

# **The Green Revolution Revisited and The Road Ahead<sup>1/</sup>**

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## **Introduction**

It is a great pleasure to be here in Oslo, nearly 30 years after I was awarded the Nobel Peace Prize. I wish to thank the Norwegian Nobel Institute and the U.S. Embassy in Norway for arranging this lecture. Today, I am here to take stock of the contributions of the so-called “Green Revolution,” and explore the role of science and technology in the coming decades to improve the quantity, quality, and availability of food for all of the world’s population.

Although I am an agricultural scientist, my work in food production and hunger alleviation was recognized through the Nobel Peace Prize because there is no Nobel Prize for food and agriculture. I have often speculated that if Alfred Nobel had written his will to establish the various prizes and endowed them fifty years earlier, the first prize established would have been for food and agriculture. However, by the time he wrote his will in 1895 establishing the prize, the horrors of the widespread potato famine that had swept across western Europe in 1845-51– taking the lives of untold millions – had been forgotten (Daly, 1996). The subsequent migration of millions of western Europeans to the Americas during 1850-60 restored a reasonable, yet still tenuous balance in the land-food-population equation. Moreover, the European food supply was further greatly increased during the last three decades of the 19<sup>th</sup> century through the application of improved agricultural technology developed earlier in the century (i.e., restoration of soil fertility, better control of diseases, and use of improved varieties and breeds of crops and animals). Hence, when Alfred Nobel wrote his will, there was no serious food production problem haunting Europe.

I am now in my 56<sup>th</sup> year of continuous involvement in agricultural research and production in the low-income, food-deficit developing countries. I have worked with many colleagues, political leaders, and farmers to transform food production systems. Despite the successes of the Green Revolution, the battle to ensure food security for hundreds of millions of miserably poor people is far from won.

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Mushrooming populations, changing demographics and inadequate poverty intervention programs have eaten up many of the gains of the Green Revolution. This is not to say that the Green Revolution is over. Increases in crop management productivity can be made all along the line – in tillage, water use, fertilization, weed and pest control, and harvesting. However, for the genetic improvement of food crops to continue at a pace sufficient to meet the needs of the 8.3 billion people projected in 2025, both conventional breeding and biotechnology methodologies will be needed.

### **Dawn of Modern Agriculture**

Science-based agriculture is really a 20th century invention. Until the 19th century, crop improvement was in the hands of farmers, and food production grew largely by expanding the cultivated land area. As sons and daughters of farm families married and formed new families, they opened new land to cultivation. Improvements in farm machinery expanded the area that could be cultivated by one family. Machinery made possible better seedbed preparation, moisture utilization, and improved planting practices and weed control, resulting in modest increases in yield per hectare.

By the mid-1800s, German scientist Justus von Liebig and French scientist Jean-Baptiste Boussingault had laid down important theoretical foundations in soil chemistry and crop agronomy. Sir John Bennett Lawes, produced super phosphate in England in 1842, and shipments of Chilean nitrates (nitrogen) began arriving in quantities to European and North American ports in the 1840s. However, the use of organic fertilizers (animal manure, crop residues, green manure crops) remained dominant into the early 1900s.

Groundwork for more sophisticated genetic crop improvement was laid by Charles Darwin in his writings on the variation of life species (published in 1859) and by Gregor Mendel through his discovery of the laws of genetic inheritance (reported in 1865). Darwin's book immediately generated a great deal of interest, discussion and controversy. Mendel's work was largely ignored for 35 years. The rediscovery of Mendel's work in 1900 provoked tremendous scientific interest and research in plant genetics.

The first decade of the 20<sup>th</sup> century brought a fundamental scientific breakthrough, followed by the rapid commercialization of that breakthrough. In 1909, Nobel Laureate in Chemistry (1918), Fritz Haber, demonstrated the synthesis of ammonia from its elements. Four years later, in 1913, the

company BASF, thanks to the innovative solutions of Carl Bosch, began operation of the world's first ammonia plant. The expansion of the fertilizer industry was soon arrested by WWI (ammonia used to produce nitrate for explosives), then by the great economic depression of the 1930s, and then by the demand for explosives during WWII. However, after the war, rapidly increasing amounts of nitrogen became available and contributed greatly to boosting crop yields and production.

It is only since WWII that fertilizer use, and especially the application of low-cost nitrogen derived from synthetic ammonia, has become an indispensable component of modern agricultural production (nearly 80 million nutrient tonnes consumed annually). It is estimated that 40% of today's 6 billion people are alive, thanks to the Haber-Bosch process of synthesizing ammonia (Vaclav Smil, University Distinguished Professor, University of Manitoba).

By the 1930s, much of the scientific knowledge needed for high-yield agricultural production was available in the United States. However, widespread adoption was delayed by the great economic depression of the 1930s, which paralyzed the world agricultural economy. It was not until WWII brought about a much greater demand for food to support the Allied war effort that the new research findings began to be applied widely, first in the United States and later in many other countries.

Maize cultivation led the modernization process. In 1940, U.S. farmers produced 56 million tons of maize on roughly 31 million hectares, with an average yield of 1.8 t/ha. In 1999, U.S. farmers produced 240 million tons of maize on roughly 29 million hectares, with an average yield of 8.4 t/ha. This more than four-fold yield increase is the impact of modern hybrid seed-fertilizer-weed control technology!

Following WWII, various bilateral and multilateral agencies, led by the United States and the Food and Agriculture Organization (FAO) of the United Nations, initiated technical-agricultural assistance programs in a number of countries in Europe, Asia, and Latin America. In the beginning, there was considerable naiveté especially about the transferability of modern production technology from the industrialized temperate zones to the tropics and subtropics. Most varieties from the United States, for example, were not well suited in the environments in which they were introduced.

There was another model of technical assistance that preceded these public sector foreign technical assistance programs, which ultimately proved to be superior. This was the Cooperative Mexican Government-Rockefeller Foundation agricultural program, which began in 1943. This foreign assistance program initiated research programs in Mexico to improve maize, wheat, beans, and potato technology. It also invested significantly in human resource development, training scores of Mexican scientists and helping to establish the national agricultural research system.

### **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 using agricultural science to develop modern techniques for the Third World. It began in Mexico with the “quiet” wheat revolution in the late 1950s. During the 1960s and 1970s in India, Pakistan, and the Philippines received world attention for their agricultural progress (Table 1). Since 1980, China has been the greatest success story. Home to one-fifth of the world’s people, China today is the world’s biggest food producer. With each successive year, its cereal crop yields approach that of the United States.

**Table 1. Cereal Production in Asia, 1961-99**

		<b>Milled Rice</b>	<b>Wheat</b>	<b>All Cereals</b>
		<b>(million tonnes)</b>		
<b>China</b>	<b>1961</b>	48	14	91
	<b>1970</b>	96	29	163
	<b>1999</b>	170	114	390
<b>India</b>	<b>1961</b>	46	11	70
	<b>1970</b>	54	20	93
	<b>1999</b>	112	71	186
<b>Dev’ing Asia</b>	<b>1961</b>	155	44	248
	<b>1970</b>	233	71	372
	<b>1999</b>	449	242	809

Source: FAO AGROSTAT, April 2000

Over the past four decades FAO reports that in Developing Asia, the irrigated area has more than doubled – to 176 million hectares. Fertilizer consumption has increased more than 30-fold, and now stands at about 70 million tonnes of nutrients, and tractor in use has increased from 200,000 to 4.6 million (Table 2).

**Table 2. Changes in Factors of Production in Developing Asia**

	<b>Irrigation</b>	<b>Fertilizer Nutrient</b>	<b>Tractors</b>
	<b>Million ha</b>	<b>Consumption</b>	<b>Millions</b>
		<b>Million tonnes</b>	
1961	87	2	0.2
1970	106	10	0.5
1980	129	29	2.0
1990	158	54	3.4
1998	176	70	4.6

Source: FAO AGROSTAT, April 2000

I often ask the critics of modern agricultural technology what the world would have been like without the technological advances that have occurred, largely during the past 50 years. For those whose main concern is protecting the “environment,” let’s look at the positive impact that the application of science-based technology has had on land use.

Had the global cereal yields of 1950 still prevailed in 1999, we would have needed nearly 1.8 billion ha of additional land of the same quality – instead of the 600 million that was used – to equal the current global harvest (see Figure 1 at the end of text). Obviously, such a surplus of land was not available, and certainly not in populous Asia, where the population has increased from 1.2 to 3.8 billion over this time period. Moreover, if more environmentally fragile land had been brought into agricultural production, think of the impact on soil erosion, loss of forests and grasslands, biodiversity and extinction of wildlife species that would have ensued.

### **Poverty 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. Of the roughly 1.3 billion people in this sub-region,

500 million live on less than US\$ 1 per day, 400 million are illiterate adults, 264 million lack access to health services, 230 million to safe drinking water, and 80 million children under 4 are malnourished (*Eliminating World Poverty*. UK White Paper, 1997).

A comparison of China and India – the world’s two most populous countries – which both have achieved remarkable progress in food production – is illustrative of the point that increased food production, while necessary, is not sufficient alone to achieve food security (Table 3). Huge stocks of grain have accumulated in India, while tens of millions need more food but do not have the purchasing power to buy it.

**Table 3. Social Development Indicators in China and India**

	<b>China</b>	<b>India</b>
1961 population, millions	669	452
2000 population, millions	1,290	1,016
Population growth, 1985-95, %/year	1.3	1.9
GDP per capita, US\$’s, 1995	620	340
Percent in agriculture, 1990	74	64
Poverty, % pop below \$1/day, 1995	29	53
Child malnutrition, % underweight, 1989-95	17	63
% Illiterate population (over 15), 1995	22	50

Sources: 1997 World Bank Atlas; 1998 FAOSTAT

China has been more successful in achieving broad-based economic growth and poverty reduction than India. Nobel Economics Laureate, Professor Amartya Sen, attributes this to the greater priority the Chinese government has given to investments in rural education and health care services. Nearly 80 percent of the Chinese population is literate while only 50 percent of the Indian population can read and write. India has more than half of its population below the poverty line whereas China has less than 30 percent. Only 17 percent of Chinese children are malnourished compared to 63 percent in India. With a healthier and better-educated rural population, China’s economy has been able to grow about twice as fast as the Indian economy over the past two decades and today China has a per capita income nearly twice that of India.

## **Water Resources**

Water covers about 70 percent of the Earth's surface. Of this total, only about 2.5 percent is fresh water, and most of this is frozen in the ice caps of Antarctica and Greenland, in soil moisture, or in deep aquifers not readily accessible for human use. Indeed, less than 1 percent of the world's freshwater – that found in lakes, rivers, reservoirs, and underground aquifers shallow enough to be tapped economically – is readily available for direct human use (World Meteorological Organization, 1997). Irrigated agriculture – which accounts for 70 percent of global water withdrawals – covers some 17 percent of cultivated land (about 275 million ha) yet accounts for nearly 40 percent of world food production.

The rapid expansion in world irrigation and in urban and industrial water uses has led to growing shortages. The UN's 1997 Comprehensive Assessment of the Freshwater Resources of the World estimates that, "about one third of the world's population live in countries that are experiencing moderate-to-high water stress, resulting from increasing demands from a growing population and human activity. By the year 2025, as much as two-thirds of the world's population could be under stress conditions."

In many of the irrigation schemes, especially in developing Asia, proper investments were not made originally in drainage systems to prevent 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 – 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.

In future irrigation schemes, water drainage and removal systems should be budgeted 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.

There are many technologies for improving the efficiency of water use. Wastewater can be treated and used for irrigation. This could be an

especially important source of water for peri-urban agriculture, which is growing rapidly around many of the world's mega-cities. Water can be delivered much more efficiently to the plants and in ways to avoid soil waterlogging and salinization. Changing to new crops requiring less water (and/or new improved varieties), together with more efficient crop sequencing and timely planting, can also achieve significant savings in water use.

Proven technologies, such as drip irrigation, which saves water and reduces soil salinity, are suitable for much larger areas than currently used. Various new precision irrigation systems are also on the horizon, which will supply water to plants only when they need it. There is also a range of improved small-scale and supplemental irrigation systems to increase the productivity of rainfed areas, which offer much promise for smallholder farmers.

Clearly, we need to rethink our attitudes about water, and move away from thinking of it as nearly a free good, and a God-given right. Pricing water delivery closer to its real costs is a necessary step to improving use efficiency. Farmers and irrigation officials (and urban 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 the farmers. Farmers' water user associations in the Yaqui valley in northwest Mexico, for example, have done a much better job of managing the irrigation districts than did the Federal Ministry of Agriculture and Water Resources previously.

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

### **World Food Production**

In 1998, global food production of all types stood at 5.03 billion metric tons of gross tonnage and 2.48 billion tons of edible dry matter (Table 4). Of this total, 99% was produced on the land – only about 1% came from the oceans and inland waters.



**Table 4. World Food Supply, 1998**

<b>Commodity</b>	<b>Production, million metric tons</b>		
	<b>Gross Tonnage</b>	<b>Edible Matter<sup>1/</sup></b>	<b>Dry Protein<sup>1/</sup></b>
<b>Cereals</b>	<b>2,072</b>	<b>1,725</b>	<b>172</b>
Maize	613	539	56
Wheat	589	519	61
Rice	577	391	33
Barley	139	122	12
Sorghum/millet	89	80	7
<b>Roots &amp; Tubers</b>	<b>652</b>	<b>174</b>	<b>11</b>
Potato	299	65	8
Sweet potato	139	42	2
Cassava	162	60	1
<b>Legumes, oilseeds, oil nuts</b>	<b>162</b>	<b>110</b>	<b>38</b>
<b>Sugarcane &amp; sugar beet<sup>3/</sup></b>	<b>152</b>	<b>152</b>	<b>0</b>
<b>Vegetables &amp; melons</b>	<b>615</b>	<b>72</b>	<b>6</b>
<b>Fruits</b>	<b>430</b>	<b>59</b>	<b>3</b>
<b>Animal products</b>	<b>951</b>	<b>188</b>	<b>83</b>
Milk, meat, eggs	830	157	63
Fish	121	31	22
<b>All Food</b>	<b>5,034</b>	<b>2,480</b>	<b>313</b>

1/ At zero moisture content, excluding inedible hulls and shells

2/ Sugar content only

Source: FAOSTAT, 1999

Plant products constituted 92 percent of the human diet, with about 30 crop species providing most of the world's calories and protein, including eight species of cereals, which collectively accounted for 70 percent of the world food supply. Animal products, constituting 8 percent of the world's diet, also come indirectly from plants.

Had the world's food supply been distributed evenly, it would have provided an adequate diet in 1998 (2,350 calories, principally from grain) for 6.8 billion people – about 900 million more than the actual population. However, had people in Third World countries attempted to obtain 70

percent of their calories from animal products – as in the USA, Canada, or EU countries – only about half of the world population would be fed.

These statistics point out two key problems. The first is the complex task of producing sufficient quantities of the desired foods to satisfy needs, and to accomplish this Herculean feat in environmentally and economically sustainable ways. The second task, equally or even more daunting, is to distribute food equitably. Poverty is the main impediment to equitable food distribution, which, in turn, is made more severe by rapid population growth.

### **Projected World Food Demand**

A medium projection is for world population to reach about 8.3 billion by 2025, before hopefully stabilizing at about 10-11 billion toward the end of the 21st century. At least in the foreseeable future, plants – and especially cereals – will continue to supply much of our increased food demand, both for direct human consumption and as livestock feed to satisfy the rapidly growing demand for meat in the newly industrializing countries. It is likely that an additional 1 billion tonnes of grain will be needed annually by 2025. Most of this increase must be supplied from lands already in production, through yield improvements. Using these estimates, I have come up with following projections on future cereal demand and the requisite yields needed by the year 2025 (Table 5).

**Table 5. Current and Projected World Cereal Production and Demand (million tonnes) and Yield Requirements (t/ha)**

	Actual Production		Projected Demand	Yield t/ha		
	1990	1999	2025	Actual	Required	
Wheat	592	585	900	2.6	2.7	3.8
Rice, paddy	528	607	900	2.4	3.1	4.3
Maize	483	605	1,000	3.7	4.1	5.9
Barley	178	127	140	2.4	2.7	2.9
Sorghum/millet	87	86	100	1.1	1.1	1.6
<b>All Cereals</b>	<b>1,953</b>	<b>2,074</b>	<b>3,100</b>	<b>2.5</b>	<b>2.9</b>	<b>4.1</b>

Source: FAO Production Yearbook and author's estimates

## **Africa is the Greatest Worry**

More than any other region of the world, food production south of the Sahara is in crisis. High rates of population growth and little application of improved production technology resulted during the last two decades in declining per capita food production, escalating food deficits, and deteriorating nutritional levels, especially among the rural poor. While there are some signs during the 1990s that smallholder food production is beginning to turn around, this recovery is still very fragile.

Sub-Saharan Africa's extreme poverty, poor soils, uncertain rainfall, increasing population pressures, changing ownership patterns for land and cattle, political and social turmoil, shortages of trained agriculturalists, and weaknesses in research and technology delivery systems, all make the task of agricultural development more difficult. But we should also realize that to a considerable extent, the present food crisis is the result of the long-time neglect of agriculture by political leaders. Even though agriculture provides the livelihood to 70-85 percent of the people in most 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 lowland tropical environments – especially the forest and transition areas – are fragile ecological systems, where deeply weathered, acidic soils lose fertility rapidly under repeated cultivation. Traditionally, slash and burn shifting cultivation and complex cropping patterns permitted low yielding, but relatively stable, food production systems. Expanding populations and food requirements have pushed farmers onto more marginal lands and also have led to a shortening in the bush/fallow periods previously used to restore soil fertility. With more continuous cropping on the rise, organic material and nitrogen are being rapidly depleted while phosphorus and other nutrient reserves are being depleted slowly but steadily. This is having disastrous environmental consequences, such as serious erosion and weed invasions leading to impoverished fire-climax vegetations.

In 1986 I became involved in food crop production technology transfer projects in sub-Saharan Africa, sponsored by the Sasakawa Foundation and its Chairman, the late Ryoichi Sasakawa, and enthusiastically supported by former U.S. President Jimmy Carter. Our joint program is known as

Sasakawa-Global 2000, and currently operates in 11 sub-Saharan African countries. Working with national extension services during the past 14 years, SG 2000 has helped small-scale farmers to grow more than half a million production test plots (PTPs), ranging in size from 1,000 to 5,000 square meters. These PTPs have been concerned with demonstrating improved technology for basic food crops: maize, sorghum, wheat, cassava, rice, and grain legumes.

The packages of recommended production technology 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 participating 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 in the marketplace are more favorable.

Virtually without exception, PTP yields are two to three times higher than the control plots employing the farmer's traditional methods. Hundreds of field days, attended by thousands of farmers, have been organized to demonstrate and explain the components of the production package. In areas where the projects are operating, farmers' enthusiasm is high and political leaders are taking much interest in the program.

Despite the formidable challenges in Africa, the elements that worked in Latin America and Asia will also work there. If effective seed and fertilizer supply and marketing systems are developed the nations of sub-Saharan Africa can make great strides in improving the nutritional and economic well being of their populations. The biggest bottleneck that must be overcome is lack of infrastructure, especially roads and transport, but also potable water and electricity. Improved transport systems would greatly accelerate agricultural production, break down tribal animosities, and help establish rural schools and clinics in areas where teachers and health practitioners are heretofore unwilling to venture.

### **Crop Research Challenges**

Agricultural researchers and farmers worldwide face the challenge during the next 25 years of developing and applying technology that can increase

the global cereal yields by 50-75 percent, and to do so in ways that are economically and environmentally sustainable. Much of the yield gains will come from applying technology "already on the shelf" but yet to be fully utilized. But there will also be new research breakthrough, especially in plant breeding to improve yield stability and, hopefully, maximum genetic yield potential.

### **Genetic Improvement**

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 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. In rice and wheat, three distinct, but inter-related strategies are being pursued to increase genetic maximum yield potential: changes in plant architecture, hybridization, and wider genetic resource utilization (Rajaram and Borlaug, 1996; Pingali and Rajaram, 1997). Significant progress has been made in all three areas, although widespread impact on farmers' fields is still probably 10-12 years away. IRRI claims that the new "super rice" plant type, in association with direct seeding, could increase rice yield potential by 20-25 percent (Khush, 1995).

In wheat, new plants with architecture similar to the "super rices" (larger heads, more grains, fewer tillers) could lead to an increase in yield potential of 10-15 percent (Rajaram and Borlaug, 1997). 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 transgenic wheats are used as parent material in the production of hybrid wheats (Kazi and Hettel, 1995).

The success of hybrid rice in China (now covering more than 50 percent of the irrigated area) has led to a renewed interest in hybrid wheat, when most research had been discontinued for various reason, 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 plant material could be 25-30 percent above the current germplasm base.

Maize production has really begun to take off in many Asia 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 is an important research breakthrough for 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 than are currently available in the best varieties and hybrids. In addition, there is good evidence that further heat and drought tolerance can be built into high-yielding germplasm.

### **Crop Management**

Crop productivity depends both on the yield potential of the varieties and the crop management employed to enhance input and output efficiency. Productivity gains can be made all along the line – in 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. Plant height and lodging are reduced, leading to 5-10 percent increases in yields and better grain quality. Water use is reduced 20-25 percent, a spectacular savings, and input efficiency (fertilizers and herbicides) is also greatly improved by 30 percent.

Already adopted in Mexico and growing in acceptance in other countries, Shandong Province and other parts of China are now preparing to extend

this technology rapidly (personal communications, Prof. Xu Huisan), President, Shandong Academy of Agricultural Science, July 7, 1999). Similar methods are now moving into commercial use in irrigated agriculture in India and Pakistan. Think of the water use and water quality implications of such technology!

Conservation tillage (no-tillage, minimum tillage) is spreading rapidly in the agricultural world. The Monsanto Company estimated that there were 75 million ha using conservation tillage in 1996 and this area is projected to grow to 95 million ha by the year 2000. Conservation tillage offers many benefits. 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. This leads to higher production and lower production costs. Conservation tillage also controls weed populations and greatly reduce the time that small-scale farm families must devote to this backbreaking work. Finally, the 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 build up of diseases and insects that find a favorable environment in the crop residues for survival and multiplication.

### **What Can We Expect from Biotechnology?**

During the 20<sup>th</sup> century, conventional breeding has produced – and continues to produce – a vast number of varieties and hybrids that have contributed immensely to much higher grain yields, stability of harvests and farm incomes, while also sparing vast tracts of land for nature (wildlife habitats, forests, outdoor recreation). There also have been important improvements in resistance to diseases and insects, and in tolerance to a range of abiotic stresses, especially soil toxicities, but we also must persist in efforts to raise maximum genetic potential, if we are to meet with the projected food demand challenges before us, without serious negative impacts on the environment.

In the last 20 years, biotechnology has developed invaluable new scientific methodologies and products which need active financial and organizational support to bring them to fruition. In animal biotechnology, we have bovine somatotropin (BST) now widely used to increase milk production.

Transgenic varieties and hybrids of cotton, maize, potatoes, containing genes from *Bacillus thuringiensis*, which effectively control a number of serious insect pests, are now being grown commercially on large areas in the United States, Argentina, Canada, and China. The use of such varieties will greatly reduce the need for insecticide sprays and dusts. Considerable progress also has been made in the development of transgenic varieties or hybrids of cotton, maize, oilseed rape, soybeans, sugar beet, and wheat, with tolerance to a number of herbicides. This can lead to a reduction in overall herbicide use through much more specific interventions and dosages. Not only will this lower production costs; it also has important environmental advantages.

Good progress has been made during the past 15-20 years – using traditional breeding methods – in developing cereal varieties with greater tolerance for soil alkalinity, free soluble aluminum, and iron toxicities. These varieties help to ameliorate the soil degradation problems that have developed in many existing irrigation systems. They also have allowed agriculture to succeed in tens of millions of hectares with highly-leached acid soils that had never been cultivated, such as the *Cerrados* in Brazil, (and later will also benefit similar soils in central and southern Africa) thus adding more arable land to the global production base.

Greater tolerance of abiotic extremes, such as drought, heat, and cold, will benefit irrigated areas in several ways. First, we will be able to achieve “more crop per drop” through designing plants with reduced water requirements and adoption of improved crop/water management systems.

Virus diseases have for centuries caused heavy losses in animal and crop production. Within the past decade, varieties of tomato, pepper, cucumber, potato, squash, and papaya have been developed, and are being grown commercially, with coat-protein mediated resistance to one or more important virus diseases. These breakthroughs, using biotechnology transgenic gene-splicing techniques, reduce pesticide use and crop losses, while improving crop quality (Beachy et al, 1990). Virus-resistant varieties of sugar beets, rice, barley and wheat are now in various stages of field evaluations.

There are also hopeful signs that we will be able to improve fertilizer use efficiency as well. For example, by genetically engineering wheat and other crops to have high levels of glutamate dehydrogenase (GDH), preliminary



evidence suggests that yields can be increased 20-30 percent with the same amount of fertilizer (Smil, 1999).

I would like to share one dream that I hope scientists will solve in the not-too-distant future. Among all the cereals, rice is unique in its immunity to the rusts (*Puccinia* spp.) All the other cereals – wheat, maize, sorghum, barley, oats, and rye – are attacked by two to three species of rusts, often resulting in disastrous epidemics and crop failures. Much of my scientific career 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 (3-7 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.

The majority of agricultural scientists including myself anticipate great benefits from biotechnology in the coming decades to help meet our future needs for food and fiber. Indeed, the commercial adoption by farmers of transgenic crops has been one of the most rapid cases of technology diffusion in the history of agriculture. Between 1996 and 1999, the area planted commercially to transgenic crops has increased from 1.7 to 39.9 million hectares (James, 1999).

However, since most of this research is being done by the private sector, which patents its inventions, agricultural policy makers must face up to potentially serious problems. How will resource-poor farmers of the developing world, for example, be able to gain access to the products of biotechnology research? How long, and under what terms, should patents be granted for bio-engineered products? Further, the high cost of biotechnology research is leading to a rapid consolidation in the ownership of agricultural life science companies. Is this desirable? These issues are matters for serious consideration by national, regional and global governmental organizations.

At the same time, developing country governments need to be prepared to work with – and benefit from – the new breakthroughs in biotechnology.

First and foremost, governments must establish a regulatory framework to guide the testing and use of genetically modified crops. These rules and regulations should be reasonable in terms of risk aversion and cost effective to implement. Let's not tie science's hands through excessively restrictive regulations. Since much of the biotechnology research is underway in the private sector, the issue of intellectual property rights must be addressed, and accorded adequate safeguards by national governments.

I believe that it is also important for governments to fund significant programs of biotechnology research in the public sector. Such publicly funded research is not only important as a complement and balance to private sector proprietary research, but it is also needed to ensure the proper training of new generations of scientists, both for private and public sector research institutions.

### **Research Entrepreneurship**

Agricultural research has become a substantial enterprise in both the public and private sectors over the past century, so extensive that no research director can keep abreast of the many advances in science nor can any scientist stay on top of all the changing conditions in agricultural production. Certainly, there are many management problems that must be addressed to improve the efficiency of agricultural research. But what needs to be done is far from clear.

The international agricultural research centers (IARCs) and national agricultural research systems (NARS) in the developing world certainly have advanced the frontiers of knowledge over the past four decades. However, I believe their more significant contribution has been the integration of largely known scientific information and its application in the form of improved technologies to raise farmers' incomes in order to overcome pressing crop production problems and food shortages. This should continue to be their primary mission. Moreover, impact on farmers' fields should be the primary measure by which to judge the value of IARC and NARS work. Sadly, the twin organizational evils of bureaucracy and complacency have begun to invade many international and national research institutions today.

I agree with the late Nobel Economist, T.W. Schultz, that most working scientists are research entrepreneurs and that centralized control is an anathema to progress.

“In the quest for appropriations and research grants all too little attention is given to that scarce talent which is the source of research entrepreneurship. The convenient assumption is that a highly organized research institution firmly controlled by an administrator will perform this important function. But in fact a large organization that is tightly controlled is the death of creative research. No research director... can know the array of research options that the state of scientific knowledge and its frontier afford.

Organization is necessary. It too requires entrepreneurs... But there is an ever-present danger of over-organization, of directing research from the top, of requiring working scientists to devote ever more time to preparing reports to ‘justify’ the work they are doing, and to treat research as if it was some routine activity.”

Unfortunately, agricultural science – like many other areas of human endeavor – is subject to changing fashions and fads, generated from both within the scientific community and imposed upon it by external forces, especially the politically-induced ones. Increasingly, I fear, too much of international and national research budgets are being directed towards “development bandwagons” that will not solve Third World food production problems, and for which scientists are ill-equipped to solve.

### **Educating Urbanites about Agriculture**

The current backlash against agricultural science and technology evident in some industrialized countries is hard for me to comprehend. How quickly humankind becomes detached from the soil and agricultural production! Less than 4 percent of the population in the industrialized countries (less than 2 percent in the USA) is directly engaged in agriculture. With a low-cost food supplies and urban bias, is it any wonder that consumers don’t understand the complexities of re-producing the world food supply each year in its entirety, and expanding it further for the nearly 85 million new mouths that are born into this world each year. I believe we can help address this “educational gap” in industrialized urban nations by making it compulsory in secondary schools and universities for students to take courses on biology and science and technology policy.

As the pace of technological change has accelerated the past 50 years, the fear of science has grown. Certainly, the breaking of the atom and the prospects of a nuclear holocaust added to people’s fear, and drove a bigger wedge between the scientist and the layman. Rachel Carson’s book *Silent Spring*, published in 1962, which reported that poisons were everywhere, also struck a very sensitive nerve. Of course, 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 often literally into “our own backyards.”

We all owe a debt of gratitude to environmental movement in the industrialized nations, which has led to legislation over the past 30 years to improve air and water quality, protect wildlife, control the disposal of toxic wastes, protect the soils, and reduce the loss of biodiversity.

However, I agree also with environmental writer Gregg Easterbrook, who argues in his book, *A Moment on the Earth*, that “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.”

However, Easterbrook goes on to warn 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.”

In his writings, U.S. Professor Robert Paarlberg, who teaches at Wellesley College and Harvard University, sounded the alarm about the deadlock between agriculturalists and environmentalists over what constitutes “sustainable agriculture” in the Third World. 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 science-based agricultural modernization projects 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 10-11 billion people, 90 percent of whom will begin life in a developing country, and probably in poverty. Only through dynamic agricultural development will there be any hope to alleviate poverty and improve human health and productivity and reducing political instability.

### **Closing Comments**

Thirty years ago, in my acceptance speech for the Nobel Peace Prize, I said that the Green Revolution had won a temporary success in man’s war

against hunger, which if fully implemented, could provide sufficient food for humankind through the end of the 20th century. But I warned that unless the frightening power of human reproduction was curbed, the success of the Green Revolution would only be ephemeral.

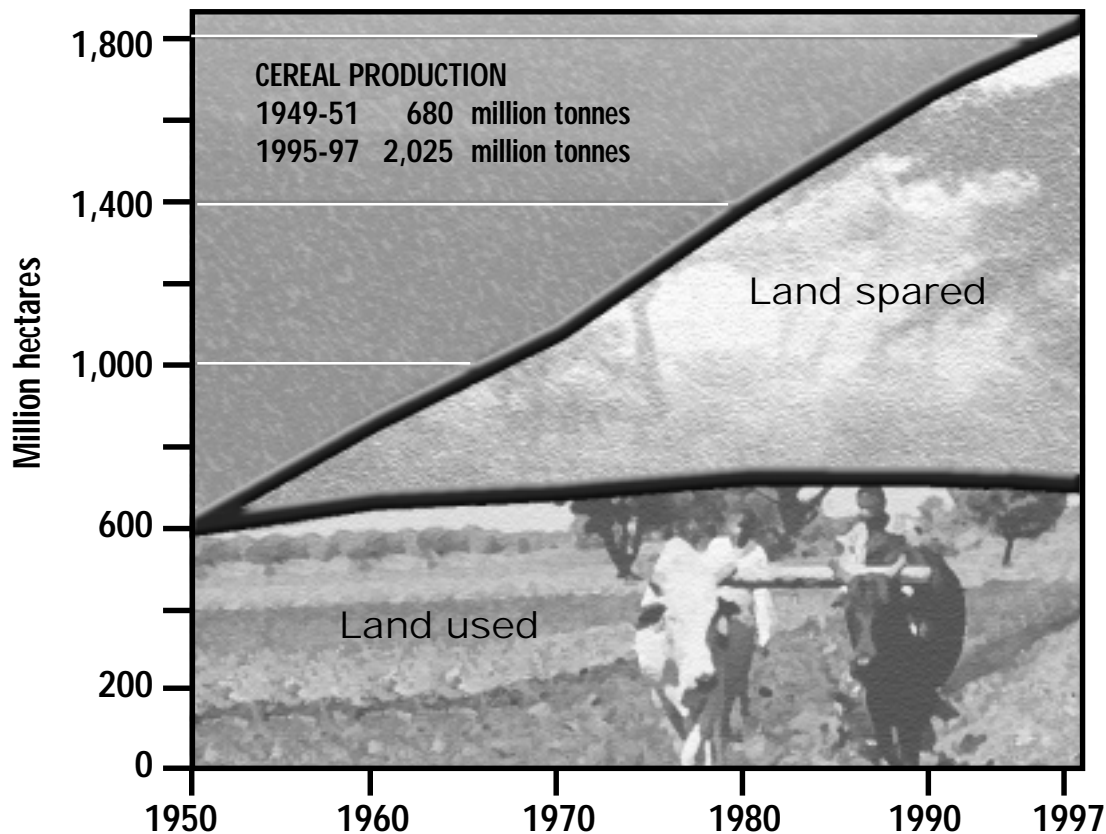
I now say that the world has the technology – either available or well advanced in the research pipeline – to feed on a sustainable basis a population of 10 billion people. The more pertinent question today is whether farmers and ranchers will be permitted to use this new technology? While the affluent nations can certainly afford to adopt ultra low-risk positions, and pay more for food produced by the so-called “organic” methods, the one billion chronically undernourished people of the low-income, food-deficit nations cannot.

It took some 10,000 years to expand food production to the current level of about 5 billion tons per year. By 2025, we will have to nearly double current production again. This cannot be done unless farmers across the world have access to current high-yielding crop-production methods as well as new biotechnological breakthroughs that can increase the yields, dependability, and nutritional quality of our basic food crops.

Moreover, higher farm incomes will also permit small-scale farmers to make added investments to protect their natural resources. As Kenyan archeologist Richard Leakey likes to remind us, “you have to be well-fed to be a conservationist!” We need to bring common sense into the debate on agricultural science and technology and the sooner the better!

Most certainly, agricultural scientists have a moral obligation to warn the political, educational, and religious leaders about the magnitude and seriousness of the arable land, food, population and environmental problems that lie ahead. These problems will not vanish by themselves. Unless they are addressed in a forthright manner future solutions will be more difficult to achieve.

# World Cereal Production—Area Saved Through Improved Technology, 1950-1998



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A detailed retrospective of the Green Revolution, its achievement and limits in terms of agricultural productivity improvement, and its broader impact at social, environmental, and economic levels is provided. Lessons learned and the strategic insights are reviewed as the world is preparing a "reduced" version of the Green Revolution with more integrative environmental and social impact combined with agricultural and economic development. Core policy directions for Green Revolution 2.0 that enhance the spread and sustainable adoption of productivity enhancing technologies are specified.

global p Today, I am here to take stock of the contributions of the so-called "Green Revolution," and explore the role of science and technology in the coming decades to improve the quantity, quality, and availability of food for all of the world's population. I wish to thank the Norwegian Nobel Institute and the U.S. Embassy in Norway for arranging this lecture. Today, I am here to take stock of the contributions of the so-called "Green Revolution," and explore the role of science and technology in the coming decades to improve the quantity, quality, and availability of food for all of the world's population.

nobelprize.org. Save to Library. The Green Revolution Revisited and. The Road Ahead. 1/. Norman E. Borlaug2/ 1970 Nobel Peace Prize Laureate. Introduction It is a great pleasure to be here in Oslo, nearly 30 years after I was awarded the Nobel Peace Prize. 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 using agricultural science to develop modern techniques for the Third World. It began in Mexico with the "quiet" wheat revolution in the late 1950s. During the 1960s and 1970s in India, Pakistan, and the Philippines received world attention for their agricultural progress (Table 1). Since 1980, China has been the greatest success story.