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Prospects for World Agriculture in the Twenty-First Century

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I. INTRODUCTION

The rice–wheat system of South Asia is an extremely important cropping system. It covers nearly 14 million hectares and accounts for one fourth of the rice and one third of the wheat produced in the region. Despite the importance of this system to the regional agricultural economy, its productivity has been limited by soil and water and crop management problems associated with the turnaround phases between the rice and wheat crops. Thus, identification of improved crop management practices that enhance the productivity of the rice–wheat farming system in environmentally sustainable ways is of paramount importance to the region and the world.

II. PERFORMANCE OF THE GLOBAL FOOD SYSTEM

Thanks to a continuing stream of high-yielding varieties that have been combined with improved crop management practices, food production has more than kept pace with global population growth during the past 40 years. Contemporary per capita world food supplies are 23% higher and real prices are 65% lower than they were in 1961 (IFPRI, 2001). Despite these achievements, there is no room for complacency regarding food production and poverty alleviation.

Fertilizer use, and especially the application of low-cost nitrogen derived from synthetic ammonia, only became an indispensable component of modern agricultural production after World War II. Nearly 80 million nutrient tons of nitrogen are now consumed annually (FAOSTAT, 2002). It is estimated that 40% of the 6 billion people who inhabit the earth today are alive thanks to the Haber–Bosch process of synthesizing ammonia (Smil, 1999). It would be impossible to replace this amount of nitrogen using only organic sources.

Agricultural intensification has made major contributions to the protection of environmental resources. This is true despite problems such as salinization, caused by poorly engineered and managed irrigation systems, and the local pollution of some ground- and surface water resources, caused in part by excessive use of fertilizers and crop protection chemicals. By increasing yields on the lands best suited to agriculture, world farmers have been able to preserve vast areas of land for other purposes. For example, if cereal yield levels of 1950 had failed to increase to the year 2000, we would have had to use nearly 1.8 billion hectares of land to produce the current global harvest, rather than the 600 million hectares that were used for production. Much of this land would not have been available, especially in highly populated Asia. Moreover, had more environmentally fragile land been brought into agricultural production, the impact on soil erosion, loss of forests, grasslands, and biodiversity, and extinction of wildlife species would have been enormous.

Humans have been able to expand food production to the current level of about 5 billion gross tons per year over the past 10,000 to 12,000 years. By 2020, we will need to expand the current annual harvest by 40%–50%. This will be impossible unless farmers across the world have access to existing high-yielding crop production methods as well as new biotechnological breakthroughs. They offer great promise for improving the yield potential, yield dependability, and nutritional quality of our food crops, as well as for improving human health in general.

III. GREEN REVOLUTION IN ASIA

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 applications of technology for the Third World. It began in Mexico with the "quiet" wheat revolution in the late 1950s. During the 1960s and 1970s, India, Pakistan, and the Philippines received world attention for their agricultural progress, as reflected by data in Table 1.

South Asian countries have been able to achieve great increases in cereal production, especially in wheat. Today the region is a net exporter of wheat and rice. India's current grain stocks include nearly 30 million tons of wheat and 20

Table 1 Growth in Rice and Wheat Production, South Asia and Developing Regions of Asia

	1961	1970	1980 (million tons)	1990	2000	% Increase 1961–2000
South Asia[a]						
Rice, milled	49	58	74	100	121	+147
Wheat	15	28	44	66	100	+567
Developing Asia[b]						
Rice, milled	122	183	233	31	357	+193
Wheat	44	51	128	202	232	+427

[a] South Asia region includes Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka.
[b] Developing Asia region includes all developing countries, from Turkey in West Asia to China in East Asia.
Source: FAOSTAT (2001).

million tons of rice. Pakistan has considerably expanded its exports of wheat and rice. They range from 1 to 2 million tons annually. Bangladesh and Sri Lanka are net importers of wheat. Each imports around 1 million tons annually. Bangladesh also imports around 0.5 million tons of rice (FAOSTAT, 2001).

China has been Asia's greatest food success story since 1980. It has achieved enormous productivity-led increases in total food supply, and it has been able to distribute this food more equitably to poor segments of the population. China's agricultural and rural development successes have greatly facilitated rapid industrial and urban development. Indeed, agriculture in the developing Asia region as a whole has made remarkable strides forward since the food crisis of the 1960s. However, despite the great improvements in quality of life for most rural Asians, hundreds of millions still live in poverty. They continue to experience lower levels of health and education than their urban counterparts.

FAO and other data in Table 2 indicate changes in the factors of production that have occurred in developing Asia (developing countries stretching from Turkey in the west to China in the east) over the past four decades. Irrigated area has more than doubled—to 176 million hectares; fertilizer consumption has increased more than 30-fold; and tractor use has increased from 200,000 to 4.6 million units during this same period of time.

The battle to ensure food security for millions of poor people, who live in misery, is far from won, especially in South Asia. This is true despite the important contributions of smallholder Asian farmers to the 300% increase in grain production through the application of Green Revolution technologies, which took place over the past 30 years.

Table 2 Changes in Factors of Production in Developing Asia

	Modern varieties			Fertilizer nutrient	
	Wheat (million ha% area)	Rice	Irrigation (million ha)	Consumption (million tons)	Tractors (millions)
1961	0/0%	0/0%	87	2	0.2
1970	14/20%	15/20%	106	10	0.5
1980	39/49%	55/43%	129	29	2.0
1990	60/70%	85/65%	158	54	3.4
1998	70/84%	100/74%	176	70	4.6

Sources: FAOSTAT (2001); CIMMYT and IRRI impact data; authors' estimates.

Data from China illustrate that increased food production, although a necessary condition for food security, is not a sufficient condition for it. As shown in Table 3, huge stocks of grain have accumulated in India and China. However, hundreds of millions of people in India suffer from hunger, because they lack the purchasing power to buy food, while China continues to make great strides forward in this regard. Nobel Economics Laureate, Professor Amartya Sen, has argued that this difference is due to differences in the relative emphasis being given to broad-based economic growth and poverty reduction. He argues that China's greater success is a result of the higher priority its government has given to investments in rural education and healthcare services. Nearly 85% of the Chinese population is literate compared to only 55% of the Indian population. Forty-five percent of India's population is below the poverty line, as compared

Table 3 Socioeconomic Development Indicators in China and India

Development Indicators	China	India
Population in 1961 (millions)	669	452
Population in 2000 (millions)	1,290	1,016
GDP per capita income in 1999 (US$)	780	440
Annual population growth, 1990–1999	1.1%	1.8%
Population in agriculture in 1995	47.0%	64.0%
Population with income less than $ 1/Day (1984–1999)	4.6%	35.0%
Malnutrition: children underweight (1993–1999)	9.0%	45.0%
Population over 15 illiterate in 1995	16.0%	45.0%

Sources: World Bank (2001); FAOSTAT (2001).

to China's population. And only 9% of the children in China are malnourished as compared to 35% of the children in India. Healthier and better-educated rural populations in China have made it easier for that nation's economy to grow about twice as fast as that of India during the past two decades. Today, China's per capita income is 77% higher than that of India.

High levels of illiteracy among populations over 15 years of age exist in all countries of South Asia, except Sri Lanka. Data in Table 4 also indicate that infant mortality rates in Sri Lanka are much lower than in other nations, which may be related to its lower illiteracy levels. Other South Asian nations also have higher levels of child malnutrition and absolute poverty, suggesting that they need to implement universal, free primary education for boys and girls. They also need to ensure that secular curricula are taught, to allow students to attain minimum levels of proficiency in reading, writing, arithmetic, basic science, and history. The crisis in primary education in South Asia will need to be solved, especially in rural areas, in order to reduce poverty and malnutrition. This is true despite the size of their grain surpluses.

IV. AFRICAN AGRICULTURE STILL IN CRISIS

Sub-Saharan Africa food production is in crisis in comparison with other regions of the world. No Green Revolution has occurred in Africa. Serious food deficits and deteriorating nutrition, especially among the rural poor, are related to high rates of population growth and lack of application of improved agricultural technologies. Recovery is still very fragile despite recent signs that smallholder agriculture is beginning to improve.

Agricultural development in this region has been affected by many factors, including extreme poverty, poor soils, uncertain rainfall, increasing population

Table 4 Quality of Life Indicators in South Asia

Nation	Infant mortality per 1000	Child malnutrition under 5	Adult illiteracy M	Adult illiteracy F	Population below 1 $/day 1984–1999
Bangladesh	61	56%	49%	71%	36%
India	71	45%	33%	57%	35%
Nepal	75	47%	43%	78%	42%
Pakistan	90	38%	42%	71%	34%
Sri Lanka	15	33%	6%	12%	25%

Source: World Bank (2001).

pressures, changing ownership patterns for land and cattle, political and social turmoil, shortages of trained agriculturalists, inadequate research and technology delivery systems, and HIV/AIDS. Despite these formidable challenges, the agricultural development formula that worked in Latin America and Asia, including use of fertilizers and improved seeds, and improved agronomic practices, will also work there.

To a large degree, Africa's food crisis has been a result of political leaders' long-term neglect of agriculture. Although this sector is the source of livelihood for 70%–85% of the population in most African nations, agriculture and rural development have received low priority. Investments in distribution and marketing systems and in agricultural research and education have been woefully inadequate. Many governments have chosen to pursue a policy of providing cheap food for politically volatile urban populations at the expense of providing production incentives for farmers.

Many African environments, especially the forest and transition areas, are fragile ecological systems. They have deeply weathered, acidic soils that lose fertility rapidly under repeated cultivation. Slash-and-burn shifting cultivation and complex cropping patterns permitted low-yield, but relatively stable, food production. However, expanding populations, increased food requirements, and increased numbers of farms have resulted in shortened bush/fallow periods and have pushed farmers onto marginal lands. More continuous cropping is depleting organic material, nitrogen, marginal phosphorus, and other nutrient reserves. Disastrous environmental consequences are resulting, such as serious erosion and weed invasion, that lead to impoverished fire climax vegetations.

As shown in Table 5, only about 10 kg of fertilizer nutrients are used per hectare of arable land in sub-Saharan Africa. This compares with rates that are

Table 5 Total Fertilizer Use per Hectare of Arable Land, 1999

World region	Total fertilizer nutrient consumption (1000 tons)	Per capita arable land (1000 hectares)	Per capita fertilizer use (kg/hectare)
Sub-Saharan Africa	1,320	138,799	10
Developing Asia	74,079	448,972	165
European Union	17,340	74,740	233
NAFTA nations[a]	24,265	247,310	99
Latin America[b]	10,405	120,396	86

[a] North American Free Trade Association (Canada, United States, Mexico).
[b] Latin American Integration Association (15 nations).
Source: FAOSTAT (2001).

9 to 23 times higher in other regions. Because of the inordinately low fertilizer-use levels, massive nutrient depletion has occurred in most countries. Over the past 30 years, sub-Saharan African soils are estimated to have experienced a net nutrient loss of 700 kg of nitrogen, 100 kg of phosphorus, and 450 kg of potassium per hectare (Sanchez et al., 1996). Resulting deterioration of agricultural productivity will seriously undermine the foundations of economic growth in Africa. Without more chemical fertilizer, sub-Saharan African agriculture is destined to failure.

Transportation is another major constraint to agricultural development in sub-Saharan Africa. High transportation costs often result in fertilizer costs that are generally double and frequently triple those paid in industrialized nations. Similarly, farm gate produce values are often only 50% of those obtained in urban centers. Inadequate infrastructure in sub-Saharan Africa—especially roads, potable water, and electricity—is a major obstacle to rural and economic development. A comparison of road infrastructure in Africa and other regions are found in Table 6. It highlights the vast gulf in infrastructure between most of Africa and the developed world. 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 leg of women."

Efficient transport facilitates production and enables farmers to bring their products to markets. Intensive agriculture is highly dependent on vehicle access. Improvements in transport systems would reduce rural isolation, thus helping to break down tribal animosities and to facilitate establishment of rural schools and clinics in areas where teachers and health practitioners have been unwilling to settle. Finding ways to provide effective and efficient infrastructure in sub-

Table 6 Kilometers of Paved Roads per Million People in Selected Nations

Country	Kilometers of paved road	Country	Kilometers of paved road
United States	20,987	Guinea	637
France	12,673	Ghana	494
Japan	6,584	Nigeria	230
Zimbabwe	1,586	Mozambique	141
South Africa	1,402	Tanzania	114
Brazil	1,064	Uganda	94
India	1,004	Ethiopia	66
China	803		

Source: *Encyclopedia Britannica* (2001).

Saharan Africa underpins all other efforts to reduce poverty, improve health and education, and secure peace and prosperity.

V. AGRICULTURAL CHALLENGES IN THE 21ST CENTURY

Most experts believe that the world population will increase from the current 6 billion people to over 7.5 billion people by the year 2020. The demand for cereals, which account for 70% of the world's food supply, will increase by 40%–50%. Increases in animal feed use are driven by rising meat and milk demand, and they will account for 35% of the increased demand for cereals between 1997 and 2020 (Pinstrup-Andersen and Pandya-Lorch, 2000). Demand for maize as an animal feed will be greater than that of all other cereal crops in the developing world.

Population growth, urbanization, and rising incomes will result in a massive increase in the demand for animal products (Pinstrup-Andersen and Pandya-Lorch, 2001). Data in Table 7 suggest that developing countries are likely to consume 100 million more tons of meat and 223 million more tons of milk than they did in 1993. The greatest increase in demand will be for poultry products. By 2020, China will become the world's largest meat producer and India will remain the world's largest milk producer.

Table 7 Actual and Projected Meat Consumption by Region

	Total meat consumption (1,000,000 tons)		
Region	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
Industrialized world	88	97	115
World	139	184	303

Source: IFPRI (2001).

As the above data suggest, the livestock subsector will become increasingly important. However, supply increases of livestock products are coming primarily from industrial production, because of the undeveloped state of traditional smallholder livestock systems. Appropriate policies that encourage improvements in animal health and nutrition have the potential to benefit smallholder producers.

China is the second-largest maize producer in the world. Nearly 80% of it is fed to livestock. Recognizing that quality protein maize (QPM) can significantly improve feed conversion rates, especially for swine, China embarked on QPM research in the mid-1970s. This research has been continued to date by a new generation of breeders at CAAS and nine provincial research centers. A half-dozen QPM hybrids were released during the 1990s and are now grown on about 350,000–400,000 ha. Some of this production is part of a rural poverty-reduction program promoted by the local extension services. Smallholder farmers feed their swine with QPM grain with rice middlings and green "chop," leading to higher weight gains and resulting additional income.

A. Dwindling Land Resources

Global arable land area and the potential for further expansion is limited in most regions, including densely populated Asia and Europe. Large unexploited tracts exist only in sub-Saharan Africa and South America; and only *some* of this land should eventually come into agricultural production. Very little uncultivated land exists in Asia. Indeed, some land should be taken *out* of cultivation because of high susceptibility to soil erosion.

Thus, most increases in the global food supply, including more than 85% of cereal production growth, must come from increasing yields of agricultural lands already in production (Pinstrup-Andersen and Pandya-Lorch, 2000). These productivity increases will require the introduction of varieties with higher genetic yield potential and greater tolerance of drought, insects, and diseases. Advances in both conventional and biotechnology research will be needed, as are improvements in soil and water conservation, tillage, fertilization, weed and pest control, and postharvest handling.

Bringing potentially arable lands into agricultural production poses great challenges. The Brazilian *Cerrado*, or savannah, is a good example. It spans a geographic area from latitude 24° to 4° S and varies in elevation from 500 m to 1,800 m, with unimodal precipitation that varies from 900 to 1,800 mm annually. A new generation of crop varieties (forage grasses, rice, soybean, maize, and wheat) was developed possessing tolerance to aluminum toxicity, but had low grain yield potential and other defects, especially susceptibility to various diseases.

The creation in 1973 of the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA)—the national Brazilian Agricultural Research Corporation—pro-

Table 8 Cereal and Meat Production in the *Cerrado* in 1990

Land use	Area (million ha)	Productivity (t/ha/year)	Production (million ton)
Crops (rainfed)	10.0	2.00	20.0
Crops (irrigated)	0.3	3.00	0.9
Meat (pasture)	35.0	0.05	1.7
Total	45.3		22.6

Source: Macedo (1995).

vided a major impetus to research aimed at the *Cerrado*. During the 1980s, EMBRAPA and several international agricultural research centers, especially CIMMYT and CIAT, began more intensive collaboration to develop a third generation of crop varieties combining tolerance to aluminum toxicity with high yield, better resistance to major diseases, and better agronomic type. This new generation of improved crop varieties is now moving on to farmers' fields.

As shown in Table 8, about 10 million ha of rainfed crops were grown with an average yield of 2 t/ha and a total production of 20 million tons in 1990. The irrigated area is only 300,000 ha. The average production yield for it was 3 t/ha, and total production was 900,000 tons. The *Cerrado* also contained 35 million ha of improved pasture, with an annual meat production of 1.7 million tons.

Macedo (1995) notes that farmers had the potential to attain 3.2 t/ha average yield and 64 million tons of production if available technologies were used on the 20 million ha of arable rainfed land in the *Cerrado* in 1995. As shown in Table 9, irrigated area could have been increased to 5 million ha, with an expected average yield 6 t/ha. Meat production could also have been increased fourfold with improved pastures. In total, food production could have been increased from the 22.6 million to 98 million tons.

Table 9 Potential Food Production if Technology Available in 1995 Is Adopted on *Cerrado* Area Already in Production

Land use	Area (million ha)	Productivity (t/ha/year)	Production (million t)
Crops (rainfed)	20.0	3.2	64
Crops (irrigated)	5.0	6.0	30
Meat (pasture)	20.0	0.2	4
Total	45.0		98

Source: Macedo (1995).

The *Cerrado* can help ensure adequate world food supplies for the next two decades if wise policies are used to stimulate production. Advances made in that region have the potential to be expanded into the *llanos* in Colombia and Venezuela and into central and southern African countries where they have similar soil problems.

B. Increasing Water Scarcity

Water covers about 70% of the earth's surface, but only about 2.5% is fresh water. And most is found in the ice caps of Antarctica and Greenland, in soil moisture, and in deep aquifers not readily accessible for human use. Less than 1% of the world's fresh water is readily available for direct human use (World Meteorological Organization, 1997). Irrigated agriculture accounts for 70% of global water withdrawals. It covers about 17% of cultivated land—about 275 million ha—and accounts for nearly 40% of world food production.

The rapid expansion in world irrigation and in urban and industrial water use has led to growing shortages. "About one third of the world's population lives in countries that are experiencing moderate-to-high water stress, resulting from increasing demands from a growing population and human activity" (WMO, 1997). By the year 2025, as much as two thirds of the world's population could be under stress conditions (WMO, 1997). Appropriate initial investments were not made in many irrigation schemes, especially in developing Asia. Serious salinization has resulted on many irrigated soils, especially in drier areas, and serious water logging in more humid areas. Asian irrigation schemes account for nearly two thirds of all irrigated land, and many are seriously affected by both problems. Thus, 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. Adding such costs to new projects will often result in a poor return on investment, so nations will have to decide how much they are willing to subsidize new irrigation development.

Many technologies exist to improve water-use efficiency. Wastewater can be treated and used for irrigation. It is an important source of water for peri-urban agriculture, which is growing rapidly around many of the world's megacities. New crops and improved varieties that require less water, together with more efficient crop sequencing and timely planting, can achieve significant savings in water use. Proven technologies, such as drip irrigation, save water and reduce soil salinity. Various new precision irrigation systems, which will supply water to plants only when they need it, are also on the horizon. Improved small-scale and supplemental irrigation systems can increase the productivity of rainfed areas and offer much promise for smallholder farmers.

Humanity will need to bring about a "Blue Revolution" in the 21st century to complement the so-called Green Revolution of the 20th century in order to feed a growing world population within the parameters of likely water availability. The Blue Revolution will require that water-use productivity be wedded to land-use productivity.

VI. NEW CROP IMPROVEMENT TECHNOLOGY

Agricultural researchers and farmers worldwide will be challenged during the next 20 years to develop and apply technology to increase global cereal yields by 50%–75%. They must do so in ways that are economically and environmentally sustainable. Most yield gains will come from applying underutilized "shelf technology."

Continued genetic improvement of food crops—using both conventional as well as biotechnology research tools—is needed to shift the yield frontier higher. Biotechnology research tools offer much promise, as do conventional plant-breeding methods. The latter continue to make significant contributions to improved food production and enhanced nutrition. In rice and wheat, interrelated changes in plant architecture, hybridization, and wider genetic resource utilization are being pursued to increase genetic maximum yield potential (Rajaram and Borlaug, 1997). Widespread impact on farmers' fields is still probably 10 to 12 years away. New "super rices," in association with direct seeding, can increase rice yield potentials by 20%–25% (Khush, 1995).

New wheat plants with architecture similar to the "super rices"—larger heads, more grains, and fewer tillers—could lead to an increase in yield potential of 10%–15% (Rajaram and Borlaug, 1997). The introduction of wild species genes into cultivated wheat can result in important sources of resistance for several biotic and abiotic stresses, and in higher yield potential, especially if the transgenic wheats are used as parent material in the production of hybrid wheats (Mujeeb-Kazi and Hettel, 1995).

The success of hybrid rice in China (now covering more than 50% of the irrigated area) has led to a renewed interest in hybrid wheat costs. With better heterosis and increased grain filling, the yield frontier of the new wheat genotypes could be 25%–30% above the current germplasm base. 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, further nutritional "quality" enhancements in the cereals are likely in years to come.

VII. IMPROVED CROP MANAGEMENT TECHNOLOGY

Crop productivity depends on both variety yield potential and crop management to enhance input and output efficiency. Productivity gains are possible through improved tillage, water use, fertilization, weed and pest control, and harvesting.

An outstanding example of new Green/Blue Revolution technology in irrigated wheat production is the "bed planting system," which has multiple advantages over conventional planting systems. The system reduces plant height and lodging and results in 5%–10% increases in yields and better grain quality. It reduces water use by 20%–25%, and efficiencies in fertilizer and herbicide use reduce their use by 30%.

Conservation tillage is spreading rapidly in many parts of the world. Monsanto has estimated that farmers used conservation tillage practices on 95 million ha in 2000 (1997 Annual Report). Turnaround time on lands that are double- and triple-cropped can be significantly reduced through its use, leading to higher yields and lower production costs. Conservation tillage also controls weed populations and greatly reduces the time that small-scale farm families must devote to this backbreaking work.

Mulch left on the ground reduces soil erosion, increases moisture conservation, and builds up the organic matter in the soil—all very important factors in natural resource conservation. It does, however, require modification in crop rotations to avoid the buildup of diseases and insects that find a favorable environment in the crop residues for survival and multiplication.

VIII. BIOTECHNOLOGY POTENTIAL

Biotechnology based on recombinant DNA has developed invaluable new scientific methodologies and products in food and agriculture during the last 20 years. The new biotechnology permits hybridization across taxonomically distinct genera, families, orders, or kingdoms. Recombinant DNA methods have enabled breeders to select and transfer single genes. This has reduced the time needed in conventional breeding to eliminate undesirable genes and has allowed breeders to access useful genes from other taxonomic groups. These gene alterations have conferred producer-oriented benefits, such as resistance to pests, diseases, and herbicides. Biotechnology and plant breeding will result in varieties with greater tolerance to drought, water logging, heat, and cold—important traits given current predictions of climate change. Many consumer-oriented benefits, such as improved nutritional and other health-related characteristics, are also likely to be realized over the next 10 to 20 years.

Despite the formidable opposition in certain circles to transgenic crops, commercial adoption of the new varieties reflects one of the most rapid processes of technology diffusion in the history of agriculture. As shown in Table 10, the

Table 10 Transgenic Crop Coverage, 2001

Region	Area (million ha)	Crops	Area (million ha)
United States	35.7	Soybeans	33.3
Argentina	11.8	Maize	9.8
Canada	3.2	Cotton	6.8
China	1.5	Canola	2.7
Others	0.4		
Total	52.6		

Source: James (2002).

area planted commercially to transgenic crops has increased 30-fold between 1996 and 2001. Transgenic crops were planted on 52.6 million ha in 13 countries by 5.5 million farmers in 2001, compared to only 1.7 million ha in 1996 (James, 2002). During this period, herbicide tolerance has been the dominant trait, accounting for 77% of the area. One quarter of the global transgenic crop area is now found in developing countries. The highest year-on-year percentage growth occurred in China between 2000 and 2001. Its Bt cotton area tripled from 0.5 to 1.5 million ha.

Most existing transgenic crops reduce production costs per unit of output. In theory, they are especially appropriate to the developing world, where over half the population is still engaged in agriculture, and where cost-reducing, yield-increasing technologies are the key to poverty reduction. Because biotechnology is packed into the seed, transgenic crops can help to simplify input delivery, often a major bottleneck in reaching smallholder farmers.

Several genetic engineering breakthroughs could bring enormous benefits to the poor producer and the consumer. Rice is unique in its immunity to rusts (*Puccinia spp.*). All the other cereals are attacked by two to three species of rusts, often resulting in disastrous epidemics and crop failures. Imagine the benefits to humankind if the genes for rust immunity in rice could be transferred into wheat, barley, oats, maize, millet, and sorghum. The world could free itself of the scourge of rusts, which have led to so many famines over human history.

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

A growing potential exists for science to improve the nutritional quality of our food supply. Biotechnology can help achieve further nutritional "quality" enhancements in cereals and other foods at a much faster rate. Gene transfers 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. Vitamin A deficiencies are a major cause of blindness, and iron deficiencies are a major cause of anemia.

Plants also have the potential to be used to vaccinate people against diseases, such as hepatitis B and the Norwalk disease, simply by growing and eating them. This offers tremendous possibilities in poor countries (ACSH, 2000). This line of research and development should be pursued aggressively, and probably through private–public partnerships, since traditional vaccination programs are costly and difficult to execute.

To date, no reliable scientific information exists 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. This has also been the case in genetically modified foods. Seed industries have ensured that their transgenic crop varieties are safe to plant and that food from them is safe to eat.

Most agricultural scientists anticipate great benefits from biotechnology in the coming decades. However, new forms of public–private collaboration are likely to be needed to ensure that all farmers and consumers have the opportunity to benefit from this new genetic revolution. In particular, public biotechnology research will be needed to balance and complement private sector research investments. This is true for industrialized countries as well as those in the developing world.

An urgent need exists for developing nations to put regulatory frameworks in place to guide the development, testing, and use of transgenic crops in order to protect people and the environment. Intellectual property rights of private companies should be safeguarded by this process to ensure fair returns to past investments and to encourage greater future investments. The regulatory frameworks should neither be overly bureaucratic, nor have unreasonable risk-aversion expectations. The seed industry should have primary responsibility for ensuring the safety of its products.

Private sector investment is the primary driver of agricultural research and development in industrialized countries. Some argue that the fastest way to get a new technology to poor people is to "speed up the product cycle," so that the technology can spread quickly, first among rich people and later among the poor. This interpretation of the diffusion process may have validity. However, private life science companies would need to establish concessionary pricing in the low-income countries so that poor farmers can also benefit from new transgenic products. Large transnational companies will also need to share their expertise with public research institutions and scientists concerned with smallholder agriculture. They will also need to form partnerships to work on crops and agricultural problems not currently of priority interest in the main transnational markets. Indeed, private biotechnology companies are showing considerable willingness to form such partnerships. Monsanto has led establishment of developing country initiatives in agricultural product and technology cooperation; Syngenta is doing likewise, building partnerships with national and international agricultural research centers to address production problems in Africa and elsewhere. The Donald Plant Science Center in St. Louis, Missouri, was co-founded in 1998 by Monsanto, a consortium of universities, public research institutes, and private foundations. It is an especially exciting development, given its strong Third World orientation in its research agenda and in its training programs.

IX. CONCLUSIONS

The current backlash against agricultural science and technology evident in some industrialized countries is hard to comprehend. It shows how quickly humans become detached from soil and agricultural production! Less than 4% of the population in the industrialized countries is directly engaged in agriculture. Low-cost food supplies and urban bias help to explain why consumers fail to understand the complexities of reproducing the annual world food supply and expanding it further to feed the nearly 80 million new mouths that are born each year. This "educational gap" can be treated in urban nations by making it compulsory for students to take biology, science, and technology policy courses in secondary schools and universities.

The fear of science has grown as the pace of technological change has accelerated during the past 50 years. The development of nuclear power and the prospects of a nuclear holocaust added to people's fear and drove a bigger wedge between the scientist and the layman. The book *Silent Spring* (Carson, 1962) reported that poisons were everywhere and struck a very sensitive public nerve. This perception was not totally unfounded. By the mid-20th century, air and water quality had been seriously damaged through wasteful industrial production systems that pushed effluents literally into "our own backyards."

A debt of gratitude is owed to environmental movement in the industrialized nations. It resulted in legislation over the past 30 years to improve air and water quality, to protect wildlife, to control the disposal of toxic wastes, to protect soils, and to reduce the loss of biodiversity. However, as Gregg Easterbrook (1996) argued, "In the Western world the Age of Pollution is nearly over. . . . Aside from weapons, technology is not growing more dangerous and wasteful, but cleaner and more resource-efficient. Clean technology will be the successor to high technology." Easterbrook (1996) also warned that, "As positive as trends are in the First World, they are negative in the Third World. One reason why the West must shake off its instant-doomsday thinking about the United States and Western Europe is so that resources can be diverted to ecological protection in the developing world.'' This protection includes clean water and sanitation systems for human settlements, and soil and water conservation.

More recently, Lomborg (2001) has provided a powerful critique of the way many extremist environmental organization distort scientific evidence. He concludes on the basis of his research that more reasons exist for environmental optimism than pessimism. He emphasizes the need for clear-headed prioritization of resources to tackle real, not imagined, problems in the future.

Paarlberg sounded the alarm nearly a decade ago about the deadlock between agriculturalists and environmentalists over what constitutes ''sustainable agriculture'' in the Third World (Paarlberg, 1994). This debate has confused—if not paralyzed—many in the international community. Afraid of antagonizing powerful environmental lobbying groups, they have turned away from supporting science-based agricultural modernization projects, which are still needed in much of smallholder Asia, sub-Saharan Africa, and Latin America.

The agriculturalist–environmentalist deadlock must be broken in order to focus on the enormous job before us to feed future generations. Ninety percent of newborns will begin life in a developing country, and many in poverty. Only through dynamic agricultural development will there be any hope to alleviate poverty, improve human health and productivity, and reduce political instability.

The world can count on available technology and technology that is well advanced in the research pipeline to sustainably feed the 10 billion people projected to inhabit the planet earth by the end of the 21st century. Pertinent questions are (1) whether farmers and ranchers will be permitted access to the continuing stream of new technologies needed to meet agricultural, food, and nutrition challenges that lie ahead and (2) whether the scourge of poverty can continue to be abated, so that the ever-growing proportion of the world's people are assured the minimum nutrition needed for health and human development.

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