# Dædalus

Journal of the American Academy of Arts & Sciences

Fall 2015

## The Future of Food, Health & the Environment of a Full Earth

*Inside front cover:* A composite image illustrating healthy and Earth-friendly food "moons" orbiting our planet. A wealth of research has shown that a diet high in vegetables and fruits, nuts and seeds, whole grains, and fish can offer many health benefits when compared to diets characterized by demand for grain-fed beef and other animal-based products. Moreover, such a diet largely supports a sustainable global agriculture. Food photographs used to create the satellites © Eric Cerretani and David Tilman. "Blue Marble: Next Generation" (2002) Earth image courtesy of NASA Goddard Space Flight Center. Image by Reto Stöckli and Robert Simmon. Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group; USGS EROS Data Center; USGS Terrestrial Remote Sensing Flagstaff Field Center; Defense Meteorological Satellite Program.

*Dædalus* is designed by Alvin Eisenman.

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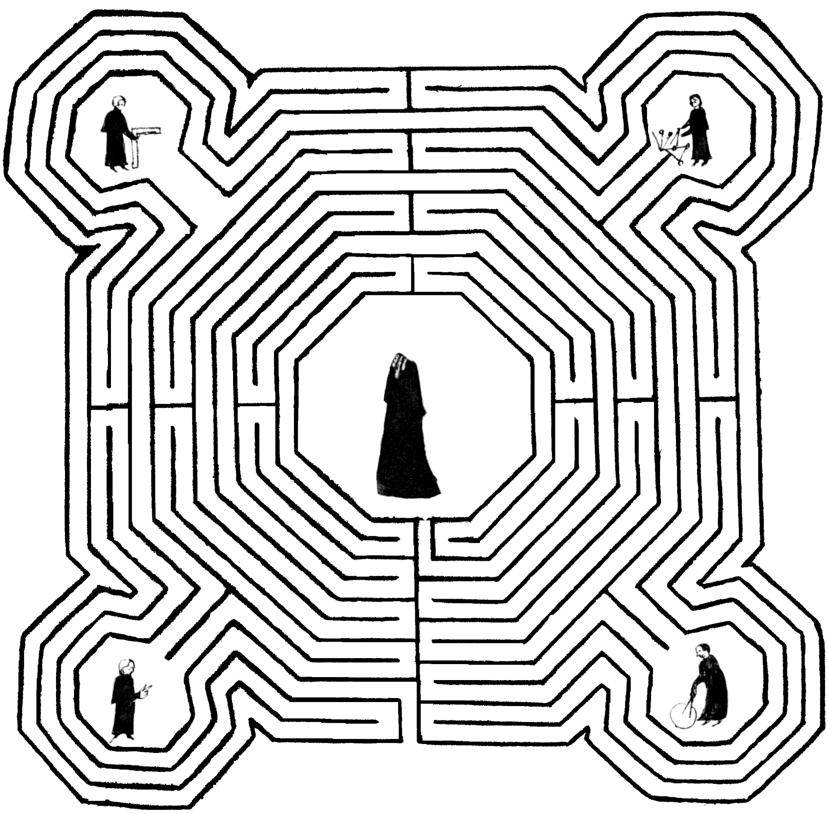

The pavement labyrinth once in the nave of Reims Cathedral (1240), in a drawing, with figures of the architects, by Jacques Cellier (c. 1550 – 1620)

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The American Academy of Arts & Sciences, like its journal, brings together distinguished individuals from every field of human endeavor. It was chartered in 1780 as a forum "to cultivate every art and science which may tend to advance the interest, honour, dignity, and happiness of a free, independent, and virtuous people." Now in its third century, the Academy, with its nearly five thousand elected members, continues to provide intellectual leadership to meet the critical challenges facing our world.

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# Food & Health of a Full Earth

*David Tilman*

DAVID TILMAN, a Fellow of the American Academy since 1995, is Regents Professor and McKnight Presidential Chair in the College of Biological Sciences and Director of the Cedar Creek Ecosystem Science Reserve at the University of Minnesota. He is also a Professor at the Bren School of Environmental Science and Management at the University of California, Santa Barbara. He is the author of *Functional Consequences of Biodiversity: Empirical Progress and Theoretical Extensions* (with Ann P. Kinzig and Stephen Pacala, 2002), *Plant Strategies and the Dynamics and Structure of Plant Communities* (1988), *Resource Competition and Community Structure* (1982), and more than two hundred scientific papers.

The world is about to be full. Within two or three generations, our global population – currently seven billion people – will level off between ten billion and eleven billion. Although humanity steadily increased in size as it spread from Africa across the habitable lands of Earth, it was not until the 1920s that this growth turned explosive. In 1850, the global population was 1.1 billion people, on a trajectory to double every one hundred fifty years. This low growth rate held until World War I, after which the emergence of modern medicine and sanitation led to increasingly rapid annual growth rates. When this rate hit its peak in 1970, the global population was on course to double every thirty-five years. Now, our population growth rate – though still positive – is steadily slowing as we approach our maximum Earth density.

What will life be like on a full Earth? Can we provide eleven billion people with a secure supply of nutritious foods? Is it even possible for so many people to live on Earth without destroying its remaining natural ecosystems? Agriculture already accounts for more than 25 percent of global greenhouse gas emissions and occupies 55 percent of Earth's ice- and desert-free land area. Can we feed up to eleven billion people and still maintain a livable climate? Will the ethics, customs, rights, and laws established when the world had one billion or fewer people adequately guide a world that is ten times more populous? Or will new ethical principles be needed to live sustainably in this new context?


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The answers to these and related questions must also consider a second major way we fill Earth: our consumption. Many, but by no means all, of the less-developed nations of the world have rapidly growing economies. Based on current growth trajectories, citizens in developing nations are likely to gain three to five times more buying power within the next forty years. This is a continuation of a trend that began in earnest in the early 1900s: from 1900 to 2000, the buying power of the typical person on Earth increased 360 percent, while the global population increased 270 percent. What might the totality of global consumption look like in 2050?

Consider the World Bank forecasts of the global economy and the United Nations projections of the global population. Per capita inflation-adjusted incomes are on a trajectory to increase 140 percent from 2000 to 2050, while the global population should increase 50 percent. The cumulative effect of these global increases is a 260 percent increase in consumer buying power between 2000 and 2050. Urbanization also accompanies economic growth: in 1960, slightly less than one billion people lived in cities. By 2013, more than 3.5 billion people were urban. By the time that the great human expansion reaches its limit, the vast majority of the peoples of the world will be living in large cities and have incomes associated with middle-class lifestyles.

Because incomes determine how much an individual can consume, the full environmental impact of nine billion people in 2050, or ten to eleven billion by the end of the century, will be much greater than is suggested by the increase in population alone. Moreover, greater consumption does not necessarily lead to better lives. This is especially true for food. The world's two billion overweight or obese people would likely be harmed, rather than benefit, from increased caloric consumption. Indeed, increasing global incomes and urbanization are strongly associated with dietary and lifestyle shifts that degrade health. However, the world's eight hundred million malnourished people would greatly benefit from increased incomes and better diets.

The future of humanity, including our ability to live on Earth in ways that would allow future generations to enjoy a quality of life at least as high as ours, will depend on the decisions we make in the coming decades. These decisions will impact our diets, our health, and the abilities of managed and natural ecosystems to supply us with vital services, and will also determine how many other species will share the planet with us. Some of these decisions will be pragmatic; others will be ethical. The world faces many unavoidable tradeoffs. Actions that provide a net benefit or profit to one individual, such as a farmer applying more fertilizer to cropland to increase yields, may come at a cost to the environment and to the health of others. On a full Earth, the actions of any one person are likely to impact the well-being of someone else; just as the actions of any one nation may impact all other nations.

The essays in this issue of *Dædalus* address issues related to agriculture, diets, health, and the environment, as well as the ethics and value systems needed to assure equity and well-being within each generation and across all future generations. Our essays begin with a broad overview of the current environmental impacts of agriculture, how growth in incomes and population will influence the future of the environment, and how these environmental impacts may be avoided. In doing so, my essay with coauthor Michael Clark also briefly touches on many of the themes developed in depth in the rest of this volume.

Catherine Bertini highlights the central role that women play as the primary providers of food in most of the world, as well as their need for equity and voice if, especially in the developing world, women are to be empowered to solve malnutrition, children's health, and other major problems related to food, diet, and agriculture. The essay by Jaquelyn Jahn, Meir Stampfer, and Walter Willett is an informative and insightful synthesis of decades of research on nutrition and health, addressing such global problems as undernutrition, obesity, and diet-dependent metabolic imbalances that lead to noncommunicable diseases such as diabetes and heart disease.

The next three essays all address agriculture, its sustainability, and the environment from different vantage points. Nathaniel Mueller and Seth Binder open the discussion with quantitative analysis of the increases in global food supplies that could be attained by intensifying agriculture in developing nations. Their analysis highlights the social, political, and economic barriers that have kept crop yields so low in these nations, and suggests how these might be overcome. Next, Andrew Balmford, Rhys Green, and Ben Phalan question if such intensification indeed is the best way to meet food demand and preserve nature, or if conservation of endangered wildlife would be better achieved via low-intensity agriculture. G. Philip Robertson concludes this trio by discussing if agriculture could be made sustainable and still feed a full Earth. He does so in the context of the ethical assertion that sustainability requires current agricultural practices not to limit the ability of future generations to provide themselves with diets and a quality of life at least as good as exists now.

Our volume ends with Brian Henning's essay on the ethics of food, biofuels, and animal feed. His perspective as an ethicist adds a depth and nuance to all of the preceding contributions. Who, he asks, should have the greater right to consume the global food supply: people (who directly consume 60 percent of all crops), livestock (which consume 35 percent) or automobiles (which consume 5 percent)? Are livestock and cars more worthy of food than the eight hundred million undernourished people of Earth?

# Food, Agriculture & the Environment: Can We Feed the World & Save the Earth?

*David Tilman & Michael Clark*

*Abstract: Secure and nutritious food supplies are the foundation of human health and development, and of stable societies. Yet food production also poses significant threats to the environment through greenhouse gas emissions, pollution from fertilizers and pesticides, and the loss of biodiversity and ecosystem services from the conversion of vast amounts of natural ecosystems into croplands and pastures. Global agricultural production is on a trajectory to double by 2050 because of both increases in the global population and the dietary changes associated with growing incomes. Here we examine the environmental problems that would result from these dietary shifts toward greater meat and calorie consumption and from the increase in agricultural production needed to provide this food. Several solutions, all of which are possible with current knowledge and technology, could substantially reduce agriculture's environmental impacts on greenhouse gas emissions, land clearing, and threats to biodiversity. In particular, the adoption of healthier diets and investment in increasing crop yields in developing nations would greatly reduce the environmental impacts of agriculture, lead to greater global health, and provide a path toward a secure and nutritious food supply for developing nations.*

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*(*See endnotes for complete contributor biographies.)*

The importance of food is undeniable. Stable societies require adequate and predictable supplies of food.[1] Modern industrial societies require that most of their members have differentiated and specialized skills, which is only possible when high-yielding crops allow a few people to feed the many. Societies also depend on a multitude of services provided by ecosystems, including the production of pure drinking water, the decomposition of wastes, the creation of fertile soils, the removal and storage of much of the greenhouse gasses released by society, the amelioration of flooding provided by intact ecosystems, and the support of a multitude of other species that provide food, crop pollination, timber, fiber, medicines, and the functioning of Earth's ecosystems.[2]

Agriculture – as currently practiced – poses major threats to the environment. Agriculture and food production are responsible for more than 25 percent of total global greenhouse gas (GHG) emissions to


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the atmosphere. Each year, global agriculture is responsible for the application of fertilizer possessing more nitrogen and phosphorus than is supplied by the natural processes of all terrestrial ecosystems.[3] In many cases, crops do not take up the majority of these nutrients; rather, they leach out of farmed fields and pollute aquifers, lakes, and rivers in a process called *eutrophication*.[4] When these excess nutrients enter the ocean, they can create low-oxygen "dead zones" that devastate local aquatic ecosystems and the fisheries on which we rely.[5] Agricultural nutrients can also be transported through the atmosphere and deposited on terrestrial ecosystems, where they can reduce biodiversity and harm the functioning of these ecosystems. Many agricultural herbicides, insecticides, and fungicides are long-lived and enter terrestrial and aquatic ecosystems where they can negatively impact ecological and human health.[6]

An equally great environmental impact of agriculture comes from the immense amount of Earth's land area devoted to agriculture. Earth has approximately nine billion hectares of ice-free, nondesert land generally suitable for human life. Global croplands and pasturelands already occupy five billion hectares.[7] Habitat destruction and fragmentation resulting from the conversion of native ecosystems into croplands and pasturelands is a major reason why so many plant and animal species are now threatened with extinction. The loss of Earth's biodiversity is irreversible, forever foreclosing on societies' ability to benefit from any future value that this "natural capital" might have provided.[8] In addition, many of the simplified low-diversity agroecosystems created by farming are less able to provide society with valued ecosystem services.[9] Finally, habitat destruction and fragmentation by agriculture can harm nearby natural ecosystems by causing them to lose biodiversity.[10]

A secure supply of nutritious food and a livable environment are of central importance to humanity, but are increasingly in conflict.[11] Because global demand for food and animal feed is expected to approximately double in the coming forty to fifty years, the environmental harm caused by agriculture expansion in the coming decades could be considerable.[12] In this essay, we 1) analyze the drivers behind what might be a doubling of global food demand during the next half century; 2) review the environmental impacts associated with the last doubling of global food; 3) project the potential environmental impacts of the anticipated doubling of food; and 4) propose several potential solutions that could plausibly allow us to greatly reduce harm to the global environment while feeding a world of eleven billion people.



The twentieth century introduced an era of unprecedented human population growth, primarily resulting from falling mortality rates associated with advances in sanitation and medicine.[13] The global population doubled from 1900 to 1957, and doubled again by 1995, only thirty-eight years later. The UN forecasts that the global population will increase from 7.3 billion people in 2015 to 9.6 billion people by 2050, and then peak at about 10.9 billion people by 2100.[14] At this point, from a human perspective, we will have reached a "full Earth." If agricultural practices were to stay the same and per capita food demand did not increase, population expansion alone would increase demand for agricultural production by 30 percent by 2050 and 50 percent by 2100.

Per capita incomes, which are rising around the world, are a strong driver of human dietary choices.[15] The net effect of income on diet is that demand for agricultural crops is increasing at a much faster rate than global population. Indeed, a recent analysis forecasts that global food demand in 2050 will be double that of 2005, with income-driven dietary shifts responsible for about 70 percent of this increase and the growing global population responsible for the remaining 30 percent.[16]

There are two major ways in which increases in income affects diets. First, as incomes increase, people tend to consume more animal products like meat, dairy, and eggs (Figure 1).[17] Second, diets also shift toward increased caloric consumption, and in particular toward more sugars, oils, fats, and alcohols, which are commonly referred to as "empty calories."

For a typical citizen of one of the fifteen richest nations, daily food demand – measured as food that enters the household per person – is about 3,500 calories.[18] Up to 25 percent of this food is wasted after it reaches the household. About 20 percent of daily calories consumed in these wealthy nations come from meat, milk, and eggs; 38 percent of daily calories are from empty calories; and the rest come from other plant-based foods. In comparison, the average person's daily food demand in the twenty or so poorest economies is about 2,000 calories, much less of which is wasted, with only 3 percent of the total coming from meat, milk, and eggs, and 12 percent from empty calories. One effect of this income-dependent disparity in caloric demand and consumption is that 2.1 billion people are overweight or obese globally because of excess consumption while, at the same time, another eight hundred million of the world's poorest people suffer from malnutrition or undernourishment related to a lack of access to adequate and appropriate food.[19]

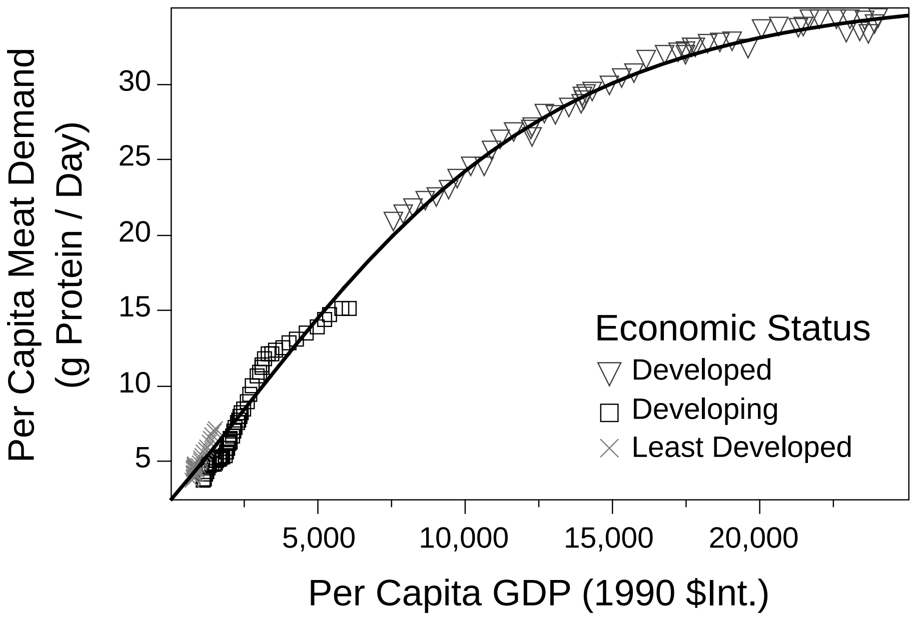
The shift toward greater per capita consumption of animal products has a major impact on societal demand for agricultural crops. In richer nations, about 8,000 calories per day of agricultural crop production are required to provide the 3,500 calories of food brought into the household by the average person.[20] The 4,500 calorie difference between the caloric content of the crops that must be grown and the caloric content of food brought into the household mainly represents the calories fed to the animals used to produce animal-based foods.

The reason that increased demand for meat, milk, and eggs results in large increases in agricultural production is directly related to the inefficiency with which various animals convert feed crops into edible animal-based foods. For example, for cattle to create one kilogram of edible beef protein they must eat twenty kilograms of plant protein, for a ratio of 1:20. The ratio is 1:5.7 for pork; 1:4.7 for poultry; 1:4.4 to 1:4.8 for aquaculture production of halibut, salmon, cod, and arctic char; 1:3.9 for milk; and 1:2.6 for eggs.[21] In total, more than half of all agricultural crop production and land use in richer nations feeds livestock, rather than producing crops for direct human consumption.[22] Animal production is not only calorie-intensive, but is also land-intensive: approximately 80 percent of global agricultural land is used to graze livestock and a significant portion of cropland is for animal feeds.[23]

In summary, the major reason why a world with about 30 percent more people in 2050 would demand about 100 percent more production of agricultural crops is because of the feed necessary to meet increased demand for animal-based foods resulting from the rising incomes of billions of people in the developing world.[24] Increased demand for empty calories directly consumed by people, often in the form of sugars, fats, oils, and alcohols, also contributes to this demand, though to a lesser extent.

These dietary shifts also have major implications for human health. The global trend toward consuming more total calories, more empty calories, and more meats and dairy is called the *global nutrition tran-*

*Figure 1*
The Dependence of Meat Consumption on Income




Results for the one hundred most populous nations of the world are based on averages calculated by grouping nations by their economic status (developed, developing, least developed). The average for each group is shown for each year from 1961 – 2007. Figure is based on analyses of data from Food and Agriculture Organization of the United Nations. See David Tilman, Christian Balzer, Jason Hill, and Belinda L. Befort, "Global Food Demand and the Sustainable Intensification of Agriculture," *Proceedings of the National Academy of Sciences* 108 (50) (2011): 20260 – 20264; and David Tilman and Michael Clark, "Global Diets Link Environmental Sustainability and Human Health," *Nature* 515 (2014): 518 – 522.

*sition*.[25] Driven by increases in income and urbanization, the global nutrition transition results in increased rates of obesity, diabetes, heart disease, and other diet-related chronic noncommunicable diseases in both developing and developed countries.[26] For instance, as China industrialized from 1980 to 2008, the incidence of diabetes increased from less than 1 percent of its population to more than 10 percent, and is still increasing.[27] Even when viewed at a global level, the increased incidences of noncommunicable diseases are large. For instance, the age-adjusted global incidence of diabetes increased 45 percent from 1990 to 2013.[28] The incidences of all noncommunicable diseases are increasing so rapidly that such diet and lifestyle-dependent diseases are projected to become the major burden of disease for the world by 2030.[29]

The "green revolution" began when the agronomist Norman Borlaug bred new strains of wheat capable of much greater yields (defined as crop production per unit of area) than local varieties if provided with fertilizer and, if needed, water. Yield increases in wheat were followed by work that led to similar increases in rice production. When this technology was adopted rapidly, as it was for wheat production by both Pakistan and India between 1965 and 1970, yields almost doubled. On the global scale, production of cereal grains doubled from 1960 to 1995 mainly because of green-revolution technologies (but also because of land being cleared to create new cropland), even though such technologies had not been adopted by most African nations. This rapid increase in the global food supply helped meet the demands of a rapidly growing global population, thus averting what had been anticipated to be global episodes of mass starvation.[30] The benefits of the green revolution were immense; but to illuminate the potential impacts driven by the anticipated doubling of global crop production over the next forty to fifty years, it is necessary to consider some of the green revolution's harmful impacts on human health and the environment.

Use of nitrogen fertilizer, phosphorus fertilizer, and irrigated water increased greatly during the green revolution. From 1960 to 1995, the annual global application of nitrogen fertilizer on agricultural land increased from ten million to seventy million metric tons. Phosphorus fertilization tripled and irrigation doubled.[31] The doubling of food production thus increased nitrogen application seven-fold, tripled phosphorus application, and doubled irrigation. The global use of these inputs has continued to increase: more than one hundred million metric tons of nitrogen fertilizer were applied in 2010, a rate comparable to all natural inputs of biologically available nitrogen into ecosystems.[32]

Because of agriculture, humans are now the dominant force controlling the terrestrial dynamics of the global nitrogen and phosphorus cycles.[33] Although crops capture about half of these fertilizers, the nitrogen and phosphorus not incorporated into plants can be carried by erosion or leach into aquifers, rivers, and lakes, or enter the atmosphere. The net effect is nutrient pollution of terrestrial and aquatic ecosystems. In lakes, these agricultural pollutants can, in extreme cases, ruin freshwater fisheries and cause blooms of blue-green algal species that can make the water toxic for livestock and human drinking.[34] Where large rivers drain agricultural runoff into oceans, these nutrients create massive blooms of algae and subsequent oxygen-free dead zones where fish cannot survive.[35] Moreover, irrigation of croplands accounts for about 75 percent of humanity's consumptive use of freshwater.[36] Some of the world's larger rivers have so much water removed for human use that there are years when the rivers no longer flow into their receiving oceans. In the United States, for example, the Colorado River reached the Sea of Cortez just once in the last sixteen years (in 2014).

Global use of herbicides, insecticides, and other pesticides expanded equally dramatically during the green revolution. Applications of these chemicals increased six-fold over a span of thirty-five years, from about one-half million metric tons per year in 1960 to more than three million metric tons per year by 1995.[37] Some localized pesticides are redistributed globally, both in water supplies and in the atmosphere, causing health impacts in humans, fish, birds, and mammals.

The green-revolution doubling of global food production required the clearing of one hundred fifty million hectares of cropland, which is about the size of Alaska. At the same time, about three hundred million hectares of pastureland were cleared, which is one-third the area of the United States.[38] This conversion of forests, savannas, and grasslands to agriculture destroyed high-diversity native ecosystems and replaced them with frequently disturbed systems planted with one or a few crop or pasture species. Such habitat destruction is a major threat to global biodiversity, with the risk of extinctions escalating as more land is cleared.[39]

What we eat may have a greater impact on greenhouse gas emissions than what form of transportation we use. On a global scale, agriculture accounts for more than 25 percent of total greenhouse gas emissions.[40] In contrast, all forms of transportation, including automobiles, airplanes, trains, trucks, and ships, account for only 14 percent of global emissions.[41] In terms of warming potential, expressed as the number of gigatonnes (billion tonnes) of carbon released as carbon dioxide, total agricultural emissions were about four gigatonnes in 2010, while transportation emissions were about two gigatonnes.[42]

What are the major sources of agricultural greenhouse gas emissions? The three greatest sources are methane (1.7 gigatonnes per year), nitrous oxide (1.6 gigatonnes per year), and land clearing (0.9 gigatonnes per year). Methane emissions are largely from livestock production, especially cattle and sheep. Nitrous oxide emissions mainly result from nitrogen fertilization. Land clearing releases carbon dioxide to the atmosphere when vegetation is burned or decomposed and when soil organic matter is decomposed when tilled. Additional, but smaller, emissions come from agricultural combustion of fossil fuels.

Foods differ greatly in their greenhouse gas emissions, whether these are measured per calorie, per gram of protein, or per serving.[43] Plant-based foods generally have the lowest emissions, followed by eggs, then nontrawled marine fish, then poultry, pork, dairy, and aquaculture, then trawled fish, and finally ruminant meats, including lamb, goat, and beef (Figure 2).

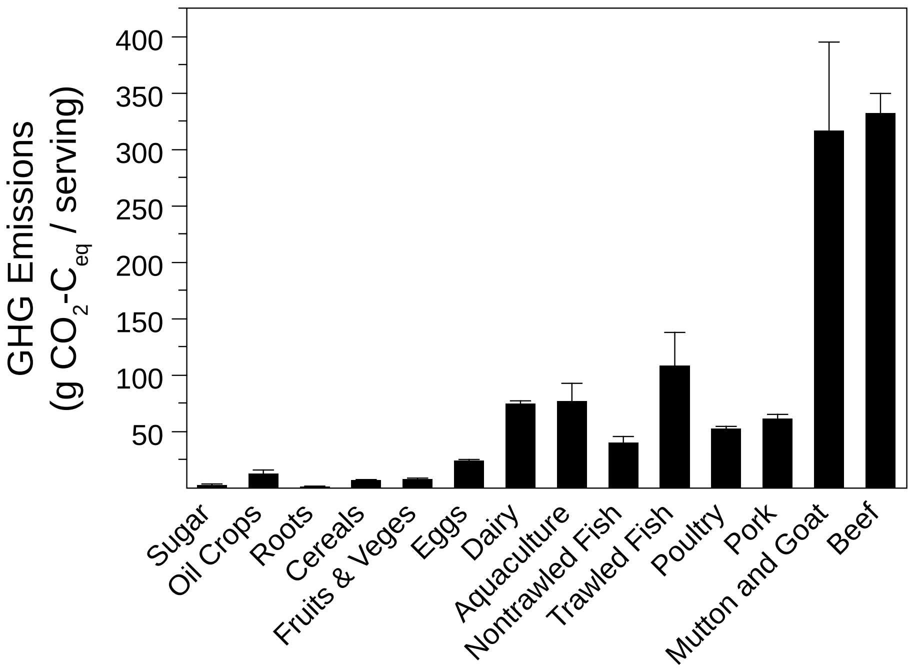
Contrary to popular perception, fossil fuel emissions associated with food transportation are a minor component of total agricultural greenhouse gas emissions.[44] Rather, agricultural emissions are overwhelmingly from beef and lamb production, nitrogen fertilization, and land clearing.[45] Minimizing beef and lamb consumption, eating moderate amounts of other meats and low-fat animal products, eating crops grown with moderate fertilization, and minimizing food waste are effective ways for individuals to decrease their dietary greenhouse gas emissions.



The environmental impacts of the green revolution suggest that a second doubling of global crop production might cause substantial increases in global land clearing, fertilizer use, pesticide use, and greenhouse gas emissions.[46] Analyses based on past trends, relationships, and methods and practices estimated that a 170 percent increase in nitrogen fertilization, a 140 percent increase in phosphorus fertilization, a 190 percent increase in irrigation, and a 170 percent increase in pesticide use might be required to double global food production by 2050.[47] Because these greater inputs are associated with increased yields, only a 23 percent increase in cropland and a 16 percent increase in pastureland were forecast.[48]

Doubling global crop production is also predicted to increase global agricultural greenhouse gas emissions by an amount equal to current emissions from all forms of transportation combined.[49] These increased emissions would come from methane emissions from increased production of cattle, sheep, and rice; nitrous oxide emissions from increased nitrogen fertilizer application; and increases in agricultural fossil fuel combustion. If global agriculture were to continue on its current trajectory, we have estimated that global agricultural greenhouse gas emissions from food production in 2050 would be about six gigatonnes per year: a 50 percent increase from current levels.[50]

*Figure* 2
Lifecycle Greenhouse Gas Emissions per USDA-Defined Serving Associated with the Production of Various Types of Crops or Animal/Livestock-Based Foods




Source: Figure uses results of hundreds of lifecycle analyses, as summarized by David Tilman and Michael Clark, "Global Diets Link Environmental Sustainability and Human Health," *Nature* 515 (2014): 518–522.

Although global agriculture seems capable of feeding ten billion people by 2050, the resulting environmental impacts – if agriculture grew along established global trajectories – would be great.[51] Moreover, the global health impacts of the nutrition transition are also serious.[52] There are, however, several major ways to reduce the environmental impacts of agriculture while still providing a fully populated Earth with healthy and nutritious diets. These include increasing crop yields, avoiding or reversing the shift to less healthy and more environmentally harmful diets, reducing crop and food waste, and using fertilizers and irrigation water more efficiently.

Much of the world's croplands produce significantly less food than their potential. The difference between the crop yields that could be obtained on a piece of land by using current technology and management techniques and the yields that are actually obtained is called the *yield gap*.[53] Nations with lower per capita incomes tend to have larger yield gaps. For instance, much of sub-Saharan Africa has maize, wheat, and rice yields that are only 20–25 percent of what could be attained in those nations using improved technologies and practices (yield gaps of 75 percent to 80 percent).[54] These yield gaps suggest that improved agronomic methods could increase the food supplies of these nations by 300–400 percent while using only the existing croplands of these nations. One reason for these immense yield gaps is that the poorest nations currently apply less than five kilograms of nitrogen fertilizer per hectare (and similarly low amounts of other inputs), whereas the richest nations apply thirty times that amount. Similarly, of the one hundred most populous nations, the fifteen nations with incomes nearest the global median income have fertilization rates that are less than half those of the fifteen richest nations, and yields that are one-third of those of the richest nations.[55]

Some analyses suggest that increasing yields in nations with large yield gaps may cause less environmental harm from greenhouse gas emissions and habitat destruction than would the clearing of natural ecosystems to create the new cropland needed to produce this amount of food at current yields.[56] For instance, green-revolution technologies doubled global crop production while only increasing global cropland by 10 percent, thus sparing millions of hectares from clearing.[57] Because of the immense amounts of greenhouse gasses that are released when land is cleared and, for several subsequent decades, tilled, the green-revolution technologies applied to existing croplands lead to lower net greenhouse gas emissions than would result from doubling crop production by simply doubling the land area being farmed.[58]

Closing the global yield gap should be a top global priority.[59] It would increase food supply in the nations that have the most malnourished people, as well as in the nations currently experiencing the most rapid increase in food demand from population growth and dietary shifts.

A recent study found that should all nations achieve yields of 95 percent of their attainable levels (a 5 percent yield gap), no new land would be needed to meet 2050 global food demand.[60] Similarly, shrinking the yield gap by using fertilizer at rates of about 80 percent of those in the richest nations, which would decrease environmental harm from overfertilization, could increase global crop production by 70 percent.[61]

In the 1960s and 1970s, the green revolution approximately doubled the maximum achievable crop yield of several major crops through crop breeding and increased fertilizer use. The rate at which global yields subsequently increased was then mainly dependent on the rate at which green-revolution crop strains and nutrient management techniques were adopted in various nations. Post–green revolution advances in breeding and agronomic techniques have led to continual increases in crop yield maxima.[62] However, the annual yield increases of three major crops – soybeans, rice, and wheat – have consistently shrunk over the past forty years, with their average annual rate of increase for 1990 to 2007 being only 0.8 percent. Moreover, yields of some crops seem to be approaching biophysical yield ceilings.[63] Wheat yields in The Netherlands, the United Kingdom, and France, which are among the highest wheat yields in the world, have not increased over the past ten to fifteen years. Similar yield plateaus were reached for rice in Korea, Indonesia, and California about fifteen to twenty years ago. These plateaus suggest that crop yields have an upper limit. But many other crops that are important elements of diets, including roots, vegetables, fruits, nonmajor cereals, and seed and oil crops, have not undergone intensive breeding programs and likely would greatly benefit from use of new breeding and agronomic techniques.

The nutrition transition is creating a global pandemic of obesity, diabetes, and heart disease that is decreasing the quality of life and increasing mortality rates for multitudes of people around the world.[64]

As per capita caloric consumption, empty calorie consumption, and meat consumption increased, global incidences of obesity, diabetes, and heart disease also increased.[65] Researchers anticipate that global rates of diet-related diseases will continue to increase as diets shift toward increased calorie, empty calorie, and meat consumption, causing noncommunicable diseases to become the world's greatest disease burden.[66]

Just as nutrition transition diets are the cause of these health problems, so can alternative diets be their solution. A diet high in vegetables and fruits, nuts and seeds, whole grains, and fish – such as the Mediterranean diet or the DASH (Dietary Approaches to Stop Hypertension) diet[67] – can offer many health benefits when compared to the diets resulting from the global nutrition transition. Consider, for instance, the health benefits of Mediterranean and vegetarian diets. Both diets have a much greater portion of their calories and protein coming from plant, rather than animal, sources. When controlling for a number of potentially confounding factors, and when compared to persons consuming the usual omnivorous diet of a given region, people who consume a Mediterranean or vegetarian diet have between 15 – 40 percent lower incidences of diabetes and 20 – 25 percent lower mortality from coronary heart disease.[68] Pescetarian diets, which basically are vegetarian diets that include seafood in place of some of the dairy and eggs, have similar health benefits.[69]

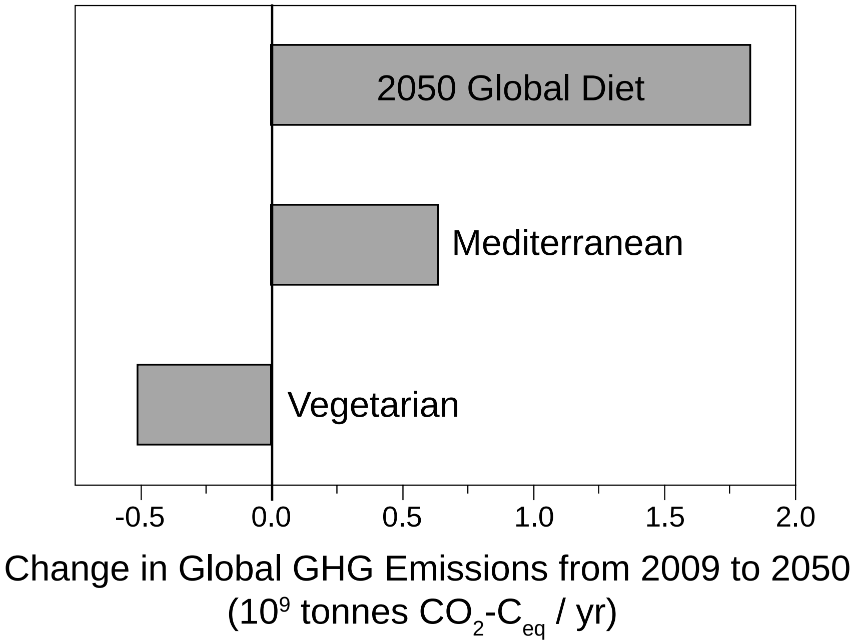
Healthier diets also provide major environmental benefits. Compared to the greenhouse gas emissions forecast to result from the nutrition transition, these alternative diets would lead to significantly lower global emissions (Figure 3) while decreasing global land clearing between now and 2050 by about five hundred million hectares.[70] The major reason for these environmental benefits is that the healthier diets involve lower consumption of empty calories and meat, and greater consumption of vegetables and fruits, thus reversing the trajectory of the nutrition transition.

Approximately one-third of global agriculture production is wasted.[71] The proportion of food waste in society tends to increase alongside its members' incomes. Further, waste tends to shift from primarily agricultural production waste toward more household food waste as incomes increase. Should all food waste be cut in half by 2050, we could reduce 2050 agricultural land use by approximately three hundred million hectares and cut greenhouse gas emissions from crop production by one-fifth.[72]

Reducing food waste in developing and developed economies is feasible. In developing economies, better crop harvesting and storage, as well as increased access to refrigeration, could reduce substantial waste.[73] In developed economies, reducing waste in retail stores and households has great promise. For instance, encouraging the use of abnormally shaped or slightly blemished produce, as is done by the French supermarket Intermarché, or incentivizing sales of foods about to reach "stale dates" can reduce waste, as could selling foods in smaller portion sizes.

Numerous studies have shown that yields can be maintained, or even improved, via more efficient use of fertilizers, irrigation, and pesticides.[74] This was demonstrated in the European Union in the 1990s upon adoption of regulations designed to increase water quality by reducing excess application of nitrogen fertilizers. Since then, crop yields in several large EU nations have continued to increase along their established temporal trajectories, but use of nitrogen fertilizer has decreased by 20 – 30 percent. These outcomes (and other studies) suggest that the environmentally detrimental impacts of agricultural fertilization can be significantly decreased without imposing a cost to crop yields.[75]

*Figure* 3
How Healthier Diets would Impact Future Changes in Greenhouse Gas Emissions from Agricultural Production




Using 2009 production emissions from global agriculture as the baseline (setting 2009 values to zero), emissions from the global diet that may be generated by the nutrition transition (2050 Global Diet) are compared to those if diets shifted to be either a Mediterranean or vegetarian diet. Source : Figure prepared by the authors.

Eating local or organic foods is another idea for limiting the negative environmental and health consequences of agriculture. Local and organic foods are likely to be fresher, better tasting, and biased toward vegetables and fruits. As such, they could encourage adoption of healthier diets. The greenhouse gas emissions from organic and local systems are, in general, no lower than those from conventional systems. However, if adoption of local or organic foods led to lower consumption of meat and empty calories, it could offer both health benefits and reduced greenhouse gas emissions. The extent of any such reduction, though, might be somewhat tempered by the lower yields of some organic crops.[76]

Increasing the proportion of agricultural production consumed by humans would have positive impacts on food security and the environment. Globally, about 60 percent of grain production is used as human food, 35 percent as animal feed, and 5 percent as biofuels.[77] Greater direct consumption of plant-based foods, preferential consumption of low feed-input animal-based foods such as eggs, milk, and poultry meat, and elimination of food-based biofuels would allow current crop production to feed approximately an additional one billion people without increasing agricultural land requirements, and would reduce agricultural greenhouse gas emissions.[78]

Agricultural trade among nations can also be environmentally beneficial. Because of climatic and soil conditions, different nations are better suited to produce different combinations of crops, thereby giving them a comparative advantage in their production. Trade among nations based on such comparative advantages can allow nations to produce the crops for which they have the highest relative yields and trade them internationally to meet their needs for other crops. The net effect of such trade is to increase global yields and thus decrease the amount of land and inputs needed to meet global food demand.

If the anticipated doubling in global crop production were achieved by following the agricultural trajectories of the past forty years, it would impose major environmental harm through global greenhouse gas emissions, excessive fertilizer use in developed nations, and land clearing in developing nations. Moreover, the dietary transition now underway is causing a global pandemic of noncommunicable diseases.[79] The same dietary changes that would prevent this epidemic would also prevent much environmental harm.

Food is essential for life; people will do whatever they can to obtain it. Neither nature reserves nor their fences and guards will do anything more than shift the land being cleared from one location to another. Increasing yields by shrinking or closing yield gaps could, on current cropland, meet 70 percent or more of the food demand anticipated by 2050.[80] It could save global biodiversity by reducing the need for land clearing. Indeed, it is hard to imagine any other means by which biodiversity could be saved except by decreasing the need to destroy ecosystems to grow food. Most important, the peoples of developing nations deserve adequate and nutritious diets and the health that such diets bring. They deserve secure food supply systems that can help assure stable governments and increase access to educational and economic opportunities.[81] The single most important action for meeting all of these goals is to invest in increasing yields in developing nations.

## ENDNOTES

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# Invisible Women

*Catherine Bertini*

*Abstract: Women are ubiquitous and critical to the nutritional well-being of their families, yet they are often invisible to policy-makers, public officials, community leaders, and researchers. Effecting significant decreases in the number of hungry poor people, as well as the improvement of nutritional and economic outcomes, requires policy in addition to operational and research priorities that are directed at the needs of women and girls.*

Food is grown to be consumed: by livestock, fish, even vehicles. But of course, the primary consumer of food is humankind. And the primary providers of food as meals – in virtually all of the developing world and much of the developed world – are women. As I remarked in my plenary address to the Fourth World Conference on Women in September 1995 in Beijing, China:

> Women eat last. In almost every society in the world, women gather the food, prepare the food, serve the food. Yet most of the time, women eat last. A woman feeds her husband, then her children, and finally – with whatever is left – she feeds herself. Even pregnant women and breast feeding women often eat last when, of all times, they should eat first.[1]

Should you be tempted to assume such practices are no longer the norm, consider the findings outlined in the Institute for Developmental Studies' 2014 BRIDGE report *Gender and Food Security: Towards Gender-Just Food and Nutrition Security*: "Even during pregnancy, 'special care is not always taken to ensure women receive enough food.'"[2]

Twenty years after the Fourth World Conference on Women, it is not just the household pecking order for food consumption that is a concern, but also the invisibility of women when it comes to policy-making at every level: from the household, to the community, to the private sector, to research, to local, regional, and national governments.

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Women are the key human ingredient to adequate diets for families. As such, their voices should be sought after, listened to, and acted upon.

Adequate nutrition depends on a well-balanced diet. For those who can afford almost no food – the 795 million people who, according to the Food and Agriculture Organization (FAO) of the United Nations, are chronically undernourished – the struggle to obtain any food is a daily challenge.[3] For the rest of the world, including the very poor, eating the "right" balance of foods is key. In fact, the word *malnutrition* has taken on an expanded meaning. Its use no longer connotes only those who have too little to eat, but also those who consume too much or lack dietary balance. In other words, an obese person is also "malnourished."

Obesity is growing in virtually every region in the world. It has fast become a major source of the world's most widespread diseases, commonly called noncommunicable diseases (NCDs), including high blood pressure, diabetes, heart disease, asthma, liver disease, and sleep disorders. NCDs are now the leading cause of human death in the world.[4]

There are now almost as many people worldwide who are obese (600 million) as are chronically undernourished (795 million).[5] It won't be many years until those numbers intersect; obesity rates are dramatically rising while undernourishment rates are gradually decreasing, even as the global population increases. Some of the most dramatic growth in obesity rates is among children under five years of age. For instance, between 2000 and 2013, the prevalence of overweight in children under five in Southern Africa rose from 1 to 19 percent.[6]

The Chicago Council on Global Affairs report *Healthy Food for a Healthy World: Leveraging Agriculture and Food to Improve Global Nutrition* predicts that the decline in global productivity due to illness and death from these chronic diseases will reach $35 trillion by 2030.[7] The report also points out that adults who were undernourished as children earn 20 percent less in income than those who were not.[8]

Malnutrition is costly in other ways, too: 4–9 percent of most countries' GDP is spent on medical costs related to overweight or obesity.[9]

There are many reasons behind these trends, including increased consumption of overly processed foods that add sugars and salts in place of nutrients, overconsumption of food generally, and lack of dietary variety (most commonly manifested as too few fruits and vegetables and too much starch). Some of these factors stem from poverty. In order to maximize the amount of food she has available to feed her family, a poor mother might buy cheaper foods that are higher in starch: potatoes, rice, and flour-based breads. In the United States, cheaper foods may also mean large bottles of sugary drinks. It seldom means more fruits and vegetables.

Fruits and vegetables are not only more expensive than processed foods, they are also less readily available to consumers. Their perishability causes huge shifts in availability and cost in countries where refrigeration technology is minimal. For a few weeks, the market is swamped with a certain vegetable or fruit, causing the price to drop; later, availability is scarce and the price is high. In the United States, the Supplemental Nutrition Assistance Program (SNAP; formerly known as food stamps) allocation is distributed once monthly for all recipients, leaving smaller stores no reason to stock perishables past the predictable once-monthly period of major food purchases.

Back to the pregnant woman: while culture and society, not to mention household priorities, should ensure that she has enough of the right foods to eat, she still too often does not. Developed countries like the United States are taking action to address this discrepancy: for example, the United States created the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC) in 1974, under the Nixon administration, to support the nutritional needs of poor pregnant mothers and their infants and toddlers through distribution of specific foods and nutrition education. It is commonly considered the most effective national nutrition program.

During my term at the United States Department of Agriculture (USDA) in the early 1990s, we created a special food package for breastfeeding mothers in the WIC program. After all, until then the government encouraged women to breastfeed but only gave poor women infant formula. UNICEF's data on incidence of breastfeeding confirmed that the U.S. rates for low-income women began to increase (although still not at high enough levels) following implementation of the program. (Clayton Yeutter, then–Secretary of the USDA under President George H.W. Bush, recognized the program's importance; he cut the ribbon on the first WIC clinic in 1974.)

The World Health Organization (WHO) has concluded that "Exclusive breastfeeding – defined as the practice of only giving an infant breast milk for the first six months of life – has the single largest potential impact on child mortality of any preventive intervention."[10] A multiyear, multicountry WHO study proved that infant growth outcomes are similar whether the mother is from Norway or Ghana – from a rich or poor country – as long as the mother receives adequate nutrition herself.[11]

The most critical period in the development of a human is from her time *in utero* until age two (some experts say age five). This is the period when she grows physically and intellectually, when her cells are multiplying fastest. Without adequate nutrition during this period – which comes from her mother – she will be stunted in some way, and she can never make up the loss in later years. A person who goes hungry for months at age twenty-five or fifty can recoup losses; a one-year-old child who goes hungry for months cannot. In fact, for a child who had been stunted, significant weight gain later in life, even later in childhood, often results in obesity. The lack of physical and/or intellectual capacity caused by a lack of food and nutrition in early childhood impacts a person's economic well-being for life. And if a stunted young woman becomes pregnant while she still has an inadequate diet, she will give birth to a child who, if he survives, will be stunted himself. Thus, malnutrition perpetuates the cycle of poverty.

The recent International Food Policy Research Institute (IFPRI) report *Women's Empowerment and Nutrition* tells us that nearly half (43 percent) of the decreases in children underweight between 1970 and 1995 have been due to the empowerment of women, as measured through improvements in women's education.[12] For example, the Helen Keller International Program in Burkina Faso found that educating women in farming households via women extension agents led to increased dietary diversity and decreased wasting, anemia, and diarrhea among the women and their children.

The nutrition-based cycle of poverty is most prevalent in rural areas of the developing world. Urban poverty is a growing scourge in many parts of the world, but the poorest and hungriest people are still those whose major source of income is cultivating food. They may be subsistence farmers or they may work for extremely low wages on other farms. A high percentage of these farmers are women. The FAO estimates that women make up 43 percent of all agriculture laborers in developing countries, including at least 50 percent in sub-Saharan

Africa.[13] This figure undercounts the millions who work for no pay as part of their household and familial responsibilities.

Women's and men's agricultural jobs vary in different communities, different climates, and different regions. Often, men are responsible for the large cash crops like tobacco, maize, and wheat. Women may weed or help plant these crops, but they may also be primarily responsible for indigenous crops like cassava or millet. In livestock, men care for the larger animals; women typically manage milking and care for smaller animals.

And in almost all cultures in which women and men work in agriculture, the man's workday starts and finishes in the field. But the woman's job starts when the babies cry and need food before dawn, when the cow needs to be milked, when breakfast is cooked, when the children are dressed to go to school, and it continues after a full day in the field when she fetches water and firewood and food for the evening meal, and cooks the meal, milks the cow, and tends to her children and husband.

Yet women and men do not have the same access to agricultural inputs – to seeds and fertilizer, land, and extension services. The FAO estimates that if they did, women's agricultural production would increase 10 – 20 percent.[14] The CGIAR (Consultative Group for International Agricultural Research) Research Program on Water, Land and Ecosystems notes, in *Water-Smart Agriculture in East Africa*, that "increasing the resources that women control has been shown to improve the nutritional, health, and educational outcomes of their children."[15]

The IFPRI, who is without peer in its research and writing about gender and agriculture, has argued that educated farmers are more productive than noneducated farmers; women are illiterate at higher rates than men; and women are more likely to follow the successful farming practices of other women than those of men. Yet the agricultural advice offered by most countries' extension workers are offered by men to men.

Once a farm becomes slightly more successful, it might mechanize a function. This mechanized function then often shifts to the male purview, even if it was earlier considered a "female" role.

Muhammad Yunus, founder of the microfinance organization Grameen Bank, which launched in Bangladesh and now operates in many countries around the world, has spoken openly about differences in resource use across genders. The IFPRI and other experts have validated Yunus's findings that resources that enter a household and are controlled by women are highly likely to be spent on the needs of the household and all of its members. Men, by contrast, are more likely to use finances under their control for nonhousehold related matters.[16]

Stunningly, an extra $10 in the hands of a woman will add the same nutritional benefit for the household as an additional $110 given to a man.[17]

So far in this paper, women are everywhere. The adequate nutrition of mothers is essential to ensuring that their children are well-nourished and growing. From predawn to past sundown, their lives are critical to the functioning of the household and to obtaining and allocating resources to support it. Yet when policy-makers or grantmakers look at community needs, the dearth of women in leadership or spokesperson roles prevents them from learning what is really required to best support the community.

So feedback comes from men, and it predictably centers on what the men need. When I was Executive Director of the United Nations World Food Programme, I once visited an area in rural Angola where the fields had recently been demined following a truce in the civil war. The farmers told us that they could not work in the fields because they did not have any implements. "What do you need?" we asked; "Hoes," they answered. There were perhaps one hundred hoes – implements with long poles and rectangular metal spades – stacked up against a fence. "What is wrong with these?" I asked. "They are male hoes," they answered.

Did you know that in Angola, hoes are gender differentiated? I did not, and clearly the well-meaning NGO who ordered the hoes did not either. Why? The NGO had not talked to the women. In that region of Angola, women were the only people who tilled the fields, but they did not use the long-poled hoes. Women's hoes, it turned out, had shorter wooden handles and shovel-like spades at the end. Unlike the "male" hoes that were used from a standing position, women had to squat to use the "female" hoe, a preferred technique because women worked most of the day with babies strapped to their backs, and squatting put less stress on the back than leaning over, weighed down by a child.

For me, this story became a metaphor for the importance of always speaking with the people who know what their needs are, and that those who do not specifically seek out women in order to understand their needs may waste their entire contribution to the good they seek to accomplish.

It also reminds me that women are generally not in community leadership roles and are too often politically invisible. In fact, it may be their "job" not to speak up; anyway, they are busy in the home and the fields all day and night. While women are the font of life for the family, they are not first call for community knowledge, though they should be.

For women to be seen and heard, and for societies to benefit from their knowledge, skills, and perspectives, we must:

- *Educate girls*. The latest data from the United Nations Millennium Development Goal (MDG) project show that the goal of universal primary education has mostly been met.[18] But those data measure "enrollment" and not attendance, participation, progress, or the quality of education received. The data also show that the biggest gender gap comes in the transition from primary to secondary school. Further, there are still less girls than boys in schools. Yet when girls are educated, they have fewer children than their uneducated sisters, maternal mortality declines, their children see better nutritional and general health outcomes (and are also more likely to attend school), the women are more productive farmers, and their economic opportunities and lifelong earnings increase.
- *Start research with women's needs*. The most wonderful new seed, capable of growing drought- and pest-resistant crops at volumes multiple times greater than in the past, could be useless if the taste and cooking time are not palatable to the lives of the cooks: the women. Include them in the process.
- *Enhance women's health support*. A mother's health is directly related to that of her children. Health care centers, research, and education all can make her stronger.
- *Support breastfeeding*. One model of support is that employed by the American advocacy group 1000 Days. They promote the idea that the days between conception and a child's second birthday are the most critical days in a human's life. Another effort is the UNICEF/WHO Baby-Friendly Hospital Initiative (BFHI), a twenty-four-year-old campaign to make every hospital "baby friendly" so that women giving birth receive the information and support they need to exclusively breastfeed their infants.

- *Improve women's literacy*. Even if more girls are in school now, most of their mothers were not schooled. Training girls to teach their mothers how to read and count is a viable contribution.
- *Create agricultural extension programs* that both include women and reach women.
- *Expand microbanking* loans and insurance to more poor women, who have been shown to dedicate resources to their household more effectively than men.
- *Create legal rights for women to own and inherit land*, and promote those rights so women know what is available to them.
- *Consider societal gender roles in all development thinking*. The established roles of women and men in a given community or arena of society are critical considerations in development work. Talk to both the women and the men, and design programs to reach the stated objective in a manner that is sensitive to distinct gender norms and needs.

**Visible women can change the world.**

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# Food, Health & the Environment: A Global Grand Challenge & Some Solutions

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*Abstract: The dual burden of obesity and undernutrition is a significant public health challenge worldwide, especially in the context of a changing climate. This essay presents the most recent nutritional evidence for the optimal diet for long-term health, and offers some commentary on how production of these foods affects the environment. Current dietary research supports a diet rich in fruits and vegetables; nuts, legumes, fish, and some poultry as protein sources; unsaturated fats replacing saturated fats; whole grains replacing refined grain products; dairy foods in low to modest amounts; and minimal amounts of red meat and added sugar. This healthy dietary pattern also supports sustainable agriculture and environmental preservation.*

Public health efforts worldwide have traditionally focused on alleviating undernutrition – inadequate calories and protein for optimal growth and development – but obesity has simultaneously risen as a major contributor to morbidity and mortality worldwide. Urbanization and globalization have enabled the widespread availability of foods of low nutritional quality and, compounded by declining physical activity, these result in positive energy balance and weight gain. For example, in Mexico, the prevalence of obesity has been steadily rising since the 1980s, and about 70 percent of the Mexican population is now overweight or obese.[1] Concurrently, undernutrition remains a significant challenge in many low- and middle-income countries, where the double burden of overnutrition and undernutrition is particularly severe among low-socioeconomic strata in rural areas. Total caloric intake is often adequate, but the diet quality is declining: consumption of saturated and trans fats, sugar, and refined wheat or other grains have increased, while people are eating fewer legumes and whole-grain cereals. Despite the dramatic increase in knowledge regarding the impact of diet on human health over the past several decades, the prevalence of diabetes and other noncommunicable diseases is increasing worldwide, in-

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dicating serious metabolic imbalance. In this essay, we discuss the major macronutrients (protein, fat, and carbohydrates), provide brief comments on micronutrients (vitamins), and offer some tentative conclusions on the optimal diet for long-term health and the environment.

Average protein consumption in the United States substantially exceeds bodily requirements, and adequate intake can be maintained on a wide range of diets.[2] The specific sources of dietary protein are more important for health than the total protein intake.

In affluent countries, red meat (beef, pork, and lamb) and especially processed red meat consumption is strongly associated with an increased risk of diabetes, total mortality, cancer mortality, and cardiovascular disease mortality.[3] A recent meta-analysis that included 719,361 individuals found a 29 percent increased risk of all-cause mortality associated with total red meat consumption.[4]

Accumulating evidence suggests that eating red and processed meat is significantly associated with incident stroke and stroke mortality,[5] as well as with an increased risk of type 2 diabetes.[6] We found that increasing red meat by more than one-half serving per day was associated with a 48 percent elevated risk of diabetes in the subsequent four-year period, whereas reductions in red meat intake by more than one-half serving per day was associated with a 14 percent lower risk of diabetes over the same period.[7] Reducing red meat intake will likely decrease the incidence of cardiovascular disease, stroke, diabetes, colon cancer, and possibly premenopausal breast cancer. Components other than fat, such as heat-induced carcinogens or iron, may be responsible for some of the adverse effects of red meat consumption.

Notably, these analyses on red meat intake were conducted in Western populations, but meat consumption varies substantially across the globe. By contrast, in a pooled analysis of Asian cohort studies, red meat consumption did not appear to increase the risk of all-cause or cancer mortality.[8] This discrepancy may be explained in part by the fact that Asian populations eat much less meat. In 2007, average meat consumption in the United States was 122.8 kilograms per year (kg/y), whereas consumption in China, Japan, and South Korea ranged from 46.1 to 55.9 kg/y. As noted by the authors of that analysis, the discrepancy could be attributed to meat recently being more readily available to East Asians of higher socioeconomic status, who also have better overall health, and thus, the current levels of red meat intake do not reflect long-term intakes.

Even though eating red meat has been shown to adversely affect long-term health, meat can be useful for nutrient deficient populations in which diets otherwise consist mainly of starchy staples because it is rich in protein, iron, zinc, vitamin B12, and other nutrients. Growing children especially require a positive protein balance, and animal proteins can help fill important nutritional gaps; but red meat is not the best choice. As meat consumption rises around the world, it will become increasingly important to understand the relationship between red meat consumption and mortality and chronic disease rates, which are also rising rapidly in most of these populations.

In the United States, a key distinction is between unprocessed and processed red meat. Processed meats – such as cold cuts, sausages, and bacon – contain four-fold higher levels of sodium and 50 percent higher nonsalt preservatives, including nitrate, nitrites, and nitrosamines, which are important to the biologic mechanisms of coronary heart disease (CHD), stroke, and diabetes. Processed meats simply have no place in a healthy diet.

While low consumption of red meat appears to be desirable for long-term health, poultry fat is relatively unsaturated compared to red meat. Eggs are an efficiently produced protein source and contain many vitamins. Despite public statements to the contrary, recent research has shown that moderate egg consumption does not increase the risk of heart disease, except in diabetics.

Fish is another healthful protein source and is linked with lower risk of cardiovascular disease (CVD) mortality, stroke, and total mortality. One comprehensive analysis estimated that eating about two grams per week of omega-3 fatty acids in fish, equal to about one or two servings of fatty fish per week, reduces the chances of dying from heart disease by more than one-third. Conversely, excess mercury exposure in fish can be dangerous, especially for pregnant women because of the risk of fetal developmental impairments. King mackerel, shark, swordfish, and tilefish are reported to have the highest levels of mercury and should be avoided by pregnant and lactating women. However, eating more than two servings of fish per week or taking fish oil supplements during pregnancy is beneficial for child cognitive performance.[9]

Nuts are nutrient-dense and contain unsaturated fatty acids, fiber, vitamins, minerals, antioxidants, and phytosterols. Observational and intervention studies have demonstrated beneficial effects of nut consumption on biologic mediators of chronic disease such as oxidative stress, inflammation, visceral adiposity, hyperglycemia, and insulin resistance. The PREDIMED trial of the Mediterranean dietary pattern has also demonstrated significantly reduced mortality among those randomly assigned to eat three or more servings of nuts per week.[10] Nuts reduce the risk of CHD and type 2 diabetes, likely because they are high in unsaturated fatty acids, though perhaps due to other nutritional components as well. In our prospective cohorts, we found that those who eat nuts frequently had a 20 percent lower death rate compared with those who did not eat nuts.[11] These findings are supported by similar results from several other studies. Moreover, despite being a calorie-dense food, nut consumption strongly induces satiety and is associated with reduced weight gain, waist circumference, and lower risk of obesity in observational studies and clinical trials.

Legumes are high in bioactive compounds such as soluble-fiber, vitamin E, folic acid, selenium, and phytoestrogens, though their effect on chronic disease is relatively understudied. In controlled feeding studies, legumes have been shown to lower low-density lipoprotein (LDL) cholesterol concentrations and blood pressure.[12] In a large cross-sectional study, eating legumes more than four times per week was associated with a 22 percent lower risk of CHD.[13] Legumes may also be linked to a lower risk of colon cancer, perhaps by substituting for red meat, and may help prevent diabetes and metabolic syndrome by improving glycemic control. Phytoestrogens in soy foods have a similar function to endogenous estrogens, and may protect against hormone-related cancers. In the Shanghai Women's Health Study, soy food consumption during childhood was strongly inversely associated with the risk of premenopausal breast cancer.[14]

A high intake of dairy products, at least three servings per day, has been widely touted for bone health and fracture prevention,[15] but the optimal calcium intake remains uncertain. However, U.S. recommendations of 1,200 milligrams per day are derived from balance studies lasting less than two weeks,[16] which likely reflect transient movements of calcium in and out of bone rather than long-term requirements. Global guidelines are lower: around 500–700 milligrams daily. Large prospective studies show that high consumption of calcium or milk is not associated with lower overall fracture incidence. The small randomized trials of calcium without vitamin D found no significant reduction in fracture risk, and there is scant evidence that it prevents cardiovascular disease.[17] High intake of calcium may even increase risk of advanced prostate cancer.[18] Overall, recommendations for high dairy intake are not supported by the evidence. Although low-fat dairy may be preferable for health, nearly all the dairy fat stripped to produce low-fat milk goes into the human food supply, often as butter or ice cream.

For individuals who are in caloric balance, any change in a macronutrient intake must be balanced by an offsetting change in intake of another macronutrient. Hence, for macronutrients, it is most useful to think in terms of substitution, rather than simply increases or decreases. A recent substitution analysis showed that replacing one serving per day of total red meat with fish, poultry, nuts, legumes, low-fat diary, or whole grains was associated with a lower risk of diabetes and total mortality.[19] Thus, the replacement of red meat with a combination of nuts, fish, poultry, and legumes as protein sources seems optimal for overall long-term health (see Figure 1).

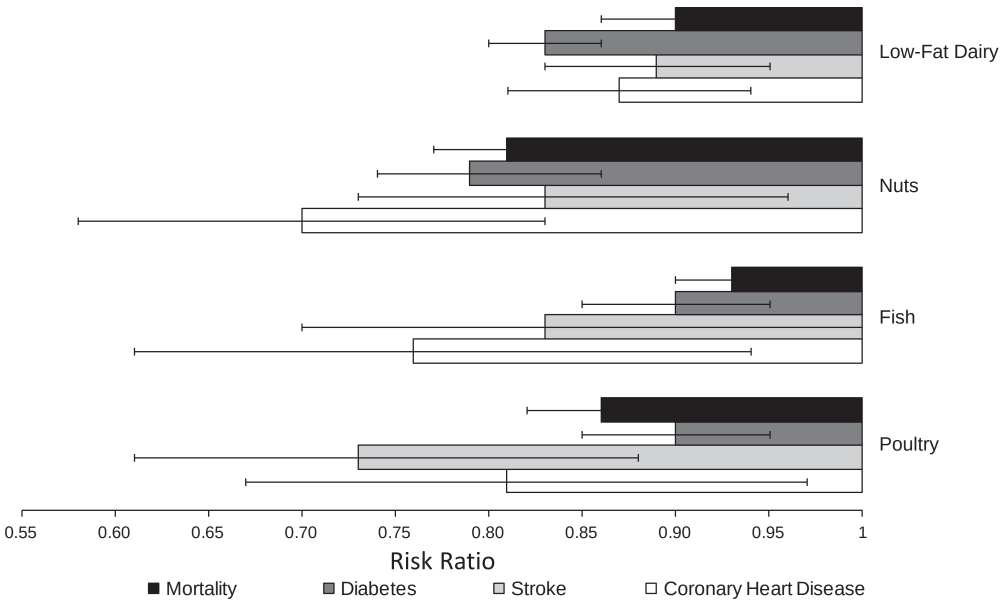
Until recently, dietary recommendations suggested reducing total fat intake to decrease coronary disease and cancer. Recommendations were based on the observation that total serum cholesterol, increased by saturated fat, predicted coronary disease risk. However, high-density lipoprotein (HDL) cholesterol is strongly protective against CHD, and the ratio of total cholesterol to HDL is a far better predictor of CHD risk than total cholesterol.[20] Indeed, substitution of carbohydrate for saturated fat, the basis of most dietary recommendations until recently, reduces beneficial HDL. In contrast, a diet that substitutes unsaturated fat for saturated fat is more beneficial because it reduces atherosclerotic LDL without affecting HDL (see Figure 2).[21] Furthermore, contrary to popular belief, data from many large prospective studies, a pooled analysis, and two large randomized trials indicate that total fat intake consumed by middle-aged women does not increase breast cancer risk.[22]

Polyunsaturated fat consumption is recommended by the American Heart Association for up to 10 percent of daily energy intake, compared with U.S. averages of approximately 3 percent in the 1950s and 6 percent at present. Omega-3 fatty acids appear to have a crucial role in the prevention of fatal arrhythmias that can complicate coronary disease. Alpha-linolenic acid is an N-3 fatty acid (mainly from plant sources) that also appears to reduce coronary disease risk and may be particularly important when fish intake is low. Furthermore, in dietary intervention trials, incidence of CHD is reduced when dietary polyunsaturated fat replaces saturated fat, but not when saturated fat is replaced with carbohydrate.

By weight, *trans*-fatty acids have the most adverse health effects of all fats. Small amounts of trans fats come from the ruminant animal products, but most trans-fatty acids in the U.S. diet are formed by the partial hydrogenation of liquid vegetable oils for margarine and vegetable shortening. In India, Dalda – a type of "vegetable ghee" – has a trans-fat level of approximately 50 percent and is a major source of domestic culinary oils. Trans fat increases LDL and decreases HDL, and is much more strongly linked to coronary disease risk than saturated fat.[23] The United States is in the process of eliminating partially hydrogenated oils from the food supply by classifying them as not "generally recognized as safe." Use of industrially produced trans fats has been banned in many jurisdictions around the world.

Palm and soybean oils are the most widely consumed oils globally. Palm oil is low

*Figure 1*
Replacing Red Meat with Low-Fat Dairy, Nuts, Fish, or Poultry Reduces Risk of Health Outcomes

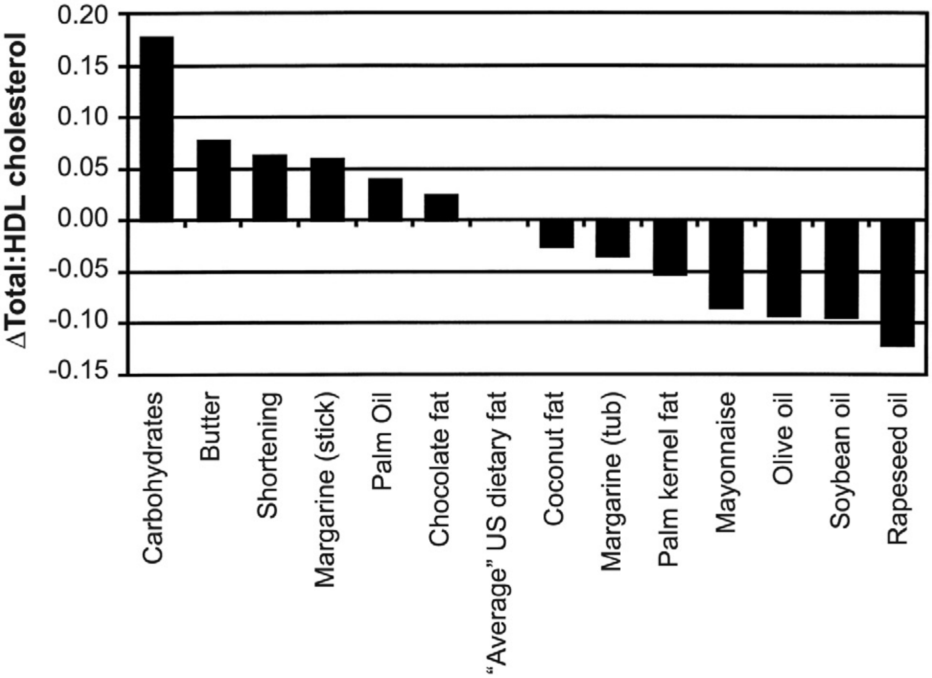



A risk ratio of less than one indicates a decreased risk. Source: An Pan, Qi Sun, Adam M. Bernstein, Matthias B. Schulze, JoAnn E. Manson, Meir J. Stampfer, Walter C. Willett, and Frank B. Hu, "Red Meat Consumption and Mortality: Results from 2 Prospective Cohort Studies," *Archives of Internal Medicine* 172 (7) (2012): 555–563, doi:10.1001/archinternmed.2011.2287; Adam M. Bernstein, Qi Sun, Frank B. Hu, Meir J. Stampfer, JoAnn E. Manson, and Walter C. Willett, "Major Dietary Protein Sources and Risk of Coronary Heart Disease in Women," *Circulation* 122 (9) (2010): 876–883; Adam M. Bernstein, An Pan, Kathryn M. Rexrode, Meir Stampfer, Frank B. Hu, Dariush Mozaffarian, and Walter C. Willett, "Dietary Protein Sources and the Risk of Stroke in Men and Women," *Stroke: A Journal of Cerebral Circulation* 43 (3) (2012): 637–644, doi:10.1161/STROKEAHA.111.633404; and An Pan, Qi Sun, Adam M. Bernstein, Matthias B. Schulze, JoAnn E. Manson, Walter C. Willett, and Frank B. Hu, "Red Meat Consumption and Risk of Type 2 Diabetes: 3 Cohorts of U.S. Adults and an Updated Meta-Analysis," *The American Journal of Clinical Nutrition* 94 (4) (2011): 1088–1096, doi:10.3945/ajcn.111.018978.

in polyunsaturated and high in saturated fat, and is consumed mostly in developing countries. Studies in humans and animals have demonstrated elevations in blood LDL cholesterol levels associated with palm oil, and in a study in Costa Rica, palm oil consumption was significantly associated with myocardial infarction compared to other oils.[24] Soybean oil, on the other hand, is rich in polyunsaturated fatty acids. The monounsaturated fatty acids and antioxidant effects of olive oil are very likely to be beneficial for CHD prevention. The PREDIMED trial found that compared with a low-fat diet, a diet high in olive oil reduced incidence of cardiovascular events[25] and was associated with better long-term cognitive performance.[26]

Because it raises triglycerides and reduces HDL cholesterol, especially in those with insulin resistance, a high-carbohydrate diet can have adverse metabolic consequences.[27] Insulin resistance is largely caused by overweight, and overweight persons are less able to tolerate a high-carbohydrate diet compared to those who are lean and active. Most Asian populations

*Figure* 2
Substituting Unsaturated Fats for Saturated Fats Improves the Total-to-HDL Cholesterol Ratio




Δ: predicted change. Source: Ronald P. Mensink, Peter L. Zock, Arnold D.M. Kester, and Martijn B. Katan, "Effects of Dietary Fatty Acids and Carbohydrates on the Ratio of Serum Total to HDL Cholesterol and on Serum Lipids and Apolipoproteins: A Meta-Analysis of 60 Controlled Trials," *The American Journal of Clinical Nutrition* 77 (5) (2003): 1146–1155. © 2003 by American Society for Nutrition.

have a higher prevalence of insulin resistance compared with European populations, which is hypothesized to be due to genetic determinants: the "thrifty gene" maintains caloric reserves in times of food scarcity.[28] Until recently, these populations were generally highly active and lean and thus protected from the adverse effects of this genetic predisposition. However, with more sedentary lifestyles and alarming increases in overweight, these populations are experiencing a massive diabetes epidemic.

Carbohydrates have traditionally been categorized by their chemical structures as either simple or complex. However, this distinction has no basis in physiology. Some forms of complex carbohydrates, such as starch in potatoes, are very rapidly metabolized to glucose. Instead, the glycemic index, which indicates the glycemic response after carbohydrate intake, is a better basis for carbohydrate characterization. Highly refined, as opposed to less-refined, carbohydrates result in a greater glycemic response and increased plasma insulin levels, which compound other adverse metabolic changes from carbohydrate consumption.

Instead of distinguishing between simple and complex carbohydrates, dietary recommendations should emphasize whole-grain and other less-refined complex carbohydrates as opposed to the highly refined products and sugar that make up such a large portion of the U.S. diet. Globally, cassava is grown for its resilience in semi-arid conditions, but when refined into flour, it has very low nutritional value and a high glycemic load. Such products are rapidly digested and absorbed, resulting in rapid swings in insulin levels; they cause further harm by displacing foods that provide fiber and micronutrients that are lost in the milling process. For example, white – but not brown – rice is associated with a higher risk of diabetes, and replacing the same amount of white rice with brown rice decreases the risk of diabetes. In general, higher intakes of refined starches and sugar, particularly with low-fiber intake, are associated with increased risk of diabetes and CHD.[29] Higher intake of fiber from grain products, in contrast, is consistently associated with lower risks of CHD and diabetes.[30] Importantly, unrefined foods can also have high glycemic loads. Potatoes, for example, are associated with increased risk of diabetes, especially among obese and sedentary people with underlying insulin resistance.

Sugar-sweetened beverages (SSBs) are particularly problematic because of their large sugar load and rapid absorption. Observational data and randomized trials have demonstrated a significant association between SSB consumption and weight gain, and when SSBs are reduced, weight loss ensues.[31] Global consumption of SSBs is rising. In Mexico, SSBs supply roughly 10 percent of total calories. In Brazil and China, per capita Coca-Cola consumption increased by 269 percent between 2000 and 2010. SSB intake in the United States declined between 2000 and 2008, but SSBs remain the largest contributor to added sugar in U.S. diets and a leading source of calories.[32] Denmark, Hungary, France, and Mexico have imposed taxes on SSBs, and though the long-term population health effects remain to be seen, one study found an inverse relationship with SSB taxation and obesity.

Substantial evidence indicates that fruit and vegetable consumption is also important for cardiovascular disease prevention.[33] High intake of vegetables reduces blood pressure; the active factors remain unclear, but potassium is a likely contributor. Higher fruit and vegetable consumption may also lower the risk of neural tube defects, the most common severe birth defect, due to higher folic acid intake.[34] Carotenoids lutein and zeaxanthin are found in green leafy vegetables and have been inversely related to the risk of cataracts and, possibly, age-related macular degeneration.[35] The flavonoids found in berries and other fruits may help prevent Parkinson disease and type 2 diabetes.[36] The benefits of fruit do not necessarily apply to juice because it contains less fiber and naturally has a high sugar content. Large quantities of juice can be consumed rapidly, which contributes to weight gain and glucose intolerance.

In contrast to its benefits in preventing other chronic diseases, overall fruit and vegetable consumption has little effect on cancer prevention after adjusting for differences in other lifestyle factors such as smoking and body mass index.[37] However, reductions in risk of renal cell and estrogen receptor-negative breast cancer have been documented,[38] and specific fruits or vegetables may be beneficial against specific cancers. For example, some evidence suggests that lycopene, mainly from tomato products, reduces risk of advanced prostate cancer.[39]

Fruits, vegetables, and other foods are often processed or preserved for availability year-round. Large amounts of salt are used in processed foods, and commercially prepared foods contribute 75 percent of the sodium in the U.S. diet. Excess consumption of salt (sodium chloride) is irrefutably linked to high blood pressure. An estimated 22 percent reduction in stroke incidence and 16 percent reduction in CHD, in addition to the prevention of fifty thousand to ninety thousand cardiovascular deaths per year in the United States, would result from reducing sodium intake by three grams per day.[40] Many studies have shown an association between the consumption of salty and pickled foods and stomach cancer. Frozen fruits and vegetables are of equal nutritional value to those that are fresh, and usually avoid the added salt of canned goods.

Any potential benefit of vitamin or mineral supplements depends on the individual's baseline levels. A full discussion of the role of vitamin supplements is beyond the scope of this essay, but briefly, some supplementation can counteract micronutrient deficiencies. In particular, a large fraction of the U.S. population and the vast majority of African Americans have insufficient vitamin D, which is a risk factor for a wide array of diseases. A daily supplement of one thousand to two thousand IU (International Units) will bring most people to an adequate level, although those with darker skin and little sun exposure likely need more. Globally, insufficient iron is also common in premenopausal women. Multivitamins can ensure adequate levels of a variety of micronutrients, but few trials of multivitamins on long-term health have been completed. The Physician's Health Study II trial showed an 8 percent reduction in total cancer incidence in a large eleven-year trial among physicians.[41] One may speculate that less-well-nourished persons could accrue greater benefits.

Whole-diet intervention studies have validated the components of a healthy diet. The landmark 4.8-year PREDIMED randomized trial in Spain demonstrated that the Mediterranean diet, supplemented with additional olive oil or nuts, substantially reduced major cardiovascular events, as compared with conventional low-fat dietary advice.[42] The Mediterranean diet includes olive oil, nuts, fruits, vegetables, moderate fish and poultry, legumes, and moderate alcohol consumption, and discourages SSBs, spreadable fats, dairy products, red and processed meats, and sweets. Our group developed the Alternative Healthy Eating Index (AHEI) based on foods and nutrients predictive of chronic disease risk, and in observational studies this pattern is associated with lower risk of cardiovascular disease, diabetes, and cancer.[43]

Obesity is a global challenge: it is a major cause of diabetes, cardiovascular disease, and some forms of cancer. In the United States, long-term weight gain is most strongly driven by consumption, often in large amounts, of foods and beverages of low nutritional quality, such as potatoes and potato chips, refined grains, SSBs, and processed and unprocessed meats, along with increased sedentary behaviors such as watching television and sitting at a computer, and declining physical activity. Obesity has a considerable environmental toll as well. Obese adults require more energy to maintain their biomass. The global additional caloric need due to overweight is the equivalent of feeding about 120 million adults. If the global population had the same age/sex BMI (body mass index) distribution as the United States, this number would rise to nearly half a billion. Obesity also increases material and transportation costs.[44]

Genetic modification (GM) of fruits, vegetables, and other foods is increasing. Supporters of GM foods laud their potential to increase food production, while others are concerned that GM foods threaten biodiversity and disrupt ecosystems. GM crops have been developed for insect and drought resistance, herbicide tolerance, and taste. Genetic modification can make plants produce beneficial nutrients and oils, as with beta-carotene rice and unsaturated fatty acids in GM soybean oil. Corn, cotton, and soybeans make up the majority of GM crops. The USDA has reported that GM crops, with lower insecticide use, generally have higher yields due to fewer pests. Yet there is concerning evidence demonstrating the evolution of insect resistance to GM corn.[45] Some argue that use of GM crops removes incentives for hybridization solutions to improve the nutritional profile of foods or to mitigate blight and drought. There is no credible evidence to indicate any direct adverse health effects from consuming GM foods.

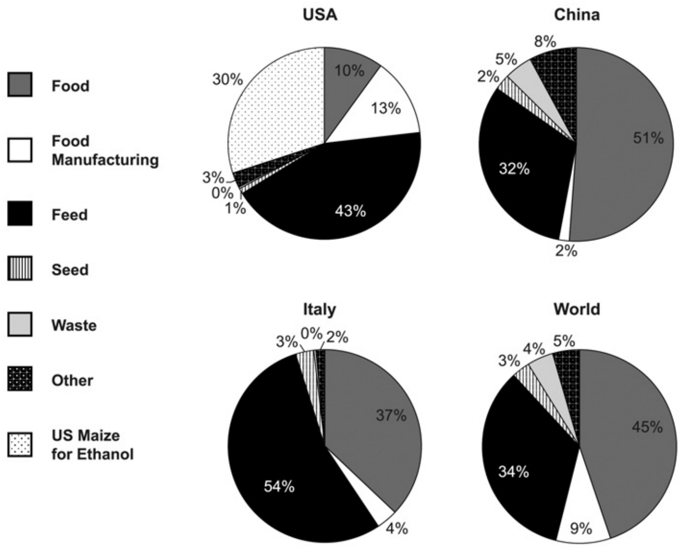
The resurgence of local food consumption has supported community economic development and helped avoid the increased carbon emissions associated with distant food transport. However, "food miles" is an imperfect metric for evaluating the carbon footprint of food transport, since the efficiency of large-scale shipping can at times offset the environmental gains of increased regional trucking. Emissions also vary by food type, with red meat having the worst impact. One study found that replacing one day per week's calories from red meat and dairy products with chicken, fish, eggs, or vegetables achieves more greenhouse gas reduction than buying all locally sourced food.[46]

In terms of environmental and public health impact, organic products may be less harmful because organic farms do not use synthetic pesticides or antibiotics. Though recent studies and EPA announcements have concluded that pesticide residue levels in conventionally produced foods are safe for consumption, the long-term health effects of many pesticides remain understudied or unknown. Even at low doses, pesticide exposure has been linked to the development of Parkinson's disease,[47] impaired child neurological development,[48] and other diseases. Growing antibiotic resistance from livestock meat and dairy production at conventional farms is another reason some consumers prefer organic foods. But rather than a simplistic dichotomy of organic/not, a more nuanced approach might be useful in determining the most effective types of fertilizers and pest-control strategies to increase production of healthful foods while minimizing adverse impacts on health and the environment. In terms of nutrient content, organic foods do not appear to be better than conventionally grown foods.[49]

Fortunately, the diets that promote human health and environmental sustainability broadly intersect. Most important, high consumption of red meat has many adverse health effects, while livestock-pasture expansion drives climate change through the release of carbon and methane into the atmosphere, depletion of water resources, and destruction of biodiversity. Further, most grain – produced with massive environmental impacts – is not used for human consumption: 34 percent of all grain globally is used as animal feed, while 30 percent of the grain produced in the United States is used for ethanol biofuels (Figure 3). Fish consumption may be an exception to the convergence of health and environmental considerations: fish has important benefits for human health, but overfishing has damaged many marine ecosystems. Thus, development and enforcement of sustainable production practices is required.

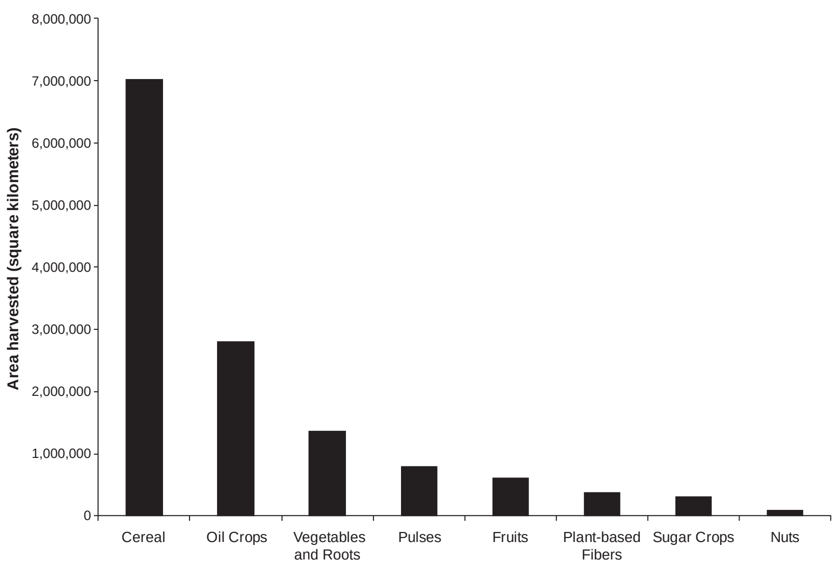
Nutritional evidence encourages major reductions in red meat and dairy intake, which would reduce the water contamination, biodiversity loss, and soil and air pollution from animal feeding operations. Livestock production uses 70 percent of the world's agricultural land and continues to expand through deforestation. The current global land-use distribution (Figure 4) favors cereals, largely used as animal feed. Multiple analyses project dramatic environmental benefits if U.S. farmland were diversified with healthy fruits and vegetables instead of the current corn- and soy-

*Figure 3*
Domestic Uses of Grain in the United States, China, Italy, and the World (Total)




Grains represented in data include wheat, rice, barley, maize, rye, oats, millet, sorghum, and other cereals. Data on maize used for ethanol were only available for the United States. China uses 19 percent of the total grain used in the world; the United States uses 15 percent; Italy uses 1 percent. Source: Food and Agriculture Organization of the United Nations, Statistics Division, FAOSTAT, "Food Balance: Food Balance Sheets," http://faostat3.fao.org/home/E.

*Figure 4*
Global Land Use in 2012 for Cereals, Oil Crops, Vegetables and Roots, Pulses, Fruits, Plant-Based Fibers, Sugar Crops, and Nuts




Source: Food and Agriculture Organization of the United Nations, Statistics Division, FAOSTAT, "Production: Crops," http://faostat3.fao.org/browse/Q/QC/E.

bean-dominated landscape. A recent report from the Union of Concerned Scientists concluded that diets high in plants and low in meat and dairy, as described in the Harvard Healthy Eating Plate, have a smaller environmental footprint than the USDA's MyPlate, which recommends red meat and high dairy intake.[50]

Current evidence for healthy eating supports elimination of trans fats from hydrogenated oils, a shift from saturated to unsaturated fats, low consumption of dairy products, and avoidance of red meat and added sugar. Nuts, legumes, fish, and some poultry should be emphasized as protein sources, grains should be in whole rather than refined form, and a variety of fruits and vegetables should be consumed daily. This healthy dietary pattern is consonant with sustainable agriculture and environmental preservation.

ENDNOTES

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# Closing Yield Gaps: Consequences for the Global Food Supply, Environmental Quality & Food Security

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*Abstract: The social, economic, and environmental costs of feeding a burgeoning and increasingly affluent human population will depend, in part, on how we increase crop production on under-yielding agricultural landscapes, and by how much. Such areas have a "yield gap" between the crop yields they achieve and the crop yields that could be achieved under more intensive management. Crop yield gaps have received increased attention in recent years due to concerns over land scarcity, stagnating crop yield trends in some important agricultural areas, and large projected increases in food demand. Recent analyses of global data sets and results from field trials have improved our understanding of where yield gaps exist and their potential contribution to increasing the food supply. Achieving yield gap closure is a complex task: while agronomic approaches to closing yield gaps are generally well-known, a variety of social, political, and economic factors allow them to persist. The degree to which closing yield gaps will lead to greater food security and environmental benefits remains unclear, and will be strongly influenced by the particular strategies adopted.*

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The grand challenge of feeding a growing global population will require a diversity of solutions if we are to simultaneously protect natural resources and enhance food security. One frequently cited strategy is to increase food production on existing agricultural lands: the continued "intensification" of agriculture.[1] Increasing productivity has the potential to augment food supply while sparing natural ecosystems from conversion to agriculture.[2] Much of the worlds' croplands have experienced growth in crop yields (production per unit area), beginning, perhaps most dramatically, with the advent of green revolution technologies during the mid-twentieth century. However, not all regions have uniformly achieved gains; in many areas, a *yield gap* persists between the crop yields that are achieved and the crop yields that are achievable using the right cultivars, inputs, and other management practices.

Because yield gaps are the end result of myriad interacting biological, physical, and economic forces,


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the conceptual simplicity of the yield gap is deceptive. Plant breeders develop new crop varieties, seeking both to increase potential yields and remain one step ahead of continuously evolving pests and diseases. Farmers operate within geographic and financial constraints, seeking to make the best decisions possible – not always maximization of yield – in the context of local policies, markets, and infrastructure.

Efforts to close yield gaps – or simply understand their existence – must engage with these complexities. In this essay, we attempt to do so. To begin, we discuss the increased scientific attention on yield gaps in recent years, and why closing yield gaps through agricultural development may be critical for the future of the global food supply. We continue by describing recent efforts to quantify yield gaps: their magnitudes, spatial distribution, and potential contributions toward meeting future food demand. We then explore from agronomic and socioeconomic perspectives how yield gaps may be "closed" and the potential consequences of these changes for food security and the global environment.

While yield gaps have been described and documented by agricultural scientists for decades, scrutiny of the topic in the agriculture-environment research community has increased in recent years due to concerns about land scarcity.[3] Cropland and pasture systems already have a massive land footprint, replacing natural ecosystems across nearly 40 percent of the earth's ice-free land.[4] While land conversion for agriculture has slowed, it remains a major source of greenhouse gas emissions and a critical threat to biodiversity.[5] Pressure for continued conversion will only build if the demands of a growing and increasingly affluent population outstrip the rate of improvement in crop yields.

In fact, steadily increasing crop yields in many of our most important agricultural regions can no longer be taken for granted. A recent analysis of 2.5 million yield observations from national agricultural census records documented widespread stagnation of yield growth across 24 – 39 percent of global maize, wheat, rice, and soybean areas.[6] Other studies using alternate analytical approaches and data sets have arrived at similar conclusions, showing stagnant areas across wide swathes of both developing and developed countries.[7] Areas of stagnant wheat and rice yield are of particular concern; unlike maize and soybean, the vast majority of wheat and rice production feeds people, not livestock.[8] Hotspots of stagnation include France (79 percent of harvested wheat area), China (79 percent of harvested rice area), and India (70 percent of harvested rice area).[9]

While yield growth has begun to stagnate, growth in food demand is expected to accelerate. In the recent past, most food supply increases were met by greater production on existing agricultural lands. Between 1985 and 2005, crop production increased approximately 28 percent while the land footprint of global croplands increased by only 2.4 percent, due to crop yield increases of nearly 20 percent and an increase in harvest frequency (due to multi-cropping and a decrease in fallowed area) of approximately 7 percent.[10] However, with rising incomes in developing nations and the increased adoption of diets rich in animal products, demand for food and feed from global croplands is expected to roughly double between 2005 and 2050.[11]

The prospect of increasing global food scarcity poses both a challenge and an opportunity for low- and middle-income nations, where the interest in closing yield gaps has been motivated by the potential for enhanced agricultural productivity to alleviate poverty and spur economic development. Growth in the agricultural sector, it is widely believed, is an important catalyst for broader economic growth in many developing countries, where agriculture directly or indirectly supports the livelihoods of more than two billion people. If policy intervention can enable under-yielding farmers to intensify production profitably – without incurring substantial additional risk – then closing yield gaps could go hand-in-hand with supporting the livelihoods and ensuring the food security of some of the world's poorest populations.

Recent efforts have quantified and identified global patterns in yield gaps, creating the foundation upon which to explore the possibilities and consequences of geographically targeted initiatives to enhance yields. The ability to assess yield gaps at the global scale improved dramatically in 2008, with the release of a data set of crop-harvested area and yield information created by sustainability scientist Chad Monfreda and colleagues. This data set fuses remote sensing and national agricultural census reports published circa 2000.[12] Much of the census data collection was undertaken through the Agro-MAPS project, a collaboration between the United Nations Food and Agriculture Organization, the International Food Policy Research Institute, and the Center for Sustainability and the Global Environment at the University of Wisconsin. The Monfreda data set has informed three analyses of global yield gaps, which largely agree on the spatial distribution of yield gaps and the potential of closing yield gaps to increase the global food supply.[13]

Global yield gap studies use sampling or statistical methods to provide a landscape-scale estimate of best-in-class yields (also known as "attainable yields"). As these studies use census data – which are aggregated and averaged across space to some degree – they do not predict the absolute biophysical "potential yield" of a crop that is grown without any management limitations. Such values are more often derived from field trials and crop simulation computer models.[14] The global studies also calculate potential yields using average climate and average yields; in contrast, local studies may calculate the unique yield potentials for growing conditions in each year. To incorporate chronic water limitation into yield gap analyses, local and regional studies often calculate potential yields separately for rainfed (often called "water-limited yield potential") and irrigated conditions. In the case of the global study by Mueller and colleagues, crop-specific irrigation data and a statistical approach were used to identify maximum rainfed yields.[15]

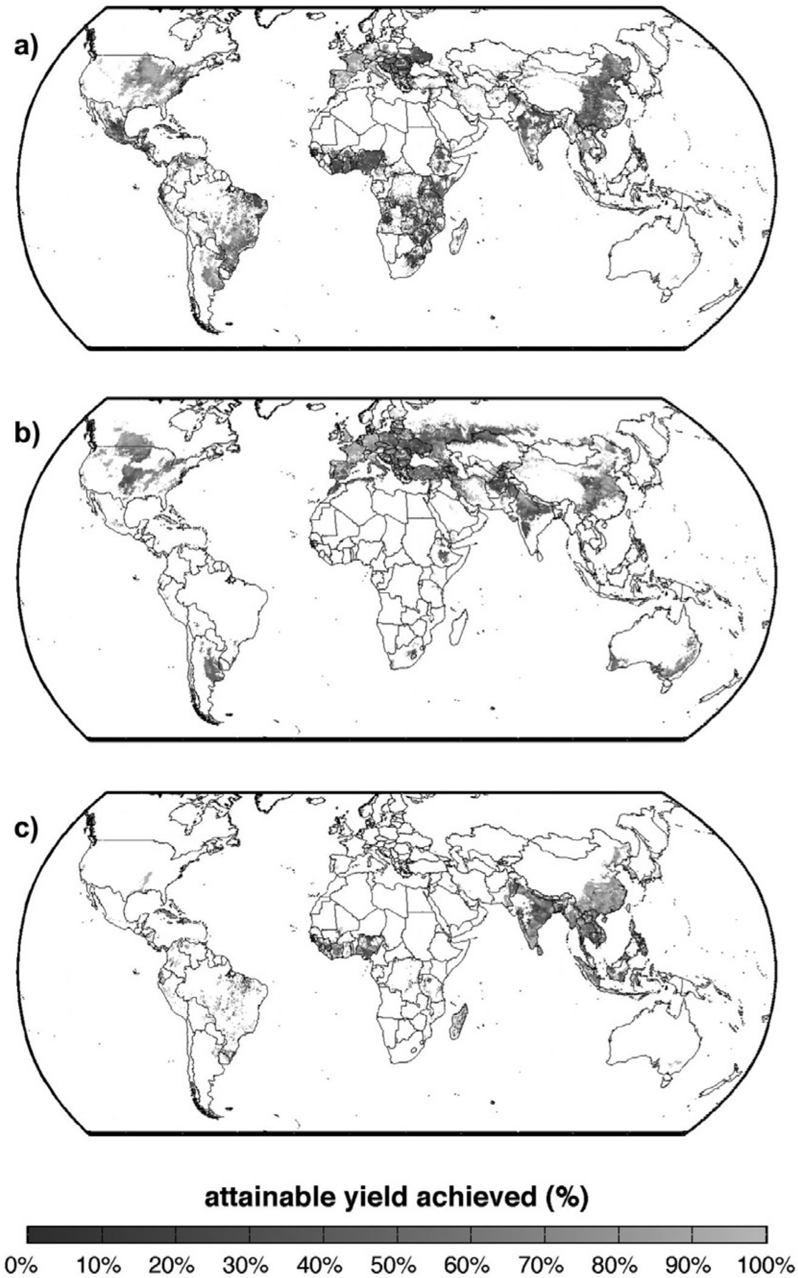
The potential contributions of closing yield gaps to the food supply are substantial. With colleagues, we have previously estimated that complete closure of yield gaps (to best-in-class yields within climate zones) could increase production by 45–70 percent for most of the seventeen crops we examined.[16] For maize, wheat, and rice, the potential production changes were estimated at 64 percent, 71 percent, and 47 percent, respectively. A report by the Australian Centre for International Agricultural Research (ACIAR) has scaled up field-level yield gap assessments, estimating potential production changes of 98 percent, 50 percent, and 71 percent for maize, wheat, and rice, respectively.[17] Differences between the estimates are unsurprising, given the divergent methodological approaches. However, both sets of results suggest that efforts to close yield gaps are necessary – but insufficient – to meet the expected doubling of future food demand. Enhancing crop yield potential through breeding, decreasing food waste, and shifting diets are other important leverage strategies that could increase total food availability and improve sustainability of the food system.

Generally speaking, the largest yield gaps exist in sub-Saharan Africa (SSA), Eastern Europe and Russia, and South Asia. Maize yield gaps in SSA are some of the world's largest: yields circa 2000 were around one and a half tons per hectare, while attainable yields across maize-growing areas in SSA were estimated to be around five tons per hectare. These "top-down" estimates are relatively consistent with the "bottom-up" estimates of the ACIAR, which reports farm yields of around one and a half tons per hectare for both East and West Africa, and potential yield estimates of seven and five tons per hectare, respectively. It is also expected that Eastern Europe and Russia could realize large increases in wheat production from closing yield gaps. Kathleen Neumann, a scholar of human-environmental interactions, and colleagues have estimated wheat yield gaps of one to three tons per hectare across most of the region, consistent with our estimates of attainable yields around four and a half tons per hectare and yields of two tons per hectare, circa 2000. In South Asia, extensive regions of wheat and rice cultivation with moderate yield gaps create large possibilities for production increases. Moderate yield gaps for maize in East Asia, along with large harvested areas, create a similar production opportunity in that region. While maize yields in China are around five tons per hectare, researchers estimate attainable yields to be between nine and ten and a half tons per hectare. The spatial patterns of yield gaps are visualized for maize, wheat, and rice in Figure 1.

Looking forward, opportunities are increasing to enhance our understanding of yield gaps at the global scale, in part due to increasing data availability. One promising development is the independent data collection and processing effort by International Food Policy Research Institute scientist Liangzhi You and colleagues, which has produced new maps of crop-harvested area and yield.[18] As the data set utilizes an independent collection of census statistics and different assumptions to disaggregate the census information down to individual grid cells, new analyses with this data set are helping us understand the sensitivity of yield gap calculations to different source data.[19] Additionally, the data set produced by University of Minnesota Global Landscapes Initiative senior scientist Deepak Ray and colleagues to analyze crop yield trends provides enhanced temporal resolution, and now contains approximately 2.5 million observations, from 1961 – 2008, for maize, wheat, rice, and soybean.[20] Analyses with this data set will allow us a greater understanding of how both yield potentials and yield gaps have changed over time. Efforts are also underway – under the banner of the Global Yield Gap Atlas project – to scale up yield gap estimates derived from process-based crop models.[21] These models simulate crop growth and development over the course of a growing season. They are sensitive to planting and harvest times, daily weather variations, fine-scale soil conditions, and characteristics of particular crop varieties. While these models are often successful at simulating yields at the field or farm level, they are not as often applied at larger scales. The Global Yield Gap Atlas project seeks to fill this gap, and eventually, all of these new efforts will improve our understanding of yield gaps at both local and global scales.

Even as the science paints an increasingly detailed picture of the type, extent, and global distribution of yield gaps, understanding *why* yield gaps exist (and persist) presents a critical challenge to developing appropriate and effective solutions to the related problems of food scarcity, food insecurity, and environmental degradation. The determinants of yield gaps are as much social as they are environmental. Sociopolitical and economic conditions, which influence farmer decision-making, drive which management practices are adopted; in turn, a variety of these management practices, alongside local environmental factors, in-

*Figure 1*
Estimated Yield Gaps circa 2000 for Maize, Wheat, and Rice




Yield gaps for maize (A), wheat (B), and rice (C) presented as the percent of attainable yields achieved. Source: Nathaniel D. Mueller, James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley, "Closing Yield Gaps through Nutrient and Water Management," *Nature* 490 (2012): 254 – 257.

fluence the biophysical growing conditions experienced by a particular crop during its development.

Agricultural scientists have amassed a sound understanding of the biophysical factors that can limit yields. Planting and harvest dates, crop variety, and planting density all influence the yield potential a crop can achieve in a given environment.[22] As the plant develops, deficiencies in growing conditions may lead to a yield gap. Moisture may either be limiting (causing water stress) or in excess (leading to waterlogged soils). Critical micronutrients or macronutrients (nitrogen, phosphorus, and potassium) can limit plant growth. Inadequate soil conditions, such as low organic matter content or undesirable pH, may limit yields (if not ameliorated by the farmer). Weeds, diseases, pests, and even atmospheric pollutants (such as tropospheric ozone) can also lead to yield losses.[23]

The relative contribution of these factors to existing yield gaps is an area of active research. Global studies using statistical models have, not surprisingly, confirmed the importance of fertilizers and irrigation as major controls on existing yield gaps.[24] Enhanced resolution at the regional scale is made possible by administering surveys to agricultural experts in different cropping systems, as shown in a 2010 study of farming systems across SSA and Asia.[25] For wheat in highland temperate systems of SSA, the authors find that major constraints limiting rice yield include the unavailability of quality seed, nitrogen fertilizer deficiency, and wheat rusts (fungal pathogens). For intensive rice and rice-wheat systems in South Asia, experts identified weed competition, nitrogen fertilizer deficiency, low soil fertility, and drought and intermittent water stress as primary constraints.

Farmers utilize a diverse mix of conventional and agroecological management practices to address these constraints and improve yields. The development and deployment of high-yielding crop varieties that are responsive to agronomic inputs has been critical to increasing potential yields. In some cases (such as U.S. maize), new cultivars are able to better withstand increased planting density, which allows for greater yield.[26] Given sufficient investment and ample water supplies, irrigation can be used to overcome chronic water stress. Further, installation of tile drainage systems can alleviate excessive moisture. Soil fertility constraints can be addressed through the use of both organic and inorganic fertilizers, appropriate crop rotations, mixed crop-livestock systems, and multi-cropping systems. In Brazil – and elsewhere in the tropics – acidic soils and aluminum toxicity are offset by additions of lime and phosphorus. Weeds, pests, and diseases can be addressed through a variety of practices as well. In the case of pests, biological control and integrated pest management can provide a chemical-free – but knowledge-intensive – alternative to pesticides. The economic feasibility and environmental impact of these various practices in different socioecological contexts will ultimately determine the contours of the policy landscape in which society attempts to close yield gaps.

Yield gaps are the cumulative result of decision-making by individual farmers who have weighed the perceived costs and benefits of changing their current agricultural practices and found the prospect either unattractive or unattainable. These decisions largely reflect the reasoned calculus of risk-averse, cash-constrained farmers who are either unwilling or unable to experiment with higher-yielding management techniques. Notwithstanding some evidence of irrational behavioral biases working against the purchase of fertilizer, such decisions are mostly consistent with economist T. W. Schultz's notion of the "poor but efficient" farmer.[27] Understanding the persistence of yield gaps thus requires attention to the incentives and constraints that under-yielding farmers face.

Market, policy, and sociopolitical failures all contribute to yield gaps by creating or exacerbating important differences in the costs and benefits of intensification for farmers in poorer countries relative to those in richer countries. Markets typically fail to provide poor, rural farmers adequate access to credit and insurance. In the absence of formal insurance, farmers may pursue a number of alternative strategies that often result in lower yields. These include: applying less fertilizer; forgoing the benefits of specialization and scale in order to reduce risk, as by planting a greater diversity of crops than would maximize yield alone; and shifting labor to nonfarm work in order to diversify income sources. Incomplete credit markets typically leave households unable to borrow at reasonable rates – if at all – inhibiting productive investments in livestock, irrigation pumps or seasonal fertilizer inputs that are critical for achieving higher yields. When households can neither insure against risk nor borrow in times of need, they are often forced to sell off productive assets. This coping strategy can lead to overinvestment in disposable assets, such as livestock, at the expense of higher-yielding alternatives, such as the purchase of more fertilizer, and can result in a cycle of declining yields over time.[28]

Whereas the governments of wealthy countries tend to lavish their relatively small agricultural sectors with subsidies of all kinds, poorer nations' governments have historically placed much of the tax and policy burden on their comparatively large and important agricultural sectors.[29] These perverse policies contribute to hyper-intensification in already high-yielding countries, while blunting the incentives to enhance productivity where yields are lowest. Such policies are often manifestations of underlying weaknesses in institutional quality, which give rise to other problems, including poorly established or minimally enforced property rights and an underprovision of public goods and services, such as agricultural research, extension programs, and transportation infrastructure. Insecure property rights make access to credit more difficult and heighten the risks of eviction, making investments in the land even less attractive.[30] Poor transportation infrastructure also inhibits the adoption of yield-improving technologies, particularly those requiring input intensification. Long, hazardous transport routes lead to higher fuel expenditures, and the loss of labor time and perishables in transit reduces the net prices that farmers receive. Farmers who face high costs of buying and selling in markets may choose to diversify their crop mix to satisfy their own demand for a variety of goods rather than investing in yield-increasing technologies for a smaller subset of crops.[31]

Were routine and pervasive market and policy failures not sufficient obstacles to yield improvement, farmers in many countries must also contend with episodes of civil and ethnic violence, and chronic political instability. These factors can disrupt supply chains, reduce demand, siphon human capital from the farm, deplete on-farm capital (including the quantity and variety of seed stocks), and generally heighten risks. Thus, they reduce the quantities of inputs and effort that farmers are willing and able to apply to the land. They may disproportionately affect the areas where additional inputs are needed most. The Rwandan civil conflict of the early 1990s provides the *ne plus ultra* example of such effects. Average yields (measured in terms of the per hectare caloric content of nutritional crops harvested) in the five-year period following the conflict fell by more than 20 percent relative to the five-year period preceding the conflict, with no evidence of a preexisting trend of decline.

Together, all of these factors – political, social, and economic – contribute to a poverty trap that is at once cause and consequence of under-yielding.

Breaking the cycle of poverty and low yields has the potential to enhance local and global food security and – ideally – reduce the environmental impact of agriculture. Food security is the state "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."[32] Closing yield gaps is not sufficient for ensuring food security (nor is it strictly necessary), but it can substantially improve a country's capacity to achieve this goal. If yield gaps are closed through improvements in technology or the elimination of market, policy, and social failures – rather than by an increase in inputs alone – farmers' production and income can expand even while greater supply drives down prices for urban households. The ripple effects of growth in the agricultural sector may augment urban food security not simply via the price mechanism, but by strengthening the economy and indirectly enhancing urban incomes.

Technological improvements may take a variety of forms, and strategies based on the adoption of high-yielding varieties and input intensification will have much different social and environmental consequences than strategies based on the adoption of agroecological technologies. Each strategy, in its ideal implementation, holds considerable promise for enhancing food security. Input-intensive technologies have the potential to vastly improve livelihoods and food security where transport infrastructure allows marketing of surplus production beyond the vicinity of the local community; credit and insurance markets are robust and accessible; and high-yielding varieties have been bred for local conditions. Alternatively, there exists potential to greatly reduce downside risk, promote diversity and self-sufficiency in food production, and even enhance expected yields and profits through the increasing adoption of agroecological principles. Adoption of these practices depends upon strong social networks among farmers that allow the transmission of best practices, and links between farmers, scientists, and civil society organizations.[33] These strategies need not be mutually exclusive, and there is considerable promise in the merging of best practices from both approaches.

The extent to which these best practices are adopted will likely determine the degree to which closing yield gaps leads to net benefits for local and global environmental quality. Concern is warranted, given that intensive management practices have led to soil degradation, widespread water pollution and nitrous oxide emissions from excess fertilizer application, use of toxic chemicals for pest and weed control, and overuse of water supplies.[34] Despite historic trends, promising evidence exists that yield gaps can be closed – and have closed, to some degree – in ways that minimize negative environmental consequences. University of Essex professor Jules Pretty and colleagues have documented the effects of 286 interventions to increase productivity in 57 developing countries.[35] While environmental outcomes were not explicitly documented, the authors focus on interventions that emphasized "resource-conserving" management practices: a broad description that includes integrated pest management, integrated nutrient management, conservation tillage, agroforestry, aquaculture, water harvesting, and livestock integration. The aggregate results are striking: these generally low-impact management changes led to an average yield increase of 80 percent for intervention participants. The greatest gains were possible for those farmers that started with the lowest current yields (achieving less than two tons per hectare), emphasizing the large increases in food supply possible from focusing on the most under-yielding areas.

Another encouraging example comes from agronomic trials aiming to improve the production and environmental performance of maize cultivation in China.[36] The study focused on nutrient management. This is a major problem in China, which experiences widespread pollution from agricultural fertilizers. In the trials, computer modeling and soil testing guided split doses of nitrogen throughout the growing season. Combined with balanced doses of phosphorus and potash, optimal planting dates, and appropriate planting density, the experimental trials were able to double maize yield while eliminating mass balance excess nitrogen. (The same amount of nitrogen was applied to the field and removed in the grain.) This study emphasizes the importance of the cropping system and the way inputs are utilized to realize more productive and environmentally friendly agricultural systems.

The availability and sustainability of water resources is also a major concern when considering yield gap closure. While irrigation is obviously an effective approach to ameliorating water stress, irrigation infrastructure can be expensive. Building such infrastructure requires either high energy or labor inputs and access to sufficient and – in the long run – sustainable water supplies. Rainwater harvesting is an alternative to ground- or surface-water-based irrigation schemes, and uses rainwater capture combined with irrigation to allow farmers to overcome intermittent dry spells. Conservation farming techniques that reduce soil evaporation (including no-till, mulching, intercropping, and windbreaks) can also preserve soil water for use by crops.[37]

Finally, we must also consider whether closing yield gaps will truly be able to spare land for nature, which is the major environmental benefit presumed to occur from yield gap closure. The rationale seems simple: given the massive growth in projected crop demand, achieving yield growth on existing lands will avoid biodiversity loss and carbon emissions from land clearing otherwise necessary to meet demand. However, the extent of the land-sparing effect is a topic of substantial debate.[38] Central to this debate is the degree to which yield-enhancing technology makes conversion of new lands to agriculture more profitable, even as it increases supply from existing land and leads to lower prices. The environmental benefits of sparing land will depend on where the "sparing" occurs relative to the intensification, and to what extent various intensive agricultural practices affect local biodiversity.

While full treatment of this complex issue merits its own article, historical trends provide strong evidence for the importance of the land-sparing mechanism. Even with constant patterns of per capita demand, an alternate world with no yield improvements after 1961 would have experienced a doubling of the cropland footprint and an additional two gigatonnes of carbon emissions per year.[39] As food demand continues to increase, we expect yield improvements and the closing of yield gaps to be necessary but not sufficient to spare land for nature. Enhanced governance and conservation efforts are also necessary.[40]

Recent research has put yield gaps on the map, both literally and figuratively. These efforts can inform and catalyze further inquiry into the causes of yield gaps and effective strategies for their closure that improve human well-being. More specific, we suggest that well-being can be advanced through food system changes that enhance food security and improve environmental quality. As the scientific literature on yield gaps continues to grow, research can contribute to these objectives by developing yield gap metrics that are increasingly nuanced in their accounting for local conditions, such as: the current health or fragility of agroecosystems; climate variability and projected climate change; assessments for locally important "orphan" crops; and the use of local crop varieties or landraces that may provide advantages other than – and possibly at the cost of – average yields. In doing so, yield gap research will become even more connected with agronomic and agroecological knowledge, and can inform the creation of more vibrant, productive, and biodiverse landscapes.

ENDNOTES

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# Land for Food & Land for Nature?

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*Abstract: Opinions on how to limit the immense impact of agriculture on wild species are divided. Some think it best to retain as much wildlife as possible on farms, even at the cost of lowering yield (production per unit area). Others advocate the opposite: increasing yield so as to limit the area needed for farming, and then retaining larger areas under natural habitats. Still others support a mixture of the two extremes, or an intermediate approach. Here we summarize a model designed to resolve this disagreement, and review the empirical evidence available to date. We conclude that this evidence largely supports the second, so-called land-sparing approach to reconciling agriculture and biodiversity conservation, but that important questions remain over the generality of these findings for different biota and for ecosystem services, how best to increase yields while limiting environmental externalities, and whether there are effective, socially just, and practical mechanisms for coupling yield growth to habitat retention and restoration.*

Cultivating crops and keeping livestock have radically transformed the scale and complexity of human society, and have had greater impacts on the rest of the planet than any other human activity.[1] Crop production and permanent pasture now cover a combined 38 percent of Earth's ice-free land surface, including around half of all former temperate deciduous forests and savannas, and almost three-quarters of the world's grasslands. Continued conversion for farming is the leading cause of tropical deforestation by a considerable margin. Taken together, agriculture and related land use are responsible for 17 – 31 percent of all anthropogenic greenhouse gas emissions. On top of this, farming accounts for around 70 percent of human use of freshwater, and the manufacture of inorganic fertilizers is the main reason for the doubling in nitrogen fixation and resulting rise in eutrophication seen over the past century. Given the magnitude of these environmental alterations it is not surprising that agriculture threatens many more species with extinction than any other sector.[2]

Serious as the situation already is, it seems inescapable that the footprint of farming will increase. The expansion of the human population from about

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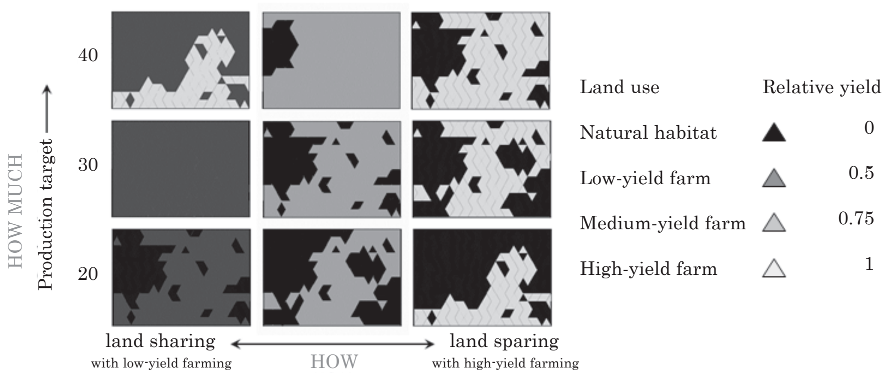
7.4 billion today to between 9 and 10 billion, coupled with rapidly rising per capita demand for noncrop products (such as biofuels and rubber) and for animal protein (especially in newly emerging economies) mean that total agricultural demand is likely to double between 2000 and 2050.[3] Demand-side interventions could help curb this growth and, insofar as hunger and undernourishment are more about food distribution and pricing than overall production, could do so without negatively impacting food security.[4] Much could be done to reduce the 30 – 40 percent post-harvest loss of potentially usable food in both developing and developed countries. Food consumption in general and that of meat, dairy products, and eggs in particular could be reduced among well-off consumers.[5] We strongly support such efforts. Nevertheless, given very limited progress on these fronts to date, we consider it likely that demand for crops and livestock will rise dramatically over the next half century.

The question that therefore arises for conservationists, and that occupies us for the rest of this essay, is how the demand for agricultural products can be met by the planet's limited supply of land at the least cost to other species. One option, widely advocated by conservationists and reflected in the European Union's €5 billion per year program of agri-environment payments to farmers, is land sharing: producing both food and wildlife in the same parts of the landscape by maintaining or restoring the conservation value of the farmed land itself, through providing nonfarmed habitat elements (such as shade trees and ponds), limiting the use of harmful chemicals, and other interventions (see the left panels of Figure 1).[6] A very different approach, put forward by agricultural scientists in response to the observation that land-sharing interventions typically lower yields and therefore require a larger area to be farmed to achieve a given production target,[7] is land sparing: increasing yields on farmed land while at the same time sparing remaining habitat or freeing up land for habitat restoration elsewhere (right panels, Figure 1).[8] Thus, while land sharing focuses on enhancing biodiversity within farmland, land sparing seeks to offset the impacts of high-yield production by coupling it to conservation in nonproductive parts of the landscape. Many other options between these extremes are also possible (central panels, Figure 1).[9]

In the following sections, we summarize a simple trade-off model[10] we devised for identifying which of these approaches will maximize the persistence of the native wild species inhabiting a region; we also review the empirical evidence so far available for assessing their relative merits. We then discuss a series of objections to our approach – some of which we consider to be misconceptions about the model's scope, as well as some important challenges. We end with a brief exploration of other contexts besides food production in which the land-sharing/sparing framework might usefully be applied.

Our trade-off model evaluates plausible alternative farming systems – all of which meet a region's production targets – according to their consequences for the long-term persistence of its species.[11] We infer the probability of long-term persistence of each species from its expected total population size in all of the region's farmed and unfarmed land combined, relative to what its population would be in the absence of farming. To make options comparable, we only consider scenarios that meet the same production target for the region (solutions occupying the same row of Figure 1). This could be achieved by farming the entire region at the lowest yield sufficient to meet the target (extreme land sharing), farming some of it at the highest achievable yield and maintaining (or restoring) the rest as

Figure 1
Schematic Illustration of Land Sharing, Land Sparing, and Mixed-Yield Landscapes



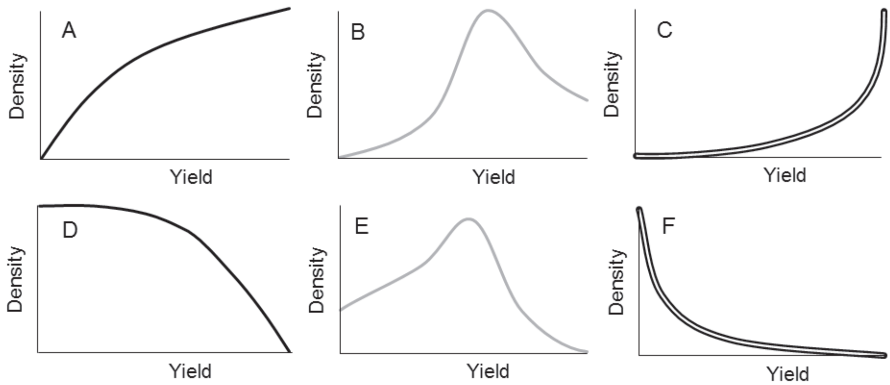

Each of the nine panels is a schematic map of a region with natural habitat (black : agricultural yield = 0 units), low-yield farmland (dark grey : yield = 0.5 units), medium-yield (mid-grey : yield = 0.75 units), and high-yield farmland (light grey : yield = 1.0 units). Region maps in the same row all produce the same quantity of agricultural products, but with different amounts of high-, medium-, and low-yield farming and with natural habitat on all land not needed to provide the production target. The three rows show results (from bottom to top) for low (120 units), medium (180), and high (240) production targets. Source : Figure prepared by authors.

intact habitat (extreme land sparing), or by some intermediate solution.

The key to quantifying how the total population size of a species (and hence its likelihood of persistence) varies across these options is how its mean population density is related to the agricultural yield of a piece of land: a response we term its density-yield curve. Some species can be considered beneficiaries of agriculture ("winners") because they live at consistently higher densities in farmed land than in their natural, zero-yielding habitat (panels A, B, and C in Figure 2). Given that these are likely to have larger regional populations under any form of farming than they had before the arrival of agriculture, such species are of limited conservation concern. Other species ("losers") occur at lower densities in farmed land than in unfarmed habitat (panels D, E, and F). Their region-wide populations will thus be smaller under some or all farming regimes than in the absence of farming. These loser species are the primary focus of our concern.

For both winners and losers, the approach to farming that maximizes their regional population size depends on the shape of their density-yield curves. Mathematical modeling shows that for those with simple concave curves (panels A and D) their total population size is greatest when the entire region is farmed at the lowest yield capable of meeting the production target (extreme land sharing). This is easiest to see for loser species (panel D), because their densities decline only slightly under low-yield farming but fall steeply under the high-yields associated with land sparing. The situation is very different for species with simple convex curves (panels C and F). For these, farming some land at maximal yield and retaining or restoring the remainder as natural habitat (extreme

*Figure* 2
Illustrative Density-Yield Curves for "Winner" and "Loser" Species




Illustrative density-yield curves for species whose total population sizes (on farmed and unfarmed land combined) are larger (winners, top row) or smaller (losers, bottom row) when farming is present in a region, and greatest under land sharing (A, D), intermediate-yield farming (B, E), or land sparing (C, F).

land sparing) is optimal. Again, considering loser species (panel F) helps explain why: in this case, their population densities fall sharply even under low-yield farming, whereas high-yield farming can help safeguard more of the intact habitat on which they (more or less) depend. Species with more complex curves (such as those shown in panels B and E) may have maximum population sizes under intermediate-yield strategies, though this will depend on the production target for the region.[12]

Parameterizing this model and hence evaluating the consequences of alternative farming approaches for a given set of species in a region can be challenging.[13] It requires estimating current and likely future production targets and developing plausible land-use scenarios of how these might be met. Density-yield curves are needed for all species of interest, which should be as representative a sample of wild species as possible. Fitting density-yield curves requires data on the population density of each species across sites of known yield, ranging from natural, baseline habitats to the highest-yielding system possible in the region, and matched for all variables (such as soil type, climate, and topography) besides agricultural inputs that might affect either yields or densities. Sites should be of a size that is relevant to major land management decisions and to the life cycles of the species concerned (see below), and they must be within sufficiently large land-use blocks that abundance estimates are not swamped by edge or spillover effects from neighboring blocks with very different yields. Choice of baseline sites can be particularly problematic, especially in regions that have lost their natural vegetation or where major elements of the Pleistocene biota are extinct. Baseline habitats suitable for survey are unfarmed areas with native vegetation typical of what could be retained or restored within the region.

The results from the land-use scenarios and density-yield curves are then combined to calculate the expected total populations of each species across farmed and nonfarmed land combined. This approach ignores possible differences in demographic processes among land-use types. Ideally, these differences would be known so that the expected whole-region population of each species could be obtained from a spatially explicit population model. However, the data this would require are only available for a handful of species. Given that the trade-off assessment is only meaningful when done in the same way for an entire suite of species, we argue our simpler density-based method is at present the only practical approach.

Given these difficulties, few studies have been able to test the land-sharing/sparing trade-off appropriately. What do the results so far show us?

Published studies have parameterized density-yield curves of large numbers of species in only three regions: Southwest Ghana (for birds and trees), Northern India (birds and trees), and Southern Uganda (birds) (see Table 1).[14] All show remarkably similar results across taxa and across regions (Figure 3). In every case, there are more loser species than winners, and most losers would have larger total population sizes under land sparing than under a land-sharing (or any intermediate-yielding) strategy. These outcomes are more marked for trees (not shown) than for birds, and for species with small global ranges that are more likely to be of conservation concern (compare the left and right panels in Figure 3). The preponderance of losers and, among those, of species that fare better with land sparing than land sharing increases as production targets rise (moving from left to right within the panels in Figure 3). Importantly, however, most loser species benefit from land sparing even if production targets are below current levels. Hence, even if – by tackling food waste, population growth, and diet – demand were somehow to fall, land sparing would still be the least bad option for most loser species in the taxa studied. Addressing the needs of loser species that are associated with low-yield farming will require careful attention in land-use planning,[15] but for each of the groups examined so far, and in each region, the conservation status of most species would be better under high-yield farming coupled with retention of remaining nonfarmed habitat.

A handful of other studies have addressed the land-sharing/sparing question using different analytical frameworks and abundance-based measures of the persistence of species (Table 1).[16] In the Colombian Andes, simulations show that total populations of most bird and dung beetle species would be larger under land sparing than in land-sharing landscapes that produce the same quantity of agricultural goods. In the United Kingdom, overall butterfly abundance is expected to be greater for a combination of conventionally farmed land and grassland reserves than with organic farming (unless the yield of organic farming is exceptionally high). Studies on birds in Argentina, Sabah, and Thailand have reached the same general conclusion: more species would persist under land sparing than land sharing.

Results from a roughly equal number of analyses are interpreted as supporting either intermediate strategies or land sharing (Table 1).[17] Mostly, these authors do not perceive there to be a trade-off between improving the wildlife value of farmed habitats and maximizing retention of natural habitats; but none of these studies compare sparing and sharing while keeping overall land areas and production targets constant, so they do not have a strong basis from which to conclude there is no trade-off. Most important, none of these studies calculate population-wide consequences of different land-use strategies for individual species. Our view is that summary metrics such as species richness

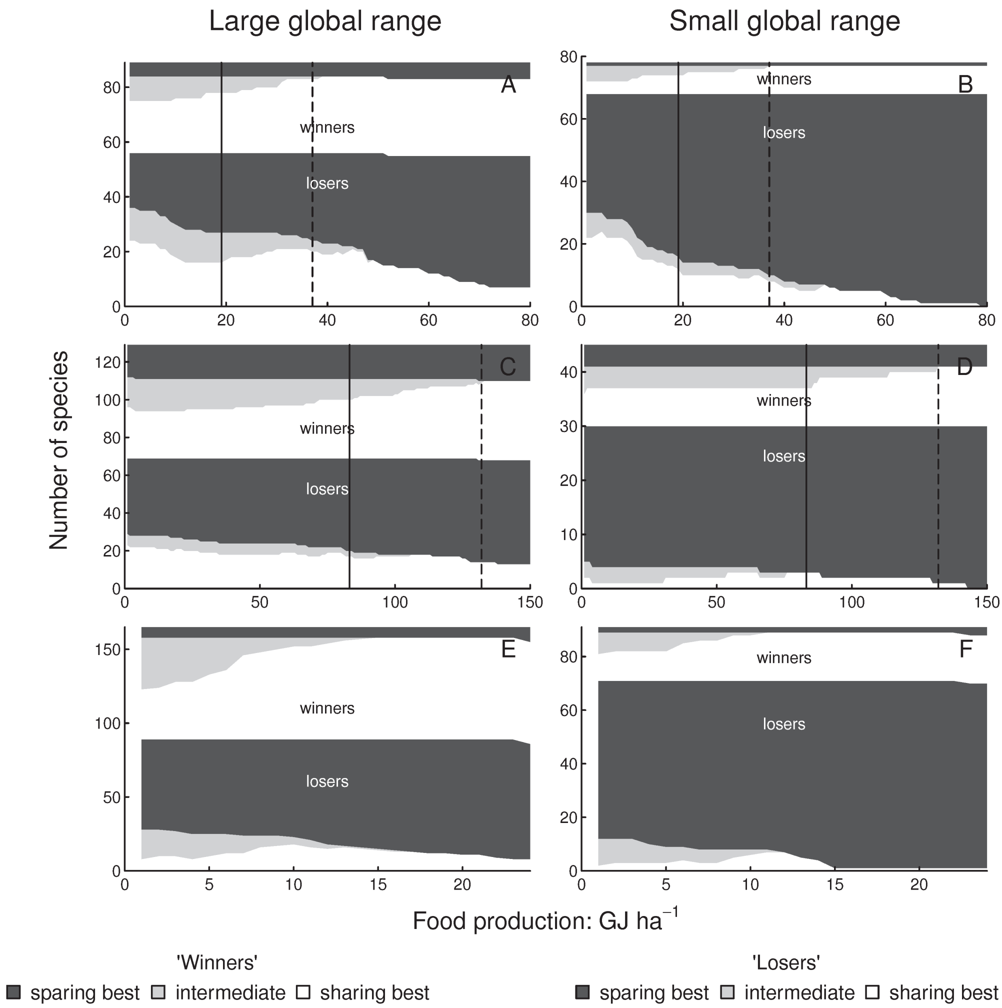
*Table 1*
Examples of Studies Addressing the Question of How to Reconcile Agricultural Production with Biodiversity Conservation

| Location | Agricultural System | Include Baseline | Measure Abundance or Density | Calculate Total Population Effects | Quantify Yields | Taxa | Primary Strategy Supported |
|---|---|---|---|---|---|---|---|
| Uganda[18] | Multiple crops | X | X | X | X | Birds | Sparing |
| Ghana, India[19] | Multiple crops | X | X | X | X | Birds, trees | Sparing |
| Thailand[20] | Oil palm | X | X | | | Birds | Sparing |
| Sabah[21] | Oil palm | X | X | | | Birds | Sparing |
| Colombia[22] | Livestock | X | X | (X) | (X) | Birds, dung beetles | Sparing (unless <500m from contiguous forest) |
| Argentina[23] | Arable, livestock | X | (X) | | X | Birds | Sparing |
| Amazon[24] | Mainly livestock | (X) | (X) | | | Birds | Sparing |
| United Kingdom[25] | Arable, livestock | X | X | (X) | X | Butterflies | Sparing (but depends on yield ratio & nature of spared land) |
| Costa Rica[26] | Coffee | X | (X) | | (X) | Birds | "Small-scale" sparing |
| United States[27] | Arable | X | (X) | | | Plants | "Small-scale" sparing |
| United Kingdom[28] | Arable | | (X) | | X | Eight plant & animal taxa | Depends on taxon & yield contrast |
| Argentina[29] | Pasture | X | X | | X | Birds | Intermediate |
| U.S. Great Plains[30] | Arable, some livestock | X | X | | | Birds | Intermediate |
| New South Wales, Australia[31] | Arable, livestock | X | (X) | | | Bats | Intermediate |
| Western Ghats[32] | Arecanut | X | | | | Birds | Sharing |
| South-eastern Australia[33] | Livestock | X | | | X | Plants | Sharing |
| Sulawesi[34] | Cocoa | | | | X | Nine plant, fungus & animal taxa | Sharing/intermediate |
| Mexico[35] | Coffee | (X) | | | X | Birds | No trade-off |

Columns give assessments of whether the studies include an appropriate baseline, measure the abundance or density of individual species, estimate the effect of alternative approaches on total population sizes (on farmland and natural habitat combined), and quantify yields. We have included our interpretation of the primary strategy supported by the authors of each study. Ticks in parentheses refer to studies that partly meet the criterion (for example, by measuring an attribute but not including it in the main analysis). Source: Table built by authors from the sources cited.

*Figure 3*
The Breakdown of Bird Species According to the Farming Strategy that Maximizes Their Total Population Size, in Relation to Production Target






GJ ha$^{-1}$ = Gigajoules per hectare. Data are for Southwestern Ghana (top row), Northern India (middle), and Southern Uganda (bottom), shown separately for species with global ranges above (left) and below (right) three million square kilometers. Within each panel, winner species are plotted above losers and are split by whether their populations are greatest under land sparing (dark grey), intermediate-yield farming (light grey), or land sharing (white). The vertical lines indicate estimated production targets for 2007 (solid) and 2050 (dashed). Source: Ben Phalan, Malvika Onial, Andrew Balmford, and Rhys E. Green, "Reconciling Food Production and Biodiversity Conservation: Land Sparing and Land Sharing Compared," *Science* 333 (6047) (2011): 1289–1291; and Mark F. Hulme, Juliet A. Vickery, Rhys E. Green, Ben Phalan, Dan E. Chamberlain, Derek E. Pomeroy, Dianah Nalwanga, David Mushabe, Raymond Katebaka, Simon Bolwig, and Philip W. Atkinson, "Conserving the Birds of Uganda's Banana-Coffee Arc: Land Sparing and Land Sharing Compared," *PLoS ONE* 8 (2) (2013): e54597.

should not be used to draw conclusions about the relative merits of sharing and sparing for biodiversity.[36] A site's species richness includes species traveling between or reliant on other land-use types, and is affected by time-lags between habitat loss and relaxation to extinction.[37] Simple richness scores also do not include information about species' identities. When an area of natural habitat is converted to agriculture, species richness may be maintained, but perhaps only through the replacement of narrowly distributed, disturbance-sensitive species by widespread generalists. We found evidence of this in the Ghana study, where the overall species richness of birds in low- and intermediate-yielding farm mosaics was similar to that in baseline sites, even though the abundance of most narrowly distributed and forest species was far lower in farmland.[38] All of these effects mean richness measures are likely to give an inflated view of the relative conservation value of farmland.

Our assessment of the literature is therefore that all studies that have assessed both yields and their population-wide consequences for individual species across sites ranging from zero-yielding baselines right through to high-yield farming have concluded that land sparing would enable more species to persist than would land sharing. This conclusion makes intuitive sense. As biologists know, most species are specialists. It is therefore unsurprising that very many of them are highly sensitive to substantial habitat modification (as happens under conversion even to low-yield farming). That said, the studies that have used what we consider appropriate methods are few and have covered a limited range of regions, biomes, and taxonomic groups. More data are clearly needed for groups other than birds, for predominantly open biomes,[39] and in areas whose biota have potentially been purged of many sensitive species by repeated exposure to natural disturbance events such as glaciation. To address this, our group is currently involved in projects to evaluate land-sparing and land-sharing outcomes for a range of taxa in Kazakhstan, the Pampas, Poland, and Yucatán.

Alongside these gaps in knowledge about the sensitivity of populations to changes in the yield of the land they are living on, several other issues about the merits and demerits of the land-sharing/sparing framework have been raised.[40] Here we examine nine issues, starting with what we believe to be five misconceptions.

1. *Land sparing only needs to be considered if agricultural demand grows dramatically in the future, and this can be avoided.* Analyses to date suggest the relative advantage to wild species of land sparing compared with land sharing increases as production targets rise (Figure 3). However, these analyses also indicate that sparing would be preferable in terms of maximizing species persistence even if demand were to shrink substantially below present-day levels. Whichever strategy is pursued, the overall impact of farming on wild species will be less negative the more that demand for agricultural products can be curbed – through cutting waste, limiting consumption of animal protein, and lowering demand for biofuels.

2. *It is unclear at what spatial grain size sharing becomes sparing.* Individual farms and fields in land-sharing landscapes will often comprise a mix of crop and noncrop elements (such as trees and ponds). Some authors have argued that because these might resemble at a very fine scale the region-wide mosaics of farmland and natural habitat blocks envisioned under land sparing, land sharing is therefore a special case of sparing.[41] We contend this is not helpful, because overall approaches to agriculture should be evaluated at the scale at which major land-use decisions are made, which we suggest is typically that of landholdings

through to regions, rather than individual hedgerows and trees. At this scale – that of entire panels in Figure 1 – the structure of sharing and sparing landscapes and their ability to support the species evaluated so far (such as birds) are very different. Large blocks of forest or wetland in land-sparing landscapes may support viable populations of sensitive species while a similar total area of trees or wetland comprising small woodlots or ponds does not.[42] A related point is whether there is an upper limit to the grain size at which land sparing might be beneficial. Here we agree with others that sparing at very large scales – say, entire states or countries – would not be appropriate.[43] Assigning extremely large areas entirely to agriculture and others entirely to habitat protection would compromise livelihoods and food security, risk the extinction of many narrowly distributed specialists whose ranges fell entirely within farmland, and be exceptionally difficult to implement.

3. *Intermediate-yielding approaches might be optimal but are not considered by the trade-off model.* Our model considers species with density-yield curves of any shape, including those where densities peak at intermediate yields (see panels B and E in Figure 2). Some – but not all[44] – of this last group of species would have their largest population sizes when yields are below maximum but above the minimum needed to meet production targets. However, studies to date indicate such species are relatively infrequent, especially among losers. More commonly found are species with highest population densities at yields that are lower than the minimum required to meet production targets. Where sparing of natural habitats would be insufficient to conserve such species, sparing of very low-yielding farmland (permitted by increasing yields elsewhere) might be needed.

4. *Land sparing reduces landscape heterogeneity.*[45] Farmland that is low-yielding because of the inclusion of many noncrop elements is likely to be more heterogeneous than high-yielding farmland and may therefore contain more species. However, the extra species will often be quite widespread generalists. More significant, when viewed at a larger scale, land-sharing landscapes have smaller blocks of nonfarmed habitat than equally productive land-sparing landscapes (compare panels within rows in Figure 3). Because many natural habitats are highly heterogeneous within themselves, they provide many niches not found at all within farmed land, and thus, land-sparing landscapes can generally support many more specialists than is possible under land sharing.

5. *Land sparing is especially vulnerable to the effects of increasing demand.* Rising demand for agricultural goods is bad for biodiversity regardless of which approach to farming is adopted: it will increase pressure both to expand farmland at the expense of natural habitat and to raise yields within existing farmland. But it is not evident that land sparing is more likely to stimulate demand growth than is land sharing. On the one hand, if high-yield farming techniques lower prices of agricultural commodities for which demand is elastic, then demand is likely to increase, and if high yields boost agricultural wages, they may increase rural demand in particular.[46] On the other hand, these effects are less likely for staple goods (for which demand is relatively price-inelastic). Perhaps most important, land sparing is not just about yield growth but about setting land aside for conservation (see below). Such restrictions on agricultural expansion will tend to raise prices and hence limit demand growth under land sparing. Whatever the balance of these effects, it is clear that increasing demand will compromise biodiversity under any strategy, reinforcing the point that restricting demand growth – by tackling waste reduction and excessive consumption – must re-

main a high priority for conservation, and a necessary condition for the long-term success of either sparing or sharing.

We consider the previous points to have arisen from misunderstandings about the idea of land sparing. However, there are several other areas where additional work is required.

6. *Identifying mechanisms for linking the sparing of natural habitats to high-yield farming.* Land sparing comprises two interdependent elements: raising yields on agricultural land and at the same time either decreasing conversion of natural lands to agriculture or freeing up former farmland for habitat restoration. Ensuring yield growth and habitat conservation are coupled is essential for land sparing to succeed. Insofar as demand is fixed, increasing yields can spare land directly, even in the absence of additional interventions. Statistical analyses and economic modeling of historical changes in yields and land cover show that such passive land sparing does occur, sometimes to a greater degree than expected.[47] This is more likely when demand for products is inelastic, where yield growth is directed away from conversion frontiers, and where yield-improving practices use up labor or capital[48] – suggestions that have important implications for which crops, areas, and technologies land-sparing strategies might most effectively target. However, we believe additional, explicit interventions are needed to tie within-farm yield growth much more closely to land sparing elsewhere. Possibilities include:

- Command-and-control measures, such as land-use planning and regulation, that simultaneously restrict the footprint of farming and protect or restore natural habitats;[49]
- Use of public funds to provide financial incentives to landowners or cooperatives to spare large blocks of their land through agricultural subsidies and taxes, Payment for Ecosystem Service schemes, and other means;[50]
- Strategic deployment – away from frontiers of habitat conversion or in exchange for conservation agreements – of investments capable of enhancing yields, such as new or improved roads or irrigation,[51] agricultural extension officers, and micro-finance; and
- Market-based approaches such as certification or preferential access to markets or credit for crops produced from land-sparing landscapes.[52]

Much work is now needed to develop, test, and refine these and other ideas in order to assemble a toolbox of practical methods for implementing land sparing.

7. *Increasing yields while lowering the externalities of farming.* High-yield farming need not consist of vast monocultures dependent on such high inputs of pesticides, fertilizers, mechanization, and irrigation that they jeopardize agriculture and biodiversity both on farms and elsewhere. As conservationists interested in land sparing, we back calls for sustainable intensification, in which negative impacts of yield increases are avoided or minimized.[53] Of course, finding ways of lowering negative environmental impacts per unit of agricultural production is also central to land sharing. Many different but often complementary approaches are possible.[54] A great variety of new developments deploying both conventional breeding and new genetic technologies (including genetic modification, or GM) have enormous potential to raise attainable yields through 1) improving the ability of crops to acquire water and minerals and use them efficiently; 2) increasing their tolerance to drought and to salinization; and 3) enhancing their defenses against pests and diseases. Radical innovations – such as the prospect of transfer-

ring $C_4$ metabolism into $C_3$ grasses, and of perennializing currently annual crops – offer the promise of substantially lowering the inputs to agriculture. But alongside these highly technical developments much can be done – especially in sub-Saharan Africa – to narrow existing yield gaps by adopting practices that are already widespread elsewhere, such as using improved seed varieties and modest amounts of inorganic fertilizer. Promoting agriculturally important ecosystem services such as pollination and pest control will also raise overall yields, provided these services more than offset the production lost on the land needed for their maintenance. Integrated pest management, organic methods, coculture, drip irrigation, and precision application of fertilizers and pesticides can all help to lower inputs. In our view the key to bringing about sustainable intensification is to avoid dogma and instead explore the likely effects of all promising options – on yield but, critically, also on net negative externalities per unit of production, on prices and livelihoods, and in terms of likelihood of uptake by farmers.

8. *Refining our understanding of how land-use patterns affect long-term persistence of populations.* Our trade-off model is simple and could be developed in several ways so that it more fully captures the demographic consequences of alternative land-use configurations.[55] In particular, it could usefully include edge effects: both of farmed environments on adjacent natural habitat patches and effects in the opposite direction. Likewise it could incorporate the configuration of habitat patches across the landscape and the permeability of farmland to dispersing individuals, and hence address issues of interpatch connectivity and metapopulation dynamics. Our group is attempting some of these refinements, but there are no *a priori* reasons to expect them to alter our findings in a consistent direction. For example, while edge effects will reduce the biodiversity value of all natural habitat patches, they will do so disproportionately in small fragments with high-edge-to-area ratios, increasing the relative advantage of land-sparing landscapes (with larger habitat blocks) for retaining habitat-interior specialists. Likewise, while high-yield practices may make farmland more hostile to species associated with natural habitats, thus lowering connectivity by reducing their dispersal between habitat fragments, this effect is likely to be offset by two others. First, the distance between relatively intact patches of habitat can be considerably shorter under land sparing (compare distances between dark blocks in different panels of the same row in Figure 1), perhaps making movements between patches easier. Second, because under land sparing natural habitat patches are bigger and thus less impacted by edge effects, they may support higher densities with greater reproductive rates and hence higher production of dispersing individuals.

9. *Incorporating other societal objectives into the land-sharing/sparing debate.* Our analysis has focused on the trade-off between food production and species persistence, but conservation is also about safeguarding the provision of ecosystem services.[56] Much research remains to be done on this topic. In terms of climate regulation, retrospective global analyses suggest that yield growth since the 1960s has avoided substantial greenhouse gas emissions that would otherwise have occurred, with the effects of avoided land conversion more than outweighing those of increased emissions from soil and from fertilizer manufacture. However, the magnitude of the savings depends on how far historic yield growth lowered prices and hence fueled rising demand.[57] For cattle ranching, a regional modeling exercise and a landscape-level study again suggest that high-yield production and land sparing may help reduce emissions relative to lower-yield systems.[58]

The consequences of alternative farming strategies for other ecosystem services (and disservices) have been less well explored but may again be quite complex. High-yield farming might reduce downstream water availability, but if it contributes to safeguarding wetlands and forests it may help regulate water flows. Likewise the practices needed to substantially increase farm yields would probably diminish people's enjoyment of farmland but might offer greater prospects of experiencing large and diverse natural habitats. In the context of the spread of zoonotic diseases, the intensification of animal production might increase transmission of pathogens among livestock but reduce transmission rates between livestock and humans.[59] Of course, other considerations are also crucial: the effects of different farming systems on people's livelihoods and values, how well they fit local institutions and cultural conditions, their consequences for equity and gender issues, and, above all, their impacts on food security. Clearly, analysis of density-yield curves gives no information on these other issues, but understanding them will be important for developing effective interventions that address multiple societal objectives.[60]

The land-sharing/sparing debate remains controversial, with many important issues as of yet unresolved. However, we suggest that it has provided a valuable framework that forces us to be explicit about our objectives in evaluating alternative approaches to food production. The recognition that lowering the local environmental costs of production might reduce yields – with important knock-on effects elsewhere since more area is therefore required to meet demand – also has considerable relevance in other contexts:

- In the case of forestry, it is possible that the overall biodiversity value of production landscapes is maximized by a system of intensive logging linked to complete protection of other areas that retain species dependent on old-growth forests, rather than by adopting lighter harvesting regimes across the landscape as a whole.[61]
- In the context of urban planning, increasing attention is focusing on whether compact growth – decreasing the size of gardens for instance, thus enabling larger greenspaces to be retained – reduces the impact of urbanization on biodiversity.[62] A recent study from Brisbane suggests generalist and nonnative species fare better under urban sprawl, whereas specialists are more likely to persist if growth occurs via urban intensification.[63]
- We suspect similar trade-offs might exist at sea.[64] For example, which would better promote biodiversity: a seascape that is fished entirely using relatively benign techniques, or one yielding the same catch, sustainably, but through large areas open to less-regulated fishing plus large, strictly enforced no-take zones? This might be an interesting line of inquiry in charting a sustainable future for capture fisheries.

For agriculture and conservation, our assessment is that the empirical evidence to date largely points to land sparing as having the greatest potential to limit the ecological cost of food production. Separating land for food and land for nature (while recognizing their interactions) may be better than managing land for both. But this is far from certain, and important gaps in knowledge remain: for many taxonomic groups and regions, for many ecosystem services, and in terms of how best to increase yields while minimizing negative externalities. Crucially, high-yield farming at present largely only provides the opportunity to spare land for wild species; it does not ensure that sparing occurs. Hence, a major challenge is how to make yield growth conditional on habitat conservation.

Our suggestion that high-yield farming could be linked to land sparing to enhance the conservation of biodiversity and perhaps some ecosystem services is somewhat counterintuitive, and is clearly an uncomfortable proposition for many. Nonetheless, we believe that the evidence to date suggests there would be considerable benefits from conservationists working with agricultural technologists, policy-makers, development experts, and the food sector to identify ways of linking yield growth to habitat retention and restoration. We believe an equivalent approach may yield similarly unexpected but potentially useful insights in other contexts in which biodiversity and human interests compete for space.

ENDNOTES

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# A Sustainable Agriculture?

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*Abstract: The defining challenge of sustainable agriculture is the production of food and other agricultural products at an environmental cost that does not jeopardize the food security and general welfare of future generations. Feeding another three billion people in the face of climate change, biodiversity loss, and an environment already saturated with excess nitrogen and other reactive pollutants requires new approaches and new tools in the design and deployment of workable solutions. Solutions will be local but all will require an ecological systems approach that considers sustainable farming practices in the full context of ecosystems and landscapes. And their deployment will require an understanding of the social systems capable of building incentives that produce socially desired outcomes. Socioecological models for agriculture provide an opportunity to explore feedbacks, trade-offs, and synergies that can optimize and strengthen emerging connections between farming and society. With the right incentives, innovative research, and political will, a sustainable agriculture is within our reach.*

For the past twenty-five years, agricultural stakeholders ranging from "Big Ag" to public nonprofits have asserted the need for a more sustainable agriculture. Over the same period, agricultural production has intensified. In the developed world, we now produce more food, fiber, and fuel than ever before, on a land base that is either largely stable or shrinking. There are myriad problems associated with agriculture as it is currently practiced. Calls for a reformed, sustainable approach are welcome and have accelerated.

What, exactly, *is* sustainable agriculture? Definitions of agricultural sustainability abound, ranging from the encyclopaedic to the legislative.[1] Strictly defined, sustainable agricultural systems are those capable of persevering.[2] Few would argue, however, that this definition is sufficient.

A more useful definition of sustainable agriculture identifies human intent, most succinctly embodied in the legal construct of *usufruct*, which, back in Thomas Jefferson's time, referred to "the right to make all the use and profit of a thing that can be made without injuring the substance of the thing itself."[3] Jefferson used the concept in his 1789 letter to James Madison:

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> The question Whether one generation of men has a right to bind another . . . is a question of such consequences as not only to merit decision, but place also, among the fundamental principles of every government . . . I set out on this ground, which I suppose to be self-evident, "*that the earth belongs in usufruct to the living*."[4]

Jefferson used *usufruct* to lay out the constitutional foundation for intergenerational equity. More than two centuries later, this notion was broadly adopted by the sustainable development community, which has commonly defined sustainability as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs."[5]

When applied to agriculture, sustainability quickly becomes constrained by scale. The romantic vision of farming has centered around a self-contained subsistence or village-based farm, persisting successfully for centuries if not millennia. This makes sense for medieval England and was the historical norm in most places around the world only a century or two ago. But the ideal quickly dissolves when a growing population largely not based on farms requires intensified production on an arable landbase that has little room to grow. For example, U.S. producers today farm five million fewer acres than they did one hundred years ago, while feeding the 98 percent of the population that does not farm. On top of this, they produce excess for export. From 1910 to 2013, the U.S. population increased by 224 million people, while cropland decreased from 3.6 acres per capita to 1.1 acres per capita. In 1910, it took approximately 4 acres to feed each person in the United States, whereas today it takes approximately 1 acre (with far fewer working farmers).[6]

This general pattern has repeated across the globe. Global agriculture, which is arguably the world's largest industry, feeds seven billion people and contributes immeasurably to human welfare. Even where agricultural territory is expanding, as with soybean farming in the Amazon, intensification is the rule: producing more yield on fewer acres.

But with intensification comes resource use, depletion, and degradation. The environmental ills associated with modern agriculture are legion and distressingly recalcitrant.[7] They include the loss of topsoil and biodiversity; escape of nutrients from fertilized fields and animal production facilities to groundwater, lakes, streams, and coastal waterways; the exacerbation of acid rain and climate warming by gases produced by microbes in farmed soils and domestic animals; and the poisoning, by pesticides, of organisms other than pests.

These disconcerting facts beg the question: *can intensive agriculture be sustainable?* Moreover, can we feed three or even four billion more people, providing the meat-rich diets increasingly demanded by a wealthier world, without further jeopardizing the quality of life for future generations?

Today, general consensus and a growing body of scientific evidence identifies which economic, social, and environmental components are central to the concept of sustainability. The components interlock, and their interdependence is often illustrated by a three-part Venn diagram with overlapping circles representing each of the economic, social, and environmental dimensions of sustainability. There is less agreement, however, about the degree to which these elements should or must overlap to provide sustainability writ large – a question that is more likely to be contextual.

Economic sustainability can be most simply defined as the capacity for a system to continuously provide goods and services whose values exceed the cost of production. For monetized goods, services, and costs, the calculation is straightforward and forms the basis for agricultural trade.

However, the calculus becomes tricky when trying to value inputs and products that are either taken for granted, such as soil biodiversity, or externalized, such as nitrate pollution. For agriculture, this is a huge problem, and has created an intensive area of economic inquiry.[8]

Social sustainability embraces the capacity of a system to continue to meet society's expectations for social justice and security, including intergenerational equity. Food security, or the promise of a stable, adequate, and accessible food supply is a principal requirement of a just society, followed by community health, rural vitality, and gender equity. These issues, among a host of other social factors, contribute to human welfare by either promoting opportunity or alleviating misery.

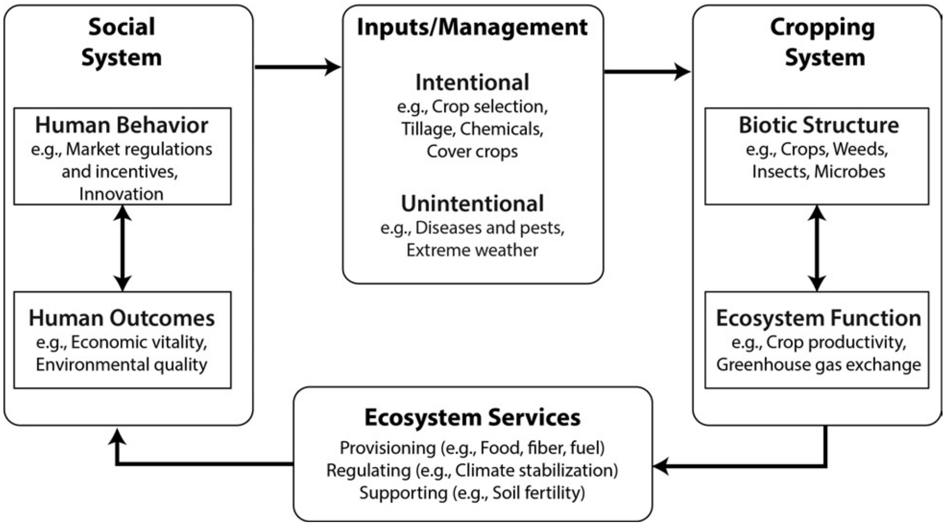
Advances in sustainability science, including the recent development of coupled natural-human systems models, provide a new context for integrating knowledge about systems interactions.[9] These models provide the opportunity to organize and examine outcomes as a function of both ecological and social dynamics within a sustainability context. The dynamics are linked: the natural systems provide ecosystem services, also known as nature's benefits for people, to the social systems. Ecosystem services can be separated into four classes identified by the Millennium Ecosystem Assessment: *provisioning*, such as food, fiber, and drinking water; *regulating*, such as flood and disease control; *supporting*, such as soil formation and nutrient cycling; and *cultural*, such as aesthetic and recreational amenities.[10]

How services affect people influences how ecosystems, which provide those services, are managed. Biologist Scott Collins and colleagues, for example, present a social-ecological model[11] that has been adapted to agriculture.[12] The adapted model (Figure 1) shows ecosystem services (at the bottom of the diagram) as outcomes of cropping system interactions between biotic structure (the organisms that inhabit agricultural ecosystems) and ecosystem function (their activities). For example, plants, insects, and microbes interact to capture carbon dioxide, produce biomass, and mobilize nutrients. These interactions result in outcomes that benefit people by providing services such as food, climate stabilization, and soil fertility. How people perceive these services and how they consequently modify behaviors and policies result in changes to ecosystem inputs and management. Some changes are direct and intentional and happen at the field scale; others are indirect and unintentional and happen on broader scales. Inputs and management affect the cropping system's delivery of ecosystem services, and the cycle continues.

Consider changes in crop varieties and agrochemical use, which are intentional management drivers that derive from the social system, as an example. Farmers actively manage cropping systems to provide the kinds of food that people will buy at a sustainable price. Climate alteration and exposure to invasive pests, on the other hand, are unintentional drivers influenced by the social system. Farmers adjust reactively to these changes, designing adaptive management strategies to retain yields and profits. The iterative nature of the system provides the capacity to examine and test linkages between the social and biophysical (cropping system) domains – of crucial importance for addressing questions about sustainability, which ultimately are socio-ecological in nature.

Agriculture provides important ecosystem services, with the provision of food, fuel, and fiber the most appreciated. Less recognized, however, are agriculture's contributions to biogeochemical services, such as stabilizing climate and providing clean water, and to biodiversity services, such as pollination or suppression of pest and disease. Agriculture can also provide disser-

*Figure 1*
A Socioecological Model for Agriculture




Source : G. Philip Robertson and Stephen K. Hamilton, "Long-Term Ecological Research at the Kellogg Biological Station LTER Site : Conceptual and Experimental Framework" in *The Ecology of Agricultural Landscapes : Long-Term Research on the Path to Sustainability*, ed. Stephen K. Hamilton, Julie E. Doll, and G. Philip Robertson (New York : Oxford University Press, 2015), 1 – 32.

vices to ecosystems : creating nitrate pollution rather than clean water, or causing soil erosion rather than soil conservation.[13] At times, it can be useful to view an ecosystem service as the reduction of a disservice, as, for example, when comparing a new practice to business as usual.[14]

Another important consideration is scale : agricultural sustainability is entirely scale-dependent.[15] For example, an agricultural or land management practice that is sustainable within an individual field may lack sustainability at the larger farm scale, especially if the inputs required to maintain stable production eventually exceed the capacity of the farm to provide them. Likewise, farm-scale sustainability is nested within the capacity of local and regional systems to both sustain resources and mitigate harm. Even though the long-term supply of fertilizer might be stable, for example, and the economic cost of fertilizer to the farmer is easily repaid via increased grain production, the system becomes less sustainable at the regional scale : through a process known as *eutrophication*, reactive nitrogen and phosphorus that escape from the farm pollute groundwater drinking supplies and damage freshwater lakes and coastal waters through harmful algal blooms and attendant "dead zones."[16]

Ultimately, sustainability must be judged at the global scale, a precept driven home by the recent debates over the climate cost of indirect land use associated with biofuels expansion. Converting land from food production into fuel production in one location (for example, the U.S. Midwest) logically results in new land conversion for food production elsewhere (for example, Amazonia). This conversion process releases greenhouse gases and substantially reduces the global climate benefit of biofuels.[17] In another example, national environmental policies that depress food production in one region of the globe may lead to expansion or chemical intensification of food production elsewhere. In some cases, this outcome will lead to no net environmental benefit at the global scale, but rather to a geographic shift in agriculture's environmental burden; at worst, it can lead to the perverse outcome of a global environment that is worse off. To recognize these geographic tradeoffs requires scaling the consequences of local practices to the globe.

The concept and vision of sustainable agriculture arose in the United States in the 1980s, rooted in the moral and political values of John Locke's writings in the 1600s and Thomas Jefferson's in the 1700s and, more recently, in the sense of place introduced by the poetry and writings of Wendell Berry and Wes Jackson.[18] Conservation and the preservation of natural resources – concepts largely derived from the writings of Aldo Leopold, Louis Bromfield, and Edward Faulkner – are also integral to the vision.[19] Robert Rodale extended this notion to regenerative agriculture, which not only conserves but builds the productive potential of the natural resource base.[20]

The management of soil organic matter looms large in these works, and is embodied in the "humus farming" school as practiced in England and Europe, and popularized as organic agriculture in the United States by Jerome Rodale in 1945.[21] The interconnectedness of soil, plant, animal, and human health provided a philosophical foundation for organic farming. Today, organic agriculture continues to focus on cultivating the "living soil": optimizing the use of biological processes, especially soil-based, while avoiding synthetic chemicals and fertilizer use. The notion of sustainable intensification incorporates the goal of optimizing biological processes to reduce reliance on synthetic chemicals, but does not necessarily advocate their elimination.[22]

In the United States, the 1980s farm crisis added urgency to the social dimensions of agriculture. Declining farm incomes, the deterioration of rural communities, and the steady disappearance of midsized farms forced sustainable agriculture to broaden its vision. It began to incorporate rural community health and the well-being of farm families. Globalization – with its emphasis on cost efficiencies and emerging competitors in geographically distant places – has added new pressures.

One outcome of intensification is the newly vertical orientation of animal agriculture. This integration marks some major changes. First, the labor force no longer resembles family farms of the past. Second, in many parts of the world, there is a massive, ongoing replacement of integrated farm-livestock operations by large animal-feeding operations. Third, animals are becoming more and more geographically distant from both their main source of food and from sites where their manure could be efficiently used as fertilizer.

Today, the boundaries of sustainable agriculture extend well beyond the farm. Those structuring and designing food systems now consider interdependencies among farm community developments. Farm size, community interaction, and the globalization of trade and capital markets all interact to effect both social and economic well-being in major ways. A recent call to broaden the definition of sustainable intensification to explicitly include issues of social justice, in particular the equitable distribution of food, and decision processes that include individual empowerment, reflects this growth.[23]

The current vision for sustainable agriculture thus draws on a rich philosophical base, informed by a growing body of systems-level research that has made substantial progress toward identifying key processes and actors. Ultimately, of course, the vision and its enactment reflect societal values; sustainability is, after all, a social construct. Science identifies the component parts and players and outlines how they interact in different contexts to produce different outcomes. Society prioritizes those outcomes and decides which policies and behaviors will be most effective in achieving them.

Because the marketplace does not value many of the services and products of agriculture that are critical to environmental and human welfare, and because the political process either cannot or will not do the same, there is a high level of disarray with respect to operationalizing the concept of sustainable agriculture.[24] We can conceptualize sustainable agriculture narrowly as the production of food and other agricultural products in a manner that protects the ability of future generations to do so, and more broadly as production that enhances human and environmental welfare. However, because much of today's debate about agricultural sustainability reflects differences in values that have not yet been sorted out, there is less agreement about what *practices* constitute sustainable agriculture. The current debate over genetically modified organisms reflects precisely this conflict. Do we value profitability over environmental risk? Intellectual property rights over equitable access to technology? Convention over novelty? Here, science provides some useful guidance but few absolute answers.

So what agricultural practices are sustainable? As noted earlier, sustainability demands that practices be economically viable, environmentally safe, and socially acceptable. Research over the past few decades has taught us that there is no single prescription. There are as many permutations of sustainable practices as there are combinations of cropping systems, local environments, and social contexts. Nevertheless, locally sustainable systems share at least two attributes: they are resource conservative and they rely more on internal ecosystem services than on external inputs.[25]

Resource conservation means that agronomic management conserves, if not enhances, the resources that promote production. Soil, water, and biodiversity resources come first to mind. As foundational building blocks, they provide the basis for sustained crop and animal productivity. The basic principle of humus farming still holds: the soil sustains. Avoid erosion and build soil organic matter, and good will follow. Soil organic matter typically declines 40 – 60 percent upon conversion of natural lands to cropland or pasture. But this organic matter is vital, providing habitat and energy for beneficial soil microorganisms, a soil structure that is favorable for root growth and water retention, and a chemical composition that delivers nutrients to microbes and plants when they need it.

We are only beginning to understand the importance of biodiversity in agriculture, which historically has opted to reduce plant diversity and largely ignore insect and soil microbial diversity. We now know that plant diversity can improve crop performance: both rotational diversity that increases the number of crop species within a multiyear rotation, and landscape diversity that increases the number of plant species, both crop and native, in the larger landscape. Rotational benefits are related to nutrient availability, soil organic matter accumulation, and pathogen suppression. Landscape benefits are related to insect pest suppression and pollination: landscape diversity provides habitats for natural enemies of crop pests as well as for pollinators, especially during times of the year when crops are not present or not flowering. Soil microbial diversity, on the other hand, is still largely a black box waiting to be explored. With new genomic tools we are beginning to know which species are present in soil. Many are beneficial; by and large, however, we do not understand their functional significance. The little we know suggests that these species have functions that promote growth and plant nutrient acquisition, suppress pathogens, and consume greenhouse gases. As we continue to probe soil microsites and the plant microbiome, these resources are likely to become ever more valued.

The reliance on processes internal to the farm, rather than external inputs, means soil and biodiversity resources are managed in a way that maximizes their delivery of ecosystem services. The ready availability of synthetic chemicals has displaced many of the services that could otherwise be delivered or might have, in the past, been provided by the original, unconverted ecosystem. Nitrogen fertilizer, for example, has largely removed the need for biological nitrogen fixation by legume crops in modern cropping systems. Yet we know that legumes – plants that obtain their nitrogen from the air via symbiosis with soil bacteria – can provide ample nitrogen to subsequent crops, especially if grown as cover crops first. In one long-term cropping system experiment in Michigan, legumes provided two-thirds of the nitrogen needed by corn and wheat in the rotation.[26]

Likewise, in natural ecosystems, insect herbivory is suppressed by structural and trophic complexity that provides habitat and food for insects and birds that also prey on pests. In most intensively farmed systems, pests are controlled with insecticides; in some cases, as with transgenic "Bt" corn and other crops, the insecticide is produced by the plant itself. Building greater plant diversity into a cropping system – whether within fields, at field edges, or in the landscape – could allow the ecosystem to provide more pest protection, which is now provided by external inputs. At the moment, many of these services are being provided unknowingly. For example, entomologist Douglas Landis and colleagues estimated that lady bird beetles, who have a voracious appetite for aphids, saved soybean farmers in four Midwest states (Iowa, Michigan, Minnesota, and Wisconsin) $239 million in insecticide costs for 2008 alone.[27] And their later work showed that simplified landscapes with greater quantities of corn crops for increased production of corn ethanol significantly suppress this valuable service.[28]

Full knowledge of the benefits provided by reintroduced or enhanced ecosystem services means evaluating potential tradeoffs as well. For example, no-till soil management (planting a crop without plowing) can help to build soil organic matter by slowing decomposition and thus is a resource-conserving sustainable cropping practice. Plowing, however, is used to control early season weeds; so in the absence of plowing, weeds must be controlled with additional herbicides. Likewise, recycling animal manure back onto fields can save the greenhouse gas cost of manufactured fertilizer and help to build soil organic matter. However, manure can become a source of pollution rather than a valuable service if applied to fallow fields without crops to capture the manure's nitrogen and phosphorus.

With sufficient knowledge, such tradeoffs can be minimized and practices with multiple cobenefits can be encouraged. For example, winter cover crops, which are grown on winter-fallowed fields and killed prior to establishment of the main crop in the spring, can build soil organic matter, suppress weeds without additional herbicides, and reduce off-season nitrate leaching, phosphorus runoff, and soil erosion. Evaluating each cropping practice as part of a whole system can provide a more complete picture of direct benefits, indirect synergies, and trade-offs.

With a number of sustainable practices widely recognized, why are farmers not adopting them? Education, cultural norms, and access to technology play a part, but social science research tells us that the main barrier to the adoption of sustainable practices by farmers is economic cost. For practices that can be adopted with clear financial benefits and short payback periods, adoption is rapid. Glyphosate-resistant soybeans, for example, which permit the substitution of a less toxic herbicide (glyphosate) for ones that are both longer lived and more toxic and mobile in the environment, achieved over 90 percent adoption rates by U.S. farmers over a decade.[29] Continuous no-till soil management, on the other hand, has been feasible for more than thirty years but is presently used on only 12 percent of U.S. corn acreage.[30]

Agricultural and resource economist Scott Swinton and colleagues asked Michigan grain farmers why they aren't adapting sustainable practices like no-till.[31] They found that those practices known to provide environmental benefits were most likely to be adopted without further incentives if they saved labor or inputs, or improved farmstead health such as by raising drinking water quality without reducing expected crop revenue. Perhaps more important, they also discovered that almost all farmers and especially those managing large farms were willing to accept reasonable payments for adopting specific practices. Their willingness to accept payments was revealed in experimental auctions that asked how many of their acres they would enroll in a particular set of practices for a given payment amount. Results revealed that less payment would be required for practices they believed would provide benefits close to home. For example, adopting practices that build soil organic matter and reduce nitrate leaching would require lower payments than would practices that reduce greenhouse gas emissions, which they considered more of a global problem.



Swinton and colleagues concluded that the most important drivers of current practices are past practices, cultural norms, available technology, and, most of all, policies and markets that support sustained profitability. While most farmers value environmental stewardship, history teaches us that sustained profitability is necessarily an overriding concern.[32] Clearly, then, the absence of economic incentives is one of the main barriers to farmers' adoption of more sustainable practices. When it comes to marketplace demands for low-cost food and society's demand for a healthful environment, most farmers are caught in the middle.[33]

While it is true that solutions to some of the most recalcitrant environmental ills of agriculture require not new knowledge but the political will to incentivize change, it is also true that solutions difficult to incentivize are – in essence – solutions that do not work.[34] We need new approaches, informed by innovative research. But what are the biggest challenges facing the discovery and deployment of effective solutions?

The single biggest challenge to the development of sustainable cropping systems is integration: ensuring that the systems we farm are sufficiently well understood to allow us to know how changes in one part will affect others, and ultimately deliver the mix of ecosystem services deemed optimal for a particular context. At present we largely lack this understanding, which requires a systems approach to ecological questions and a socioecological approach to understand the factors that affect management decisions.[35] Achieving this understanding will move us toward the adoption of sustainable practices much more quickly than the alternative piecemeal approach, which, in the past, has often led to unwelcome surprises and environmental regret.

Other, less conceptual challenges loom large, such as the need for further agricultural intensification to feed billions more people in the face of climate change, biodiversity loss, and an environment awash in nitrogen and other reactive molecules. United Nations population projections suggest that world population growth will grow to about 10 billion people by 2050, and by another billion by 2100. This represents a 35 percent increase in the number of people that must be fed over the next forty years. This population jump will be coupled with growing affluence that will allow people in many regions to afford more meat and dairy products in their diets, placing unprecedented demands on our global food systems. Conservative estimates suggest a doubling of the food supply will be necessary.[36] Little new land is available for production without sacrificing conservation goals, which means most of this new production should come from existing crop and range lands.

Recent analyses by environmental scientist and ecologist Jonathan Foley and colleagues have identified the potential for closing yield gaps, which can help with much of this future production.[37] Yield gaps represent the difference between actual and attainable yields in a given region, with attainable yields judged on the basis of field trials that use the best available technology to provide nutrients and water to crops. Foley and colleagues suggest that most major cereal crops – those on which the world now depends for 80 percent of its caloric needs – can be increased by 45 – 70 percent if best management practices were uniformly applied to existing crops.[38] For the most part, this involves effective use of irrigation where available and adequate provision of nitrogen, phosphorus, and potassium fertilizers. They suggest that the remaining gap between current crop production and future food needs could also be closed by reducing food waste and by shifting the protein sources of human diets from meat and dairy to grain.

Arguably, climate change trumps all as the biggest environmental threat with the most unknown consequences for agricultural sustainability. Because climate change is long-term and hidden by year-to-year variability, it can be difficult to document and fully understand. Nevertheless, changing rainfall and temperature patterns are already affecting farmer decisions and patterns of productivity in the United States. Changes in climate patterns observed in the Midwest already include longer growing seasons, more frequent extreme weather events (such as intense rainfalls), and significant increases in nighttime temperatures.[39]

On the one hand, longer growing seasons will benefit crops with high or broad temperature optima, including many vegetables. For grain crops, however, higher growing-season temperatures result in faster growth, which accelerates grain filling: the movement of sugars within the plant to grain. Faster grain filling means less time for photosynthesis during this period, leading to lower yields since less sugar is available for grain. Higher temperatures also reduce pollination success and accelerate crop water use, while benefiting weeds and pests, which flourish in warmer environments, then migrate. Higher temperatures are expected to decrease yields of most crops, and may have already depressed corn and wheat yields globally.[40]

Long-term changes in total precipitation are more difficult to detect and predict, but in the U.S. Midwest, rainfall has become less frequent but more intense.[41] As this trend continues, there will be a greater risk of summer drought and an increased risk of intense precipitation and seasonal flooding. This can delay crop planting, increase plant diseases, retard plant growth, and cause flooding, runoff, and erosion – all of which affect crop yields and exacerbate the loss of nutrients and soil to the environment.

The one bit of good news here is that additional carbon dioxide in the atmosphere can promote plant growth in some crops. Though only for the next few decades, the detrimental effects of high temperatures on wheat and soybeans will likely be more than offset by the positive effects of greater carbon dioxide.[42] However, this will not be the case for other crops, like corn and rice. Further, weeds will also benefit from increasing carbon dioxide, often more than crops. And nonlegume forage quality will likely decline because plant nitrogen and protein concentrations typically decline with higher carbon dioxide concentrations.

The number of species and their biodiversity – the extent of genetic variability in those species – can affect the productivity, stability, and invasibility of ecosystems, as well as their susceptibility to disease and pests and their propensity to lose nutrient pollutants.[43] Plant biodiversity is especially important: as primary producers, plants provide habitat and substrates of varying compositions and complexities at different times of the year, thereby providing a foundational influence on the diversity and composition of other taxa.

Humans have a huge impact on the biodiversity of most ecosystems, both intentional and inadvertent. In cropping systems, biodiversity is tightly constrained to those species known to benefit growth and yields. In natural systems, biodiversity is unintentionally affected by human-influenced changes in climate and precipitation chemistry as well as by the introduction of exotic and invasive species and – potentially – new genes introduced by genetically engineered organisms.

Many of the effects of biodiversity loss are poorly understood; indeed, for microbial taxa, we barely know what is present. Better known are the economic costs of invasive species, estimated at more than $100 billion per year in the United States.[44] Invasive weeds in rangelands and croplands are obvious culprits. Less obvious are the pathogens and pests enabled by invasive plants and the beneficial organisms that invasive species displace, ranging from pollinators to biocontrol agents to symbionts. We know little about the susceptibility of different ecosystems – including crop and rangeland – to invasion, and therefore little about the attributes of plant systems that make them more or less invasive and the mechanisms that could be employed to better protect and enhance the services provided by biodiversity. Less still is known about the effects of genetically engineered organisms in the environment, in particular the controls on (and consequences for) gene flow from crop to wild populations.[45]

A further biodiversity challenge is understanding how lost biodiversity can be replaced or enhanced on crop and rangelands of low fertility. Rebuilding plant communities that can better provide provisioning, biogeochemical, and biodiversity services requires knowledge of key plant-associated taxa: beneficial insects and members of the soil, rhizosphere, and endophytic microbial communities, in particular. This will become especially important as we consider the use and restoration of marginal lands by biofuel crops.

Nitrogen fertilizer is both a boon and bane of modern agriculture. Over the past century, global rates of nitrogen fertilizer consumption have increased from 0.2 kilograms of nitrogen per person in 1900 to approximately 14 kilograms per person in 2000.[46] The annual production of nearly one hundred teragrams of synthetic nitrogen fertilizer per year for agriculture now represents over twice the amount of nitrogen fixed in natural preindustrial ecosystems.[47] The benefits of this use are unquestionable, and careful augmentation in some regions will be important for closing yield gaps, particularly in sub-Saharan Africa.[48] There are, however, big environmental costs to this use: of the twelve teragrams of nitrogen applied to U.S. agriculture in fertilizer each year, only about two teragrams are consumed by people. The remainder is added to the environment, where it impacts ecosystems downwind and downstream.[49]

Ecosystem alterations include coastal hypoxia caused by riverine nitrate export; climate change caused, in part, by the production of the greenhouse gas nitrous oxide, which is about three hundred times more effective than carbon dioxide at trapping heat in the lower atmosphere and also destroys protective ozone in the stratosphere; nitrogen deposition caused by the volatilization of ammonia gas and the microbial production of the gas nitric oxide, which contributes to acid rain and ozone production in the lower atmosphere; and, finally, groundwater nitrate pollution that hits levels exceeding human health thresholds.

Other reactive chemicals applied to agriculture – phosphorus and pesticides, in particular – also create harm when they escape from farm fields, though pesticide effects tend to be more localized due to less environmental mobility. Nevertheless, nutrient and pesticide conservation in general provide a major challenge for sustainable agriculture.

The potential for agriculture to be sustainable – to produce sufficient food and other agricultural products for today in a manner that promotes human and environmental welfare and protects the ability of future generations to do so – is strong. Meeting the sustainability challenges of further intensification, climate change, biodiversity loss, and other environmental changes will be difficult; but with the right incentives, innovative research, and political will, it can happen.

Is today's agriculture sustainable? Not by a long shot. Tomorrow's could be, if we care enough to act.

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# The Ethics of Food, Fuel & Feed

*Brian G. Henning*

*Abstract: As the collective impact of human activity approaches Earth's biophysical limits, the ethics of food become increasingly important. Hundreds of millions of people remain undernourished, yet only 60 percent of the global harvest is consumed by humans, while 35 percent is fed to livestock and 5 percent is used for biofuels and other industrial products. This essay considers the ethics of such use of edible nutrition for feedstock and biofuel. How humanity uses Earth's land is a reflection of its values. The current land-use arrangements, which divert 40 percent of all food to feed animals or create fuels, suggest that dietary and transportation preferences of wealthier individuals are considered more important than feeding undernourished people, or the stability of the wider biotic community.*

As the collective impact of human activity approaches Earth's biophysical limits, the ethics of food become increasingly important. Human agriculture has a tremendous impact on global ecosystems. Worldwide agriculture has already "cleared or covered 70 percent of the grassland, 50 percent of the savanna, 45 percent of the temperate deciduous forest, and 27 percent of the tropical forest biome."[1] Despite the scale of global agricultural production, more than eight hundred and seventy million people remain undernourished.[2] It is striking, then, that only 60 percent of the global harvest is consumed by humans, while another 35 percent is fed to livestock and the remaining 5 percent is used for biofuels and other industrial products.[3]

This essay considers whether such use of edible nutrition for feedstock and biofuel production is ethically justified. The analysis will proceed in two parts: the first part builds on earlier work that examines the impact of using feedstock to create meat and other animal-based food products; the second part considers the ethics of biofuel production, which has been left out of earlier analysis.[4] I conclude that although there are important and morally relevant differences between various modes of agricultural production, given the present and projected size of the

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human population, eating grain-fed animals and converting food to fuel are difficult to ethically justify.

How the human community chooses to use the land available to it is a reflection of its values. The current land-use arrangements, which divert 40 percent of all food to feed animals or create fuels, reflect values suggesting that the dietary and transportation preferences of wealthier individuals are more important than both feeding the malnourished and stabilizing the wider biotic community.

As the ethicist Paul Thompson has noted, the term ethics is sometimes misunderstood in scientific contexts, where its meaning is often limited to codes of conduct within a professional field.[5] In this context, to act ethically often means little more than to act in accordance with professional protocol. However, when philosophers use the term, it refers to fundamental conceptions of how moral agents ought to act within their world relative to competing conceptions of what is good or has value. Thus, as Thompson notes, "While philosophical ethics does not necessarily shy away from prescriptive statements that say what people should be doing, the point of a philosophical analysis is to illustrate and analyze the background assumptions and context in which the prescription is grounded."[6] In this sense, the present analysis is a work of philosophical ethics.

In a previous article, I systematically considered the impact of intensive, feedstock-based livestock production on human health and the environment.[7] I demonstrated that human health is greatly affected by both the overconsumption and production of animal products. Indeed, by contributing to the prevalence of chronic diseases and to the spread of both antibiotic resistant infections and infectious diseases, the mass production and overconsumption of meat constitutes one of the single greatest threats to public health.[8]

Grain-fed livestock production also has significant consequences for Earth's water, land, and air. Globally, livestock and their feed crops consume large quantities of freshwater and contribute to the pollution of waterways through agricultural runoff and untreated waste, along with the natural aftereffects of giving livestock access to waterways.[9] Also, by motivating significant land-use changes (LUC) for pasture and feed crops, livestock production is a leading cause of species extinction, deforestation, and soil erosion.[10] Finally, by contributing to deforestation and producing direct methane and indirect nitrous-oxide emissions, livestock are a significant source of the anthropogenic greenhouse gases (GHG) changing the climate.[11] Overall, agriculture is the single largest anthropogenic source of GHG, accounting for approximately 35 percent of all emissions.[12] This figure is more "than the emissions from worldwide transportation (including all cars, trucks, and planes) or electricity generation."[13] Livestock production represents nearly one-half of these agricultural GHG emissions (14.5 percent).[14] However, to properly understand the ecological impact of meat production, it is important to place the activity within the context of both expected population growth and projected rates of meat consumption.

Given the projected growth of the global middle class, the consumption of animals and animal-based products is expected to grow 73 percent between 2010 and 2050.[15] As the Food and Agriculture Organization (FAO) of the United Nations has noted, reducing the ecological impact of intensive livestock production is critically important. This reduction can be achieved by pricing water and the commons, decreasing or eliminating subsidies, and implementing manure management practices, among other techniques. Further, the FAO reports that deployment of current technologies and practices could reduce livestock-sector GHG emissions by up to one-third.[16]

However, ecologists Nathan Pelletier and Peter Tyedmers have demonstrated that these changes would not likely be sufficient – even if they were widely implemented – given the projected growth in meat consumption. Their analysis shows that if human activity is to remain within sustainable "environmental boundary conditions" for GHG emissions, reactive nitrogen mobilization, and anthropogenic biomass appropriation, agriculture will increasingly need to move away from the profligate use of edible nutrition to feed to livestock (and, as we will see, biofuels).[17] All human activity – including food production, energy production, and transportation – must fall within these limits if humanity is to avert "irreversible ecological change."[18]

While recognizing that their model embodies "considerable uncertainty," Pelletier and Tyedmers's conservative estimate is that "by 2050, the livestock sector alone may either occupy the majority of, or considerably overshoot, current best estimates of humanity's safe operating space in each of these domains."[19] Specifically, by 2050, in order to meet FAO projected demand for animal products, livestock production will require 70 percent of the sustainable boundary conditions for greenhouse gas emissions, 294 percent of sustainable reactive nitrogen mobilization, and 88 percent of sustainable biomass appropriation.[20] Again, these are the sustainable boundary thresholds for all human activity, not merely agriculture. As a point of comparison, Pelletier and Tyedmers noted that if humans derived their nutrition entirely from plant sources, agriculture could use only 1.1 percent of sustainable GHG emissions, 69 percent of sustainable reactive nitrogen mobilization, and 1.1 percent of sustainable biomass appropriation.[21] Pelletier and Tyedmers claim that as "the human species runs the final course of rapid population growth before beginning to level off midcentury, and food systems expand at commensurate pace, reining in the global livestock sector should be considered a key leverage point for averting irreversible ecological change and moving humanity toward a safe and sustainable operating space."[22]

The mass production and consumption of grain-fed animals is a significant source of human disease and is a leading cause behind the depletion and pollution of freshwater sources, the degradation and deforestation of land, the extinction of species, and the warming of the planet. Further, increasing demand to eat animals decreases the total nutrition available to humans, making the task of feeding eight hundred and seventy million malnourished people all the more difficult. As ecologist Jonathan Foley has stated, "Using highly productive croplands to produce animal feed, no matter how efficiently, represents a net drain on the world's potential food supply."[23] This use of edible nutrition reflects the human community's ethical values. Given the current and projected quantity of edible nutrition used to feed livestock, preserving the ability of wealthier individuals to consume animals appears to have far greater value than achieving the most sustainable means possible for feeding a growing world population. But what, then, are the values reflected in the diversion of edible nutrition to create biofuels?[24]

Though biofuel production diverts significantly less of the global harvest than livestock production (5 percent devoted to fuels compared to the 35 percent that is allocated to feed), the amount is not inconsequential.[25] For instance, in 2011, 40 percent of all corn grown in the United

States was turned into ethanol.[26] Further, biofuel production is often mandated by laws requiring the production of certain quantities of biofuel. For instance, in the European Union, biofuels must account for 10 percent of all fuel by 2020; in the United States, 36 billion gallons must be produced annually by 2022.[27] As the Nuffield Council on Bioethics notes in its report on biofuels, the motivations behind the creation of biofuel quotas are diverse and complex: "The expectation of some was that they [biofuels] would solve these great challenges all at once: i.e., provide a new source of income for farmers and revenue from 'clean' technology, as well as renewable – and therefore endless – sources of fuel, leading to far less greenhouse gas (GHG) emissions than fossil fuels."[28] But as we will see, all of these claims about biofuels have been brought into question. Let us first examine the claims that biofuels mitigate GHG emissions.

When burned, both petroleum-based and plant-based fuels release large quantities of carbon dioxide into the atmosphere. However, unlike fossil fuels, the plants used for biofuels remove carbon dioxide from the atmosphere during their growing phase. From this fact follows the widespread claim that biofuels can be used without significantly adding to the net release of carbon dioxide into the atmosphere. Indeed, the International Energy Agency estimates that biofuels could reduce current fossil fuel–related carbon dioxide emissions from cars by 20–50 percent.[29] However, several studies have questioned the potential for biofuels to mitigate GHG emissions.[30] In particular, research has shown that corn-based ethanol in the United States likely leads to a net increase in GHG.[31]

Proponents of biofuels contend that the problem is not with biofuels per se but with the crops being used. If, for instance, corn were replaced with a new, second generation of more efficient biofuels, such as miscanthus or jatropha, the GHG mitigation potential of biofuels could be achieved. The FAO estimates that if such second-generation biofuels are grown on 25 percent of all agricultural land, they could replace up to 14 percent of all transportation fuels.[32] Indeed, the Nuffield Council concludes that, since the demand for liquid transport fuels is not likely to decrease in the coming decades, there is a duty to support the development of second-generation biofuels.[33] Ideally, these biofuels would satisfy five ethical principles:

1) The development of biofuels should not come at the expense of essential human rights (including comprehensive health and work rights, access to sufficient food and water, and land entitlements).

2) Biofuels should be environmentally sustainable.

3) Biofuels should contribute to the net reduction of total GHG emissions; they should not exacerbate global climate change.

4) Biofuels should develop in accordance with trade principles that are fair and recognize the rights of people to just reward, including labor rights and intellectual property rights.

5) The costs and benefits of biofuels should be distributed in an equitable way.[34]

There is not enough space here to examine each of these principles. At present, the pressing question to answer is: can second-generation biofuels meet the principles set out by the Nuffield Council?

Although second-generation fuels are very likely to be more efficient than their predecessors, some studies have indicated that, if indirect land-use changes (iLUC) are considered, these gains may be absorbed, or even lost, if land that is currently a carbon sink is converted into a source.[35] When lands that could be used for growing food or feed crops are instead used to grow biofuels, this creates pressures to convert marginal or forested land to agricultural production.[36] If one's analysis includes these iLUC, it is likely that even second-generation biofuels will lead to a net increase in GHG, violating the Nuffield Council's third principle.[37] Yet beyond the technical viability of second-generation biofuels to achieve much-needed GHG reductions, we must also ask whether it would be ethically defensible to divert 25 percent of all agricultural land – which is currently used to grow crops to feed humans – to replace 14 percent of transportation fuels.

Further, critics of biofuels claim that the diversion of edible food crops to biofuel production decreases the global supply of food commodities. This decrease in supply increases the price of food commodities, and such price increases disproportionately harm the poor. Thus, biofuels are criticized as unethical for exacerbating and contributing to worldwide hunger. Wealthy individuals are filling their vehicles with fuels created from crops that could have been used to feed the poor. This dimension of the debate over biofuel production first came to the fore in 2006, when biofuels were blamed for a dramatic spike in global food prices, which caused widespread suffering and instability in developing nations.[38] The food versus fuel debate reached its zenith in 2007, when Jean Ziegler, the United Nations' special rapporteur, condemned biofuels as "a crime against humanity."[39]

However, as Paul Thompson has demonstrated, this analysis of the ethics of biofuels is too facile. First, it is not clear that shifting biofuels from edible plants to nonedible and more efficient crops will mitigate biofuels' effect on food prices. In a global food commodity market, it is not possible to segregate food and fuel crops. For instance, if biofuel production is shifted from corn to miscanthus, this will still result in fewer acres of corn being planted, which will have the same economic effect on food prices as having diverted the corn to biofuel production.[40] Thus, Thompson concludes: "Over the long run, relying on the use of nonfood crops as fuel feedstocks will translate into land use decisions that preserve the same food vs. fuel tensions noted in the original critiques."[41]

However, as Thompson has demonstrated, this analysis of the ethics of biofuels is still incomplete: it fails to recognize that food insecurity is highest among poor people who are themselves food producers.[42] Of the world's poor, it is primarily the 20 percent who live in urban areas and buy (rather than grow) food that are affected by the increase in food commodity prices caused by biofuel production. Thus, although biofuel production will increase food prices, harming the 20 percent of the world's urban poor, for the 80 percent of the world's poor who are food producers, increases in food commodity prices can in principle be economically beneficial.[43] Yet, as Thompson rightly notes, although there is the potential for commodity price increases to empower the food-producing poor, these theoretical benefits are unlikely to be realized in the absence of concerted implementation programs.

Although defenders of biofuels argue that they can benefit poor farmers, there is very little discussion of the peculiar vulnerabilities that poor farmers face in an era of rapid technological change. There is every reason to suspect that many of the scientists, public institutions, and private firms that are in the process of developing the next generation of biofuels operate from a position of naiveté about the most likely impact of the technology that they are developing.[44]

To summarize, there are serious technical and ethical concerns regarding the use of feedstock and biofuels. Though the technical advances in livestock and biofuel production are likely to make them more efficient, this alone does not address the underlying ethical issues regarding land use and food security for the world's poor. The underlying ethical issue of the widespread use of both feedstock and biofuels is one of resource allocation and land use. Is it ethically defensible to use land to create feed for animals when doing so is often harmful for human health, uses large quantities of increasingly scarce freshwater, contributes significantly to water pollution, exacerbates LUC that cause species extinction, and significantly contributes to global climate change, all while reducing the total nutrition available for humans? Similarly, what values are reflected in the use of land to create crops (whether edible or not) that will be turned into biofuels so that wealthier individuals can drive vehicles with a potentially lower GHG footprint, when doing so increases the price of food for at least 20 percent of the urban poor, and is unlikely to benefit the remaining 80 percent of food-producing poor, who often do not have access to markets and technology that would allow them to benefit from higher food commodity prices?

The widespread and growing use of feedstock and biofuels reflects the human community's values. The current land use arrangements, which divert 40 percent of all food to feed animals or create fuels, reflect values that suggest that dietary and transportation preferences of wealthier individuals are more important than feeding people. If food were used to feed people directly, rather than to fatten cows or create fuel, it would increase the total supply of food. As Foley and his colleagues have noted, the wholesale shift to a plant-based diet would net up to three quadrillion calories annually, a 50 percent increase in the total supply of food.[45] They add: "Naturally, our current diets and uses of crops have many economic and social benefits, and our preferences are unlikely to change completely. Still, even small shifts in diet, say from grain-fed beef to poultry, pork or pasture-fed beef, can pay off handsomely."[46]

Thus, appropriately extended to include the present analysis of biofuels, the central claim of my earlier analysis remains true: although there are important and morally relevant differences in various modes of agricultural production, eating grain-fed animals and converting food to fuel are difficult to ethically justify when more than eight hundred and seventy million people are malnourished. Given the current and projected size of the human population, it will increasingly be necessary to modify not only how meat and biofuels are produced, but also dietary and transportation preferences themselves.

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3 Jonathan A. Foley, "Can We Feed the World and Sustain the Planet?" *Scientific American* 305 (5) (2011): 62.

[4] Brian G. Henning, "Standing in Livestock's 'Long Shadow': The Ethics of Eating Meat on a Small Planet," *Ethics & the Environment* 16 (2) (2011): 63–93.

[5] Paul B. Thompson, "The Agricultural Ethics of Biofuels: The Food *vs.* Fuel Debate," *Agriculture* 2 (4) (2012): 340.

[6] Ibid.

[7] Henning, "Standing in Livestock's 'Long Shadow.'"

[8] Ibid., 66.

[9] Ibid., 70. As the Nuffield Council notes in its report, biofuels are also a very large source of freshwater use and pollution. See Nuffield Council on Bioethics, *Biofuels: Ethical Issues* (London: Nuffield Council on Bioethics, 2011), 33; and Henning, "Standing in Livestock's 'Long Shadow,'" 69–71.

[10] Henning, "Standing in Livestock's 'Long Shadow,'" 72–73.

[11] Food and Agriculture Organization of the United Nations, *Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities* (Rome: Food and Agriculture Organization, 2013), xii, 15, http://www.fao.org/docrep/018/i3437e/i3437e.pdf.

[12] Foley, "Can We Feed the World and Sustain the Planet?" 63.

[13] Ibid.

[14] "Total GHG emissions from livestock supply chains are estimated at 7.1 gigatonnes $CO_2$-eq per annum for the 2005 reference period. They represent 14.5 percent of all human-induced emissions using the most recent IPCC estimates for total anthropogenic emissions. " See Food and Agriculture Organization of the United Nations, *Tackling Climate Change through Livestock*, 15.

[15] "Driven by strong demand from an emerging global middle class, diets will become richer and increasingly diversified, and growth in animal-source foods will be particularly strong; the demand for meat and milk in 2050 is projected to grow by 73 and 58 percent, respectively, from their levels in 2010. . . . With demand for livestock products projected to grow by 70 percent by 2050, concerns about the unbalanced nature of this growth and its attendant environmental and socio-economic consequences are increasing. To date, most of the increase in demand has been met by rapidly growing, modern forms of production while hundreds of millions of pastoralists and small-holders, who depend on livestock for survival and income, have little access to emerging opportunities for growth." See ibid., 1, 83.

[16] Ibid., xiii, 83.

[17] Nathan Pelletier and Peter Tyedmers, "Forecasting Potential Global Environmental Costs of Livestock Production 2000–2050," *Proceedings of the National Academy of Sciences* 10 (1073) (2010): 1–4; and Nathan Pelletier and Peter Tyedmers, "Supporting Information," *Proceedings of the National Academy of Sciences* 10 (1073) (2010): 1–4.

[18] Pelletier and Tyedmers, "Forecasting Potential Global Environmental Costs of Livestock Production 2000–2050," 3.

[19] Ibid., 2.

[20] Ibid. Given that their analysis is limited to *direct* emissions and biomass appropriation, Pelletier and Tyedmers's analysis is, if anything, overly conservative. For more on this, see Henning, "Standing in Livestock's 'Long Shadow,'" 84.

[21] Pelletier and Tyedmers, "Supporting Information," 3.

[22] Pelletier and Tyedmers, "Forecasting Potential Global Environmental Costs of Livestock Production 2000–2050," 3. As David Tilman rightly brought to my attention, Pelletier and Tyedmers's claim that food systems will grow at a "commensurate pace" is not quite accurate. Tilman notes that food systems have been expanding at a pace about double the rate of

population growth because of the income-dependence of dietary choices, especially per capita consumption rates for various meats and animal products.

23 Foley et al., "Solutions for a Cultivated Planet," 2.

24 The term *biofuels* will be used broadly to refer to technologies used to create liquid transportation fuels such as ethanol and biodiesel.

25 My analysis here is greatly indebted to the work of Paul B. Thompson, who is the global expert in the ethics of biofuels. See Paul B. Thompson, "The Agricultural Ethics of Biofuels: Climate Ethics and Mitigation Arguments," *Poiesis & Praxis* 8 (4) (2012): 169 – 189; and Thompson, "The Agricultural Ethics of Biofuels: The Food *vs.* Fuel Debate."

26 Madhu Khanna and Xiaoguang Chen, "Economic, Energy Security, and Greenhouse Gas Effects of Biofuels: Implications for Policy," *American Journal of Agricultural Economics* 95 (5) (2013): 1325.

27 Alena Buyx and Joyce Tait, "Ethical Framework for Biofuels," *Science* 332 (6029) (2011): 540.

28 Nuffield Council on Bioethics, "About," http://www.nuffieldbioethics.org/about; and Nuffield Council on Bioethics, *Biofuels: Ethical Issues*.

29 "Bioenergy is unique in being the only form of renewable energy that can at the same time be used for heating, electricity, and transport. Looking at transport, it is estimated by the International Energy Agency that biofuels should be able to reduce current fossil-fuel related carbon dioxide emissions from cars by 20 – 50 percent." See C. Gamborg, K. Millar, O. Shortall, and P. Sandøe, "Bioenergy and Land Use: Framing the Ethical Debate," *Journal of Agricultural and Environmental Ethics* 25 (6) (2012): 912.

30 Jason Hill, Erik Nelson, David Tilman, et al., "Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels," *Proceedings of the National Academy of Sciences* 103 (30) (2006): 11206 – 11210; Joseph Fargione, Jason Hill, David Tilman, et al., "Land Clearing and the Biofuel Carbon Debt," *Science* 319 (1235) (2008): 1235 – 1238; and Timothy Searchinger, Ralph Heimlich, R. A. Houghton, et al., "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change," *Science* 319 (5867) (2008): 1238 – 1240.

31 Searchinger et al., "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change," 1238 – 1240.

32 Cited in Gamborg, et al., "Bioenergy and Land Use," 917.

33 "If the first five Principles are respected and if biofuels can play a crucial role in mitigating dangerous climate change then, depending on additional key considerations, there is a duty to develop such biofuels." From Nuffield Council on Bioethics, *Biofuels: Ethical Issues*, 77.

34 Ibid.

35 "Thus although second-generation biofuel production is claimed to deliver greater savings in GHG emissions than first-generation biofuel production, these savings could be absorbed, or lost, in an indirect LUC, if production of the necessary biomass simply results in the displacement of cropland on to land that presently acts as a carbon sink, such as forest and pasture." From Gamborg et al., "Bioenergy and Land Use," 920.

36 Ibid., 913.

37 The Nuffield Council notes in *Biofuels: Ethical Issues* that iLUC are quite controversial and difficult to calculate.

38 Thompson's "Food *vs.* Fuel Debate" provides not only a history of the food versus fuel debate but also a careful ethical analysis. See also Nuffield Council on Bioethics, *Biofuels: Ethical Issues*, 30.

39 Grant Ferrett, "Biofuels 'Crime Against Humanity,'" *BBC News*, October 27, 2007, http://news.bbc.co.uk/1/hi/world/americas/7065061.stm. See also George Monbiot, "An Agricultural

Crime Against Humanity," *The Guardian*, November 6, 2007, http://www.monbiot.com/2007/11/06/an-agricultural-crime-against-humanity/.

40 Thompson, "Food *vs.* Fuel Debate," 347.

41 Ibid.

42 Ibid., 341.

43 Ibid., 341, 351–352. "De Schutter estimates that about 50 percent of those in extreme poverty are agricultural producers, while another 20 percent are landless laborers. The remaining 10 percent are scavengers who derive a living from accessing common pool resources available in forests and fisheries. As such, they too depend at least partially on a production-based food entitlement. Thus the presumption that rising food prices are unilaterally disastrous to the world's poorest people is based on a faulty understanding of the ethics of hunger."

44 Ibid., 355. "The empirical argument for concluding that the theoretical potential of benefit to the rural poor fails to satisfy the requirements of ethics is that such theoretical benefits are frequently unrealized in reality. . . . For reasons such as this, there is a [sic] now a broad skepticism about the ability of innovations in agricultural technology to actual [sic] benefit the poor. The skepticisms [sic] is widely in evidence in writings on biofuels." Ibid., 352.

45 Foley, "Can We Feed the World and Sustain the Planet?" 65.

46 Ibid.

*Inside back cover :* A high-diversity tropical rainforest in Panama represents the type of ecosystem that Earth will lose if diets and agricultural practices continue on their current paths. Photograph © David Tilman.

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