Feeding a world of ten billion people: A 21st century challenge

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Abstract

During the past 35 years, cereal production has more than doubled, expanding faster than world population growth. Rapid adoption of high-yield agriculture, especially in the developing countries of densely populated Asia, has driven this Green Revolution. Even with the remarkable strides since the food crisis of the 1960s, hundreds of millions still live in poverty. Over the next 30 years, world cereal demand will likely increase by 40-50%, driven strongly by rapidly growing animal feed use and meat consumption. Perhaps as much as 80% of future increases in food production must come largely from farmlands already in use. Continued genetic improvement of food crops - using both conventional as well as biotechnology research tools - is needed to shift the yield frontier higher and to increase yield stability. Irrigated lands will continue to contribute the majority of world food supplies. Growing shortages of water will require that the 21st century will need to bring about a "Blue Revolution", one in which water-use productivity is much more closely wedded to land-use productivity. Roughly half of the world's 800 million hungry people live in marginal lands and depend upon agriculture for their livelihoods. For many of these people, food security will only come through increased agricultural production and income. Biotechnology will play an important role in developing new germplasm with greater tolerance to abiotic and biotic stresses and with higher nutritional content. The world has the technology - already available or well advanced in the research pipeline - to feed on a sustainable basis a population of 10 billion people. However, access to such technology is not assured, threatened by poverty, governmental regulation and intellectual property rights.

Introduction

During the past 40 years, global food production has more than kept pace with population, thanks to a continuing stream of high-yielding varieties combined

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with improved crop management practices. Despite a 3.5 billion increase in global population since 1960, world food supplies are 20% higher per person and real prices are 40% lower than they were in 1961 (FAO 2003). Even with these great achievements, some 800 people are chronically hungry and live in fear of starvation. By the end of this century there will be at least 10 billion people in the world, possibly more. Food production will have to be doubled, and produced in more environmentally sustainable ways. Most of this production will have to come from lands already in cultivation.

Contributions of the Green Revolution

The breakthrough in wheat and rice production in Asia in the mid-1960s, which came to be known as the Green Revolution, symbolized the process of employing agricultural science to develop modern agricultural techniques for the Third World. It began with the "quiet" wheat revolution in Mexico in the late 1950s and received world attention during the 1960s and 1970s in India, Pakistan and other parts of Asia. China became the greatest success story in the 1980s, not only because of the growth in agricultural production but also because of the success in distributing these foodstuffs more equitably throughout society. China's agricultural successes preceded and greatly facilitated its subsequent rapid industrial development.

Table 1 summarizes the sweeping changes that have occurred over the past four decades in the developing countries of Asia. High-yielding, semi-dwarf varieties are now used on 84 and 74% of the wheat and rice area, respectively; irrigation has more than doubled, reaching 175 million ha; fertilizer consumption has increased more than 30-fold and now stands at about 70 million tons of total nutrients; and tractor use has increased from 200,000 to 4.8 million units. The adoption of these modern factors of production has resulted in a tripling in cereal production, from 309 to 962 million tons.

We believe that there has tended to be too much focus on the high-yielding varieties themselves, as if they alone can produce miraculous results. Certainly, modern varieties can shift yield curves higher due to more efficient plant architecture and the incorporation of genetic sources of disease and insect resistance. However, modern, disease-resistant varieties can only achieve their genetic yield potential if systematic changes are also made in crop management, such as in dates and rates of planting, fertilization, water management, and weed and pest control. Moreover, many of these crop management changes must be applied simultaneously if the genetic yield potential of modern varieties is to be fully realized. For example, higher soil fertility and greater moisture availability for growing food crops also improve the ecology for weed, pest and disease development. Thus, complementary improvements in weed, disease and insect control are also required to achieve maximum benefits.

The importance of chemical fertilizer to food security, especially nitrogen, over the past 50 years cannot be underestimated. Perhaps 40% of the world's 6.2 billion people are alive today thanks to the Haber-Bosch process of synthesizing ammonia, which produces 80 million tons per year of chemical nitrogen (Smil 1999). It would be impossible for organic sources to replace this amount of nitrogen.

Table 1. Changes in factors of production in developing Asia.

Year	Adoption of modern varieties (ha × 10^6 / % area)		Irrigation	Fertilizer nutrient consumption	Tractors	Cereal production
	Wheat	Rice	(ha × 10^6)	(t × 10^6)	(× 10^6)	(t × 10^6)
1961	0 / 0%	0 / 0%	87	2	0.2	309
1970	14 / 20%	15 / 20%	106	10	0.5	463
1980	39 / 49%	55 / 43%	129	29	2.0	618
1990	60 / 70%	85 / 65%	158	54	3.4	858
2000	70 / 84%	100 / 74%	175	70	4.8	962

Source: FAOSTAT, July 2002; author's estimates of modern variety adoption based on CIMMYT and IRRI data.

Hunger still haunts Asia

Despite the successes of smallholder Asian farmers in applying Green Revolution technologies to triple cereal production since 1961, the battle to ensure food security for millions of miserably poor people is far from won, especially in South Asia, even though huge stocks of grain have accumulated in India. Hundreds of millions still go hungry for lack the purchasing power to buy food. Nobel Economics Laureate Professor Amartya Sen attributes China's greater success than India in achieving broad-based economic growth and poverty reduction to the higher priority that the Chinese government has given to rural education and health care services. With a healthier and better-educated rural population, China's economy has been able to grow about twice as fast as the Indian economy and today China's per capita income is nearly twice that of India.

African agriculture is our greatest challenge

More than any other region, food production in sub-Saharan Africa remains in crisis. No Green Revolution has occurred here. High rates of population growth and little application of improved agricultural technology have resulted in serious food deficits and deteriorating nutrition among the rural poor. While there have been signs recently that smallholder food production is beginning to improve, recovery is still very fragile.

To a considerable extent, Africa's food crisis is the result of the long-time neglect of agriculture by political leaders. Even though agriculture provides the livelihood from 70 to 85% of the people in most African countries, agricultural and rural development has been given low priority. Investments in distribution and marketing systems and in agricultural research and education are woefully inadequate. Furthermore, many governments pursued and continue to pursue a policy of providing cheap food for the politically volatile urban dwellers at the expense of production incentives for farmers.

Many of the African environments have deeply-weathered soils that lose fertility rapidly under repeated cultivation. Expanding populations and food requirements have pushed farmers onto marginal lands and led to a shortening in the bush/fallow periods previously used to restore soil fertility and pushed farmers onto marginal lands. With more continuous cropping on the rise, organic material and nitrogen have been depleted while phosphorus and other nutrient reserves are being depleted slowly but steadily.

Only about 10 kg of fertilizer nutrients are used per hectare of arable land in sub-Saharan Africa, compared to application rates 10- to 20-times higher in other regions (Table 2). These inordinately low levels of fertilizer use have contributed to the massive nutrient depletion that has occurred in almost every country. Unless African governments, supported by the international community, do something about restoring soil fertility, deteriorating agricultural productivity will undermine all other efforts to get agriculture moving and to serve as an engine for economic growth.

Table 2. Total fertilizer use per hectare of arable land, 2001.

	Total fertilizer nutrient consumption ($t \times 10^3$)	Per capita	
		Arable land ($ha \times 10^3$)	Fertilizer use (kg/ha)
Sub-Saharan Africa	1,320	138,799	10
Asia, Developing	74,079	448,972	165
European Union (15)	17,340	74,470	233
NAFTA[1]	24,265	247,310	99
Latin America[2]	10,405	120,396	86

[1]North American Free Trade Association (Canada, Mexico and USA).
[2]Latin American Integration Association (15 nations).
Source: FAOSTAT July 2003.

Sub-Saharan Africa's extreme poverty, poor soils, uncertain rainfall, increasing population pressures, lack of roads, changing ownership patterns for land and cattle, political and social turmoil, shortages of trained agriculturalists and weak research and technology delivery systems all make the task of agricultural development more difficult. Despite these formidable challenges, increased use of fertilizers, improved seeds and better agronomic practices will also work in Africa.

In 1986, the Nippon Foundation and its Chairman, the late Ryoichi Sasakawa, asked me to establish an agricultural development initiative in sub-Saharan Africa. This initiative was enthusiastically supported by former U.S. President Jimmy Carter and the Global 2000 program of the Carter Center. Our joint initiative, known as Sasakawa-Global 2000 (SG 2000) program, has worked over the years in 14 countries and currently operates in nine countries. Working with national extension services, SG 2000 has worked with several million small-scale farmers to grow production test plots, ranging in size from 0.1 to 0.5 ha. These demonstration plots have primarily focused on maize improvement, although sorghum, wheat, cassava, rice, soybeans and grain legumes have also been included.

The improved crop production technologies we recommend include: (1) the use of the best available commercial varieties or hybrids, (2) proper land preparation and seeding to achieve good stand establishment, (3) proper application of the appropriate fertilizers and, when needed, crop protection chemicals, (4) timely weed control, and (5) moisture conservation and/or better water use if under irrigation. We also work with smallholder farm families to improve on-farm storage of agricultural production, both to reduce grain losses due to spoilage and infestation and to allow farmers to hold stocks longer to exploit periods when prices are more favorable.

With technology already available, farmers can quite easily double and triple yields in most of their food, feed and fiber crops. They do not adopt this technology because they remain caught in a cost/price squeeze - both on input and output. Largely because of high transportation costs, the price of fertilizer at the farm gate in Africa is generally more than double - and sometimes more than triple - what a farmer in an industrialized country would pay. Similarly, the price at the farm gate for produce is often as low as 50% of the market price in urban centers. Inadequate infrastructure in sub-Saharan Africa - especially roads and transport and potable water and electricity - poses a major obstacle to rural and economic development. In particular, Africa's transport infrastructure is especially inadequate. Most agricultural production in Africa is generated along a vast network of footpaths, tracks and community roads where the most common mode of transport is "the legs, heads and backs of women". Indeed, the largest part of a household's time expenditure is for domestic transport. Efficient transport is needed to facilitate production and enable farmers to bring their products to markets, and intensive agriculture is particularly dependent on vehicle access. In addition, improvements in transport systems would reduce rural isolation, thus helping to break down tribal animosities, and facilitate the establishment of rural schools and clinics in areas where teachers and health practitioners are heretofore unwilling to settle.

China has much to offer to African nations in technical expertise and financial assistance. Its success in integrated rural development is especially pertinent to Africa, which must rely on labor-intensive, low-cost methods of construction. Moreover, China already has on-the-ground experience in Africa, having been involved in major rural infrastructure development projects, such as the Dar-es-Salaam to Lusaka railroad and the so-called Chinese highway in the Ethiopian northern highlands in what today is the Amhara region. Chinese contracting companies are increasingly winning international competitions to construct road and other infrastructure projects in Africa funded by the World Bank and various regional and sub-regional development banks. It is our hope that the government of China itself will become a more significant donor for agriculture and rural development in sub-Saharan Africa in future years.

Feeding future generations

Food demand

Increases in population and wealth will largely determine future increases in global food demand. Although world population growth rates are slowing, there is still a significant growth of nearly 80 million people per year, with 90% of this growth occurring in the developing world. Recently, the UN has predicted that the population will peak at about 9 billion towards the end of the 21st century, and then will begin to decline. However, because of the continuing high levels of rural illiteracy and poverty, we think that it is likely that world population will surpass 10 billion before leveling off. Almost all of the growth will occur in the developing countries, with sub-Saharan Africa, even with the HIV/AIDS pandemic, posting the greatest gains followed by South Asia. We also expect population growth in predominately Muslim countries to stay higher than current predictions.

By the end of the 21st century, world food production will have to double, and be achieved in more environmentally sustainable ways. In the future as today, cereals will continue to be the dominant food and feed crops. It is likely that the demand for cereals will increase by at least 50% by 2030 - or one billion tons - with feed use increasing from one third of total cereal demand to 40%. Cereal demand overall in the developing countries is expected to significantly outpace supply, with net imports increasing from 109 to 265 million tons by 2030 (FAO 2002). Oil crops, including grain legumes - which earlier had been displaced by higher yielding cereals in many parts of the developing world - have now become one of the world's most dynamic agricultural sectors, accounting for a huge share of the expansion of the world's agricultural lands over the past two decades. It is estimated that oil crop will play a major role in improving food energy supplies in developing countries over the next 25 years. Rapid growth in consumption has been accompanied by the emergence, among other countries, of China, India, Mexico and Pakistan becoming major net importers of vegetable oils and grain legumes for livestock feed.

Population growth, urbanization and rising incomes are fueling a massive increase in the demand for animal products in Asia and Latin America. India has already become the world's largest producer and consumer of milk. By 2020, people in developing countries are likely to consume 100 million tons more meat than they did in 1993, with the demand for poultry meat increasing the most (Table 3).

Table 3. Actual and projected meat consumption, by geographyc region.

Region	Total meat consumption (t × 10^6)		
	1983	1993	2020
China	16	38	85
Other East Asia	1	3	8
India	3	4	8
Other South Asia	1	2	5
Southeast Asia	4	7	16
Latin America	15	21	39
West Asia/North Africa	5	6	15
Sub-Saharan Africa	4	5	12
Developing world	50	87	188
Developed world	88	97	115
World	**139**	**184**	**303**

Source: IFPRI 2001.

Globally, the livestock sub-sector will become increasingly important within agriculture. However, because of the undeveloped state of traditional smallholder livestock systems, increases in supply of livestock products are coming primarily from industrial production. Yet with appropriate policies that encourage improvements in animal health and nutrition, the rewards of a rapidly growing livestock sector could benefit the smallholder producer.

Future sources of food supply

There are three main ways to increase food production: expanding the land area, increasing the frequency in which it is cropped and raising crop yields. Globally, it is estimated that 85% of the increases needed in global food production must come from agricultural lands already in production. This must be achieved by increasing the frequency of cultivation, largely through irrigation and by increasing crop yields. While rates of agricultural intensification have been slowing over the past 20 years, there is still sufficient scope to keep production ahead of population, at least in the aggregate. While the challenge of increasing agricultural production in environmentally sustainable ways is daunting, the task of equitably distribution is equally great, if not greater.

Expanding agricultural lands

The potential for expansions in arable land is limited in the densely-populated nations, especially Asia and Europe. In populous Asia, home to more than half of the world's people, there is very little uncultivated land left. Indeed, some of the land in South Asia currently in production should be taken out of cultivation, because of high susceptibility to soil erosion. Only in the Americas and in sub-Saharan Africa do large unexploited tracts exist, and only some of this land should eventually come into agricultural production.

The Brazilian Cerrado, or acid savanna is the greatest new agricultural area. This vast expanse of mostly flat to slightly rolling grasslands, with fire-induced, semi-climax brush and stunted-tree ecotypes covering approximately 205 million ha, spans from latitude 24° to 4° S and varies in elevation from 500 to 1,800 m, with unimodal precipitation (October to March) varying from 900 to 1,800 mm annually. The central Cerrado, with 175 million ha in one contiguous block, forms the bulk of the savanna lands. Approximately 112 million ha of this block is considered potentially arable. Most of the remainder has potential value for forest plantations and improved pastures for animal production. The soils of this area are mostly various types of deep loam to clay-loam latosols (e.g. oxisols, ultisols), with good physical properties, but highly leached of nutrients. They are strongly acidic, have toxic levels of soluble aluminum (and of manganese in some areas); most of the phosphate is fixed and unavailable.

Until 30 years ago, the Cerrado was sparsely inhabited and generally considered to have little value for agriculture. Some agriculture was practiced on strips of alluvial soils along the margins of streams, which were less acidic and where there had been an accumulation of nutrients. In addition, there was some cattle production although the natural savanna/brush flora characterized by poor digestibility and nutritive quality resulted in low carrying-capacity production. Today, a great agricultural revolution is under way in the Cerrado, the result of a long process of research and development that began more than 50 years ago.

Important advances in understanding how to manage the soils and to develop appropriate varieties were made during the 1960s and 1970s. However, it was during the 1980s that major research breakthroughs were achieved by the Brazilian National Agricultural Research Organization (EMBRAPA) and several international agricultural research centers (especially CIMMYT and CIAT). Out of this work came a third generation of crop varieties that combined tolerance to aluminum toxicity with high yield, better resistance to primary diseases and better agronomic type. Today, there are good varieties with aluminum tolerance of rice, maize, soybeans, wheat and several species of pasture grasses, including panicums, pangola and vaqueria.

Commercial crop production in the Cerrado is still unfolding. Many research advances are continuing being made by public and private organizations funded by government and farmer associations. Further research is needed to develop the more exact fertilizer recommendations for different crops in the different areas. With zero tillage in widespread use, better crop rotations will be essential to minimize the foliar infection with diseases that result from inoculums remaining in the plant crop residue from the previous season or two.

Huge investments are being made to develop the transport systems that will take the harvests from the Cerrados to the ocean-going ports. Roads, railroads and barge systems will soon link much of the Cerrados to ports and greatly reduce transport costs, which has been a major obstacle to full economic development. Over the next 20 years, it is likely that total food production in the Cerrados will triple and reach 100 million tons annually, if wise policies are implemented to stimulate agricultural production in environmentally-sustainable ways. Eventually, technology similar to what made the Cerrados productive will move into the llanos of Colombia and Venezuela and later into central and southern African countries where similar soil problems exist.

Improving water availability and management

A large proportion of the world's food supply is already produced under irrigation. Irrigated agriculture accounts for 70% of global water withdrawal and covers some 17% of cultivated land (about 275 million ha). It accounts for nearly 40% of world food production and nearly 60% of global cereal production (FAO 2003). Moreover, this share is expected to further increase over the next three decades. Developing countries as a whole can be expected to increase their irrigated area by 40 million ha, up from roughly 200 million ha today. Most of this expansion will occur in densely populated, land-scarce areas where irrigation is already crucial such as South and East Asia and the Near East and North Africa. In land-abundant sub-Saharan Africa and Latin America, increases in irrigated area of 2 and 4 million ha are projected, respectively (FAO 2003). In South America, it is likely that the Parana River will be used to irrigate dry areas of Bolivia and Argentina.

The rapid expansion in world irrigation and in urban and industrial water uses has led to growing shortages, heightening the potential for conflict among different users and between nations. Since 1960, some 100 million ha of new irrigated land have been added in developing countries; China has accounted for 30% of this increase. In most of these schemes, proper investments were not made in drainage systems to maintain water tables from rising too high and to flush salts that rise to the surface back down through the soil profile. We all know the consequences, such as serious salinization of many irrigated soils, especially in drier areas, and waterlogging of irrigated soils in the more humid area. In particular, many Asian irrigation schemes, which account for nearly two-thirds of the total global irrigated area, are seriously affected by both problems. The result is that most of the funds going into irrigation end up being used for stopgap maintenance expenditures for poorly designed systems, rather than for new irrigation projects. Government must invest in drainage systems in ongoing irrigation schemes, so that the current process of salinization and waterlogging is arrested. In new irrigation schemes, water drainage and removal systems should be included in the budget from the start of the project. Unfortunately, adding such costs to the original project often will result in a poor return on investment. Society then will have to decide how much it is willing to subsidize new irrigation development.

The UN's 1997 Comprehensive Assessment of the Freshwater Resources of the World estimates that, by the year 2025, as much as two-thirds of the world's population could be under water-stress conditions (WMO 1997). Given these trends, we need to rethink our attitudes about water and move away from thinking of it as a free good. Pricing water delivery closer to its real costs is a necessary step to improving water-use efficiency. Farmers and irrigation officials (and urban and industrial consumers) will need incentives to save water. Moreover, management of water distribution networks, except for the primary canals, should be decentralized and turned over to farmers.

There are many technologies for improving the water-use efficiency in agriculture. Wastewater can be treated and used for irrigation, especially important for periurban agriculture, which is growing rapidly around many of the world's megacities. New crops requiring less water (and/or new improved varieties), more efficient crop sequencing and timely planting, can also achieve a significant saving in water use.

Proven technologies are also available that save water, reduce soil salinity and increase water productivity (yield per unit of water used). Various new precision irrigation systems, such as drip and sprinkler systems, are available that will supply water to plants only when they need it. Planting on raised beds uses water more efficiently, especially in irrigated areas where savings of 25 to 30% are possible over current practices. Conservation tillage with mulch also is a water-harvesting technology that can lead to significant yield increases in areas prone to drought. Improved small-scale and supplemental irrigation systems also are now available to increase the productivity of rainfed areas, which offer much promise for smallholder farmers.

To expand food production for a growing world population within the parameters of likely water availability, the inevitable conclusion is that humankind in the 21st century will need to bring about a "Blue Revolution" to complement the so-called Green Revolution of the 20th century. In the new Blue Revolution, water-use productivity must be wedded to land-use productivity. New science and technology must lead the way.

Improved technology

It is estimated that some 80% of future increases in crop production in developing countries will have to come from higher yields, increased multiple cropping and shorter fallow periods (FAO 2003). As it is almost certain that prime agricultural land will continue to be lost to urban uses, agricultural researchers and farmers face the challenge during the next 30 years of developing and applying technology that can increase the global cereal yields by 50 to 75%, and in ways that are economically and environmentally sustainable. Much of these yield gains will come from applying technology "already on the shelf" but yet to be fully utilized. But there will also be new research breakthroughs from biotechnology, especially in plant breeding to improve yield stability and, hopefully, maximum genetic yield potential.

Continued genetic improvement of food crops by using both conventional as well as biotechnology research tools is needed to shift the yield frontier higher and to increase stability of yield. While biotechnology research tools offer much promise, it is also important to recognize that conventional plant breeding methods are continuing to make significant contributions to improved food production and enhanced nutrition. Moreover, engineered genes, such as *Bt*, are only of value when incorporated in the very best commercial varieties and hybrids.

In rice, wheat and maize, distinct, but inter-related strategies are being pursued to increase genetic maximum yield potential: changes in plant architecture, hybridization and wider genetic resource utilization. Significant progress has been made in all three areas. IRRI claims that the new "super rice" plant type, in association with direct seeding, could increase rice yield potential by 20 to 25% (Khush 1995). In wheat, new plants with larger heads, more grains and fewer tillers could lead to an increase in yield potential of 10 to 15%. Introducing genes from related wild species into cultivated wheat can introduce important sources of resistance for several biotic and abiotic stresses, and perhaps for higher yield potential as well, especially if the lines are used as parental material in the production of hybrid wheats (Rajaram and Borlaug 1997).

The success of hybrid rice in China (now covering more than 60% of the country's irrigated area) has led to a renewed interest in hybrid wheat, when most research had been discontinued for various reasons, mainly low heterosis while trying to exploit cytoplasmic male sterility, and high seed production costs. However, recent improvements in chemical hybridization agents, advances in biotechnology and the emergence of the new wheat plant type have made an assessment of hybrids worthwhile. With better heterosis and increased grain filling, the yield frontier of the new wheat genotypes could be 25 to 30% above the current germplasm base. In addition, hybrid triticale offers the promise of higher yield potential than wheat for some areas and uses.

Maize production has really begun to take off in many Asian countries, especially China. It now has the highest average yield of all the cereals in Asia, with much of the genetic yield potential yet to be exploited. Moreover, recent developments in high-yielding quality protein maize (QPM) varieties and hybrids using conventional plant breeding methods stand to improve the nutritional quality of the grain without sacrificing yields. This research achievement offers important nutritional benefits for livestock and humans. With biotechnology tools, it is likely that we will see further nutritional "quality" enhancements in the cereals in years to come.

The recent development of high-yielding sorghum varieties and hybrids with resistance to the heretofore-uncontrollable parasitic weed, *Striga* spp., by researchers at Purdue University in the USA (see Ejeta 2005, this volume) is an important research breakthrough in many areas of Asia and Africa.

There is growing evidence that genetic variation exists within most cereal crop species for developing genotypes that are more efficient in the use of nitrogen, phosphorus and other plant nutrients as compared to the best varieties and hybrids. In addition, there is good evidence that further heat and drought tolerance can be built into high-yielding germplasm. Researchers are also optimistic that they can incorporate genes for cold/frost tolerance in temperate maize. This would permit early planting in the spring, when moisture is often more abundant and allow the maize plant to escape the mid-summer drought, which often occurs during flowering.

Crop productivity depends both on the yield potential of crop varieties and the crop management employed to enhance input and output efficiency. Thanks to the Green Revolution, global wheat, rice and maize yields grew rapidly between 1961 and 2000, including most developing countries with the exception of sub-Saharan Africa. However, at the other end of the scale, yields of sorghum, millet and pulses grew much more slowly, especially in the low-income, food-deficit nations.

With slowing population growth projected over the next 30 years, crop yields will not need to grow as rapidly as in the past. Nevertheless, yield increases will be required. In some developing countries - especially those such as China, India and others in Asia and in parts of Latin America - crops have attained high yields. But in many countries large yield gaps persist between those obtained on experiment stations and on farmers' fields. In many cases, these yield gaps can be significantly narrowed, and must be narrowed in the coming decades.

Productivity gains can be made in tillage, water utilization, fertilization, weed and pest control, and harvesting. One powerful management innovation is conservation tillage (e.g. no-tillage, minimum tillage), which is spreading rapidly in many parts of the world, and now is practiced by farmers on 75 million ha. By reducing and/or eliminating the tillage operations, turnaround time on lands that are double- and triple-cropped annually can be significantly reduced, especially rotations like rice/wheat and cotton/wheat prevalent over large areas in Asia. This leads to higher production and lower production costs. Conservation tillage controls weed populations and greatly reduces the time that small-scale farm families must devote to this backbreaking work. Finally, important soil and water conservation properties also accrue. The mulch left on the ground reduces soil erosion and increases moisture conservation, and builds up the organic matter in the soil - all very important factors in natural resource conservation. The decaying plant roots from previous crop cycles also help to channel and hold water deeper in the soil profile. Indeed, in drought-prone areas, conservation tillage may be more important as a moisture-conserving technology than a soil-conserving one. Conservation tillage does, however, require modification in crop rotations to avoid the build up of diseases and insects that find a favorable environment in the crop residues for survival and multiplication.

Marginalized people and lands

Thanks to productivity-enhancing Green Revolution technologies and widespread economic growth over the past 40 years, the proportion of food-insecure people living in developing countries has declined from 57 to 27% of the total population (FAO 2003). Despite this tremendous achievement, there are still some 800 million hungry and malnourished people in the developing world. Of this total, 232 million are in India, 200 million in sub-Saharan Africa, 112 million in China, 152 million elsewhere in Asia and the Pacific, 56 million in Latin America and 40 million in the Near East and North Africa (UN Millennium Project 2003).

About 214 million people, or 26%, have caloric intakes so low that they are unable to work or care for themselves. At least half of the world's most food-insecure people are poor smallholder farmers in low-income countries that cultivate marginal lands that are environmentally fragile, and rely on natural resources over which they have little legal control. Land-hungry farmers end up cultivating unsuitable areas, such as erosion-prone hillsides and semiarid areas where soil erosion is rapid and tropical forests where crop yields on cleared fields drop sharply after just a few years. Many of these marginal lands are critical to livelihoods of very poor people and also play critical roles in watershed and biodiversity conservation. Moreover, the poor are the most vulnerable to the impacts of ecosystem degradation. If they are to eat, most of these people will have to produce the food they need themselves (UNDP 2003).

These statistics on hunger point to the need to improve drastically the food security of farmers in higher-risk environments and remote regions and to develop poverty-reduction strategies that will provide employment options for the very resource-poor farmers, especially in marginal lands, in sectors other than agriculture. Clearly, too many people in the developing world are trying to gain their livelihoods through agriculture, with too few resources. Reducing agricultural populations, while increasing the land and water resources available to those that remain, will be one of our greatest 21st century challenges. Public projects to improve the infrastructure and environment are also needed if hunger is to be halved. Often, these social investments will be part-time employment for smallholder farmers during the "lean season".

Food-for-work programs should be organized with rural agricultural communities in highly environmentally-degraded areas to initiate high-priority eco-conservation reclamation works, such as gully rehabilitation, bunds and terraces, and tree planting, including nitrogen-fixing and nutrient-mobilizing species. In-kind food-for-work payments should be sourced from food-surplus areas of the country. Thus, multiple development goals could be accomplished: reclamation of severely degraded watersheds, increased food security and expanded market demand for domestically produced food staples.

Fisheries

Although fish account for less than 2% of the calories contained in the world food supply they contribute 16% of animal protein, as well as fats and minerals. World fish production has kept ahead of population growth over the past three decades, although at a cost. By 2000, three-quarters of ocean fish stocks were over-fished, depleted or exploited to their maximum sustainable yield (FAO 2003). The marine catch leveled off at 80-85 million tons a year during the 1990s, but was compensated by rapid growth in aquaculture, which now accounts for more than one quarter of 125 million tons of world fish production in 2000. By 2030, world annual fish production is likely to rise to 150 to 160 million tons. Aquaculture will account for virtually all of this increase, with most of this production occurring in Asia in general, and in China in particular. Nearly 40% of all fish production is now internationally traded, with developing countries playing an ever-increasing role. Earnings from fish production in developing countries now far exceed earnings from commodities such as coffee, cocoa, banana or rubber, and are increasingly seen as a source of hard currency (FAO 2003). Aquaculture species have already been improved significantly through conventional breeding, and genetic engineering is also being employed to achieve further advances. Already, a gene that codes for anti-freeze protein in the Artic flounder has been transferred to Atlantic salmon to increase its tolerance of cold waters, although it is not being marketed commercially as yet (FAO 2003). With past over-fishing of wild marine stocks, it is likely that aquaculture will continue to grow in the future, with new species being domesticated, such as halibut, cod and tuna.

What can we expect from biotechnology?

In the last 20 years, biotechnology based upon recombinant DNA has developed invaluable new scientific methodologies and products in food and agriculture. This scientific journey to the molecular level is the continuation of our progressive understanding of the workings of nature. The new biotechnology permits the crossing (hybridization) across taxonomically distinct genera, families, orders or kingdoms.

Estimates of the annual global investment in R&D in crop biotechnology range between US $4.4 and 4.7 billion, of which 4.2 billion is invested by industrialized countries. China may be investing as much as $100 million in crop biotechnology, with at least 2,000 scientists working on 50 plant species and 120 functional genes (James 2004). India is investing at least $25 million per year, including $15 million by the Indian Council of Agricultural Research (ICAR). Brazil is investing $15 million per year, mostly in public sector organizations (The Sao Paulo Research Foundation and EMBRAPA). Other developing countries investing in crop biotechnology include Pakistan, Malaysia, Thailand, Indonesia, Philippines and Vietnam in Asia; Mexico, Cuba, Argentina and Chile in Latin America; and South Africa, Egypt, Nigeria, Zimbabwe and Kenya in Africa.

Recombinant DNA methods have enabled breeders to select and transfer useful single genes from other taxonomic groups. So far, the resulting gene alterations have conferred producer-oriented benefits, such as resistance to pests, diseases and herbicides. Other benefits likely to come through biotechnology and plant breeding are crop varieties with greater tolerance to drought, waterlogging, heat and cold - important traits given current predictions of climate change. In addition, many consumer-oriented benefits, such as improved nutritional and other health-related characteristics, are likely to be realized over the next 10 to 20 years.

Despite the formidable opposition in certain circles to transgenic crops, commercial adoption by farmers of the new varieties has been one of the most rapid cases of technology diffusion in the history of agriculture. Between 1996 and 2003, the area planted commercially to transgenic crops has increased from 1.7 to 67.8 million ha (James 2004). This area is located in 17 countries, with the USA accounting for 63% and Argentina 20% of the total. From a crop perspective, in 2003 transgenic soybeans ranked first with 41 million ha, followed by transgenic maize at 16 million ha, transgenic cotton at 7 million ha and transgenic canola at 4 million ha. Herbicide tolerance is the most important trait, accounting for 77% of the total area followed by insect resistance (Bt) at 15%. Some 4 million smallholder Chinese farmers were growing Bt cotton on 2.8 million ha in 2003, an increase of 40% over 2002.

Preliminary estimates suggest that the total acreage planted to transgenic crops in the world in 2005 will again increase. A new trait in maize for the North American market - corn rootworm control - will be available in the USA and GM herbicide-tolerance soybeans are expected to continue expanding in Brazil. In addition, significant growth in Bt cotton is expected in India.

To date, there is no reliable scientific information to substantiate that transgenic crops are inherently hazardous. Recombinant DNA has been used for 25 years in pharmaceuticals, with no documented cases of harm attributed to the genetic modification process. So far, this is also the case in genetically modified foods. The seed industry has been doing a good job in ensuring that its GM seed varieties are safe to plant and the food that they produce is safe to eat.

We predict that in the not too distant future - when science rather than emotions and ideology becomes more dominant - many environmentalists will embrace GMOs as a powerful "natural" tool to achieve greater environmental protection. Already, adoption of GMOs has led to a significant decline in the use of herbicides and insecticides. So far, in cotton, maize and soybeans alone in the USA, pesticide use in 2002 was reduced by 21,000 tons, due the use of varieties with genetic resistance to insects and herbicide tolerance (Gianessi 2002).

Opposition to transgenic crops carrying the *Bacillus thuringiensis* (Bt) gene is also ironic. Rachel Carson, in her provocative 1962 book, "Silent Spring", was especially effusive in extolling the virtues of Bt as a "natural" insecticide to control caterpillars. But anti-GMO activists have decried the incorporation of the Bt gene into the seed of different crops, even though this can reduce the use of insecticides and is harmless to other animals, including humans. Part of their opposition is based upon the prospect that widespread use of Bt crops may lead to mutations in the insects that eventually will render the bacterium ineffective. This seems incredibly naive. We can be quite sure that the ability of a particular strain of *Bacillus thuringiensis* to confer insect resistance inevitably will break down, and this is why dynamic breeding programs - using both conventional and recombinant DNA techniques - are needed to develop varieties with new gene combinations to keep ahead of mutating pathogens. This has been the essence of plant breeding for more than 70 years.

There are several breakthroughs that genetic engineering could bring to the cereals that we dream might be forthcoming in the not-too-distant future. One deals with disease resistance and two others with grain quality. Among all the cereals, rice is unique in its immunity to the rusts (*Puccinia* spp.) All the other cereals (e.g. wheat, maize, sorghum, barley, oats and rye) are attacked by two to three species of rusts, often resulting in disastrous epidemics and crop failures. Enormous scientific effort over the past 80 years has been devoted to breeding wheat varieties for resistance to stem, leaf and yellow rust species. After many years of intense crossing and selecting, and multi-location international testing, a good, stable, but poorly understood, type of resistance to stem rust was identified in 1952 that remains effective worldwide to the present. However, no such success has been obtained with resistance to leaf or yellow rust, where genetic resistance in any particular variety has been short-lived (3 to 7 years). Imagine the benefits to humankind if the genes for rust immunity in rice could be transferred into wheat, barley, oats, maize, millet and sorghum. Finally, the world could be free of the scourge of the rusts, which have led to so many famines over human history.

On another front, bread wheat has superior dough for making leavened bread and other bakery products due to the presence of two proteins, namely gliadin and glutenin. No other cereals have this combination. Imagine if the genes for these proteins could be transferred to the other cereals, especially rice and maize, so that they, too, could make good-quality unleavened bread. This would help many countries, and especially the developing countries in the tropics, where bread wheat flour is often the single largest food import.

Finally, it is also important to mention the growing potential of science to improve the nutritional quality of our food supply. The development, using conventional plant breeding methods, of high-lysine, high-tryptophan quality protein maize (QPM) varieties and hybrids took some two decades of painstaking research work (see Potrykus, this volume). In the future, through biotechnology, we will see further nutritional "quality" enhancements in the cereals and other foods at a much faster rate. Recently, the transfer of genes to increase the quantity of vitamin A, iron and other micronutrients contained in rice can potentially bring significant benefits for millions of people with deficiencies of vitamin A and iron, causes of blindness and anemia, respectively. Unfortunately, "Golden rice" is now tied up in complex patent negotiations.

Beyond the food, feed and fiber production benefits that can be forthcoming through biotech products, the possibility that plants can actually be used to vaccinate people against diseases such as hepatitis B virus or Norwalk disease, which causes diarrhea, simply by growing and eating them, offers tremendous possibilities in poor countries. This line of research and development should be aggressively pursued, and probably through private-public partnerships, since traditional vaccination programs are costly and difficult to execute.

Of course, scientists and researchers employing recombinant DNA must pay attention to public values and concerns, and must explore all legitimate and reasonable questions about the potential impacts of their activities. However, today we are seeing too many opponents of biotechnology dismiss the many safety and regulatory checks that govern whether a new product is brought to the marketplace. Unfortunately, they willfully choose to emphasize highly unlikely potential risks.

In the United States, at least three Federal agencies provide scrutiny over the safety of GMOs. The data requirements imposed upon biotechnology products are far greater than they are for products from conventional plant breeding, and even from mutation breeding, which uses radiation and chemicals to induce mutations. But we must also understand that there is no such thing as "zero biological risk". It simply does not exist, which makes, in my opinion, the enshrinement of "precautionary principle" just another argument used by anti-biotech zealots to stop the advance of science and technology.

Recombinant DNA has been used for 25 years in pharmaceuticals, with no documented cases of harm attributed to the genetic modification process. So far, this is also the case in GM foods. This is not to say that there are no risks associated with particular products. There certainly could be. But we need to separate the methods by which GMOs are developed - which are not inherently unsafe - from the products, which could be if certain toxins or allergens are introduced.

A second controversial aspect of transgenic varieties involves issues of ownership and access to the new products and processes. Since most of GMO research is being carried out by the private sector, which aggressively seeks to patent its inventions, the intellectual property rights issues related to life forms and to farmer access to GM varieties must be seriously addressed. Traditionally, patents have been granted for "inventions" rather than the "discovery" of a function or characteristic. How should these distinctions be handled in the case of life forms? Moreover, how long, and under what terms should patents be granted for bioengineered products?

Ironically, it is farmers and consumers in the low-income, food-deficit nations who have most needed these new agricultural biotech products, since they can reduce production costs per unit of output, which can benefit farmer incomes, while increasing the availability and accessibility of food, so important for reducing poverty. Moreover, since the technology is packed into the seed, biotech products can help to simplify input delivery, often a major bottleneck in reaching smallholder farmers. But instead, the battle over biotech products is being fought mainly in the rich nations.

Of course, Third World nations must put into place reasonable regulatory frameworks to guide the development, testing and use of GMOs, both to protect people and the environment. In addition, the intellectual property rights of private companies also need to be safeguarded to ensure fair returns to past investments and to encourage greater investments in the future.

Public vs. private research

During the past two decades, support to the publicly-funded agricultural research in OECD countries has slowly declined, while support for international agricultural research has dropped so precipitously to border on the disastrous. The high cost of biotechnology research and development, including getting through the increasingly costly regulatory process, has led to rapid consolidation in the ownership of agricultural life science companies. If these trends continue, we risk losing the broad continuum of agricultural research organizations - from the more basic to the more applied and practical - needed to keep agriculture moving forward.

Strong public sector research programs are needed to train new generations of scientists and they also have a role to play, we believe, as "honest scientific brokers" so that farmers and consumers do not become hostages to private sector research monopolies. By this we mean, independent research funding in public institutions that is not "commissioned" research done for private companies.

One important characteristic of publicly funded research has been that the information and products that it produces historically have tended to be quite freely available, not only to national scientists but also to the international scientific community. The benefits of this scientific sharing have been enormous, and worked in multidirectional ways. They have helped to break down individual and institutional barriers that tend to isolate researchers from each other and retard the sharing of useful information and products. The problem goes beyond private proprietary research. Cooperation has also been declining among public sector institutions, partially because of the desire to protect proprietary information and partially because of problems of bureaucracy and egocentric behavior.

For example, the lack of cooperation between public sector research institutions in China and India, is becoming quite serious. With the rise of provincial research institutions and a weakening of national/federal institutions, there is a troubling trend of isolationism and unnecessary duplication of efforts, which leads to inefficiency in the allocation of resources and a retardation in the sharing of information and research products. In plant breeding such isolation can have disastrous consequences, since multi-location testing is a key element in disease and insect pest surveillance and development of resistant cultivars.

New forms of public-private collaboration are needed to ensure that all farmers and consumers worldwide will have the opportunity to benefit from the new genetic revolution. Governments should support public biotechnology research to balance and complement private sector investments. Developing nations need to be prepared to work with and benefit from breakthroughs in biotechnology. Government regulatory frameworks should have reasonable risk-aversion expectations and should not be overly bureaucratic.

Concluding remarks

During the past 20 years, a growing deadlock has developed between agriculturalists and environmentalists over what constitutes “sustainable agriculture”. This debate has confused, if not paralyzed, many in the international donor community who, afraid of antagonizing powerful environmental lobbying groups, have turned away from supporting the agricultural modernization still needed in much of smallholder Asia, sub-Saharan Africa and Latin America. This deadlock must be broken. We cannot lose sight of the enormous job before us to feed future generations, 90% of whom will begin life in a developing country and many in poverty. Only through increased investment in dynamic agricultural and rural development programs can we hope to alleviate poverty, improve human health and reduce political instability.

Moreover, it is time that those concerned with biodiversity and environmental protection recognize the significant contributions made by high-yield agriculture to ecoconservation over the past 50 years. If the average global cereal grain yield of 1950 had still prevailed in 2000, we would have needed an additional 1.1 billion ha of land of the same quality to produce the current global harvest (Figure 1).

Such land reserves no longer exist, and certainly not in highly-populated Asia. Moreover, had more environmentally fragile land been brought into agricultural

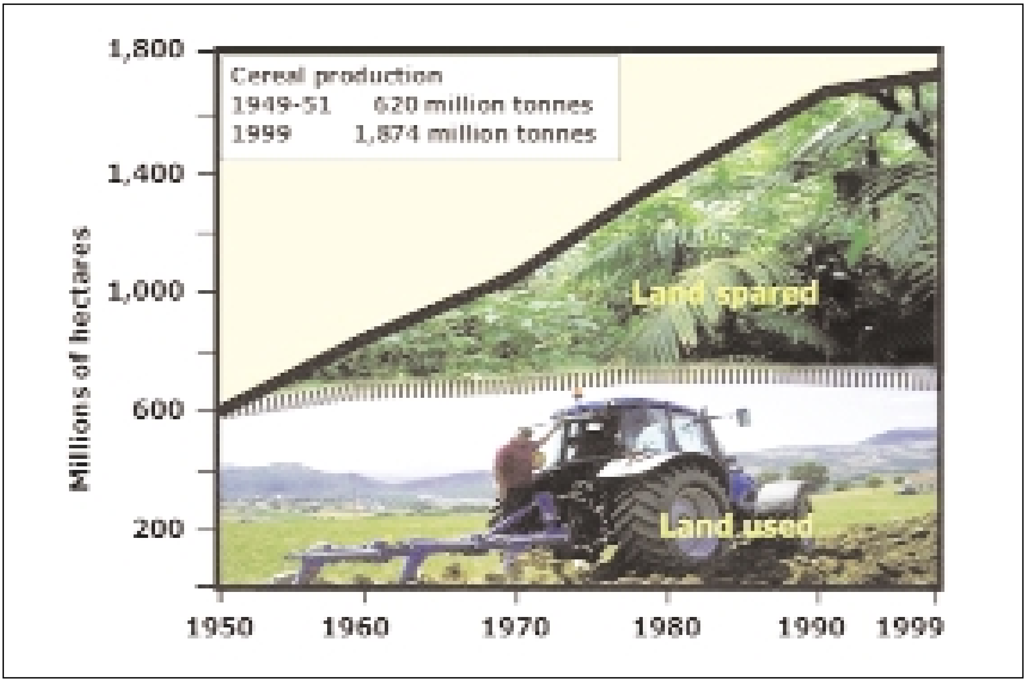

Figure 1. World cereal production (expressed in milled-rice equivalents) and area spared from deforestation through improved technology (source: FAO Production yearbooks and AGROSTAT).

production, the impact on soil erosion, loss of forests, grasslands, and biodiversity and extinction of wildlife species would have been enormous.

It has taken humankind 10,000 years to expand food production to the current level of about 5 billion gross tons per year. Within the next 30 years, we will have to expand the current harvest by at least 50% and double the world food supply sometime later in the century. This cannot be done unless farmers across the world have access to currently available high-yielding crop production methods as well as new biotechnological breakthroughs, which offer great promise for improving the yield potential, yield dependability and nutritional quality of our food crops, as well as in improving human health in general.

The world has the technology - either available or well advanced in the research pipeline - to feed on a sustainable basis 10 billion people. The more pertinent questions facing society and the scientific community are (1) whether farmers and ranchers will be permitted access to this continuing stream of new technologies needed to meet the food, fiber and nutrition challenges that lie ahead, and (2) whether a more equitable global distribution of benefits in food supplies can be assured in the future.

References

FAO (2003) World agriculture: towards 2015/2020: an FAO perspective. FAO, Rome, Italy

Gianessi L (2002) Plant biotechnology: current and potential impact for improving pest management in US agriculture. National Center for Food and Agricultural Policy, Washington, DC, USA

James C (2004) Global review of commercialized transgenic crops: 2002 feature: Bt maize. International Service for the Acquisition of Agri-Biotech Applications (ISAAA). Brief No. 30. ISAAA, Ithaca, NY, USA

Khush GS (1995) Modern varieties - their real contribution to food supply and equity. Geojournal 35:275-284

Millennium Project (2003) Halving global hunger - Background paper of the Millennium task force on hunger, UNDP, New York, NY, USA

Rajaram S, Borlaug NE (1997) Approaches to breeding for wide adaptation, yield potential, rust resistance and drought tolerance. Primero Simposio Internacional de Trigo, Cd. Obregon, Mexico, April 7-9, 1997

Sen A (2000) Democracy as freedom. Achor Books, New York, NY, USA

Smil V (1999) Long-range perspectives on inorganic fertilizers in global agriculture. Travis P. Hignett Memorial Lecture, IFDC, Muscle Shoals, AL, USA

UNDP (2003) Human development report. Millennium development goals: a compact among nations to end human poverty. UNDP, New York, NY, USA

World Meteorological Organization (1997) Comprehensive assessment of the freshwater resources of the world