Enhancing the crops to feed the poor

Jikun Huang*, Carl Pray† & Scott Rozelle‡

**Center for Chinese Agricultural Policy, Institute of Geographic Sciences and Natural Resource Research, Chinese Academy of Sciences, 917 Building, Anwai Datun Road, Beijing 100101, China*
†Department of Agricultural, Food and Resource Economics, Rutgers University, 55 Dudley Road, New Brunswick, New Jersey 08901-8520, USA
‡Department of Agricultural and Resource Economics, University of California,1 Shields Avenue, Davis, California 95616, USA (e-mail: rozelle@primal.ucdavis.edu)

Solutions to the problem of how the developing world will meet its future food needs are broader than producing more food, although the successes of the 'Green Revolution' demonstrate the importance of technology in generating the growth in food output in the past. Despite these successes, the world still faces continuing vulnerability to food shortages. Given the necessary funding, it seems likely that conventional crop breeding, as well as emerging technologies based on molecular biology, genetic engineering and natural resource management, will continue to improve productivity in the coming decades.

Billions of people struggle for a better life in the developing world, but they are able to improve their prospects of achieving this only when there is abundant and affordable food available[1]. Food security for the poor is dependent on issues such as access to the resources needed to buy or produce their own food[2]; neththertheless, welfare increased dramatically for many after the Second World War, in part because of the huge increase in agriculture's ability to produce food. Improving quality of life in the twenty-first century will likewise require as much, if not more, effort in increasing global food production. One of the great challenges of the coming decades will be to produce the food and fibre that is needed to feed and clothe those in the poorer parts of the world. And although from some perspectives this seems like an impossible task — in the same way that it must have to the doomsday forecasters since the days of Malthus — there are many reasons to believe it can be achieved.

In this review, we explore how technology can help the developing world meet its food needs in the twenty-first century. We begin by discussing the role of technology in generating past growth in productivity and output by analysing the successes and failures of the Green Revolution. Despite the past successes, the world's continuing vulnerability to food shortages is illustrated. The constraints that are holding back food production are examined, and we divide these into those that can be addressed by traditional crop breeding and agronomic techniques, and those that can be best solved by biotechnology and other high-technology approaches. We then shift our focus to the future. Drawing on a survey of prominent scientists and research administrators in China and interviews with scientists elsewhere in the world, we assess the technologies that are currently available and those that hold promise in the future. Finally, we turn our attention to who will create the new technologies and where the resources to create them will come from.

Past achievements and persistent vulnerability

With the exception of several short periods (for example, the mid-1970s), world food production has expanded continuously since the 1960s. And, while the industrialized countries have contributed significantly to the world's food supply, the developing world also has played an important role and has been a major beneficiary. From a world facing the prospects of severe global famine, the input-responsive plant varieties of the Green Revolution, together with subsequent investments in water control, intensification of chemical input use and further genetic discoveries, raised food production to levels that no one would have dared predict[3]. Global yields rose by 2.42% annually between 1961 and 1966 (Fig. 1). With the exception of Africa, farmers in developing and developed countries nearly doubled their per-hectare output of cereal production, increasing yields during this time by 3.16% annually. Sown area, although actually trending down slightly worldwide (–0.04% per year), still expanded annually by about 0.25% in developing countries. With more food available, falling food prices, increased food trade and rising consumption led the way to lower malnutrition and falling poverty rates in many parts of the world[4].

Past success, however, does not guarantee a food-abundant world in the coming decades. Growth rates of yields have slowed during the period between 1987 and 2001 (Fig. 1). Moreover, the demographic pressures in the twenty-first century will be unprecedented. The world's population will reach 8 billion by 2025. By 2020, increasingly wealthy and urbanized consumers and the 2 billion new mouths will demand 40% more food[5]. Rosegrant *et al.* estimate that food and feed production must continue to rise annually by 1.2% to satisfy the demand of the world's population by 2020 (ref. 6).

Increasing yields

Although it may seem easy to reach growth rates of food production that are approximately half the average of the past 40 years, the exhaustion of some past sources of growth makes future yield expansion as great a challenge as in the past[7]. Populations have encroached on almost all of the world's frontiers, leaving little new land that is cultivatable with current technologies. Widespread adoption of modern varieties and intensive use of inorganic fertilizers and chemical pesticides have pushed yields in many areas of developing countries to levels that rival those reached on farms in developed countries and on the experimental fields of agronomists. For example, nearly 100% of farmers in China use improved varieties of rice, wheat and maize[8], and producers in south Asia and Latin America use modern cereal varieties on more than 80% of their sown area[9]. The gap between the actual yields of farmers and those that are attainable on experimental plots, given the current resource base and economic environment, has narrowed in a

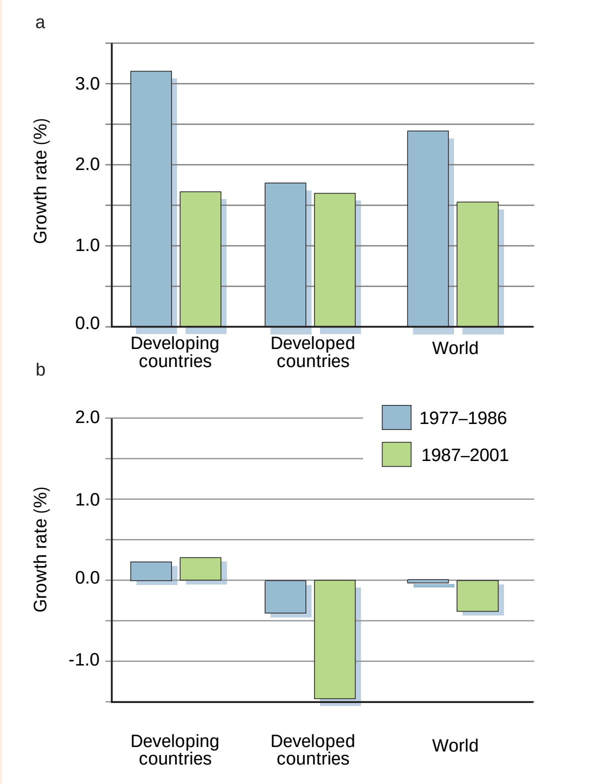

Figure 1 Annual growth rate of cereal yields and sown area in developing and developed countries, 1977–2001. Data from Food and Agriculture Organization of the United Nations.

number of the world's developing nations[7]. Whereas in the past, large increases in output per hectare could come from transferring existing technology from other parts of the world or from increasing the use of fertilizer, water and other inputs, in many parts of the world these gains have been largely exhausted.

Pressure on the environment and resource base

Environmental pressures also may threaten the sustainability of the world's food productivity gains. Some scientists have voiced concerns that the intensification of farming systems may not be sustainable because of systematic degradation of the resource base and environment[10,11]. The degradation, which is reflected in declining yields in long-term agronomic experiments and decelerating aggregate yields at the national level, appears in many intensive-cropping systems in different areas of the world and is attributable to a number of factors[12,13]. Scientists at the International Rice Research Institute (IRRI) hypothesize that rice yields fall over time owing to a decline in soil nitrogen in water-saturated soils, increased incidence of disease with high nitrogen use, and a build up of soil pests because of continuous monocropping[14]. In the highly productive Punjab region of India and Pakistan, the productivity of wheat–rice systems is declining because of falling concentrations of organic matter and phosphorus in the soil and increasing salinity in the groundwater[15,16]. At the other extreme, African farmers, who use almost no modern inputs, mine the soil's natural nutrient base by adoption of continuous cropping without the use of modern inputs and elimination of traditional fallowing practices[17].

An arms race between pests and technology is being played out with rising disease and insect pressures threatening to reduce the gains provided by modern varieties. Because the use of modern varieties allowed intensified cultivation within a season and over the year, a rise in the amount of plant matter per hectare and the shortening of the length of time between plantings, especially in the case of rice, increased the incidence of diseases and the size of insect populations[18]. Farmers fought back with chemical pesticides. Breeders reinforced the pest-control efforts of farmers by producing a second generation of pest-resistant modern varieties[19]. But although the chemical attack on pests and intense use of resistant varieties was effective in reducing pest-related damage, it triggered a number of unexpected negative effects[20]. First, in the process of killing destructive pests, pesticides also invariably destroy the predators of these pests. Second, natural selection is creating a class of pests that is becoming resistant to many of the most popular and relatively safe pesticides. It has been shown that in some developing countries, the cost of the adverse health consequences for the farmer applying the pesticide more than offsets the savings that the farmer earns by reducing the loss of pest-inflicted damage to the crop[21]. These problems, responses and subsequent reactions exemplify the delicate nature of science's long-term fight to raise enough food for a hungry and burgeoning population.

Finally, increasingly severe water shortages may constrain future yield rises. In the past, irrigation has been crucial in increasing crop yields and facilitating the shift to new technologies and more intense cultivation. India, for example, has invested more in water control than any other activity[22]. China invests more than ten times more into water control than into agricultural research[23]. Huang *et al.* illustrate that yields and income, including those of the poor, are raised by between 30 and 100% when cultivated area is irrigated[24]. However, by some accounts, water is becoming the most constraining input to agriculture in many nations[25]. Up to one-half of the world's population lives in a water-scarce environment. In other areas, lack of infrastructure allows much of the water that comes from natural sources, such as rainfall, to run off without being able to be used. Additionally, city users and industries will undoubtedly out-compete agriculture for fixed amounts of water resources in many regions.

Breaking productivity constraints

The twenty-first century needs another Green Revolution to elevate global food production. Because of the limited amount of land and water in many parts of the world, the only way to expand production is by developing a technology that increases output per unit of input. In the same way that fertilizer-responsive dwarf varieties and hybrid cultivars increased the productivity of land and other inputs after 1950, new technologies are needed to create additional productivity gains in the coming years. Some of these gains will be similar to those of the past. However, unlike the first two stages of the Green Revolution, which centred initially on favourable, irrigated areas of the world in the 1960s and 1970s, and then on more favourable (in terms of soil and other growing conditions) rain-fed areas in the 1980s and 1990s, the next generation of even more powerful technologies may be able to address a wider array of constraint sets that can allow production to rise. The job of scientists, however, will be made more complicated, as different technologies will be needed to address different sets of questions in different areas of the world.

The need to raise yield plateau

Because much of the exploitable yield gap between the farm and experimental station has been eliminated in many of the world's favourable areas, new technologies for these regions almost certainly will depend on increased investment in research on advanced breeding techniques, crop physiology and molecular biology[7]. Virmani *et al.* believe extension of hybrid-variety development to rice, wheat and other crops can increase yields by 20% (ref. 26). The spread of hybrid rice in China and the associated rise in yields demonstrates the validity of this approach[27]. China's plant breeders have been working on a new approach to producing hybrid rice, which will allow easier and cheaper seed production[28]. Plant physiologists have also created a model for a new plant type that could potentially increase rice yields

Figure 2 Comparison of traditional, improved and ideal rice plant types. Reproduced from ref. 29, with permission.

by 30% (to nearly 15 tonnes per hectare, if it is combined with hybrid-variety development) by increasing the plant's inherent production efficiency[29]. IRRI scientists report that farmers in China's subtropical provinces are already using the first generation of this new technology — after several years of testing on experimental stations in the Philippines and Indonesia, new plant-type lines that yield 20% more than traditional varieties in tropical areas have moved into seed board trials (Fig. 2).

Narrowing the yield gap

Byerlee *et al.* identify a distinct set of constraints that are holding back productivity gains in favoured areas with significant exploitable potential (referred to hereafter as semi-favourable, rain-fed areas)[7]. Whereas the yield gaps in the most favourable areas are narrow, there are still large areas of the world in which output is only one-third or less of those in local experiment stations. Farmers in these areas, which are largely in the rain-fed belts of Latin America, south Asia and Africa, currently use low levels of inputs and are poorly trained in modern farming techniques. Moisture in these areas, although variable, is sufficient for producing high yields in most years. But the crops of farmers in these areas are frequently nutrient-starved and must be planted in soils that are relatively fragile. It is not that the nutrients are absent; more often it is the case that they are unevenly spread across the landscape and frequently out of balance in terms of their nitrogen–phosphate–potassium mix and/or lack micro-nutrients.

Unlike the most favourable areas, semi-favourable, rain-fed areas need adaptive plant breeding and extension of agronomic practices and farm management techniques to overcome some of their largest constraints. Scientists at the West Africa Rice Development Association crossed Asian rice varieties with African varieties to develop new varieties called NERICA (for New Rice for Africa). These varieties combine the weed-control and drought-resistant characteristics of their African parent with the high-yielding characteristics of their Asian parent, and are now spreading rapidly in West Africa. In some case, new technologies that are simple and could simultaneously relax several constraints are possible. For example, the new rice varieties being bred with higher levels of iron and zinc to alleviate malnutrition may also increase yields in iron- and zinc-deficient soils. However, education levels, literacy and cash availability are so low and access to communications and transportation are so poor that infrastructure investments are often preconditions for overcoming the agricultural constraints in these areas.

Marginal areas, as their name implies, include those regions where yields are severely constrained by climatic stress (for example, drought), fragile soils and non-existent or non-functional infrastructure. During the last half of the twentieth century, scientists directed less of their work towards these areas[30]. Agricultural technology had less to offer, as modern varieties during this period responded to water and fertilizer; instead, some of the most productive work was done in the area of natural resource management. People in these regions did benefit from the Green Revolution, albeit indirectly, by gaining access to lower-cost foods in markets and migrating to areas where they could hire themselves out as wage earners on the farms that had adopted the labour-using new technologies.

Many of the world's poorest people live in these marginal areas, and they lack the purchasing power or labour skills to reap the indirect benefits of agricultural technologies introduced in favourable or semi-favourable areas. Because there was less work done on the problems of poor areas during the last Green Revolution, there is almost certainly much more scope for improving the livelihood of those who live there now. To ensure that people in these areas benefit from the development of the next generation of Green Revolution technologies, scientists and policy-makers need to make sure the investments in the human and physical capital are made so that farmers are able to utilize them when they become available.

Genetic engineering and other new technological approaches

In addition to the research from traditional agricultural science, plant biotechnology research — which includes genetic engineering and the transfer of genes from unrelated plants and microorganisms — started to show important benefits for farmers in developed countries in the mid-1990s and in favourable regions of developing countries in 1997 (ref. 31). Farmers in both the developed and developing world most frequently adopt Roundup Ready soya beans, *Bt* cotton (containing a gene for an insecticide derived from the bacterium *Bacillus thuringiensis*), and *Bt* yellow maize or corn. In the developing world, genetically modified (GM) crops have had the largest impact in Argentina, Brazil (where they are still not officially approved for use, but have been purchased from Argentina), China and South Africa (Fig. 3). James estimates that approximately 5.5 million farmers in developing countries currently receive direct benefits of GM technologies[32]. However, not all farmers in developing countries have access to the new technologies. Almost all the GM crops currently being grown in developing countries are temperate-region cash crops, and few are being used for food (including yellow maize, a crop used primarily as animal feed). Almost all the new genes that are in commercially grown GM crops, except for those in China's *Bt* cotton crop (which were produced by its own domestic scientists), were produced by Monsanto, a large multinational life science company, based in the United States.

Since the development of GM crops in the 1980s and their release in the mid-1990s, investments have focused on a narrow range of applications and adoption has been mainly by producers in industrialized countries. For example, half of all experimental trials in developed countries have been on varieties that have been made to be insect resistant or herbicide tolerant, or both[31]. More than two-thirds of trials in developing countries work on these same traits (Fig. 4). Because of the nature of the new technologies (which allow the private-company developers to capture part of the rent of the new technology through the sale of hybrid seeds or through sale of the chemical herbicide that must be used with the herbicide-tolerant varieties), the most enthusiastic adopters have been farmers in developed countries. Adoption in developed countries (40 million hectares), where most farmers use relatively less labour and capital is less of a constraint, exceeds that in developing countries (13 million hectares) by more than 300%. Moreover, except for the case of small cotton farmers in China, Mexico and South Africa (who adopted GM technologies on a measurable scale only in the late 1990s), adoption in developed countries and in Argentina (an exception in the developing world) is almost exclusively by commercial producers.

Benefits and limitations of genetic engineering

GM technologies have benefited the farmers who have adopted them, mainly through time-saving gains, increased yields and reduced

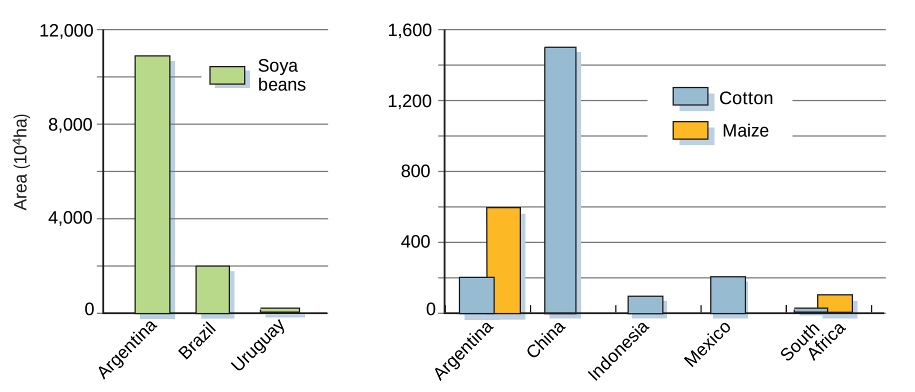

Figure 3 Area sown to genetically modified crops in developing countries in 2001. Data from ref. 31; except Brazil which is from authors' interviews.

chemical pesticide inputs. Herbicide-resistant soya beans in Argentina have reduced costs of production per hectare through a reduction in herbicide applications[33]. The average *Bt* cotton farmer in China has reduced pesticide sprayings for the Asian boll worm from 20 to 6 times per year and produces a kilogram of cotton for 28% less cost than the farmer using non-*Bt* varieties[34]. Mexican and South African *Bt* cotton farmers increased the yields at the same time that they reduced their costs[35,36]. The reduction in pesticide use not only saves farmers the financial outlay for insecticides, but also reduced the incidence of insecticide poisonings[37].

Although the potential exists in the future for increasing food production and alleviating constraints on cereal production in semi-favourable and marginal areas of developing countries, progress so far is limited. No GM varieties of a major food grain are currently being grown in developing countries, and there is very little work being done on crops grown in many marginal areas, such as millet, cassava or beans. But field trials for bio-safety clearance of GM varieties show that some major GM food crops are in the pipeline, and a few countries are actually releasing or close to releasing GM food crops. China's scientists, for example, are working on GM rice, potato and peanuts, crops that have been largely ignored in the developed world. Researchers in other developing countries are working on sugarcane, papaya and a number of other tropical crops. South Africa is leading the way in growing GM subsistence crops with the production of GM white maize, the first harvest of which will take place this year[38]. Other major food crops that are in the final stages of testing before commercial release are *Bt* rice, disease-resistant rice and *Bt* maize in China, and virus-resistant sweet potato and *Bt* maize in Kenya[32,34]. Much more than in developed countries, biosafety is emerging as a principal constraint on release of GM organisms in developing countries.

Like developed countries, the characteristics of GM crops that are in the pipeline in developing countries are overwhelmingly focused on herbicide tolerance and insect resistance. Except for China, 80% of the field trials are on varieties that contain these characteristics individually or 'stacked' together[39]. Field trials of crops that were being promoted primarily for higher yield were less that 1% of the field trials in developing countries. In China, however, scientists are experimenting with nutrition-enhanced varieties of rice, shelf-life-enhanced varieties of tomatoes, and other characteristics.

A role for other technologies

In addition to high-technology solutions, there is almost certainly a role for further research in other areas such as natural resource management and post-harvest handling and processing. Scientists working in natural resource management have developed technologies such as zero tillage and integrated pest management that have led to significant gains in some countries. The adoption of zero tillage in South America on 26 million hectares can be considered a Green Revolution in itself[40], and adoption of such systems is now occurring rapidly in south Asian rice–wheat systems. Eliminating tilling can cut production costs by 50%, save labour, and have a positive impact on the environment by reducing erosion, the volume and toxicity of agrochemicals, and tractor fuel consumption. Crop rotations that can support high yields without creating adverse environmental effects also show promise in new research[16]. Additionally, there may also be room for economic improvements in the way that food moves from the farm to the consumer, eliminating some of the waste that currently occurs.

Future food technology

Although in a fertile imagination there is no limit to the increases that science might deliver over the coming decades, it is more prudent to rely on leading scientists to assess what is possible in the foreseeable future. There is considerable debate about whether conventional plant breeding can continue to generate yield increases and provide farmers with ways of reducing input constraints. Although recent attention has focused on the products produced by plant biotechnology, conventional plant breeding has contributed much more to yield increases than has biotechnology. Despite bold promises, the application of molecular biology and knowledge-intensive technologies has been limited to a small number of traits in a limited number of crops. Only a few multinational, private life-science companies have delivered their new genetic technologies to the market place. Likewise, recent developments in computer, satellite and mechanical

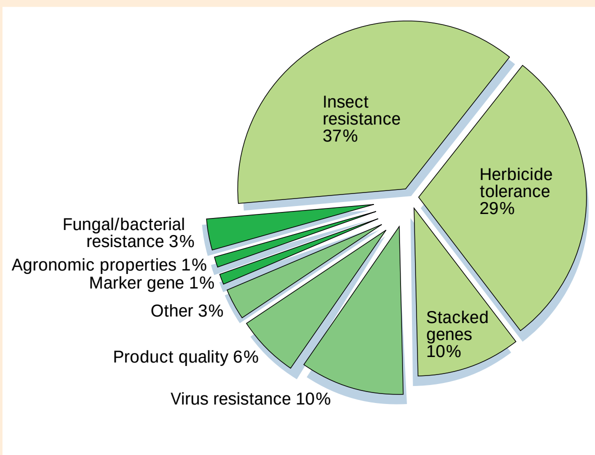

Figure 4 Genetically modified crop traits tested in developed countries, 1987–2000. Data from ref. 31.

Table 1 Crop technology breakthrough predictions in 2020 and effects on crop production in China

Technology	Expected effects on crop production (per cent of those expecting a breakthrough in the technology)				
	Likelihood of significant technological progress	Increases in yields and efficiency	Allows increase in sown area	Allows increase in cropping intensity	Other effects (e.g. on nutrition or on pollution)
Conventional plant breeding	97	49	17	10	24
Genetic engineering	97	43	23	6	28
Precision technology	71	56	11	15	18
Information technology	76	41	8	13	38
For use in water-short areas	97	49	31	10	10
Labour-saving technologies	76	53	16	14	18
For increasing nutrition	82	30	2	2	66
For sustaining productivity	85	54	14	16	16

Source: Author's survey.

equipment interfaces have met with only limited success in developed countries and are almost non-existent in poorer nations[41].

China's version of the future of technology

But many scientists, from both developing and developed countries, believe that recent achievements in plant biotechnology, precision agriculture and other new research areas are only the tip of the iceberg. A survey and interviews about the future potential of technologies show that agricultural scientists predict robust technological growth in the next 20 years. Most systematically, from a survey mailed to leading scientists in China's agricultural research system, 34 respondents gave their prediction about the types of future technologies and the nature of the impacts on producers. Although scientists in China may not be representative of the rest of the developing world, given the large size and successful past of China's research system in producing new technologies from conventional and non-conventional technologies, examining the opinions of many of the nation's leading researchers may be instructive in what future path the developing world will take.

Based on the responses of scientists from 25 research institutes and university departments in China, all but one scientist (97%) predicted important discoveries in the areas of both conventional crop breeding and genetic engineering (Table 1, rows 1 and 2). China's scientists, who were the first to create and commercially extend hybrid rice, believe they can improve the quality of hybrid rice varieties to enable them to tap the hybrid vigour that can provide up to 15–20% higher yields. Breeders are also developing hybrids for wheat, soya beans, rapeseed and other crops. Plant biotechnologists, who already have created an impressive array of GM technologies, believe that they have the potential for using transformation, marker-assisted selection and tissue culture to produce a new generation of technology (Box 1).

Although China's GM crops include those that are insect resistant, scientists work on a much broader range of products, in part because they are nearly all employed in the public sector. As such, they can undertake research on crop technologies that may be difficult to protect from the perspective of intellectual property rights. Interestingly, whereas scientists predict that the main effect of future technologies from traditional crop breeding and genetic engineering will be increasing yields, the second largest effect will be to increase the nutritional value of cereals and reduce the use of inputs that are causing environmental and health concerns. The complementarity between biotechnology and traditional crop breeding, at least in a developing country such as China, also means that the nation needs to invest in both types of programme.

Nearly all of the scientists surveyed (97%) also believed that water-saving technologies will affect agricultural production in the coming 20 years (Table 1, row 5). Breeders and molecular biologists forecast that drought-tolerant varieties would become increasingly available. Identification of genes that can combat abiotic stresses, such as short-term drought, should enable scientists to create varieties that can greatly improve yields in the favourable rain-fed areas. Agronomists foresee new types of plastics that can be used in a profitable and sustainable way for capturing soil moisture and irrigating crops more efficiently. Genetic and agronomic approaches to saving water may also be able to slow or halt the long-term trend of China's falling sown area. Because many of the new marginal areas are in relatively poor regions of the country, the new technologies will have positive, indirect effects on efforts to alleviate poverty.

A lower percentage of China's scientists believe that precision agriculture (71%) and information technology (76%) can increase the performance of agriculture during the next 20 years (Table 1, rows 3 and 4). The most frequently cited technology is the use of satellite communications to provide extension services to farmers, even in remote villages. Several scientists also believe strongly that easy-to-use electronic tools, such as soil nutrient detectors, could increase efficiency and expand yields without the high human capital requirements that are currently demanded by most computer-based precision agriculture technologies. A large fraction of the surveyed scientists also thought that labour-saving, nutrition-enhancing and environmentally friendly technologies were promising in terms of their ability to raise yields and help the poor (Table 1, rows 6 to 8).

Debate on the future of crop breeding and other programmes

Interviews with scientists from the United States, India and the international agricultural research community mostly support the findings of the China survey. Interviews with 22 leading scientists and observers of international research indicate there is still the potential to increase productivity by conventional breeding, in the form of both output per unit of land and saving on conventional inputs. In addition, these scientists believe that biotechnology will have a major impact on yield per hectare and cost of production by 2010 and will continue thereafter. They also predicted that there is scope for important impacts on water saving and labour saving technology.

Some comments, however, demonstrate differences in perceptions between scientists in developing and developed countries. One director of a large plant-breeding programme in a major international centre (that had both plant breeders and biotechnologists) believed that the prospects for further technological discoveries by conventional crop breeders would last only 10 more years. After that, most additional progress will come from biotechnology. The difference with the perception of China's scientists, who saw a long-term role for plant breeding, may be one of individual opinions. Alternatively, it may reflect the fact that in developing countries the labour costs for hiring a plant breeder are much lower and affordable than many of the capital investments that are needed to set up and maintain modern biotechnology programmes. Others have found that although the economic returns to crop breeding are linear, costs are exponential[7].

Making the investments to create the technologies

The need for new technology and the promise that it holds challenges nations in developed and developing countries to create a set of institutions that can deliver the technologies that scientists foresee as possible. After growing rapidly during the post-Second World War period, investments in agricultural research have on average decelerated, although there are differences among the regions of the world[42]. In the period 1991–1996, public agricultural research expenditures climbed at 3.6% annually in developing countries[43], compared with an annual rate increase of 0.2% in developed nations. Unfortunately, sub-Saharan Africa, the region that may need the research most, suffered a decline in agricultural research during the 1990s. By the mid-1990s, developed and developing countries spent US$33 billion per year on agricultural research, about 1.04% of the value of agricultural output. The economic rate of return to investments in agricultural research are regularly calculated to be very high, even though there are almost always lags between the time the investment is made and the time that positive returns are earned[44].

Public investments

Because many agricultural research investments are public goods, governments are responsible for making them. Public investment will almost certainly continue to be one of the main sources of funding in the coming years. Governments accounted for about two-thirds of agricultural research spending in the mid-1990s (about US$22 billion)[43]. But despite this large total, and the high returns to their investments, agricultural research in many countries is in crisis. Funding levels are insufficient to generate a steady flow of technology. Poor incentives in large public bureaucracies often dampen the effectiveness of public research organizations[45].

In developing countries, the public sector dominates research expenditures in traditional agricultural research fields and in biotechnology. Although funding of traditional fields has waned, the promises of basic biology and biotechnology have induced leaders to increase public spending on agricultural research. For example, the governments of China[34], Brazil, India[46] and South Africa[38] have each made major investments in agricultural biotechnology research in the past decade. Because of these investments, many basic scientists from research institutes and universities outside the traditional agricultural research system have begun working on agriculture-related topics.

Role of the private sector

The private sector also is assuming a larger role, especially in biotechnology research and development in developing countries. In the industrialized nations, private firms contribute more than half of all the agricultural research and fund most of the biotech research and technology development. Private firms are growing rapidly in developing countries, although at present they contribute about only about 5% (ref. 43). Despite the relatively small investments in agricultural research, private firms are the main source of plant biotechnology contributions in developing countries, accounting for at least 70% of the field trials of GM plant varieties[39].

In developing countries, the private sector will continue to have a limited role in research and technology transfer and the public sector faces a period of scarce funding[47]. As a result, the public sector agricultural research systems need to have a carefully defined agenda in order to reduce hunger. Because of the importance of spillovers in agricultural research (that is, because the research output from one region will often be able to be used by those in other regions), and because of the strong economies of scale that are present in plant breeding[48], a supra-national organization is needed to increase investment internationally. Traditionally, the Consultative Group on International Agricultural Research (the CGIAR or CG system), a group of 16 international agricultural research organizations, has taken on the responsibility of transferring technology from industrialized to developing countries and working on crops and research problems that are unique to the tropical and sub-tropical climates. Funded multilaterally, the past successes of the CG system are well documented[49,50]. In recent years, however, expenditures have fallen in real terms. The system struggles with trying to define a role that fits into the new global economy, meets the needs of developing countries, and is attractive to donor countries in the industrialized world.

Box 1

Genetically modified technologies in China

China's scientists have generated an impressive array of new technologies. From 353 applications between 1996 and 2000, China's Office of Genetic Engineering Safety Administration approved 251 cases of GM plants, animals and recombined microorganisms for field trials, environmental releases or commercialization[34]. Regulators approved 45 GM plant applications for field trials, 65 for environmental release and 31 for commercialization (of which around 20 were various *Bt* cotton varieties). Breakthroughs on food crops that have received little attention elsewhere (over 40% of the trials elsewhere in the world involve GM maize) also demonstrate China's concern for food security as a developing nation (see Table below). Transgenic rice resistant to three of China's main rice pests — stem borer (using *Bt* and cowpea trypsin inhibitor (*CpTI*) genes), planthopper and bacterial leaf blight (using the *Xa21* gene) — have passed at least two years of environmental-release trials. Researchers have moved GM wheat with resistance to barley yellow dwarf virus to field trials, and are experimenting with GM potato and peanut.

Box 1 Table **GM plants (commercialized and in trials) in China, 1999**

Crop	Introduced trait	Crop	Introduced trait
1. Cotton	Insect resistance*, disease resistance	9. Tobacco	Insect resistance
2. Rice	Insect resistance, disease resistance, herbicide resistance, salt tolerance (BADH)	10. Cabbage	Virus resistance
3. Wheat	BYDV resistance, quality improvement	11. Tomato	Virus resistance*, shelf-life altered*, cold tolerance
4. Maize	Insect resistance (*Bt*), quality improvement	12. Melon	Virus resistance
5. Soya bean	Herbicide resistance	13. Sweet pepper	Virus resistance*
6. Potato	Disease resistance, quality improvement	14. Chilli	Virus resistance
7. Rape seed	Disease resistance	15. Petunia	Coloured altered*
8. Peanut	Virus resistance	16. Papaya	Virus resistance

*Approved for commercialization; others waiting for commercialization or environmental release.
Abbreviations: BADH, betaine aldehyde dehydrogenase; BYDV, barley yellow dwarf virus.
Data from ref. 34.

Perspectives

Technology generated the production increases in the twentieth century and provided the world with inexpensive food that helped curb malnutrition and alleviate poverty. In the same way that Malthus's observations later in his life moderated his original forecast of global starvation, the record of the Green Revolution certainly has weakened the case put forth by those who had predicted serious food shortages during the postwar era. But despite the increased availability of food, today's world faces food production challenges at least as great as those that faced it several decades ago. Although the magnitude of the problems are hotly debated, many scientists and economists believe the genetic potential of existing varieties are falling, pests are becoming increasing difficult to control, and land, water and other resources are becoming scarce.

Fortunately, technological progress, as in the past, has the potential of continuing to aid the world in overcoming many of these problems and meeting its food needs in the twenty-first century. At least for the foreseeable future, scientists in both developing and developed countries have a well-defined vision of the types of technologies that they can create to overcome the constraints that limit greater increases in output. Past partnerships between publicly and privately funded research created the technologies that fuelled the rise in yields and cropping intensity. For future generations of scientist and policy makers to achieve the same success, they must create an environment conducive to creative and rapid technological change.

The creation of a research-friendly environment depends on a number of critical elements. Because research is increasingly expensive and budgets increasingly strained, clear priorities need to be established. The right mix of funding and research effort needs to be apportioned between conventional plant breeding and modern genetic technology. In the short term, conventional plant breeding still has many important roles to play. This is especially true in developing countries, in which the wage levels of scientists are low enough to allow research systems to devote considerable effort to relatively traditional means of experimentation that still hold great potential for creating technological progress. Most developing countries will have difficulty establishing and maintaining strong, modern biotechnology research programmes, as the funding needs and human capital demands often exceed their capabilities. Over the longer run, however, agricultural research will almost inevitably depend on high-technology methods.

Choices also need to be balanced in a number of other ways. There needs to be the right mix of genetics- and agronomic-based research. Scientists need to carefully choose the crops and traits that they work on; the choices will directly affect who benefits and how big of an effect there will be on poverty alleviation. As opportunities arise for private firms to invest in some types of agricultural technologies, the public sector should coordinate its efforts to take advantage of the willingness of the private sector to contribute to the search for new technologies, and focus on those areas that firms are unwilling or unable to invest in.

Ultimately, however, it is going to take a commitment by governments and citizens to take steps to support continued research on agriculture. The funding needs are as great as ever. Support for many types of research have been flagging in recent years. If the struggle to feed billions of new mouths and improve the livelihood of billions of other poor people is to be won, the same commitments that were made in the past to ensure the future of food need to be reaffirmed. □

doi:10.1038/nature01015

1. World Bank. *World Development Report, 2000* (World Bank, Washington DC, 2000).
2. Sen, A. K. On economics of life and death. *Sci. Am.* **5,** 40–47 (1993).
3. Pingali, P. L., Hossain, M. & Gerpacio, R. V. *Asian Rice Bowls* (CAB International, Wallingford,, 1997).
4. Pachico, D., Hertford, R. & de Janvry, A. Assessing the impact of agricultural research on poverty alleviation. *Food Policy* **25,** 379–388 (2000).
5. Pinstrup-Anderson, P., Pandya-Lorch, R. & Rosegrant, M. W. *World Food Prospects: Critical Issues for the Early Twenty-first Century. 2020 Vision Food Policy Report* (International Food Policy Research Institute, Washington DC, 1999).
6. Rosegrant, M. W., Leach, N. & Gerpacio, R. V. Alternative futures for world cereal and meat consumption. *Proc. Nutr. Soc.* **58,** 219–234 (1999).
7. Byerlee, D., Heisey, P. & Pingali, P. L. in *Food Needs of the Developing World in the Early Twenty First Century* 207–250 (Pontifical Academy of Sciences, Vatican City, 2000).
8. Huang, J., Rozelle, S. D. & Rosegrant, M. W. China's food economy to the 21st century: supply, demand, and trade. *Econ. Dev. Cult. Change* **47,** 737–766 (1999).
9. Pray, C. E. The green revolution: extensions, institutions, impacts and lessons. Department of Agriculture, Food, and Resource Economics Working Paper (Rutgers University, New Brunswick, NJ, 1998).
10. Pingali, P. L. in *Agricultural Technology: Policy Issues for the International Community* (ed. Anderson, J. R.) 384–401 (CAB International, Wallingford, 1994).
11. Morris, M. L. & Byerlee, D. in *Agricultural Development: the Third World* 3rd edn (eds Eicher, C. K. & Staatz, J.) 458–473 (Johns Hopkins Press, Baltimore, MD, 1998).
12. Cassman, K. G. & Pingali, P. L. in *Agricultural Sustainability: Economic, Environmental and Statistical Considerations* (eds Barnett, V., Payne, R. & Steiner, R.) 63–84 (Wiley, New York, 1995).
13. Huang, J. & Rozelle, S. D. Environmental stress and grain yields in China. *Am. J. Agric. Econ.* **77,** 246–256 (1995).
14. Cassman, K. G. *et al.* Opportunities for increased nitrogen use for improved resource management in irrigated rice systems. *Field Crop Res.* **56,** 7–39 (1998).
15. Ali, M. & Byerlee, D. Productivity growth and resource degradation in Pakistan's Punjab: a decomposition analysis. *Econ. Dev. Cult. Change* (in the press).
16. Murgai, R., Ali, M. & Byerlee, D. Productivity growth and sustainability in post-green revolution agriculture: the case for the Indian and Pakistan Punjabs. *World Bank Res. Observ.* **16,** 199–218 (2001).
17. World Bank. *World Development Report, 1992* (World Bank, Washington DC, 1992).
18. Barker, R., Herdt, R. W & Rose, B. *Rice Economy of Asia* (Resources For the Future, Washington DC, and International Rice Research Institute, Los Baños, Laguna, Philippines, 1985).
19. Evenson, R. E., Herdt, R. W. & Hossain, M. *Rice Research in Asia: Progress and Priorities* (CAB International, Wallingford, 1996).
20. Pingali, P. L. & Rola, A. C. *Public Regulatory Roles in Developing Markets: The Case of Pesticides* (International Rice Research Institute, Los Baños, Laguna, Philippines, 1994).
21. Antle, J. M. & Pingali, P. L. Pesticides, productivity and farmer health: a Philippine case study. *Am. J. Agric. Econ.* **76,** 418–430 (1994).
22. Fan, S., Hazell, P. B. R. & Thorat, S. *Linkages between Government Spending, Growth and Poverty in Rural India* Res. Rep. No. 110 (International Food Policy Research Institute, Washington DC, 1999).
23. Fan, S., Zhang, L. & Zhang, X. *Growth, Inequality, and Poverty in Rural China: The Role of Public Investments* Res. Rep. No. 125 (International Food Policy Research Institute, Washington DC, 2002).
24. Huang, Q., Rozelle, S. D., Huang, J. & Wang, J. Irrigation and yields in China's agriculture. Department of Agricultural and Resource Economics Working Paper (Univ. California, Davis, 2002).
25. Seckler, D., Molden, D. & Barker, R. *Water Scarcity in the 21st Century* (International Water Management Institute, Colombo, 1998).
26. Virmani, S. S., Khush, G. S. & Pingali, P. L. in *Hybrid Research and Development Needs in Major Cereals in the Asia-Pacific Region* (eds Paroda, R. S. & Rai, M) 61–86 (Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, 1994).
27. Huang J. & Rozelle, S. D. Technological change: rediscovering of the engine of productivity growth in China's rural economy. *J. Dev. Econ.* **49,** 337–369 (1996).
28. Yuan L. & Lu, X. Two-line rice hybridization technology and intermedium test development program. *Biol. Eng. Prog.* **20,** 2–6 (2000). [In Chinese.]
29. Khush, G. S. Modern varieties: their real contribution to food supply and equity. *Geojournal* **35,** 275–284 (1995).
30. David, C. C. & Otsuka, K. *Modern Rice Technology and Income Distribution in Asia*. (International Rice Research Institute, Los Baños, Laguna, Philippines, and Lynne Rienner Publishers, Boulder and London, 1994).
31. James, C. A. *Global Status of Commercialized Transgenic Crops, 1999* ISAAA Briefs No. 17-2000 (International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2000).
32. James, C. A. *Global Review of Commercialized Transgenic Crops, 2001* ISAAA Briefs No. 23-2001 (International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, 2001).
33. Qaim, M & Traxler, G. S. Roundup-Ready soybeans in Argentina: farm level, environmental, and welfare effects. International Conference on Agricultural Biotechnology Research, Ravello, Italy, 11-14 July 2002 <http://www.economia.uniroma2.it/conferenze/icabr/abstract/Qaim.htm> (2002).
34. Huang, J., Rozelle, S. D, Pray, C. E. & Wang, Q. Plant biotechnology in China. *Science* **295**, 674–677 (2002).
35. Traxler, G., Godoy-Avila, S., Falck-Zepeda, J. & Espinoza-Arellano, J. Transgenic cotton in Mexico: economic and environmental impacts. Department of Agricultural Economics Working Paper (Auburn Univ., Auburn, AL, 2001).
36. Ismael, Y. Smallholder adoption and economic impacts of Bt cotton in the Makhathini Flats, Republic of South Africa. Report for DFID Natural Resources Policy Research Programme, Project R7946 (Department for International Development, London, 2001).
37. Huang, J., Wang, Q. & Zhang, Y. Agricultural biotechnology development and research capacity. Center for Chinese Agricultural Policy Working Paper (Center for Chinese Agricultural Policy, Chinese Academy of Sciences, Beijing, 2001).
38. Pray, C. E. & Schimmelpfennig, D. E. Role of biotech in South Africa's agriculture. Department of Agriculture, Food and Resource Economics Working Paper (Rutgers University, New Brunswick, NJ, 2001).
39. Pray, C. E., Courtmanche, A. & Govindasamy, R. The importance of intellectual property rights in the international spread of private sector agricultural biotechnology. International Conference on Agricultural Biotechnology Research, Ravello, Italy, 11-14 July 2002 <http://www.economia.uniroma2.it/conferenze/icabr/abstract/Pray1.htm> (2002).
40. Ekboir, J. (ed.) *World Wheat Overview and Outlook 2000-2001: Developing No-Till Packages for Small-Scale Farmers* (International Maize and Wheat Improvement Center (CIMMYT), Mexico, 2001).
41. Khanna, M., Epouhe, O. F. & Hornbaker, R. Site-specific crop management: adoption patterns and incentives. *Rev. Agric. Econ.* **21,** 455–472 (1999).
42. Alston, J. M., Pardey, P. G. & Roseboom, J. Financing agricultural research: international investment patterns and policy perspectives. *World Dev.* **26,** 1057–1072 (1998).
43. Pardey, P. G. & Beintema, N. M. *Slow Magic: Agricultural R& D A Century after Mendel* (International Food Policy Research Institute, Washington DC, 2001).
44. Alston, J. M., Marra, M. C., Pardey, P. G. & Wyatt, T. J. Research returns redux: a meta-analysis of rates of return to agricultural R&D. *Aust. J. Agric. Resource Econ.* **44,** 185–215 (2000).
45. Huffman, W. E. & Evenson, R. E. *Science for Agriculture: A Long-Term Perspective* (Iowa State Univ. Press, Ames, 1993).
46. Pray, C. E. Public/private sector linkages in research and development: biotechnology and the seed industry in Brazil, China and India. *Am. J. Agric. Econ.* **83,** 742–747 (2001).
47. Pray, C. E. & Umali-Deininger, D. Private agricultural research: Will it fill the gap? *World Dev.* **26,** 1127–1148 (1998).
48. Jin, S., Huang, J., Hu, R. & Rozelle, S. D. The creation and spread of technology and total factor productivity in China. *Am. J. Agric. Econ.* (in the press).
49. Evenson, R. E. & Gollin, D. A Comprehensive assessment of the role of the CG system in increasing yields in developing countries. Economic Growth Center Working Paper (Yale Univ. Growth Center, New Haven, CT, 2001).
50. Serageldin, I. & Persley, G. J. *Promethian Science: Agricultural Biotechnology, the Environment, and the Poor* (Consultative Group on International Agricultural Research, Washington DC, 2000).