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REVIEW

Food Security: The Challenge of Feeding 9 Billion People

H. Charles J. Godfray,^{1*} John R. Beddington,² Ian R. Crute,³ Lawrence Haddad,⁴ David Lawrence,⁵ James F. Muir,⁶ Jules Pretty,⁷ Sherman Robinson,⁸ Sandy M. Thomas,⁹ Camilla Toulmin¹⁰

Continuing population and consumption growth will mean that the global demand for food will increase for at least another 40 years. Growing competition for land, water, and energy, in addition to the overexploitation of fisheries, will affect our ability to produce food, as will the urgent requirement to reduce the impact of the food system on the environment. The effects of climate change are a further threat. But the world can produce more food and can ensure that it is used more efficiently and equitably. A multifaceted and linked global strategy is needed to ensure sustainable and equitable food security, different components of which are explored here.

The past half-century has seen marked growth in food production, allowing for a dramatic decrease in the proportion of the world's people that are hungry, despite a doubling of the total population (Fig. 1) (1, 2). Nevertheless, more than one in seven people today still do not have access to sufficient protein and energy from their diet, and even more suffer from some form of micronutrient malnourishment (3). The world is now facing a new set of intersecting challenges (4). The global population will continue to grow, yet it is likely to plateau at some 9 billion people by roughly the middle of this century. A major correlate of this deceleration in population growth is increased wealth, and with higher purchasing power comes higher consumption and a greater demand for processed food, meat, dairy, and fish, all of which add pressure to the food supply system. At the same time, food producers are experiencing greater competition for land, water, and energy, and the need to curb the many negative effects of food production on the environment is becoming increasingly clear (5, 6). Overarching all of these issues is the threat of the effects of substantial climate change and concerns about how mitigation and adaptation measures may affect the food system (7, 8).

A threefold challenge now faces the world (9): Match the rapidly changing demand for food

from a larger and more affluent population to its supply; do so in ways that are environmentally and socially sustainable; and ensure that the world's poorest people are no longer hungry. This challenge requires changes in the way food is produced, stored, processed, distributed, and accessed that are as radical as those that occurred

during the 18th- and 19th-century Industrial and Agricultural Revolutions and the 20th-century Green Revolution. Increases in production will have an important part to play, but they will be constrained as never before by the finite resources provided by Earth's lands, oceans, and atmosphere (10).

Patterns in global food prices are indicators of trends in the availability of food, at least for those who can afford it and have access to world markets. Over the past century, gross food prices have generally fallen, leveling off in the past three decades but punctuated by price spikes such as that caused by the 1970s oil crisis. In mid-2008, there was an unexpected rapid rise in food prices, the cause of which is still being debated, that subsided when the world economy went into recession (11). However, many (but not all) commentators have predicted that this spike heralds a period of rising and more volatile food prices driven primarily by increased demand from rapidly developing countries, as well as by competition for resources from first-generation biofuels production (12). Increased food prices will stimulate greater investment in food production, but the critical importance of food to human well-being and also to social and political stability makes it likely that governments and other organizations will want to encourage food production beyond that driven by simple market mechanisms (13). The long-term nature of returns on investment for many aspects of food production and the importance of policies that promote sustainability and equity also argue against purely relying on market solutions.

So how can more food be produced sustainably? In the past, the primary solution to food shortages has been to bring more land into agriculture and to exploit new fish stocks. Yet over the past 5 decades, while grain production has more than doubled, the amount of land devoted to arable agriculture globally has increased by only ~9% (14). Some new land could be brought into cultivation, but the competition for land from other human activities makes this an increasingly unlikely and costly solution, particularly if protecting biodiversity and the public goods provided by natural ecosystems (for example, carbon storage in rainforest) are given higher priority (15). In recent decades, agricultural land that was formerly productive has been lost to urbanization and other human uses, as well as to desertification, salinization, soil erosion, and other consequences of unsustainable land

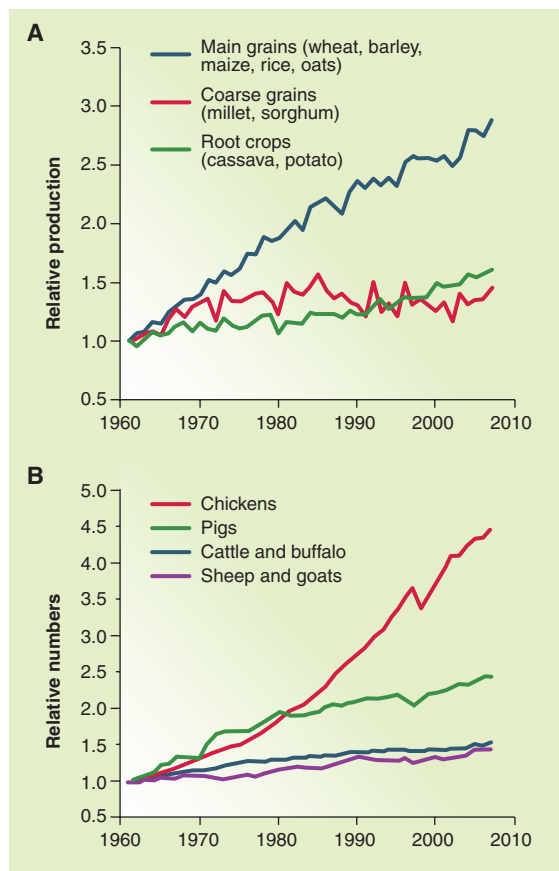


Fig. 1. Changes in the relative global production of crops and animals since 1961 (when relative production scaled to 1 in 1961). (A) Major crop plants and (B) major types of livestock. [Source: (2)]

¹Department of Zoology and Institute of Biodiversity at the James Martin 21st Century School, University of Oxford, South Parks Road, Oxford OX1 3PS, UK. ²U.K. Government Office for Science, 1 Victoria Street, London SW1H 0ET, UK. ³Agriculture and Horticulture Development Board, Stoneleigh Park, Kenilworth, Warwickshire CV8 2TL, UK. ⁴Institute of Development Studies, Falmer, Brighton BN1 9RE, UK. ⁵Syngenta AG, Post Office Box, CH-4002 Basel, Switzerland. ⁶Institute of Aquaculture, University of Stirling, Stirling FK9 4LA, UK. ⁷Department of Biological Sciences, University of Essex, Wivenhoe Park, Colchester, Essex CO4 3SQ, UK. ⁸Institute of Development Studies, Falmer, Brighton BN1 9RE, UK. ⁹Foresight, U.K. Government Office for Science, 1 Victoria Street, London SW1H 0ET, UK. ¹⁰International Institute for Environment and Development, 3 Endsleigh Street, London WC1H 0DD, UK.

*To whom correspondence should be addressed. E-mail: charles.godfray@zoo.ox.ac.uk

management (16). Further losses, which may be exacerbated by climate change, are likely (7). Recent policy decisions to produce first-generation biofuels on good quality agricultural land have added to the competitive pressures (17). Thus, the most likely scenario is that more food will need to be produced from the same amount of (or even less) land. Moreover, there are no major new fishing grounds: Virtually all capture fisheries are fully exploited, and most are overexploited.

Recent studies suggest that the world will need 70 to 100% more food by 2050 (1, 18). In this article, major strategies for contributing to the challenge of feeding 9 billion people, including the most disadvantaged, are explored. Particular emphasis is given to sustainability, as well as to the combined role of the natural and social sciences in analyzing and addressing the challenge.

Closing the Yield Gap

There is wide geographic variation in crop and livestock productivity, even across regions that experience similar climates. The difference between realized productivity and the best that can be achieved using current genetic material and available technologies and management is termed the “yield gap.” The best yields that can be obtained locally depend on the capacity of farmers to access and use, among other things, seeds, water, nutrients, pest management, soils, biodiversity, and knowledge. It has been estimated that in those parts of Southeast Asia where irrigation is available, average maximum climate-adjusted rice yields are 8.5 metric tons per hectare, yet the average actually achieved yields are 60% of this figure (19). Similar yield gaps are found in rain-fed wheat in central Asia and rain-fed cereals in Argentina and Brazil. Another way to illustrate the yield gap is to compare changes in per capita food production over the past 50 years. In Asia, this amount has increased approximately twofold (in China, by a factor of nearly 3.5), and in Latin America, it has increased 1.6-fold; in Africa, per capita production fell back from the mid-1970s and has only just reached the same level as in 1961 (2, 20). Substantially more food, as well as the income to purchase food, could be produced with current crops and livestock if methods were found to close the yield gaps.

Low yields occur because of technical constraints that prevent local food producers from

increasing productivity or for economic reasons arising from market conditions. For example, farmers may not have access to the technical knowledge and skills required to increase production, the finances required to invest in higher production (e.g., irrigation, fertilizer, machinery, crop-protection products, and soil-conservation measures), or the crop and livestock varieties that maximize yields. After harvest or slaughter, they may not be able to store the produce or have access to the infrastructure to transport the produce to consumer markets. Farmers may also choose not to invest in improving agricultural

Box 1. Sustainable intensification.

Producing more food from the same area of land while reducing the environmental impacts requires what has been called “sustainable intensification” (18). In exactly the same way that yields can be increased with the use of existing technologies, many options currently exist to reduce negative externalities (47). Net reductions in some greenhouse gas emissions can potentially be achieved by changing agronomic practices, the adoption of integrated pest management methods, the integrated management of waste in livestock production, and the use of agroforestry. However, the effects of different agronomic practices on the full range of greenhouse gases can be very complex and may depend on the temporal and spatial scale of measurement. More research is required to allow a better assessment of competing policy options. Strategies such as zero or reduced tillage (the reduction in inversion ploughing), contour farming, mulches, and cover crops improve water and soil conservation, but they may not increase stocks of soil carbon or reduce emissions of nitrous oxide. Precision agriculture refers to a series of technologies that allow the application of water, nutrients, and pesticides only to the places and at the times they are required, thereby optimizing the use of inputs (48). Finally, agricultural land and water bodies used for aquaculture and fisheries can be managed in ways specifically designed to reduce negative impacts on biodiversity.

productivity because the returns do not compare well with other uses of capital and labor.

Exactly how best to facilitate increased food production is highly site-specific. In the most extreme cases of failed states and nonfunctioning markets, the solution lies completely outside the food system. Where a functioning state exists, there is a balance to be struck between investing in overall economic growth as a spur to agriculture and focusing on investing in agriculture as a spur to economic growth, though the two are obviously linked in regions, such as sub-Saharan Africa, where agriculture typically makes up 20 to 40% gross domestic product. In some situations, such as low-income food-importing countries, investing purely in generating widespread income growth to allow food purchases from regions and countries with better production capabilities may be the best choice. When investment is targeted at food production, a further issue is the balance between putting resources into regional and national infrastructure, such as roads and ports, and investing in local social and economic capital (21, 22).

A yield gap may also exist because the high costs of inputs or the low returns from increased production make it economically suboptimal to raise production to the maximum technically attainable. Poor transport and market infrastructure raise the prices of inputs, such as fertilizers and water, and increase the costs of moving the food produced into national or world markets. Where the risks of investment are high and the means to offset them are absent, not investing can be the most rational decision, part of the “poverty trap.” Food production in developing countries can be severely affected by market interventions in the developed world, such as subsidies or price supports. These need to be carefully designed and implemented so that their effects on global commodity prices do not act as disincentives to production in other countries (23).

The globalization of the food system offers some local food producers access to larger markets, as well as to capital for investment. At the aggregate level, it also appears to increase the global efficiency of food production by allowing regional specialization in the production of the locally most appropriate foods. Because the expansion of food production and the growth of population both occur at different rates in different geographic regions, global trade is necessary to balance supply and demand across regions. However, the environmental costs of food production might increase with globalization, for example, because of increased greenhouse gas emissions associated with increased production and food transport (24). An unfettered market can also penalize particular communities and sectors, especially the poorest who have the least influence on how global markets are structured and regulated. Expanded trade can provide insurance against regional shocks on production such as conflict, epidemics, droughts, or floods—shocks that are likely to increase in frequency as climate change occurs. Conversely, a highly connected food system may lead to the more widespread propagation of economic perturbations, as in the recent banking crisis, thus affecting more people. There is an urgent need for a better understanding of the effects of globalization on the full food system and its externalities.

The yield gap is not static. Maintaining, let alone increasing, productivity depends on continued innovation to control weeds, diseases, insects, and other pests as they evolve resistance to different control measures, or as new species emerge or are dispersed to new regions.

Innovation involves both traditional and advanced crop and livestock breeding, as well as the continuing development of better chemical, agronomic, and agro-ecological control measures. The maximum attainable yield in different regions will also shift as the effects of climate change are felt. Increasing atmospheric CO₂ levels can directly stimulate crop growth, though within the context of real agricultural production systems, the magnitude of this effect is not clear (7). More important will be the ability to grow crops in places that are currently unsuitable, particularly the northern temperate regions (though expansion of agriculture at the expense of boreal forest would lead to major greenhouse gas emissions), and the loss of currently productive regions because of excessively high temperatures and drought. Models that couple the physics of climate change with the biology of crop growth will be important to help policy-makers anticipate these changes, as well as to evaluate the role of “agricultural biodiversity” in helping mitigate their effects (25).

Closing the yield gap would dramatically increase the supply of food, but with uncertain impacts on the environment and potential feedbacks that could undermine future food production. Food production has important negative “externalities,” namely effects on the environment or economy that are not reflected in the cost of food. These include the release of greenhouse gases [especially methane and nitrous oxide, which are more damaging than CO₂ and for which agriculture is a major source (26)], environmental pollution due to nutrient run-off, water shortages due to overextraction, soil degradation and the loss of biodiversity through land conversion or inappropriate management, and ecosystem disruption due to the intensive harvesting of fish and other aquatic foods (6).

To address these negative effects, it is now widely recognized that food production systems and the food chain in general must become fully sustainable (18). The principle of sustainability implies the use of resources at rates that do not exceed the capacity of Earth to replace them. By definition, dependency on nonrenewable inputs is unsustainable, even if in the short term it is necessary as part of a trajectory toward sustainability.

There are many difficulties in making sustainability operational. Over what spatial scale should food production be sustainable? Clearly an overarching goal is global sustainability, but should this goal also apply at lower levels, such as regions (or oceans), nations, or farms? Could high levels of consumption or negative externalities in some regions be mitigated by improvements in other areas, or could some unsustainable activities in the food system be offset by actions in the nonfood sector (through carbon-trading, for example)? Though simple definitions of sustainability are independent of time scale, in

practice, how fast should we seek to move from the status quo to a sustainable food system? The challenges of climate change and competition for water, fossil fuels, and other resources suggest that a rapid transition is essential. Nevertheless, it is also legitimate to explore the possibility that superior technologies may become available and that future generations may be wealthier and, hence, better able to absorb the costs of the transition. Finally, we do not yet have good enough

search on the ability of these and related programs to be scaled up to country and regional levels should be a priority (Fig. 2).

Strategies designed to close the yield gap in the poorest countries face some particular challenges (28). Much production is dominated by small-holder agriculture with women often taking a dominant role in the workforce. Where viable, investment in the social and economic mechanisms to enable improved small-holder yields,

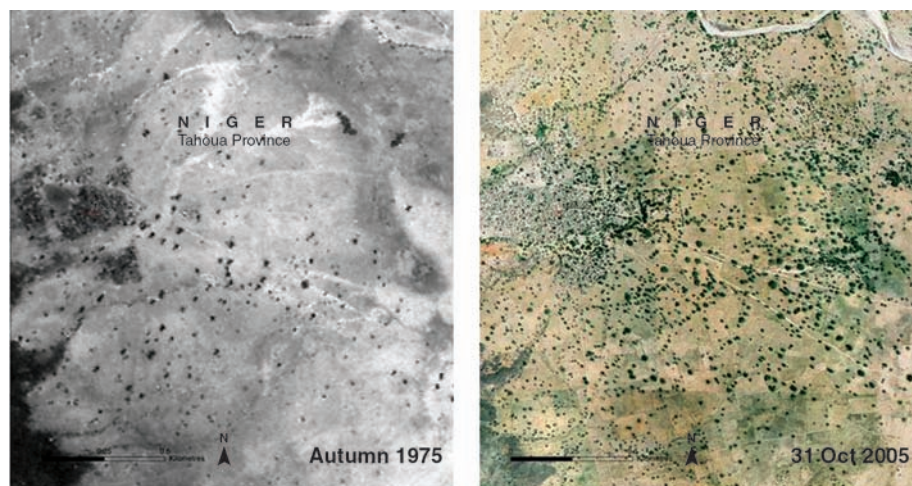


Fig. 2. An example of a major successful sustainable agriculture project. Niger was strongly affected by a series of drought years in the 1970s and 1980s and by environmental degradation. From the early 1980s, donors invested substantially in soil and water conservation. The total area treated is on the order of 300,000 ha, most of which went into the rehabilitation of degraded land. The project in the Illela district of Niger promoted simple water-harvesting techniques. Contour stone bunds, half moons, stone bunding, and improved traditional planting pits (zai) were used to rehabilitate barren, crusted land. More than 300,000 ha have been rehabilitated, and crop yields have increased and become more stable from year to year. Tree cover has increased, as shown in the photographs. Development of the land market and continued incremental expansion of the treated area without further project assistance indicate that the outcomes are sustainable (51, 52).

metrics of sustainability, a major problem when evaluating alternative strategies and negotiating trade-offs. This is the case for relatively circumscribed activities, such as crop production on individual farms, and even harder when the complete food chain is included or for complex products that may contain ingredients sourced from all around the globe. There is also a danger that an overemphasis on what can be measured relatively simply (carbon, for example) may lead to dimensions of sustainability that are harder to quantify (such as biodiversity) being ignored. These are areas at the interface of science, engineering, and economics that urgently need more attention (see Box 1). The introduction of measures to promote sustainability does not necessarily reduce yields or profits. One study of 286 agricultural sustainability projects in developing countries, involving 12.6 million chiefly small-holder farmers on 37 million hectares, found an average yield increase of 79% across a very wide variety of systems and crop types (27). One-quarter of the projects reported a doubling of yield. Re-

especially where targeted at women, can be important means of increasing the income of both farm and rural nonfarm households. The lack of secure land rights can be a particular problem for many poor communities, may act as a disincentive for small holders to invest in managing the land more productively, and may make it harder to raise investment capital (29). In a time of rising prices for food and land, it can also render these communities vulnerable to displacement by more powerful interest groups. Where the political will and organizational infrastructure exist, title definition and protection could be greatly assisted by the application of modern information and communication technologies. Even so, there will be many people who cannot afford to purchase sufficient calories and nutrients for a healthy life and who will require social protection programs to increase their ability to obtain food. However, if properly designed, these programs can help stimulate local agriculture by providing small holders with increased certainty about the demand for their products.

There is also a role for large-scale farming operations in poor-country agriculture, though the value and contexts in which this is feasible are much debated (30). This debate has been fanned by a substantial increase in the number of sovereign wealth funds, companies, and individuals leasing, purchasing, or attempting to purchase large tracts of agricultural land in developing countries. This external investment in developing-country agriculture may bring major benefits, especially where investors bring considerable improvements to crop production and processing, but only if the rights and welfare of the tenants and existing resource users are properly addressed (31).

Many of the very poorest people live in areas so remote that they are effectively disconnected from national and world food markets. But for others, especially the urban poor, higher food prices have a direct negative effect on their ability to purchase a healthy diet. Many rural farmers and other food producers live near the margin of being net food consumers and producers and will be affected in complex ways by rising food prices, with some benefitting and some being harmed (21). Thus, whereas reducing distorting agricultural support mechanisms in developed countries and liberalizing world trade should stimulate overall food production in developing countries, not everyone will gain (23, 32). Better models that can more accurately predict these complex interactions are urgently needed.

Increasing Production Limits

The most productive crops, such as sugar cane, growing in optimum conditions, can convert solar energy into biomass with an efficiency of ~2%, resulting in high yields of biomass (up to 150 metric tons per hectare) (33). There is much debate over exactly what the theoretical limits are for the major crops under different conditions, and similarly, for the maximum yield that can be obtained for livestock rearing (18). However, there is clearly considerable scope for increasing production limits.

The Green Revolution succeeded by using conventional breeding to develop F_1 hybrid varieties of maize and semi-dwarf, disease-resistant varieties of wheat and rice. These varieties could be provided with more irrigation and fertilizer (20) without the risk of major crop losses due to lodging (falling over) or severe rust epidemics. Increased yield is still a major goal, but the importance of greater water- and nutrient-use efficiency, as well as tolerance of abiotic stress, is also likely to increase. Modern genetic techniques and a better understanding of crop physiology allow for a more directed approach to selection across multiple traits. The speed and costs at which genomes today can be sequenced or resequenced now means that these techniques can be more easily applied to develop varieties of crop species that will yield well in challenging environments.

Table 1. Examples of current and potential future applications of GM technology for crop genetic improvement. [Source: (18, 49)]

| Time scale | Target crop trait | Target crops |
|------------------------------|--|---|
| Current | Tolerance to broad-spectrum herbicide | Maize, soybean, oilseed brassica |
| | Resistance to chewing insect pests | Maize, cotton, oilseed brassica |
| Short-term (5–10 years) | Nutritional bio-fortification | Staple cereal crops, sweet potato |
| | Resistance to fungus and virus pathogens | Potato, wheat, rice, banana, fruits, vegetables |
| | Resistance to sucking insect pests | Rice, fruits, vegetables |
| | Improved processing and storage | Wheat, potato, fruits, vegetables |
| Medium-term (10–20 years) | Drought tolerance | Staple cereal and tuber crops |
| | Salinity tolerance | Staple cereal and tuber crops |
| | Increased nitrogen-use efficiency | |
| Long-term (>20 years) | High-temperature tolerance | |
| | apomixis | Staple cereal and tuber crops |
| | Nitrogen fixation | |
| | Denitrification inhibitor production | |
| | Conversion to perennial habit | |
| | Increased photosynthetic efficiency | |

These include crops such as sorghum, millet, cassava, and banana, species that are staple foods for many of the world's poorest communities (34).

Currently, the major commercialized genetically modified (GM) crops involve relatively simple manipulations, such as the insertion of a gene for herbicide resistance or another for a pest-insect toxin. The next decade will see the development of combinations of desirable traits and the introduction of new traits such as drought tolerance. By mid-century, much more radical options involving highly polygenic traits may be feasible (Table 1). Production of cloned animals with engineered innate immunity to diseases that reduce production efficiency has the potential to reduce substantial losses arising from mortality and subclinical infections. Biotechnology could also produce plants for animal feed with modified composition that increase the efficiency of meat production and lower methane emissions.

Domestication inevitably means that only a subset of the genes available in the wild-species progenitor gene pool is represented among crop varieties and livestock breeds. Unexploited genetic material from land races, rare breeds, and wild relatives will be important in allowing breeders to respond to new challenges. International collections and gene banks provide valuable repositories for such genetic variation, but it is nevertheless necessary to ensure that locally adapted crop and livestock germplasm is not lost in the process of their displacement by modern, improved varieties and breeds. The trend over recent decades is of a general decline in investment in technological innovation in food produc-

tion (with some notable exceptions, such as in China and Brazil) and a switch from public to private sources (1). Fair returns on investment are essential for the proper functioning of the private sector, but the extension of the protection of intellectual property rights to biotechnology has led to a growing public perception in some countries that biotech research purely benefits commercial interests and offers no long-term public good. Just as seriously, it also led to a virtual monopoly of GM traits in some parts of the world, by a restricted number of companies, which limits innovation and investment in the technology. Finding ways to incentivize wide access and sustainability, while encouraging a competitive and innovative private sector to make best use of developing technology, is a major governance challenge.

The issue of trust and public acceptance of biotechnology has been highlighted by the debate over the acceptance of GM technologies. Because genetic modification involves germline modification of an organism and its introduction to the environment and food chain, a number of particular environmental and food safety issues need to be assessed. Despite the introduction of rigorous science-based risk assessment, this discussion has become highly politicized and polarized in some countries, particularly those in Europe. Our view is that genetic modification is a potentially valuable technology whose advantages and disadvantages need to be considered rigorously on an evidential, inclusive, case-by-case basis: Genetic modification should neither be privileged nor automatically dismissed. We also accept the

need for this technology to gain greater public acceptance and trust before it can be considered as one among a set of technologies that may contribute to improved global food security.

There are particular issues involving new technologies, both GM and non-GM, that are targeted at helping the least-developed countries (35, 36). The technologies must be directed at the needs of those communities, which are often different from those of more developed country farmers. To increase the likelihood that new technology works for, and is adopted by, the poorest nations, they need to be involved in the framing, prioritization, risk assessment, and regulation of innovations. This will often require the creation of innovative institutional and governance mechanisms that account for socio-cultural context (for example, the importance of women in developing-country food production). New technologies offer major promise, but there are risks of lost trust if their potential benefits are exaggerated in public debate. Efforts to increase sustainable production limits that benefit the poorest nations will need to be based around new alliances of businesses, civil society organizations, and governments.

Reducing Waste

Roughly 30 to 40% of food in both the developed and developing worlds is lost to waste, though the causes behind this are very different (Fig. 3) (16, 37–39). In the developing world, losses are mainly attributable to the absence of food-chain infrastructure and the lack of knowledge or investment in storage technologies on the farm, although data are scarce. For example, in India, it is estimated that 35 to 40% of fresh produce is lost because neither wholesale nor retail outlets have cold storage (16). Even with rice grain, which can be stored more readily, as much as one-third of the harvest in Southeast Asia can be lost after harvest to pests and spoilage (40). But the picture is more complex than a simple lack of storage facilities: Although storage after harvest when there is a glut of food would seem to make economic sense, the farmer often has to sell immediately to raise cash.

In contrast, in the developed world, pre-retail losses are much lower, but those arising at the retail, food service, and home stages of the food chain have grown dramatically in recent years, for a variety of reasons (41). At present, food is relatively cheap, at least for these consumers, which reduces the incentives to avoid waste. Consumers have become accustomed to purchasing foods of the highest cosmetic standards; hence, retailers discard many edible, yet only slightly

blemished products. Commercial pressures can encourage waste: The food service industry frequently uses “super-sized” portions as a competitive lever, whereas “buy one get one free” offers have the same function for retailers. Litigation and lack of education on food safety have led to a reliance on “use by” dates, whose safety margins often mean that food fit for consumption is thrown away. In some developed countries, unwanted food goes to a landfill instead of being used as animal feed or compost because of legislation to control prion diseases.

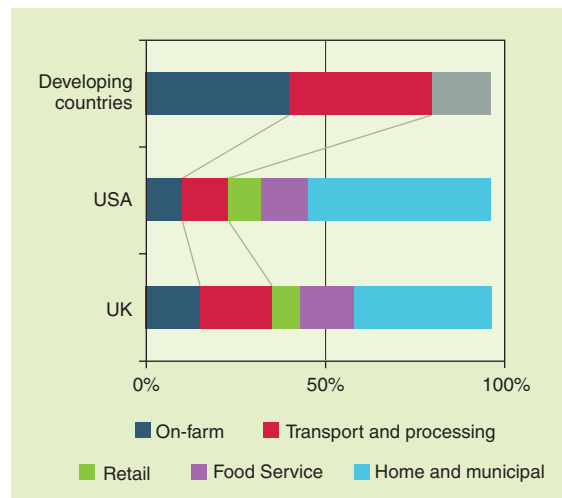


Fig. 3. Makeup of total food waste in developed and developing countries. Retail, food service, and home and municipal categories are lumped together for developing countries. [Source: (16, 37–39)]

Different strategies are required to tackle the two types of waste. In developing countries, public investment in transport infrastructure would reduce the opportunities for spoilage, whereas better-functioning markets and the availability of capital would increase the efficiency of the food chain, for example, by allowing the introduction of cold storage (though this has implications for greenhouse gas emissions) (38). Existing technologies and best practices need to be spread by education and extension services, and market and finance mechanisms are required to protect farmers from having to sell at peak supply, leading to gluts and wastage. There is also a need for continuing research in postharvest storage technologies. Improved technology for small-scale food storage in poorer contexts is a prime candidate for the introduction of state incentives for private innovation, with the involvement of small-scale traders, millers, and producers.

If food prices were to rise again, it is likely that there would be a decrease in the volume of waste produced by consumers in developed countries. Waste may also be reduced by alerting consumers to the scale of the issue, as well as to domestic strategies for reducing food loss. Ad-

vocacy, education, and possibly legislation may also reduce waste in the food service and retail sectors. Legislation such as that on sell-by dates and swill that has inadvertently increased food waste should be reexamined within a more inclusive competing-risks framework. Reducing developed-country food waste is particularly challenging, as it is so closely linked to individual behavior and cultural attitudes toward food.

Changing Diets

The conversion efficiency of plant into animal matter is ~10%; thus, there is a *prima facie* case that more people could be supported from the same amount of land if they were vegetarians. About one-third of global cereal production is fed to animals (42). But currently, one of the major challenges to the food system is the rapidly increasing demand for meat and dairy products that has led, over the past 50 years, to a ~1.5-fold increase in the global numbers of cattle, sheep, and goats, with equivalent increases of ~2.5- and ~4.5-fold for pigs and chickens, respectively (2) (Fig. 1). This is largely attributable to the increased wealth of consumers everywhere and most recently in countries such as China and India.

However, the argument that all meat consumption is bad is overly simplistic. First, there is substantial variation in the production efficiency and environmental impact of the major classes of meat consumed by people (Table 2). Second, although a substantial fraction of livestock is fed on grain and other plant protein that could feed humans, there remains a very substantial proportion that is grass-fed. Much of the grassland that is used to feed these animals could not be converted to arable land or could only be converted with majorly adverse environmental outcomes. In addition, pigs and poultry are often fed on human food “waste.” Third, through better rearing or improved breeds, it may be possible to increase the efficiency with which meat is produced. Finally, in developing countries, meat represents the most concentrated source of some vitamins and minerals, which is important for individuals such as young children. Livestock also are used for ploughing and transport, provide a local supply of manure, can be a vital source of income, and are of huge cultural importance for many poorer communities.

Reducing the consumption of meat and increasing the proportion that is derived from the most efficient sources offer an opportunity to feed more people and also present other advantages (37). Well-balanced diets rich in grains and other vegetable products are considered to be more healthful than those containing a high proportion of meat (especially red meat) and dairy products. As developing countries consume more meat in combination with high-sugar and -fat foods, they may find themselves having to deal with obesity before they have overcome undernutrition, leading to an increase in spending on health that could

Table 2. Comparison of the impact of grazing and intensive (confined/industrialized) grain-fed livestock systems on water use, grain requirement, and methane production. Service water is that required for cleaning and washing livestock housing and other facilities. Dashes indicate combinations for which no data are available (either because it cannot be measured or because the combination does not exist). This table does not include other impacts of differing livestock management systems such as (i) nutrient run-off and pollution to surface and groundwater, (ii) protozoan and bacterial contamination of water and food, (iii) antibiotic residues in water and food, (iv) heavy metal from feed in soils and water, (v) odor nuisance from wastes, (vi) inputs used for feed production and lost to the environment, (vii) livestock-related land-use change. [Source: (7, 50)]

| Water | Measure of water use | Grazing | Intensive |
|--|----------------------|--|-----------|
| | | Liters day ⁻¹ per animal at 15°C | |
| Cattle | Drinking water: all | 22 | 103 |
| | Service water: beef | 5 | 11 |
| | Service water: dairy | 5 | 22 |
| Pigs (lactating adult) | Drinking water | 17 | 17 |
| | Service water | 25 | 125 |
| Sheep (lactating adult) | Drinking water | 9 | 9 |
| | Service water | 5 | 5 |
| Chicken (broiler and layer) | Drinking water | 1.3–1.8 | 1.3–1.8 |
| | Service water | 0.09–0.15 | 0.09–0.15 |
| <i>Feed required to produce 1 kg of meat</i> | | <i>kg of cereal per animal</i> | |
| Cattle | | — | 8 |
| Pigs | | — | 4 |
| Chicken (broiler) | | — | 1 |
| <i>Methane emissions from cattle</i> | | <i>kg of CH₄ per animal year⁻¹</i> | |
| Cattle: dairy (U.S., Europe) | | — | 117–128 |
| Cattle: beef, dairy (U.S., Europe) | | 53–60 | — |
| Cattle: dairy (Africa, India) | | — | 45–58 |
| Cattle: grazing (Africa, India) | | 27–31 | — |

otherwise be used to alleviate poverty. Livestock production is also a major source of methane, a very powerful greenhouse gas, though this can be partially offset by the use of animal manure to replace synthetic nitrogen fertilizer (43). Of the five strategies we discuss here, assessing the value of decreasing the fraction of meat in our diets is the most difficult and needs to be better understood.

Expanding Aquaculture

Aquatic products (mainly fish, aquatic molluscs, and crustaceans) have a critical role in the food system, providing nearly 3 billion people with at least 15% of their animal protein intake (44).

In many regions, aquaculture has been sufficiently profitable to permit strong growth; replicating this growth in areas such as Africa where it has not occurred could bring major benefits. Technical advances in hatchery systems, feeds and feed-delivery systems, and disease management could all increase output. Future gains may also come from better stock selection, larger-scale production technologies, aquaculture in open seas and larger inland water bodies, and the culture of a wider range of species. The long production cycle of many species (typically 6 to 24 months) requires a financing system that is capable of providing working capital as well as offsetting risk. Wider production options (such as temperature and salinity tolerance and disease resistance) and cheaper feed substrates (for in-

stance, plant material with enhanced nutritional features) might also be accessed with the use of GM technologies.

Aquaculture may cause harm to the environment because of the release into water bodies of organic effluents or disease treatment chemicals, indirectly through its dependence on industrial fisheries to supply feeds, and by acting as a source of diseases or genetic contamination for wild species. Efforts to reduce these negative externalities and increase the efficiency of resource use [such as the fish in-to-fish out ratio (45)] have been spurred by the rise of sustainability certification programs, though these mainly affect only higher-value sectors. Gains in sustainability could come from concentrating on lower-trophic level species and in integrating aquatic and terrestrial food production, for example, by using waste from the land as food and nutrients. It will also be important to take a more strategic approach to site location and capacity within catchment or coastal zone management units (46).

Conclusions

There is no simple solution to sustainably feeding 9 billion people, especially as many become increasingly better off and converge on rich-country consumption patterns. A broad range of options, including those we have discussed here, needs to be pursued simultaneously. We are hopeful about scientific and technological inno-

vation in the food system, but not as an excuse to delay difficult decisions today.

Any optimism must be tempered by the enormous challenges of making food production sustainable while controlling greenhouse gas emission and conserving dwindling water supplies, as well as meeting the Millennium Development Goal of ending hunger. Moreover, we must avoid the temptation to further sacrifice Earth's already hugely depleted biodiversity for easy gains in food production, not only because biodiversity provides many of the public goods on which mankind relies but also because we do not have the right to deprive future generations of its economic and cultural benefits. Together, these challenges amount to a perfect storm.

Navigating the storm will require a revolution in the social and natural sciences concerned with food production, as well as a breaking down of barriers between fields. The goal is no longer simply to maximize productivity, but to optimize across a far more complex landscape of production, environmental, and social justice outcomes.

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53. The authors are members of the U.K. Government Office for Science's Foresight Project on Global Food and Farming Futures. J.R.B. is also affiliated with Imperial College London. D.L. is a Board Member of Plastid AS (Norway) and owns shares in AstraZeneca Public Limited Company and Syngenta AG. We are grateful to J. Krebs and J. Ingraham (Oxford), N. Nisbett and D. Flynn (Foresight), and colleagues in Defra and DfID for their helpful comments on earlier drafts of this manuscript. If not for his sad death in July 2009, professor Mike Gale (John Innes Institute, Norwich, UK) would also have been an author of this paper.

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REVIEW

Breeding Technologies to Increase Crop Production in a Changing World

Mark Tester* and Peter Langridge

To feed the several billion people living on this planet, the production of high-quality food must increase with reduced inputs, but this accomplishment will be particularly challenging in the face of global environmental change. Plant breeders need to focus on traits with the greatest potential to increase yield. Hence, new technologies must be developed to accelerate breeding through improving genotyping and phenotyping methods and by increasing the available genetic diversity in breeding germplasm. The most gain will come from delivering these technologies in developing countries, but the technologies will have to be economically accessible and readily disseminated. Crop improvement through breeding brings immense value relative to investment and offers an effective approach to improving food security.

Although more food is needed for the rapidly growing human population, food quality also needs to be improved, particularly for increased nutrient content. In addition, agricultural inputs must be reduced, especially those of nitrogenous fertilizers, if we are to reduce environmental degradation caused by emissions of CO₂ and nitrogenous compounds from agricultural processes. Furthermore, there are now concerns about our ability to increase or even sustain crop yield and quality in the face of dynamic environmental and biotic threats that will be particularly challenging in the face of rapid global environmental change. The current di-

version of substantial quantities of food into the production of biofuels puts further pressure on world food supplies (1).

Breeding and agronomic improvements have, on average, achieved a linear increase in food production globally, at an average rate of 32 million metric tons per year (2) (Fig. 1). However, to meet the recent Declaration of the World Summit on Food Security (3) target of 70% more food by 2050, an average annual increase in production of 44 million metric tons per year is required (Fig. 1), representing a 38% increase over historical increases in production, to be sustained for 40 years. This scale of sustained increase in global food production is unprecedented and requires substantial changes in methods for agronomic processes and crop improvement. Achieving this increase in food production in a stable environment would be challenging, but is undoubtedly much

more so given the additional pressures created by global environmental changes.

Global Environmental Change Alters Breeding Targets

Certain aspects of global environmental change are beneficial to agriculture. Rising CO₂ acts as a fertilizer for C3 crops and is estimated to account for approximately 0.3% of the observed 1% rise in global wheat production (4), although this benefit is likely to diminish, because rising temperatures will increase photorespiration and nighttime respiration. A benefit of rising temperatures is the alleviation of low-temperature inhibition of growth, which is a widespread limitation at higher latitudes and altitudes. Offsetting these benefits, however, are obvious deleterious changes, such as an increased frequency of damaging high-temperature events, new pest and disease pressures, and altered patterns of drought. Negative effects of other pollutants, notably ozone, will also reduce benefits to plant growth from rising CO₂ and temperature.

Particularly challenging for society will be changes in weather patterns that will require alterations in farming practices and infrastructure; for example, water storage and transport networks. Because one-third of the world's food is produced on irrigated land (5, 6), the likely impacts on global food production are many. Along with agronomic- and management-based approaches to improving food production, improvements in a crop's ability to maintain yields with lower water supply and quality will be critical. Put simply, we need to increase the tolerance of crops to drought and salinity.

In the context of global environmental change, the efficiency of nitrogen use has also emerged as a key target. Human activity has already more than doubled the amount of atmospheric N₂ fixed

Australian Centre for Plant Functional Genomics, University of Adelaide, South Australia SA 5064, Australia.

*To whom correspondence should be addressed. E-mail: mark.tester@acpfg.com.au