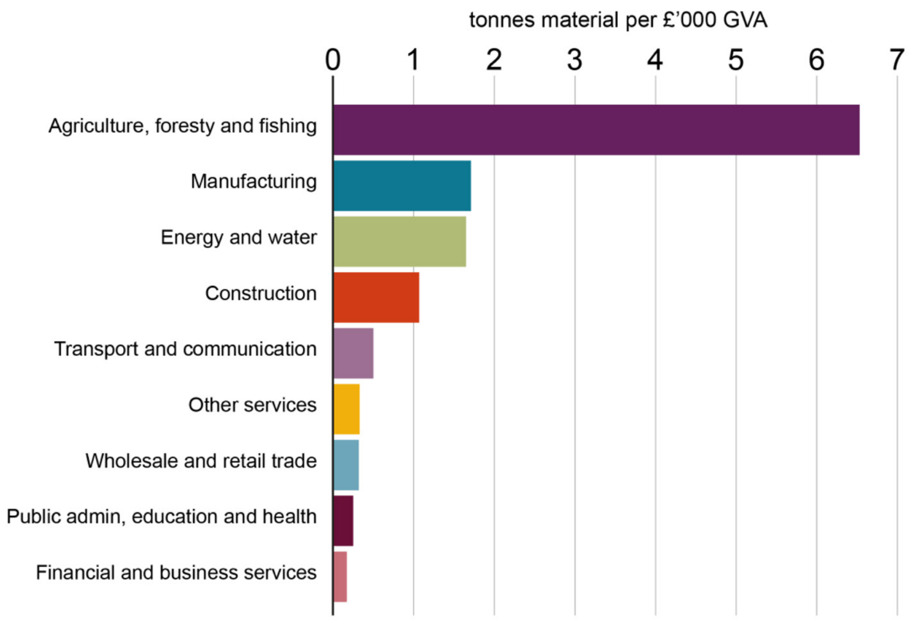


FIGURE 2-1
Agriculture, forestry, and fishing consume more natural resources per unit of gross value added (GVA) than other sectors. These data are for the United Kingdom but are representative of efficiencies elsewhere.

SOURCE: Owen, A., J. Giesekam, and J. Barrett. 2018. *Resource Efficiency Metrics—Initial Findings*. Leeds, UK: University of Leeds, p. 28, Figure 22. Contains public sector information licensed under the Open Government Licence v3.0.

to greenhouse gas emissions comes not only from fossil fuel use but also from land clearing for cropping and grazing; methane emissions from ruminant livestock, rice cultivation, and burning of manure and biomass; and nitrous oxide emissions to the atmosphere as a result of fertilizer use.[2] Agriculture uses more inputs of natural resources per unit of value added than any other sector of the economy, including manufacturing, construction, and transportation (see Figure 2-1). Furthermore, even with these outsized inputs, the current incremental rate of improvement in agricultural production is only a few percent per year. Even if all non-agricultural fossil fuel use was to stop, future greenhouse gas emissions solely from agriculture because of land clearing, ruminants, manure, rice, burning, and nitrous oxide from fertilized soils would, in total, accumulate so as to exceed the emissions limit set by the Paris Agreement for staying below a 2° Celsius global temperature increase.[3]

Challenges from climate change are often multiple and linked, like drought and saltwater intrusion for farmers, or losses due to insect pests in a warming climate. Climate change also produces tradeoffs that have to be accommodated within food systems. For example, increased carbon dioxide can cause crops to grow faster, but it can also lower the nutritional quality of the crops.

[2] Smith, P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello. 2014. Agriculture, Forestry and Other Land Use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. Contribution to Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 811–922, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J. Minx, eds. Cambridge, UK: Cambridge University Press.

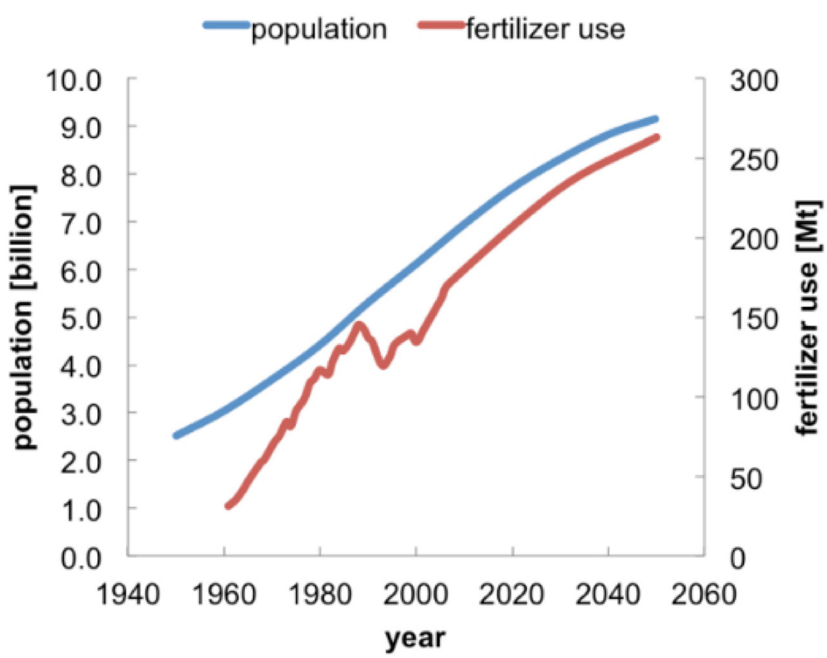
[3] Clark, M. A., N. G. G. Domingo, K. Colgan, S. K. Thakrar, D. Tilman, J. Lynch, I. L. Azevedo, and J. D. Hill. 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science* 370(6517):705–708.

The Use of Nitrogen in Agriculture

The use of nitrogen in agriculture is a good example of the complex interactions among agriculture, climate, and other environmental issues. Since the 1960s, global agricultural use of fertilizer on cropland has increased more than fivefold (see Figure 2-2).[4] This has resulted in large increases of nitrogen in the environment, including nitrates in groundwater, runoff into rivers and coastal areas, and increases in the level of nitrogen oxides and nitrous oxide in the atmosphere. Nitrogen oxides and ammonium contribute to air pollution, with an estimated 19,000 people dying prematurely every year in the United States because of particulate matter caused by these and other agricultural emissions.[5] Nitrous oxide generated largely by agriculture is already responsible for about 8 percent of anthropogenic greenhouse gas warming, a number that will go up as nitrogen use continues to increase.[6]

FIGURE 2-2
Worldwide fertilizer use has risen at roughly the same pace as the world population.

SOURCE: Meers, E. 2016. *EIP-AGRI Focus Group on Nutrient Recyling: Starting Paper on How to Improve the Agronomic Use of Recycled Nutrients (N and P) from Livestock Manure and Other Organic Sources.* EIP-AGRI FG19 Starting Paper. https://www.researchgate.net/publication/314378572. See p. 2, Figure 1.



[4] Lassaletta, L., G. Billen, J. Garnier, L. Bouwman, E. Velazquez, N. D. Mueller, and J. S Gerber. 2016. Nitrogen use in the global food system: Past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. *Environmental Research Letters* 11(9):095007.

[5] Thakrar, S. K., S. Balasubramanian, P. J. Adams, I. M. L. Azevedo, N. Z. Muller, S. N. Pandis, S. Polasky, C. Arden Pope III, A. L. Robinson, J. S. Apte, C. W. Tessum, J. D. Marshall, and J. D. Hill. 2020. Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environmental Science and Technology Letters* 7:639−645.

[6] Tian, H., C. Lu, P. Ciais, A. M. Michalak, J. G. Canadell, E. Saikawa, D. N. Huntzinger, K. R. Gurney, S. Sitch, B. Zhang, J. Yang, P. Bousquet, L. Bruhwiler, G. Chen, E. Dlugokencky, P. Friedlingstein, J. Melillo, S. Pan, B. Poulter, R. Prinn, M. Saunois, C. R. Schwalm, and S. C. Wofsy. 2016. The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature* 531:225–228.

Climate change will further boost the amount of nitrous oxide released into the environment.[7] As the use of nitrogen-intensive crops expands and moves into areas previously too cold to support such crops, nitrogen losses to the atmosphere will increase. Extreme events such as droughts and intense rainfall will depress the uptake of nitrogen by plants, causing more nitrogen to enter the broader environment. Longer growing seasons and warmer winters will lead to more mineralization of nitrogen by microorganisms from insoluble organic forms to soluble and biologically available forms. Where fertilization rates exceed what crops need, the emissions of nitrous oxide into the atmosphere from unused nitrogen increase.[8] For example, when growing switchgrass for biofuels, the production of nitrous oxide from excess fertilizer application could halve the climate benefits.[9]

Tailoring fertilizer rate to crop type and productivity could help avoid such losses.[10] For example, crop yield maps can reveal areas within fields that routinely have lower productivity than other areas. These areas could be fertilized at lower rates so that unused nitrogen does not pollute water and the atmosphere. Alternatively, fields could be subdivided so that low-yielding cropland is used for conservation and bioenergy production. Winter cover crops could be used to scavenge nitrogen, which is especially effective given that most nitrogen is lost in the off season. However, none of these solutions is sufficient to solve the problem, and all require incentivization if they are to take place.

Barriers to reducing the use of nitrogen are largely social and economic rather than technical. Today, agricultural production is aimed toward high yields, not toward greenhouse gas mitigation or nitrate conservation. However, evidence indicates that agriculture could be managed to maximize environmental benefits with only a minimal reduction in yields.[11] For example, when the European Union introduced a directive in the 1990s that requires farmers to show how much fertilizer they need to produce their crops, farmers began using less nitrogen while yields continued to increase.

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[7] Robertson, G. P., and P. M. Vitousek. 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. *Annual Review of Environment and Resources* 34:97–125.

[8] McSwiney, C. P., and G. P. Robertson. 2005. Non-linear response of N2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. *Global Change Biology* 11(10):1712–1719.

[9] Ruan, L., A. K. Bhardwaj, S. K. Hamilton, and G. P. Robertson. 2016. Nitrogen fertilization challenges the climate benefit of cellulosic biofuels. *Environmental Research Letters* 11:064007.

[10] Millar, N., A. Urrea, K. Kahmark, I. Shcherbak, G. P. Robertson, and I. Ortiz-Monasterio. 2018. Nitrous oxide (N2O) flux responds exponentially to nitrogen fertilizer in irrigated wheat in the Yaqui Valley, Mexico. *Agriculture, Ecosystems & Environment* 261:125–132.

[11] Snapp, S. S., R. G. Smith, and G. P. Robertson. 2015. Designing cropping systems for ecosystem services. Pp. 378–408 in S. K. Hamilton, J. E. Doll, and G. P. Robertson, eds. *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability*. New York: Oxford University Press.

Agriculture and Biodiversity

In addition to its effects on climate, the expansion of agriculture has caused massive losses in biodiversity around the world: natural habitats have been converted to farms and pastures, pesticides and fertilizers have polluted the environment, and soils have been degraded. Many plant and animal populations will face extinction in future decades as land clearing and agricultural production increase.[12] Agricultural ecosystems have also become less diverse as the use of crop monocultures has expanded. Even in developed countries such as the United States, directives to use more land for biofuels have caused millions of acres to be converted to monoculture crops, like corn, that had not been grown on that land before.

As with climate change, the interactions of agriculture and biodiversity run both ways. Greater biodiversity benefits agriculture through such effects as an increase in pollinators, the presence of species that reduce pests, and better soil quality. For example, work in ecology has demonstrated a strong link between biodiversity and the stability and productivity of ecosystems.[13,14,15]

Similarly, a greater diversity of crop types within agricultural systems can improve national food security and stability.[16] At a national level, some crops do better in warm years while others do better in cool years, or in wetter and drier years. By averaging across crop yields, greater crop diversity increases the year-to-year stability of national yields and the reliability of food production. Box 2-1 looks at some of the issues involved in protecting biodiversity while maintaining agricultural yields.

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[12] Tilman, D., M. Clark, D. R. Williams, K. Kimmel, S. Polasky, and C. Packer. 2017. Future threats to biodiversity and pathways to their prevention. *Nature* 546:73–81.

[13] Tilman, D., and J. Downing. 1994. Biodiversity and stability in grasslands. *Nature* 367:363–365.

[14] Isbell, F., D. Craven, J. Connolly, M. Loreau, B. Schmid, C. Beierkuhnlein, T. M. Bezemer, C. Bonin, H. Bruelheide, E. de Luca, A. Ebeling, J. N. Griffin, Q. Guo, Y. Hautier, A. Hector, A. Jentsch, J. Kreyling, V. Lanta, P. Manning, S. T. Meyer, A. S. Mori, S. Naeem, P. A. Niklaus, H. W. Polley, P. B. Reich, C. Roscher, E. W. Seabloom, M. D. Smith, M. P. Thakur, D. Tilman, B. F. Tracy, W. H. van der Putten, J. van Ruijven, A. Weigelt, W. W. Weisser, B. Wilsey, and N. Eisenhauer. 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526:574–577.

[15] Cardinale, B. J., K. Gross, K. Fritschie, P. Flombaum, J. W. Fox, C. Rixen, J. van Ruijven, P. B. Reich, M. Scherer-Lorenzen, and B. J. Wilsey. 2013. Biodiversity simultaneously enhances the production and stability of community biomass, but the effects are independent. *Ecology* 94(8):1697–1707.

[16] Renard, D., and D. Tilman. 2019. National food production stabilized by crop diversity. *Nature* 571:257–260.

BOX 2-1 Land Sharing and Land Sparing

A specific example of the interconnections between agriculture and biodiversity involves the two broad agricultural approaches known as land sharing and land sparing.[a] Land sharing entails retaining habitat features like hedgerows, copses, ponds, and other natural features of the landscape to produce patchwork farms. Though it typically reduces yields when measured in terms of production versus overall area used, it reduces chemical inputs and has other environmental benefits.

Land sparing combines high-yield farming on converted land with retention or restoration of intact habitats elsewhere in the landscape. Each approach, along with a range of intermediate approaches, balances the goals of food production and conservation, but they arrive at those goals in different ways.

Which approach is better for retaining biodiversity depends largely on how the population density of each species varies across the spectrum from land sharing to land sparing. Aggregating across large numbers of species allows a determination of which strategy is best for biodiversity as a whole. These numbers are typically difficult to measure, but work in southern Ghana and northern India has provided useful data.[b] In both areas, many species of birds and trees decline in numbers when the land is used for agriculture, but these losses were reduced, compared with land sharing, under high-yield production combined with land sparing. Similar work in other parts of the world has arrived at similar conclusions.[c] In many cases, an even better approach is to designate some land for low-yield farming that is tailored to meet the needs of particular species.[d]

High-yield farming can have many negative consequences, such as an increased use of pesticides, greater fertilizer runoff, soil degradation, and so on. These effects point to the need to identify yield-enhancing systems with relatively low environmental and social costs (as discussed in Chapter 4). Policy and market mechanisms (the subject of Chapter 5) would also need to couple yield growth with habitat conservation—for example, through land use zoning, spatially strategic investments, or new subsidy regimes.

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[a] Green, R. E., S. J. Cornell, J. P. W. Scharlemann, and A. Balmford. 2005. Farming and the fate of wild nature. *Science* 307(5709):550–555.

[b] Phalan, B., M. Onial, A. Balmford, and R. E. Green. 2011. Compared reconciling food production and biodiversity conservation: Land sharing and land sparing. *Science* 333(6047):1289–1291.

[c] Feniuk, C., A. Balmford, and R. E. Green. 2019. Land sparing to make space for species dependent on natural habitats and high nature value farmland. *Proceedings of the Royal Society B: Biological Sciences* 286(1909):20191483.

[d] Finch, T., S. Gillings, R. E. Green, D. Massimino, W. J. Peach, and A. Balmford. 2019. Bird conservation and the land sharing sparing continuum in farmland-dominated landscapes of lowland England. *Conservation Biology* 33(5):1045–1055.

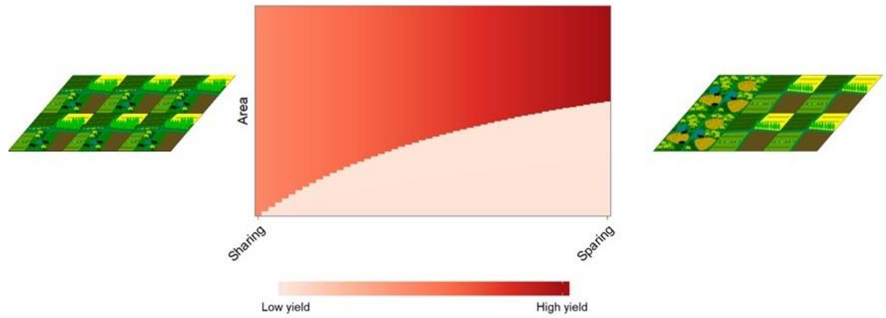

FIGURE Land sharing (left) involves retaining natural features of the landscape within less intensively farmed cropland. Land sparing (right) describes setting aside larger tracts of wildland and conducting more intensive farming on land designated for agriculture.

SOURCES: Figure in presentation "Feeding the World Without Costing the Earth" by Andrew Balmford. Images on left and right created by Tom Finch. Middle image from Finch, T., S. Gillings, R. E. Green, D. Massimino, W. J. Peach, and A. Balmford. 2019. Bird conservation and the land sharing sparing continuum in farmland-dominated landscapes of lowland England. *Conservation Biology* 33(5):1045–1055. See Figure 1.

The Current Trajectory

As global population and per capita incomes continue to grow, demand for food will increase.[17] Growing more crops for consumption by both people and livestock will require increasing yields on existing land or converting more wildland to cropland. Increasing yields on existing land implies decreasing the gaps between how much a given area of land is capable of producing and how much it produces today, which in the past has usually entailed increasing the use of fertilizer, irrigations, new kinds of cultivars, and other inputs to agriculture. But more inputs to agriculture have historically resulted in greater negative impacts on biodiversity and the environment. In addition, the yields of some crops appear to be reaching their limits as previous increases have leveled off.[18]

Agriculture will continue to adapt to new environmental conditions, as it has in the past. For example, the planting of maize has moved away from the hottest regions and toward cooler regions, which has reduced the negative effects of temperature increases.[19] In contrast, soybean production has moved toward warmer regions that boost yields. Since the early 1980s, planting of maize begins more than 10 days earlier on average and grain filling is more than 1 week longer, with a resulting increase in yields.[20]

[17] Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences* 108(50):20260–20264.

[18] Grassini, P., K. M. Eskridge, and K. G. Cassman. 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications* 4:2918.

[19] Sloat, L. L., S. J. Davis, J. S. Gerber, F. C. Moore, D. K. Ray, P. C. West, and N. D. Mueller. 2020. Climate adaptation by crop migration. *Nature Communications* 11:1243.

[20] Butler, E. E., N. D. Mueller, and P. Huybers. 2018. Peculiarly pleasant weather for US maize. *Proceedings of the National Academy of Sciences* 115(47):11935–11940.

Farmers will continue to manage crops to minimize or avoid harms to yields caused by changed conditions and take advantage of new opportunities. They will choose different crops to grow, which will result in the migration of crops across landscapes. Plants and animals will be bred to be more resistant to warmer temperatures, increased humidity, and other environmental changes. Many practices can be optimized and scaled up to advance such adaptations, including investments in infrastructure, capacity building, decision systems, market connectivity, and supply chains. Given that the drivers of change are global, adaptation will also need to take place from the perspective of the global food system.

However, it will be important to understand the limits of agricultural systems to adapt to changing environmental conditions. Farmers, for example, face severe and increasing economic pressures that are not directly related to environmental changes. Agriculture is a powerful system, but post-farm industries are even more powerful. The economic value added to a nation's gross domestic product from farming is typically a small percentage of the value added by the entire food system, including processing, distribution, and retail. In the United Kingdom, agriculture accounts for only about 8 percent of the value added in the country's overall food system.[21] Food and drink manufacturing, wholesaling, and retailing, in contrast, account for 59 percent, while cafés, restaurants, and other food sales venues account for another 29 percent. Similarly, in the United States, farms receive about 12 cents of every dollar spent by U.S. consumers. At the same time, prices for major commodities like corn, soybeans, and wheat in the United States have dropped to historical lows. While these low prices benefit consumers, the lack of revenue flowing to farmers is a major reason why farmers in these countries and elsewhere rely heavily on subsidies, while conservation receives substantially less governmental support.

The dynamics of the global food system are further challenged by imbalances among urban and rural areas, among countries, and among regions. Countries such as the United States produce more food than they require, while other countries must rely on imports to meet their needs. Mega-cities in the global South have become reliant on the global commodity trade, and their environmental footprints are rising at an even faster rate than their populations. Many aspects of the global food system have not been stress tested against environmental or social shocks that can be expected to occur in the future.

in addition to the demands made of land to produce food, pressure will grow to use land for the production of bioenergy and to sequester carbon. This pressure could increase the conversion of land to agriculture, the degradation of already farmed land, and food insecurity. Integrating bioenergy production and carbon sequestration into sustainably managed landscapes could produce fewer adverse side effects and have other positive co-benefits, such as salinity control, enhanced biodiversity, and reduced eutrophication. However, it will be necessary to figure out how contrasting land uses can work together in complementary ways.

[21] Department for Environment, Food & Rural Affairs. 2019. *Agriculture in the United Kingdom 2019*. London, UK: Department for Environment, Food & Rural Affairs.

An underlying question is how land ought to be used.[22] Land can provide food, habitat, bioenergy, climate change mitigation, amenities, housing, timber, and other services and resources. Agriculture is part of much broader systems that have many actors, many sectors, and many needs. Food security can mean many different things, including food nationalism, self-sufficiency, defense, control, resilience, risk management, capacity, and sovereignty. Analyzing and rationalizing these many services will require a multidisciplinary approach and inclusive consultation with stakeholders.

The 2009 Royal Society report *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*, adapting an earlier analysis,[23] defined sustainability as having four attributes:[24]

1. **Persistence:** the capacity to continue to deliver desired outputs over long periods of time (human generations), thus conferring predictability
2. **Resilience:** the capacity to absorb, utilize, or even benefit from perturbations (shocks and stresses) and thus persist without qualitative changes in structure
3. **Autarchy:** the capacity to deliver desired outputs from inputs and resources (factors of production) acquired from within key system boundaries
4. **Benevolence:** the capacity to produce desired outputs (e.g., food, fiber, fuel, oil) while sustaining the functioning of ecosystem services and not causing depletion of natural capital (e.g., minerals, biodiversity, soil, clean water)

Similarly, the Food and Agriculture Organization of the United Nations established five principles that must be pursued to make agriculture sustainable:[25]

1. Improve efficiency in the use of resources
2. Conserve, protect, and enhance natural resources
3. Protect and improve rural livelihoods, equity, and social well-being
4. Strengthen the resilience of people, communities, and ecosystems to climate change and market volatility
5. Promote responsible and effective governance mechanisms

Given these objectives, the challenge of sustainable agriculture is how to produce sufficient and nutritious food for all people with low environmental impacts. As discussed in the remainder of this summary, many deliberative levers of change can be used to address this challenge, including increased agricultural efficiency and yields, smarter land use, better use of markets and trade, reductions of

[22] Lang, T. 2020. *Feeding Britain: Our Food Problems and How to Fix Them*. London, UK: Penguin.

[23] Pretty, J. N. 2008. Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B* 363(1491):447–465.

[24] Royal Society. 2009. *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*. London, UK: Royal Society.

[25] FAO (Food and Agriculture Organization of the United Nations). 2014. *Building a Common Vision for Sustainable Food and Agriculture: Principles and Approaches*. Rome, Italy: FAO.

waste, and shifts in diets. In addition, forced levers of change, such as the coronavirus pandemic that gripped the world in 2020, can be expected to change food systems, though often in ways that are difficult to predict.

The Need for Change

Under a business-as-usual scenario, the deleterious environmental effects of current food systems will continue to increase. Higher levels of food production will require more fertilizer, pesticides, and irrigation and more extensive resource extraction from the land and sea. This will be the case in places where growing populations, increased demand, and existing yield gaps will exert pressures to convert more wildland to cropland in particular (see Figure 2-3). Such an approach would bring more air and water pollution, increases in greenhouse gas emissions, greater degradation and erosion of soils, more conversion of natural habitats to agriculture, greater threats to biodiversity, and intensified competition for land and other resource inputs. Given the already substantial effects of agriculture on biodiversity and the environment, such a future is not sustainable.

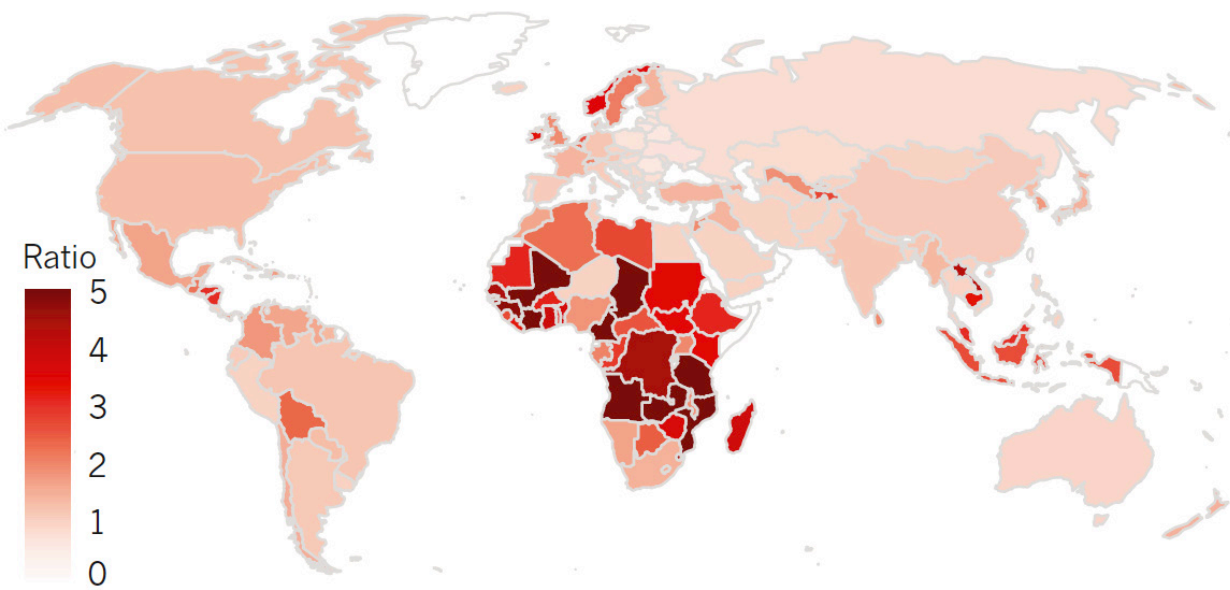

FIGURE 2-3
Under a business-as-usual scenario, land devoted to crops is projected to expand in many parts of the world, causing increased land clearing, greenhouse gas emissions, and extinctions.

NOTE: Ratio of national cropland in 2060 to that in 2010.

SOURCE: Tilman, D., M. Clark, D. R. Williams, K. Kimmel, S. Polasky, and C. Packer. 2017. Future threats to biodiversity and pathways to their prevention. *Nature* 546:73–81. See Figure 3c on p. 76.

3 Agriculture and Nutrition

In addition to its effects on biodiversity and the environment, agriculture has many direct and indirect effects on human nutrition and health. The number of people who are overweight or obese has been increasing rapidly throughout the world.[1] In the United States, about 42 percent of adults and 18 percent of children and adolescents are overweight or obese—up from 10 percent and 5 percent, respectively, in the 1970s—and the percentages are higher in the United Kingdom. At the same time, more than 2 billion people lack micronutrients like iron and vitamin A because of inadequate diets. The consumption of processed foods with added salt, sugar, and fats is too high in many countries, while the consumption of fruits, vegetables, nuts, and legumes is too low. Furthermore, consumption of unhealthy foods is increasing as incomes rise and as processed foods become more widely available.

Many of the foods associated with a higher risk of chronic diseases like diabetes and heart disease, such as red meat and highly processed foods, also have the highest environmental impacts. Eating less of these foods and more locally produced fruits, vegetables, legumes, and nuts would reduce greenhouse gas emissions while also reducing the number of years of life lost to diet-related diseases.[2,3] More sustainable and healthier diets could also have many other benefits, including increased support for farmers, greater resiliency of food systems, and increased equity among consumers.

Eating Within Planetary Boundaries

One prominent effort to understand what a healthier and more sustainable global diet would look like was the detailed study undertaken by the EAT-Lancet Commission on Food, Planet, Health, which in 2019 issued a report titled "Food in the Anthropocene: The EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems."[4] The goal of the commission, which consisted of 37

[1] Hales, C. M., M. D. Carroll, C. D. Fryar, and C. L. Ogden. 2020. *Prevalence of Obesity and Severe Obesity Among Adults: United States, 2017–2018*. NCHS Data Brief, No. 360. Hyattsville, MD: National Center for Health Statistics.

[2] Milner, J., R. Green, A. D. Dangour, A. Haines, Z. Chalabi, J. Spadaro, A. Markandya, and P. Wilkinson. 2015. Health effects of adopting low greenhouse gas emission diets in the UK. *BMJ Open* 5:e007364.

[3] Scheelbeek, P., R. Green, K. Papier, A. Knuppel, C. Alae-Carew, A. Balkwill, T. J. Key, V. Beral, and A. D. Dangour. 2020. Health impacts and environmental footprints of diets that meet the Eatwell Guide recommendations: Analyses of multiple UK studies. *BMJ Open* 10(8):e037554.

[4] Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L. J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J. A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S. E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, and C. J. L. Murray. 2019. Food in the Anthropocene: The EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems. *The Lancet* 393(10170):447–492.

scientists from 17 countries representing multiple disciplines, was to chart a course toward feeding a global population of 10 billion people by 2050 with a healthy and environmentally sustainable diet.

Using the best available evidence, the commission defined a healthy reference diet that could be available to everyone. For example, it considered the ratio of polyunsaturated to saturated fat in various foods, which is a factor in cardiovascular disease. Using this information, it defined the composition and total average calorie content of diets divided by food groups: whole grains, tubers and starchy vegetables, vegetables, fruits, dairy, protein sources, added fats, and added sugars.

The commission also defined planetary boundaries for six key environmental systems and processes: greenhouse gases, cropland use, water use, nitrogen application, phosphorus application, and the species extinction rate. It then applied a global food systems modeling framework to analyze which combinations of measures are needed to stay within planetary boundaries while still delivering healthy diets by 2050.

On the basis of this analysis, the commission concluded that feeding 10 billion people a healthy diet while boosting the sustainability of food systems is well within today's capabilities. The Planetary Health Diet developed by the commission calls for substantial increases in the consumption of fish, vegetables, legumes, whole grains, and nuts (see Figure 3-1). The diet would allow the equivalent of one glass of milk per day and one hamburger per week. Such a diet would have substantial health benefits, with a reduction of about 11 million premature diet-related adult deaths per year. It also would reduce greenhouse gas emissions caused by food consumption below today's level, as compared with almost a doubling by 2050 under the business-as-usual scenario. Further improvements in food production and a decrease in food waste could drive greenhouse gas emissions below today's levels. However, increases above the Planetary Health Diet in such areas as dairy and meat consumption, especially beef, would increase emissions substantially.

Minimizing Food Waste

An estimated 25 to 30 percent of all food produced is lost or wasted, as defined by discarding food or an alternative (non-food) use of food along the entire supply chain.[5] Reduction of this loss could mitigate environmental harms while enhancing food security and health.

Much food waste occurs with perishable foods, which could be reduced through shorter supply chains and the consumption of more local and seasonal foods.[6] Better formulations and understanding of expiration dates on packaging could also reduce the amount of food that is wasted. Research and development could focus on extending the shelf life of nutritious foods and on changes to food systems that would lower food losses from production to consumption.

[5] Ishangulyyev, R., S. Kim, and S. H. Lee. 2019. Understanding food loss and waste—Why are we losing and wasting food? *Foods* 8(8):297.

[6] NASEM (National Academies of Sciences, Engineering, and Medicine). 2019. *Reducing Impacts of Food Loss and Waste: Proceedings of a Workshop*. Washington, DC: The National Academies Press.

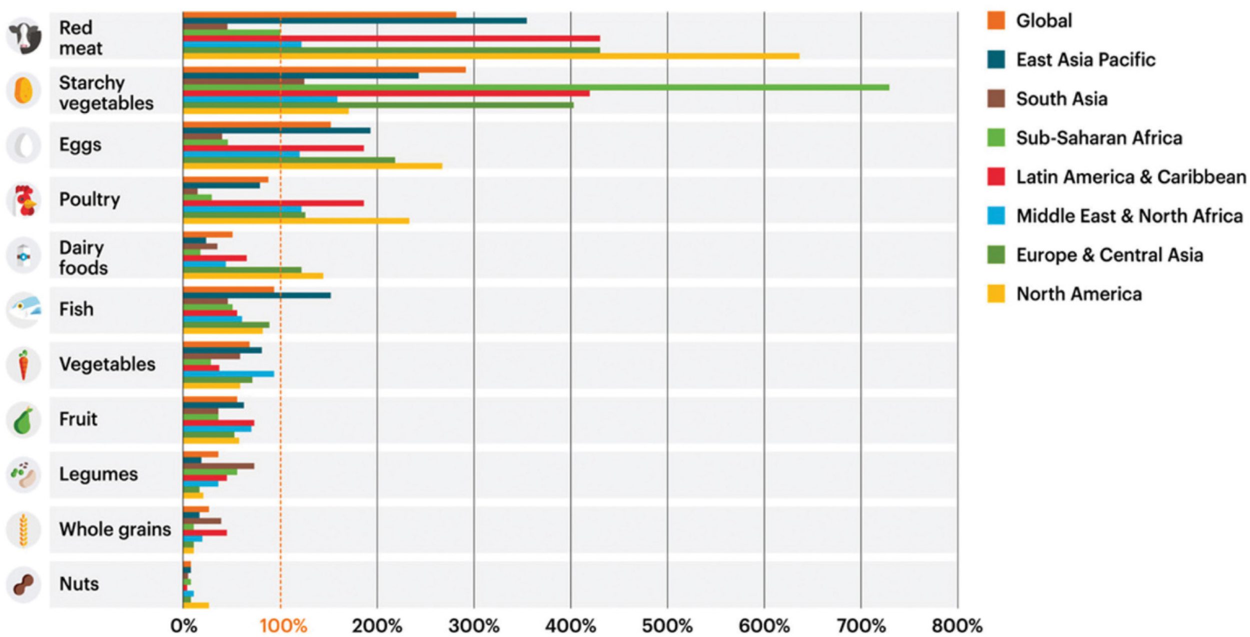

FIGURE 3-1
The Planetary Health Diet developed by the EAT-Lancet Commission calls for a decrease in the consumption of red meat and starchy vegetables in most parts of the world and for an increase in the consumption of fish, vegetables, fruit, legumes, whole grains, and nuts.

SOURCE: Willett, W., et al. 2019. Food in the Anthropocene: The EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems. *The Lancet* 393:447–492. See Figure 1 on p. 460.

The patterns of food waste tend to differ from one part of the world to another, which argues for the study of the particular factors that cause food to be lost. For example, more food is wasted where food is relatively abundant and cheap compared with places where it is less abundant and more expensive, and levels of food waste tend to track levels of obesity.[7]

Many other national and international bodies have issued recommendations that would result in healthier diets that have fewer harmful consequences. However, relatively few address sustainable agriculture, especially because incremental gains will not be enough to resolve the underlying environmental and health issues.

[7] Toti, E., C. Di Mattia, and M. Serafini. 2019. Metabolic food waste and ecological impact of obesity in FAO world's region. *Frontiers in Nutrition* 6:126.

Increasing Dietary Diversity

More diverse diets and more diverse agriculture could be healthier and more sustainable in many ways. Although there are around 30,000 edible plant species around the world, only three—rice, wheat, and maize—provide more than 50 percent of the world's plant-derived calories.[8] This minimal diversity of modern agriculture has led to excessive homogeneity and oversimplification of both farming and food systems, disrupting the ecological, biological, and social drivers of sustainable, resilient, and healthy agriculture. It also has pushed many traditional crops to the margins, both in terms of their consumption and the amount of research and development devoted to their improvement.

Increasing the diversity of diets will require a greater recognition of the values, beyond price, associated with food. Different diets could drive a more diversified agriculture, creating more mixed farms, multifunctional and resilient landscapes, and rural employment. At the same time, a greater focus on overall system efficiency could lower waste, reduce greenhouse gas emissions, and make space for land-based climate mitigation.

Research and development could explore the nutritional profiles of a wider variety of plants as well as the bioavailability of nutrients at different points in the supply chain. (Box 3-1 provides an example of the need for research and development on the major nutrients as well as on a broader range of foods.) Greater knowledge of phenotype–genotype associations could help breeders improve nutritional qualities. As a specific example, foods like brussels sprouts and quinoa have seen large increases in demand in recent years, in part because of advances in breeding that have improved their quality. If a market potential for a healthy food was identified, crops could be developed to meet that demand.

Demand side changes in diets could reduce environmental harms by altering the kinds of foods eaten. Examples range from purely vegan diets that include no animal-source foods to pescatarian and Mediterranean diets that include seafood and moderate meat consumption. Better understanding of the food system as a whole, including its dependencies, opportunities, and change levers, could foster the structural changes that are needed all the way from farms to consumers. Creating a sustainable agriculture will require a focus on food systems, not just farms; farming systems, not just crops; and landscapes, not just fields.

[8] FAO (Food and Agriculture Organization of the United Nations). *Staple Foods: What Do People Eat*. http://www.fao.org/3/u8480e/U8480E07.htm.

BOX 3-1 The Example of Fat

The knowledge base concerning fats (a term that includes solid fats like butter and liquid fats like olive oil) is a good example of the need for expanded research into all of the major nutrients. In some places, people eat too much fat; in other places, they eat too little. Some fats are unhealthy; others are very healthy. According to the Food and Agriculture Organization of the United Nations, to ensure an adequate supply of energy, fat-soluble vitamins, and essential fatty acids, 20 to 35 percent of dietary energy should come from fats.[a] Meeting this goal requires that some people increase and some people decrease their fat consumption.

For animal-source foods, the largest sources of fat globally are pork, dairy, poultry, beef, eggs, and fish. For plant-based foods, the largest sources are soybean oil, palm oil, sunflower oil, rapeseed oil, wheat, and peanuts. Other potential sources are nuts, algae, and fungi, which in the future could be grown on cellulose or food waste.[b]

Each of the major plant-based fat sources has its own sustainability issues. Expansion of palm oil production, for example, leads to deforestation, while rapeseed oil has a large dependence on pesticides. Fats from livestock and fish can be nutritious, but their production can also have major environmental consequences.

As with other nutrients, ensuring that the future production of fats will be sufficient to meet global food needs requires research, innovation, and investment.

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[a] See http://www.fao.org/nutrition/requirements/dietary-fats/en.

[b] Ritchie, H., D. S. Reay, and P. Higgins. 2018. Potential of meat substitutes for climate change mitigation and improved human health in high-income markets. *Frontiers in Sustainable Food Systems* 2(Article 16).

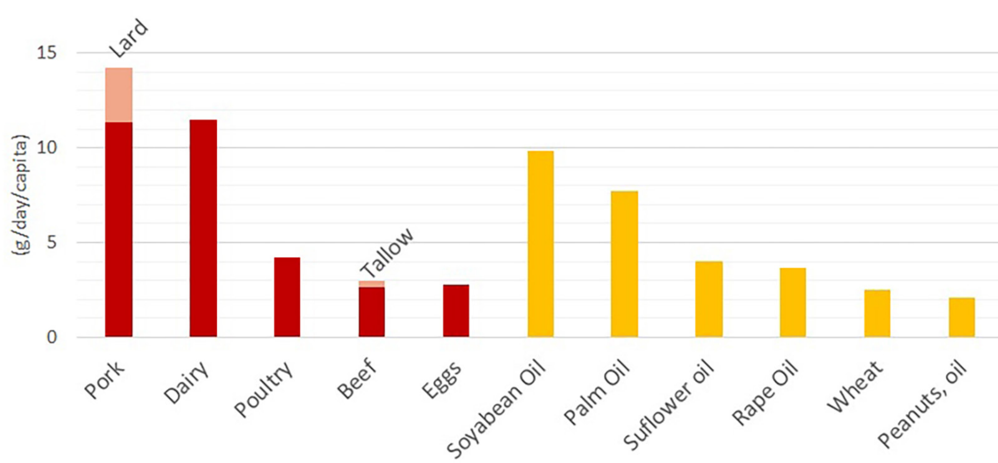

FIGURE The largest sources of fat worldwide are both animal based and plant based.

SOURCES: Figure in presentation "The Question of Fat in Sustainable Diets" by Bojana Bajzelj. Data from Food and Agriculture Organization of the United Nations New Food Balances (http://www.fao.org/faostat/en/#data/FBS).

4 Science and Technology for Sustainable Agriculture

Ensuring that everyone has access to healthy and nutritious foods without further reducing biodiversity and damaging the environment will require major changes in many aspects of food systems. Yields on agricultural land will need to go up while the pollution from agricultural production declines. Agriculture will need to become a net sink rather than a source of greenhouse gas emissions by sequestering carbon in ecosystems and in the soil. The environmental effects of livestock production will need to be reduced while the nutritional benefits of animal-source products are maximized. People will need to eat more fruits and vegetables while reducing the large amounts of food that are wasted today.

As the 2019 National Academies of Sciences, Engineering, and Medicine report *Science Breakthroughs to Advance Food and Agricultural Research by 2030* pointed out, creating a sustainable global food system will require the development and application of many new technologies and the continued pursuit of new scientific knowledge.[1] This chapter describes some of the many beneficial agricultural technologies that already exist and are on the horizon. The next chapter examines policies that will be needed to deploy those technologies and move toward a sustainable food system.

Data-Intensive Agriculture

An approach known as precision agriculture offers great potential to improve yields, reduce costs, and minimize environmental damage. Mapping farms for soil moisture, temperature, nutrients, and other indicators using ground sensors, drones, and instruments on farm equipment can provide actionable insights for farmers, suppliers, and distributors. The measurement of ground conditions combined with remote sensing and the observation of weather patterns can optimize irrigation, fertilizing, weeding, and pesticide applications. Data gathered from farms can inform the development of better livestock, advisories based on artificial intelligence, and ways of monitoring technology usage. Simulation technologies can model scenarios to inform planning and prepare for contingencies.

The main barrier to precision agriculture, especially for smallholder farmers, is the cost of data collection, but the costs are dropping rapidly. For example, connectivity to instruments in the field

[1] NASEM (National Academies of Sciences, Engineering, and Medicine). 2019. *Science Breakthroughs to Advance Food and Agricultural Research by 2030*. Washington, DC: The National Academies Press.

could be provided by devices that embed signals in unused television channels, many of which are vacant in rural areas.[2] Drones are available for $1,000 or less and can cover large areas quickly, and instruments carried by tethered balloons are even less expensive. New artificial intelligence and machine learning techniques can interpolate missing data from sensors, such as satellite data where clouds block views of the ground. Better connections between farmers and central databases can transfer data in both directions so that farmers can benefit from the analyses of the data collected on their farms and from best practice recommendations.

Farmers will also need education and training to be able to use these technologies and the information they provide, which implies, in part, working with young people to encourage them to get interested in farming and in applying these technologies. Also, the data collected by precision agriculture and the information generated from that data will be valuable and will need to be protected, with an equitable allocation of the benefits derived from that information. Some of the data can be anonymized, though this is a difficult challenge, because the data are so closely tied to location and to applications. Computer scientists will need to work with agricultural scientists and with farmers to overcome such challenges and to formulate experiments that can inform the development and deployment of technologies.

Beyond precision agriculture, a wide variety of other advanced technologies could be applied to agriculture to enhance sustainability.[3,4] New applications of technology could provide decision support to farmers and consumers, help connect the biological sciences with fields such as engineering and materials science, and ensure that data-collection methods are affordable and practical. Technologies such as robotics, artificial intelligence, process engineering, and synthetic biology could come together to shift the paradigm from "food produced by agriculture" to "food produced by manufacturing." High-tech, three-dimensional vertical farms could efficiently produce clean and organic food within urban centers. Foods requiring less energy to produce could be grown near the point of consumption to reduce transportation costs, with energy-dense commodities produced near energy sources such as hydroelectric and solar power. Synthetic milk and meat products, insect and microbial bioreactors, marine algal culturing, biofortified foods, the use of insects for livestock feed, and closed-loop livestock production could enhance diets while reducing the environmental impacts of agriculture. A new green revolution could be based on science, ecological efficiency, and the careful management of food production and distribution. Nutrition, yields, and environmental outcomes could all benefit by maximizing the efficiency of the food system as a whole.[5]

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[2] Roberts, S., P. Garnett, and R. Chandra. 2015. *Connecting Africa Using the TV White Spaces: From Research to Real World Deployments*. The 21st IEEE International Workshop on Local and Metropolitan Area Networks.

[3] European Environment Agency. 2020. *The European Environment—State and Outlook 2019. Knowledge for Transition to a Sustainable Europe*. Luxembourg: Publications Office of the European Union.

[4] Cui, Z., H. Zhang, X. Chen, C. Zhang, W. Ma, C. Huang, W. Zhang, G. Mi, Y. Miao, X. Li, Q. Gao, J. Yang, Z. Wang, Y. Ye, S. Guo, J. Lu, J. Huang, S. Lv, Y. Sun, Y. Liu, X. Peng, J. Ren, S. Li, X. Deng, X. Shi, Q. Zhang, Z. Yang, L. Tang, C. Wei, L. Jia, J. Zhang, M. He, Y. Tong, Q. Tang, X. Zhong, Z. Liu, N. Cao, C. Kou, H. Ying, Y. Yin, X. Jiao, Q. Zhang, M. Fan, R. Jiang, F. Zhang, and Z. Dou. 2018. Pursuing sustainable productivity with millions of smallholder farmers. *Nature* 555:363–366.

[5] Benton, T. G., and R. Bailey. 2019. The paradox of productivity: How agricultural productivity promotes food system inefficiency. *Global Sustainability* 2(e6):1–8.

BIOTECHNOLOGIES

Genetic technologies and other advanced biotechnologies offer tremendous potential to improve agriculture, particularly if they are integrated with agronomy and agroecology. Examples of possible advances include crops and livestock resistant to high temperatures and drought, protection against new and emerging pests and disease, greater efficiency in water use, increased nutritional value in foods, and reduced fertilizer use.

Many such biotechnologies are already available or under development. For example, a new technique known as "speed breeding" has shortened the cycle from seed to seed.[6] Agricultural biotechnologies are being developed that can insert new genes into cells, edit and delete targeted genes, and alter multiple genes at once while avoiding breeding bottlenecks and the loss of diversity in crop populations.

An example of these biotechnologies involves the protection of crops from pests. One way that grasses such as maize, rice, and wheat protect themselves from herbivores is by taking up silicon from the soil and depositing it within plant cells and in spines and hairs on the plant surface, so that herbivores are less likely to consume the plant. Higher levels of silicon also protect against drought and salinity stress, though the mechanisms behind these effects are not fully understood. Domestication has reduced silicon levels in plants by a small amount, but these defenses largely remain in place.[7] Genetically modifying how plants use silicon could therefore provide possible mechanisms of pest resistance and drought resistance. This research has already led to inexpensive methods of increasing the supplies of silicate in soils to mitigate salt stress and improve yields, such as through the application of silicate-rich steel furnace slag.[8] Success in applying such methods will require not only technological advances but also integrating crop breeding and genetic approaches with agronomical practices and practical advice for farmers.

New tools that deliver DNA, RNA, or proteins into plant cells could enhance the use of genetic technologies in producing new food, bioenergy, or medicinal applications. A plant transformation technology that is independent of plant species, efficient, nonpathogenic, and nonintegrating (in that the DNA being introduced into the cell would not integrate into the plant's DNA) would be especially valuable.[9] An example of such a technology is the ability to use new nanomaterials to

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[6] Watson, A., S. Ghosh, M. J. Williams, W. S. Cuddy, J. Simmonds, M-D Rey, M. A. Md Hatta, A. Hinchliffe, A. Steed, D. Reynolds, N. M. Adamski, A. Breakspear, A. Korolev, T. Rayner, L. E. Dixon, A. Riaz, W. Martin, M. Ryan, D. Edwards, J. Batley, H. Raman, J. Carter, C. Rogers, C. Domoney, G. Moore, W. Harwood, P. Nicholson, M. J. Dieters, I. H. DeLacy, J. Zhou, C. Uauy, S. A. Boden, R. F. Park, B. B. H. Wulff, and L. T. Hickey. 2018. Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants* 4:23–29.

[7] Simpson, K. J., R. N. Wade, M. Rees, C. P. Osborne, and S. E. Hartley. 2017. Still armed after domestication? Impacts of domestication and agronomic selection on silicon defences in cereals. *Functional Ecology* 31(11):2108–2117.

[8] Johnson, S. N., S. E. Hartley, J. M. W. Ryalls, A. Frew, J. L. DeGabriel, M. Duncan, and A. N. Gherlenda. 2017. Silicon-induced root nodulation and synthesis of essential amino acids in a legume is associated with higher herbivore abundance. *Functional Ecology* 31(10):1903–1909.

[9] Landry, M. P., and N. Mitter. 2019. How nanocarriers delivering cargos in plants can change the GMO landscape. *Nature Nanotechnology* 14:512–514.

transfer DNA, RNA, or proteins through plant cell walls with a high level of control over the molecules being delivered. For example, the introduction of the genome-editing molecule CRISPR-Cas9 using this technique could enable the modification of genes without the usual need for extensive breeding programs to eliminate DNA introduced into the genome through other techniques.[10] Such a technique could be used to modify the traits of a wide range of commercially valuable crops, from wheat and cotton to spinach and arugula (rocket). It also could be used to address critical global issues in not only food production but also advanced biofuels and the synthesis of medical therapeutics.

Compared with the use of natural or induced genetic variation, targeted changes in DNA have many advantages when the genes that control the traits are known.[11] For example, modifications of flowering have the potential to improve the agronomic properties of many crops. To take a specific example, the modification in tomatoes of the genomic network that controls flowering can modulate plant size and yield in ways that are not possible with traditional breeding techniques. Such techniques can be used, for example, to create plants that can be grown through urban agriculture in vertical farming systems.

Grand challenge problems in biotechnology, while ambitious, could yield very high returns. An example would be the introduction of nitrogen-fixing capabilities directly into crops to reduce the use of nitrogen fertilizers and to boost yields where fertilizer use is currently suboptimal. Many of the genes that would be involved in fixing nitrogen in crops already exist because they play other roles in these plants. Another option would be to modify the microorganisms present in soil that live in association with plants and provide them with nitrogen and other nutrients. Modifying these associations could also increase the sequestering of carbon in soil, enhancing soil health while also increasing yields. (Box 4-1 presents more information about the possible uses of biotechnology to enhance soil health and fertility.)

Another potentially transformative step would be the development of crops with much higher photosynthetic efficiency, which could enable large improvements in yields. As a specific example, researchers are working on lowering the energetic cost of photorespiration, with the installation of a synthetic photorespiratory pathway improving yields by up to 25 percent.[12] Tests of this concept have shown potential, and many other opportunities exist to engineer more efficient photosynthesis.

Many crops produced using genetic technologies have already been approved and are in widespread use. Though the rate of progress has been limited by cost and by regulatory burdens, further advances could greatly enhance the sustainability of food systems. Particularly important will be increased knowledge of the genetic and environmental bases of phenotypes and the integration of this knowledge with better understanding of ecosystem-based approaches to agriculture.

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[10] Demirer, G. S., H. Zhang, N. S. Goh, E. González-Grandío, and M. P. Landry. 2019. Carbon nanotube–mediated DNA delivery without transgene integration in intact plants. *Nature Protocols* 14:2954–2971.

[11] Eshed, Y., and Z. B. Lippman. 2019. Revolutions in agriculture chart a course for targeted breeding of old and new crops. *Science* 366(6466):705.

[12] South, P. F., A. P. Cavanagh, H. W. Liu, and D. R. Ort. 2019. Synthetic glycolate metabolism pathways stimulate crop growth and productivity in the field. *Science* 363(6422):45.

BOX 4-1 Applying Biotechnology to Soil

An often overlooked example of the use of biotechnology involves soil. Agriculture has tended to deplete the soil of organic matter and harm its health and fertility. Alongside its role in food production, soil can sequester large amounts of carbon from the atmosphere, depending on the management practices applied to agriculture and to soils.[a]

One way to improve soil health and carbon sequestration would be to take advantage of the rapidly growing understanding of the beneficial interactions between the soil microbiome and crop efficiency.[b] Fungi, for example, take up phosphorus and make it usable to plants, while nitrogen-fixing bacteria process atmospheric nitrogen into forms of nitrogen that plants can use. If all crops could be provided with microorganisms that perform these functions, the need for fertilizers could be substantially reduced. Today, the use of agricultural fertilizers works against these associations because plants will absorb what they need from applied fertilizers rather than from symbiotic relationships, which require that plants support the microorganisms on which they rely. Genomic technologies applied to both microorganisms and plants could modify this relationship so that plants make optimal use of nutrients from both the soil and from applied fertilizers. Such approaches could also enhance the ability of plants and microorganisms to sequester carbon in soils for long periods.

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[a] Lal, R., P. Smith, H. F. Jungkunst, W. J. Mitsch, J. Lehmann, P. K. R. Nair, A. B. McBratney, J. Carlos De Moraes Sá, J. Schneider, Y. L. Zinn, A. L. A. Skorupa, H. L. Zhang, B. Minasny, C. Srinivasrao, and N. H. Ravindranath. 2018. The carbon sequestration potential of terrestrial ecosystems. *Journal of Soil and Water Conservation* 73(6):145A–152A.

[b] Jansson, J. K., and K. S. Hofmockel. 2020. Soil microbiomes and climate change. *Nature Reviews Microbiology* 18:35–46.

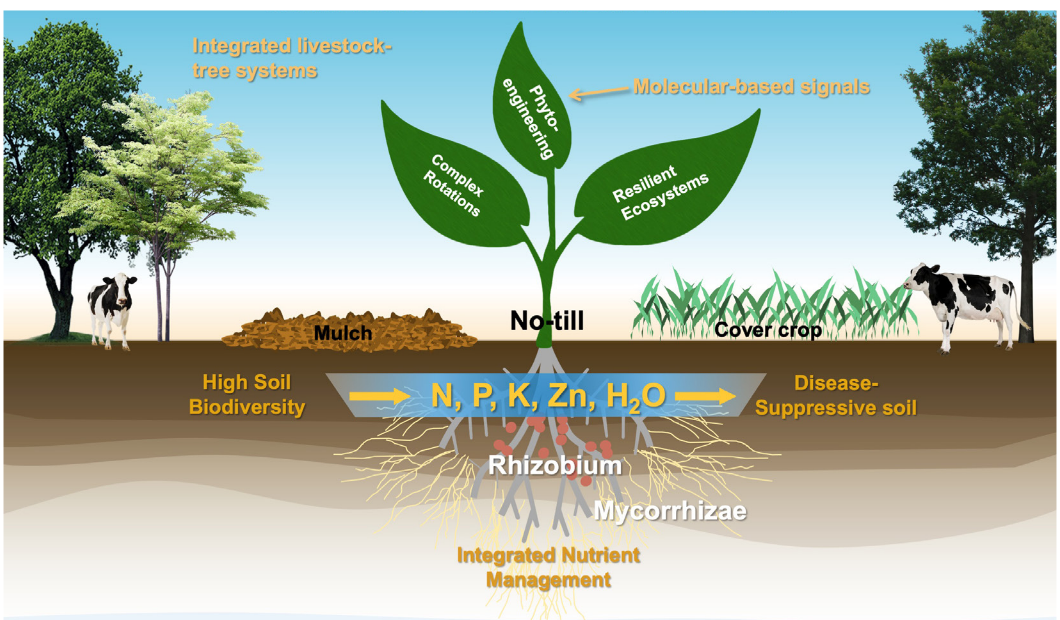

FIGURE Maintaining high soil biodiversity is part of a system of integrated agricultural management that can minimize the harmful effects on the environment.

SOURCE: Figure in presentation "Managing Soil Carbon for Food and Climate" by Rattan Lal.

The Social Sciences

Science and technology for sustainable agriculture include the social sciences. The emerging field of climate adaptation requires scenario and policy analyses. Efforts to change diets require interdisciplinary assessments of incentives and preferences. Changing the behavior of farmers and other actors in food systems requires understanding of incentives and barriers to change.

An important policy question that involves the social sciences is whether a keystone intervention could drive a transformation to sustainable agriculture or whether many complementary interventions are needed. For example, anti-smoking campaigns typically have involved many interventions, including education, taxes, regulation, and alternative products. How many policies would be needed to transform food systems from a business-as-usual model to an agrobiodiverse, regenerative, food-secure, equitable, and just system? Could a keystone intervention take the form of governmental initiatives, international coordination, or education and training to give people the skills they need to adopt sustainable and healthy diets?

Some policy levers are undoubtedly powerful, such as price changes created by a carbon tax, but whether they are enough to achieve the needed changes is unknown. For example, a carbon tax might do little to address biodiversity or the production of unhealthy foods, instead requiring multiple policy actions to achieve the desired outcomes. That said, events external to a system can sometimes produce rapid change, as has occurred with the coronavirus pandemic.

Another important question is how a transformation to sustainability can be just and fair both within and across countries. For example, many people are employed in the fossil fuel industry around the world. How can their needs and values be accommodated within such a transformation? The modeling of the entire food system and its links to other society systems could help reveal the dynamics of those systems and how they impact food availability and access (see Figure 4-1).

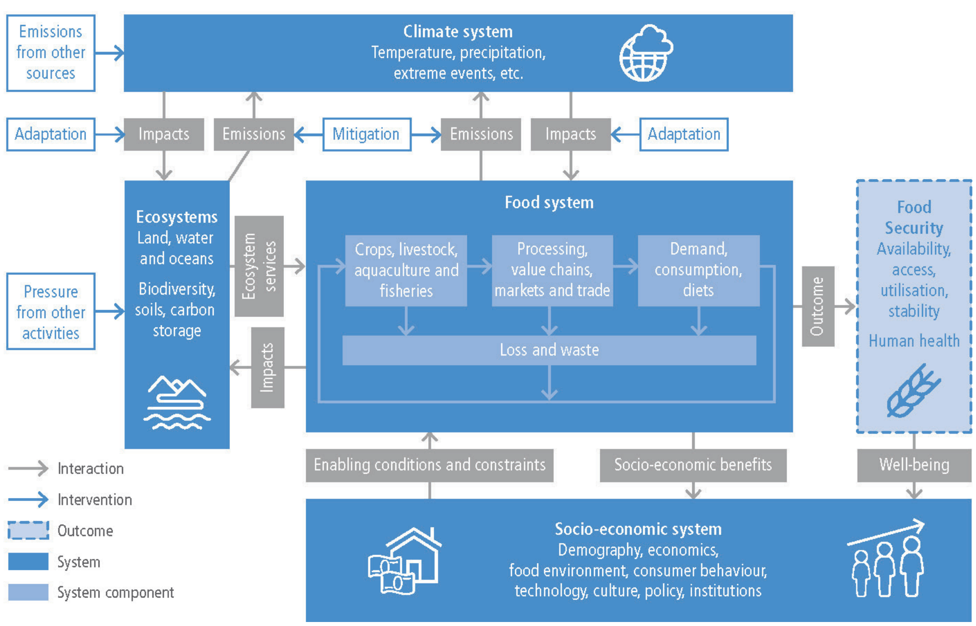

FIGURE 4-1
The food system is linked with many other natural and human systems.

SOURCE: Intergovernmental Panel on Climate Change. See https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/Figure-5.1.jpg.

5 Enacting Change

Transitioning to sustainable agriculture will involve a large set of complicated, interlocking, and contested issues. Yields will need to increase while portions of the landscape are spared to maintain biodiversity. Advanced cropping systems will be needed to move the overall system toward net negative greenhouse gas emissions. Without major changes in how meat is produced, meat consumption will need to decline to stay within planetary sustainability boundaries. Achieving these and many other goals will require changes throughout agriculture and in the broader food systems of which agriculture is a relatively small but foundational part.

Great overlap exists between decreasing climate and biodiversity risk and ensuring food and nutrition security. Sustainability goals therefore have multiple motivations and end points. In that respect, an important set of questions involves the conceptual framework for change that can coordinate and justify actions. For example, can a different way of ascribing value to agricultural products be developed—one that involves such factors as food quality, health, and sustainability—that does not depend entirely on yields? Could the economics of agricultural markets be modified so that value is more evenly distributed, with growers getting a more equitable share of the returns from the foods they produce?

The possibility of tipping points in the climate or social systems adds urgency to the need to transition to sustainable agriculture. Incremental steps may not be sufficient to produce dramatic change. When dramatic change becomes possible, researchers and policy makers will need to be prepared with solutions that can be implemented quickly. Public engagement at the local level, buttressed by the accumulation and presentation of evidence, can generate the democratic legitimacy to take on vested interests that hinder change.

The Role of Policy

There is already strong evidence that food systems are unsustainable. However, the need for policies that support sustainability exists in a crowded, long-established, and siloed policy space, with major food policies having evolved over decades and centuries. In addition, food and farming touch on many other issues—not just human health and environmental well-being but also employment, politics, and society. Policy makers do not always understand the issue of sustainability well, and even the term "sustainability" can be defined in different ways, which is not helpful in a policy-making context. The gaps among evidence, policies, and reality are real and challenging, even if they may be narrowing. It is likely that rapid, substantial change to current systems is required to act on many of the issues and evidence discussed at the forum. Policies today tend to be dominated not by sustainability but by productionism, which is the idea, formulated in the mid-20th century, that the world needs to produce more food to feed a growing population. Policy changes tend to be tweaks to this established system, even though the current challenges will not be met without larger changes to these structures. The Paris Agreement and the establishment of the Sustainable Development Goals (SDGs) were major accomplishments, but at a national level, environmental and health problems are proliferating and intensifying, and efforts to build the evidence base are not leading to changes in policy to the extent that the challenges warrant.

Transformation of the global food policy system will entail changes in the entire value chain from farm to fork, including production, transport, business, and governance. This will require a wide variety of policies affecting incentives, regulation, and broader governance frameworks. The individuals involved include consumers, shareholders, civil society organizations, farmers, and fishers. Businesses include manufacturers, agro-business, finance, transport, insurance, and retail. Governance occurs at all levels, from local to international. All of these actors are embedded within an environmental system that provides ecosystem services and biodiversity and is being harmed by land and freshwater degradation, resource depletion, and the emission of greenhouse gases.

Mechanisms that "lock in" particular policies and hinder change can sideline solutions (see Figure 5-1). These lock-in mechanisms can derive from knowledge constraints, economic and regulatory constraints, sociocultural constraints, and biophysical constraints.[1] An example of an economic and regulatory constraint is a set of perverse incentives where farmers are paid to farm in ways that harm the environment. An example of a biophysical constraint is a lack of pollinators caused by habitat loss and the use of pesticides. An example of a sociocultural constraint is limited collective identity to organize for change or act in ways that favor the environment.[2] Another such constraint is a belief in technofixes, like robotic pollinators or geoengineering to stop climate change. Focusing on just one or two lock-in mechanisms will leave the others intact to continue to impede change.

New applications of technology can help overcome lock-in mechanisms, but every technology has a resource footprint, which inevitably entails tradeoffs. One way to evaluate such tradeoffs is through lifecycle assessment, which is a systems-level tool that can be used to compare costs with benefits across interventions.[3] Systems-level analyses can be incorporated into policy design decisions proactively to reduce the potential for unintended consequences.

There is no silver bullet, and policy frameworks and sectors will need to plan for a future that is increasingly uncertain and ambiguous. The world is changing very quickly, and globalization is not necessarily going to continue and could unravel. Supply chains may get shorter and more regional.

[1] Oliver, T. H., E. Boyd, K. Balcombe, T. G. Benton, J. M. Bullock, D. Donovan, G. Feola, M. Heard, G. M. Mace, S. R. Mortimer, R. J. Nunes, R. F. Pywell, and D. Zaum. 2018. Overcoming undesirable resilience in the global food system. *Global Sustainability* 1(e9):1–9.

[2] Oliver, T. *The Self Delusion: The Surprising Science of How We Are Connected and Why That Matters*. New York: Hachette.

[3] Pourzahedi, L., M. Pandorf, D. Ravikumar, J. B. Zimmerman, T. P. Seager, T. L. Theis, P. Westerhoff, L. M. Gilbertson, and G. V. Lowry. 2018. Life cycle considerations of nano-enabled agrochemicals: Are today's tools up to the task? *Environmental Science: Nano* 5:1057–1069.

Farms could become smaller and more diverse. Systems will continue to evolve in ways that are at least partly unforeseeable. However, these systems can be shaped to ensure that they are prepared and flexible enough to cope with surprises.

		'Lock-in' mechanisms pertaining to:-		
		INDIVIDUALS	BUSINESS	GOVERNMENT
	e.g. Fig. 2 mechanism code:	1-5, 10-21	1-5, 8-12, 15-21	1, 4, 6-8, 11, 15-21
Solutions instigated by:-	INDIVIDUALS	Knowledge-exchange on best practice; information provision to inform consumer choice; change social norms around consumer choices, food waste, recycling and farming/fishing practices; promote collective identity and social responsibility; follow best practice to restore pollinators and natural enemies; implement responsible use of water, soil and natural resources	Highlight good and poor business practice; use shareholder influence and invest in sustainable initiatives; exercise consumer choice for food that is sustainably produced, manufactured and transported	Communicate sustainability concerns; debunk infeasible techno-fixes; develop and engage with civil society movements and demands; vote on sustainability credentials
	BUSINESS	Improve information on sustainability of supply chains for foods; develop innovative insurance products and financing approaches; choice editing to promote sustainable food choices; invest and innovate sustainable products and services; facilitate new crop and livestock varieties for food producers;	Knowledge-exchange on best practice; demonstrate feasibility of positive change; develop innovative insurance products and financing approaches; debunk infeasible techno-fixes; innovative water management through public-private partnerships; develop innovations in sustainable practice	Provide reports on sustainable initiatives; co-develop innovative insurance products and financing approaches; innovative water management through public-private partnerships; facilitate new crop and livestock varieties and guidelines and regulation for sustainable food production
	GOVERNMENT	Education regarding sustainable practices; information and skill provision; stimulate and protect sustainable innovations; incentivise sustainable practices and regulate/tax others; reform land tenure governance; consult and act on social contract to protect future generations; change social norms around consumer choices, food waste, recycling and farming/fishing practices; debunk infeasible techno-fixes; improve incentives, regulation and enforcement on natural resource use	Information and skills provision; stimulate and protect sustainable innovations; incentivise sustainable practices and regulate/tax others; limit power of vested interests; debunk infeasible techno-fixes; incentivise practices which restore essential biodiversity; regulate and enforce sustainable natural resource use	Monitor and raise profile of social and environmental impacts; inter-governmental alignment on food system policy; debunk infeasible techno-fixes; take responsibility on social equity and intergenerational justice; implement biodiversity targets; quantify and reduce environmental impacts from imports; cooperate internationally on pests and disease

FIGURE 5-1 Targeted leverage points can tackle lock-in mechanisms that block change.

NOTE: yellow = knowledge; blue = economic/regulatory; red = sociocultural; green = biophysical.

SOURCE: Oliver, T. H., E. Boyd, K. Balcombe, T. G. Benton, J. M. Bullock, D. Donovan, G. Feola, M. Heard, G. M. Mace, S. R. Mortimer, R. J. Nunes, R. F. Pywell, and D. Zaum. 2018. Overcoming undesirable resilience in the global food system. *Global Sustainability* 1(e9):1–9. See Figure 3 on p. 4. http://creativecommons.org/licenses/by/4.0.

Levers for Change

A wide range of policy levers exists to overcome barriers, including incentives, regulation, and the establishment of new business and policy frameworks. Agricultural subsidies could support rather than detract from sustainability—for example, moving toward rewarding positive environmental outcomes. End users could gain equitable access to appropriate innovations. Agricultural strategies could be shaped by sustainability as much as by production and efficiency—for example, moving away from the monoculture and industrial agriculture that is the current norm. A new concept of yield could be based on sustainability and quality metrics rather than simply the amount of output. This would entail a broader balancing of goals, where agriculture and the broader food system are judged on overall performance rather than individual outputs. Such strategies will need to be formulated through involvement of all stakeholders, including farmers.

Meeting the needs of the future will require both incremental and transformational change. For example, the large amount of food that is lost along food supply chains points to the need for steady and continuous improvement, as does the need to move away from traditional methods in livestock production. At the same time, substantially lowering greenhouse gas emissions from agriculture will require that current production systems be re-engineered to reduce their reliance on tillage, fertilizers, and heavy machinery powered by fossil fuels. Agronomic techniques such as intercropping, integrated pest management, the use of trees in agriculture, and irrigation water management can all yield both incremental and large-scale change.[4] Field-scale solutions are already available but are greatly underused.

An example of the potential for policies to support sustainability involves the need to restore, protect, and judiciously manage soil. Sustainable soil management requires replacing what has been removed from the soil, restoring and maintaining soil health, recycling nutrients, and predicting what will happen to soil because of anthropogenic and natural perturbations. One approach to soil management would be to supplement legislation directed toward clean water and air with similar legislation designed to foster soil health. Farmers and land managers could be empowered to restore degraded soils, increase the organic carbon stored in soil, and save soil and water for nature conservancy. As part of a Healthy Soil Act, good soil management could be rewarded as one component of a farm payment system.[5]

If food security is defined as the availability of a balanced and nutritious diet, shaping the demand for food becomes a major policy objective. Small-scale changes can shift behaviors in healthy directions, such as providing larger numbers of vegetarian options on menus and training chefs so that they can cook high-quality vegetarian food. Technologies and modern communications can help sway demand toward better choices, particularly through the deployment of modern advertising techniques.

People choose foods for different reasons, meaning that different people will respond to different incentives and nudges. People can also be educated to recognize the environmental and health benefits of changing their diets, which requires continuing research into how to shape messages that reach people and cause them to change their behaviors. Other policy mechanisms include food labeling, education and training of food producers, and bans against the import of unsustainable products.

Forces outside of the global food system can exert powerful effects. An example is the potential for infectious diseases to spread between humans and animals, such as the viruses that cause coronavirus diseases. In the case of zoonotic diseases, less intensive farming systems and buffer zones may be needed to prevent infectious agents from moving from wildlife into livestock or human populations.

[4] Pretty, J., T. G. Benton, Z. P. Bharucha, L. V. Dicks, C. Butler Flora, H. C. J. Godfray, D. Goulson, S. Hartley, N. Lampkin, C. Morris, G. Pierzynski, P. V. Vara Prasad, J. Reganold, J. Rockström, P. Smith, P. Thorne, and S. Wratten. 2018. Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability* 1:441–446.

[5] Royal Society. 2020. *Soil Structure and Its Benefits: An Evidence Synthesis.* London, UK: Royal Society.

The Influences of Price and Trade

Prices and trade are prominent factors in food system policies. For example, unless every country agrees to implement a carbon tax, other countries could undercut one nation's policies by making products that are unsustainably carbon intensive and sell them abroad. Equalizing prices would require implementing border tariffs to put an extra cost on products that are not being sustainably made.

Trade will need to be a prominent part of discussions among countries if it is to contribute to sustainable agriculture rather than detract from it. For example, many of the foods imported into northern countries are from climate vulnerable countries, raising questions about the reliability of supply chains. Eating sustainably from more local sources in places like the United Kingdom would mean eating more local foods like cabbages, root vegetables, and legumes and fewer exotic foods imported from abroad.

More generally, price is a major influence on what people choose to eat. A critical policy consideration is therefore how to include externalities related to the environment and to human health in the price of foods. Carbon or resource taxes are possible fiscal policies, based on the concept of the polluter pays. Because food systems, and especially livestock production, are carbon intensive, they would be among the first systems to respond and adapt to a carbon pricing mechanism. The revenues generated by these price changes could then be used for health promotion programs and in programs to increase food security.

A restructuring of agricultural subsidies could also help food systems transition to sustainability. According to one effort to model agricultural subsidy reform, removing all agricultural subsidies could be economically and environmentally beneficial but could negatively impact population health, mostly because of a reduction in fruit and vegetable consumption.[6] Coupling subsidies to the production of more nutritious crops could improve population health and reduce greenhouse gas emissions, but it also could have negative economic impact by reducing the overall efficiency of the agricultural sector. According to this analysis, restructuring of subsidies across countries—for example, according to their share of global population or global gross domestic product—could simultaneously result in health benefits, avoid economic losses, and reduce greenhouse gas emissions. The overall conclusion is that agricultural subsidy reform could contribute to needed food system transformation, especially for increasing the consumption of fruits and vegetables, though less so for reducing the consumption of animal-source foods.

Currently, subsidies in many countries are more likely to support ecosystem disservices than ecosystem services. If farmers could be paid for storing carbon, reducing floods, controlling pollution, and so on—without simply exporting agricultural production to other countries—subsidies could support health and sustainability rather than detracting from those goals. For example, the United Kingdom is currently planning to move toward a system where subsidies will be used to promote climate benefits, ecosystem health, and other public benefits rather than simply food production.

[6] Freund, F., and M. Springmann, 2019. *Impacts of Agricultural Subsidy Reform on Economic Welfare, Environment and Health*. Presented at the 22nd Annual Conference on Global Economic Analysis, Warsaw, Poland.

Research Needs

Researchers will continue to investigate the food system and sustainability and how best to implement new knowledge in policy. Specific research gaps identified at the forum include the following:

- Supply chains, the economics of distribution systems, and the need to minimize waste are all pressing research and policy issues.
- Research into synergies among carbon sequestration, biodiversity conservation, and sustainable agriculture can guide policy actions. A spatial analysis of synergies and conflicts in land use could help order policy priorities, as would land use plans and maps for conservation, forest management, and agriculture at a national scale.
- Research and development could identify, analyze, and evaluate policy levers for change. This research will need to be multidisciplinary, coordinated, and international, with data and computing science skills as a particular priority.
- Applications of biotechnology, implementation of integrated pest management, and better understanding of the soil microbiome could enhance crop performance and the storage of carbon in soils.

A gap between fundamental research and practical application is not currently being filled by either the public or private sectors. This gap often involves questions that are informed by the social sciences, such as land use issues, but this kind of research can fall through the cracks of policy agendas. An example is how best to integrate the manufactured foods of the future with more conventional agriculture, which will require the consideration of such goals as soil quality, net zero or negative emissions, biodiversity, and healthy diets.

In the future, the global food system could head in quite different directions. One possibility is that environmental degradation, increased inequity and injustice, exclusive reliance on global distribution networks, and homogenization of energy-dense diets will destabilize food systems. In this scenario, research might focus on commodity crops, biofortification, ultra-processed foods, long supply chains, and robotics. The result would be a food system marked by low diversity, continued high levels of waste, reliance on external inputs, inequities, and a lack of agency.[7]

An alternate future is for the global food system to become more equitable and just, more respectful of cultural and gender issues, more biodiverse through agroecological management, less wasteful, and more food secure. The research agenda could then focus on more varied diets to provide nutrients, more varied farming systems, smaller-scale farming, systemic efficiency, low waste, whole foods, less processed foods, and short supply chains. Researchers could investigate the integration of data and systems, the consequences of agricultural practices, soil health and soil–water interactions, the food system as a whole (including dependencies, touch points, immediate opportunities),

[7] Schipanski, M. E., G. K. MacDonald, S. Rosenzweig, M. Jahi Chappell, E. M. Bennett, R. Bezner Kerr, J. Blesh, T. Crews, L. Drinkwater, J. G. Lundgren, and C. Schnarr. 2016. Realizing resilient food systems. *BioScience* 66(7):600–610.

and the interaction of the food system with other sectors. They could work in closer partnerships with farmers, who will be the people responsible for implementing new techniques and approaches.

At some point, if humans are to continue to thrive on the planet, agriculture will need to transition from being sustainable to being regenerative, where the soil, crops, and livestock; the environment; and human health are restored rather than simply sustained. Animals will be part of many regenerative systems, requiring that the genetics and efficiency of animal production be studied. Other important research topics will include advanced genetics and breeding techniques, controlled agricultural environments such as urban agriculture, and enhancing productivity on fallow, marginal, and degraded land.

Coordination and Oversight

Many individuals and organizations in the private, public, and nonprofit sectors are working on sustainability issues, and their efforts could be enhanced through greater coordination and cooperation on precompetitive questions and issues. The components of food supply chains, and especially retailers, could work more directly with other parts of the food system, including farmers and consumers. Public–private partnerships can be especially effective in formulating and enacting policies for voluntary systems designed to achieve such goals as healthy diets. Individuals, businesses, or governments can all instigate interventions, but doing so in an optimal way requires coordination among the sectors involved in food systems, as well as coordination among countries.

Despite the importance of agriculture to the human future, agricultural research and development represent only a small percentage of total government research and development funding. However, private funding has increased in recent years, which has helped create new funding models and opportunities. In particular, public–private partnerships are a way to support innovative science addressing today’s food and agriculture challenges, because neither sector acting on its own can be expected to bear this entire burden. For example, in the United States the Foundation for Food & Agriculture Research is an organization that was founded to bring together public–private partnerships to shape agricultural research and production, and it has catalyzed several major initiatives focused on nutrition, food security, and sustainability. One is a partnership that connects scientists, farmers, and ranchers, beginning with coordinated precompetitive research to create customized solutions for individual farms and ranches that can then be deployed, first in the United States and then globally, in an environmentally and economically sustainable manner.

Coordination within sectors is also critical. For example, many government agencies and ministries are involved in these issues, and coordination among those agencies is often poor, just as coordination among academic disciplines is often lacking. People with different backgrounds will need to interact to learn about new possibilities and problems. In addition, coordination across borders will be essential to meet the long-term needs of humanity. An international organization could pull together people with a broad range of backgrounds and interests to provide much needed guidance and advice.

Healthy and sustainable food systems are essential to meet many of the SDGs established by the United Nations. (Indeed, a case can be made that such systems are essential to meeting all of the SDGs.) An international initiative could be established to make explicit the connections between agriculture and other human needs. An important part of such an initiative would be to create a range of positive visions for the future. For example, what would the world look like if all of the targets of the SDGs were achieved? A positive vision could inspire young people, who are being told that many of the things previous generations took for granted, such as travel, a wide variety of inexpensive foods, and good health, may no longer be guaranteed. Science could contribute to positive visions of the future by supporting and guiding both short-term and long-term actions.

Researchers could work more actively with governments to shape the outcomes of deliberative processes. As an example, science has influenced climate change policy through the Intergovernmental Panel on Climate Change (IPCC). Perhaps an Intergovernmental Panel on Sustainable Agriculture connected to the United Nations Framework Convention on Sustainable Agriculture could have a comparable influence. Collaboration between the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and the IPCC could also have beneficial effects. A wider range of countries, researchers, and issues could be involved by working with the InterAcademy Partnership. If messages about sustainability from the research community were clear and actionable, then those messages would be more likely to drive policy change.

Sustainable agriculture will be characterized by healthy ecosystems and healthy diets that ensure resilience to climate change, economic security, social inclusion, and human well-being. A clear, long-term strategy for what needs to be achieved would provide policy actors and food systems with both direction and coherence. Such a strategy would need to be based on both evidence and values, which will require dialogue among the public, people involved in food systems, policy makers, and researchers.

The health of people and the environment is indivisible over the long term—a concept that some have termed One Health. Research and policy initiatives that encourage convergent work on the challenges of food, health, and ecosystems would reflect this underlying linkage. A coalition of national and international organizations, perhaps through an ongoing forum on sustainable agriculture, could promote both the research that is needed and the translation of this research into evidence-based policies.

"Ultimately, we need to change the zeitgeist of our relationship with nature and bring its value central to decision making. To help achieve this, we, as natural scientists, must go outside our comfort zones and forge more 'radical collaborations' with social scientists, economists, engineers, and policy makers—with all the end users of our research. Only by doing that will we be able to ensure our deep knowledge about the workings of the natural world and inform the process by which high-level pledges for nature get translated into action."

—**Nathalie Seddon,** University of Oxford

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