An Evergreen Revolution

Monkombu Sambasivan Swaminathan*

ABSTRACT

The Green Revolution was the product of alteration in plant architecture and physiological properties through breeding in wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), and other crops. The semidwarf plant stature contributed to providing adequate nutrition to the plant for high productivity, without inducing lodging. It also increased the harvest index. Similarly, photoinsensitivity helped to match the crop cultivar to seasons with appropriate moisture availability. The Green Revolution led to increased production through higher productivity and, thereby, conserved arable land and forests. Green Revolution technology, however, was criticized by environmentalists, economists, and social scientists for its deficiencies. Economists stressed that, because market-purchased inputs are needed for output, only resource-rich farmers are able to take advantage of high-yielding cultivars. Environmentalists emphasized that the excessive use of fertilizers and pesticides, as well as the monoculture of a few crop cultivars, will create serious environmental problems, including the breakdown of resistance and the degradation of soil fertility. Social scientists stressed that often women were excluded from technology-based agriculture, leading to their marginalization. The Green Revolution, however, helped many developing countries, including India and China, to achieve a balance between population growth and food production. It contributed to an alignment of population growth to the human capacity to produce the needed food and other agricultural commodities.

THE CHALLENGE NOW is to add the ecological dimension to crop productivity improvement. I coined the term *Evergreen Revolution* about 15 yr ago to indicate that we should develop technologies that can help to increase productivity in perpetuity without associated ecological harm. The Evergreen Revolution technologies are based on a farming systems approach and will also involve farmer participatory breeding and knowledge management. Countries like India, China, and Bangladesh have to produce more and more food and other farm commodities from diminishing per capita arable land and irrigation water resources. Therefore, productivity enhancement is the only pathway available to us to produce more to feed the growing population. This is why an Evergreen Revolution approach is exceedingly important. An Evergreen Revolution needs the integration of frontier technologies like biotechnology and information communication technology with traditional ecological prudence. We should harness both traditional wisdom and frontier science to shape our agricultural future.

The term “Green Revolution” was coined by Dr. William Gaud of the U.S. Department of Agriculture in 1968 to describe the revolutionary progress taking place in the wheat and rice fields of South Asia, in terms of yield per hectare. The initial genetic material for the new plant architecture and physiological rhythm came from the International Maize and Wheat Improvement Centre (CIMMYT) in Mexico in the case of wheat, and the International Rice Research Institute (IRRI) in the Philippines for rice. The original genes for the semidwarf trait were derived from ‘Norin 10’ wheat from Japan and ‘Dee-gee-woo-gen’ dwarf rice of China. Increased yield came from the interaction of the genotype and high-yielding environment, which was created by the application of mineral fertilizers and irrigation water. In India, semidwarf wheat came in 1963 from the program of Dr. Norman Borlaug in Mexico. It was clear, even in the very first year of cultivation, that the semidwarf cultivars were capable of giving a quantum jump in productivity when accompanied by suitable agronomic practices.

In 1964, national demonstrations were organized in farmers’ fields to introduce new technologies. The events of the 1960s, which culminated in the wheat revolution of India in 1968, have been chronicled in a publication titled, “Wheat Revolution—A Dialogue” (Swaminathan, 1993).

During 1967, I observed that farmers in northwestern India tended to apply excessive fertilizer. There was also a tendency to make several applications of pesticides to rice, leading to premature elimination of the natural enemies of rice pests. I, therefore, made the following observations in my Presidential Address to the Agricultural Sciences Section of the Indian Science Congress held at Varanasi on 4 Jan. 1968, several months before the term *Green Revolution* was coined (Swaminathan, 1968):

> Exploitive agriculture offers great dangers if performed with only an immediate profit or production motive. The emerging exploitive farming community in India should become aware of this. Intensive cultivation of land without conservation of soil fertility and soil structure would lead, ultimately, to the springing up of deserts. Irrigation without arrangements for drainage would result in soils getting alkaline or saline. Indiscriminate use of pesticides, fungicides, and herbicides could cause adverse changes in biological balance as well as lead to an increase in the incidence of cancer and other diseases, through the toxic residues present in the grains or other edible parts. Unscientific tapping of underground water will lead to the rapid exhaustion of this wonderful capital resource left to us through ages of natural farming. The rapid replacement of numerous locally adapted varieties with one or two high-yielding strains in large contiguous areas would result in the spread of serious diseases capable of wiping out entire crops, as happened before with the Irish potato famine of 1854 and the Bengal rice famine in 1942. Therefore, the initiation of exploitive agriculture without

---

National Academy of Agricultural Sciences, and Pugwash Conferences on Science and World Affairs, Chennai 600 113, India. CSSA Betty Klepper Endowed Lectureship speech, Tuesday 8 Nov. 2005, ASA–CSSA–SSSA International Annual Meetings, Salt Lake City, UT. *Corresponding author (chairman@mssrf.res.in, msswami@vsnl.net).

Published in Crop Sci. 46:2293–2303 (2006).
Perspectives
doi:10.2135/cropsci2006.9999

677 S. Segoe Rd., Madison, WI 53711 USA

> a proper understanding of the various consequences of every one of the changes introduced into traditional agriculture, and without first building up a proper scientific and training base to sustain it, may only lead us, in the long run, into an era of agricultural disaster rather than one of agricultural prosperity.

In 1990, I introduced the term *Evergreen Revolution* to emphasize the need for enhancing productivity in perpetuity without ecological harm. In population rich, but land-hungry countries like India, China, and Bangladesh, there is no option except to increase production under conditions of diminishing per capita availability of arable land and irrigation water and expanding biotic and abiotic stresses (Swaminathan, 1996).

Evergreen Revolution is another term for sustainable agriculture and is based on tools developed by blending traditional ecological prudence and frontier technologies. E.O. Wilson (2002), supporting my concept of Evergreen Revolution, made the following observations:

> The problem before us is how to feed billions of new mouths over the next several decades and save the rest of life at the same time, without being trapped in a Faustian bargain that threatens freedom and security. No one knows the exact solution to this dilemma. The benefit must come from an Evergreen Revolution. The aim of this new thrust is to lift food production well above the level obtained by the Green Revolution of the 1960s, using technology and regulatory policy more advanced and even safer than those now in existence.

It is now widely agreed that new technologies must be not only economically viable, but also environmentally and socially sustainable. The term *ecotechnology* is used in the case of technologies that are rooted in the principles of ecology, economics, gender and social equity, employment generation, and energy conservation. Ecotechnologies will require an interdisciplinary approach and will need research based on an entire farming system (Fig. 1). Thus, there has to be a paradigm shift in research strategies from a commodity-centered approach to an integrated natural resources management procedure covering the entire cropping system. Crop–livestock integrated farming is particularly important for soil fertility buildup and for multiple sources of income.

Irrigation water will be a serious constraint in the coming decades. Similarly, land degradation threatens both sustainable agriculture and food security. Both soil restoration and enhancement, and water conservation and sustainable use are important for launching an Evergreen Revolution movement. It would be useful to consider recent advances in the improvement of wheat and rice to examine what midcourse corrections are needed for the purpose of adding the environmental dimension to productivity improvement.

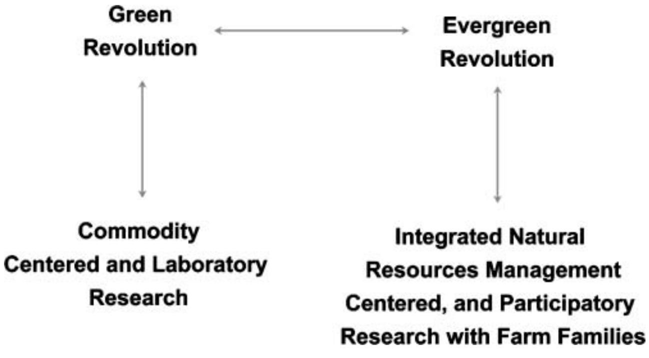

Fig. 1. Paradigm shift in research strategy.

There have been dramatic developments in crop improvement methodologies during the 20th century. Fifty years ago, commercial exploitation of hybrid vigor in a self-pollinated crop such as rice would have been considered impossible. Today, hybrid rice occupies millions of hectares in China and other countries in Africa. It should be emphasized that an improved genetic strain only offers the potential for higher productivity. The actual yield obtained will be the product of interaction between the genotype and the agronomic environment and management. The early improvements in crop productivity in Australia came mainly from soil fertility improvement. Genetic enhancement and agronomic management should, however, receive concurrent attention. Research on breeding and feeding crops for high yield should proceed in a synergistic manner. A few of the scientific developments in crop science during the 20th century are illustrated in the following examples.

WHEAT

The rediscovery of Mendel's laws of genetics in 1900 opened a new era in crop breeding. Although the art of plant breeding is as old as the beginning of agriculture nearly 12000 yr ago, systematic research in the areas of genetics and cytogenetics, which commenced in the early part of the 20th century, created uncommon opportunities for improving the productivity of several staple crops. Even before Mendel (1822–1884), plant hybridizers including Kolreuter, Knight, Gartner, and Burbank were able to produce improved cultivars of crops through careful observation and selection. Even the concept of sustainability, to which we now attach great importance, was recognized long ago as essential for sustained agricultural progress. For example, the Roman Farmer Varro explained the basic principles underlying sustainable agriculture more than 2000 yr ago: "Agriculture is a science which teaches us what crops should be planted in each kind of soil, and what operations are to be performed, in order that the land may produce the highest yields in perpetuity."

During the past 100 yr, Mendelian genetics has helped not only to exploit naturally occurring genetic variability, but has also accelerated the process of generation, manipulation, and combination of new variability. For example, H.J. Muller (1935), the pioneer of induced mutagenesis, wrote: "Organisms are found to be far more plastic in their hereditary basis than has been believed, and we may confidently look forward to a future in which the surface of the earth will be overlaid with luxurious crops, at once easy to raise and to gather, resistant to natural enemies and climate, and readily useful in all their parts."

Muller's prediction has since come true. The term *Green Revolution*, coined in 1968 by Dr. William Gaud, was triggered by the quantum jump in wheat productivity and production brought about by the semidwarf wheat cultivars originating from the wheat breeding program of CIMMYT in Mexico, under the leadership of the Nobel Laureate Norman Borlaug. In India, a special stamp entitled "Wheat Revolution" was released in July 1968 by the Prime Minister of India, Mrs. Indira Gandhi. This stamp helped to raise public awareness of the role of science in bringing about revolutionary progress in wheat production.

We are now in a state of transition from Mendelian to molecular breeding. However, it is clear that, for success in crop improvement, we will always depend on an appropriate blend of Mendelian and molecular breeding. The breeder's eye for selection and for spotting the winner will continue to play an important part in successful plant breeding.

During the period 1900 to 2000, the following significant developments took place with reference to the application of Mendelian genetics to wheat improvement: (i) selection from naturally occurring genetic diversity; (ii) collection, conservation, evaluation, and utilization of wheat genetic resources; (iii) introduction of new cultivars from other countries; (iv) hybridization and selection for a wide range of biotic and abiotic stresses and for grain quality; (v) induced mutagenesis and mutation breeding; (vi) monosomic and aneuploid analysis; (v) wide hybridization and alien gene transfer; (vi) exploitation of heterosis, using genetic and chemical methods of male sterility; (vii) apomixis and fixation of heterosis; (viii) DNA marker-assisted selection and breeding; (ix) functional genomics and molecular breeding.

It should be recorded that, in the early part of the 20th century, the first major success in achieving a yield revolution in crops was through the exploitation of hybrid vigor in maize. It is said that hybrid maize helped not only to revolutionize maize production, but it also improved the efficiency of farm management in the USA. Farmers who learned the value of good agronomic management of soil fertility and water use in maize also began to adopt good farm management practices in other crops.

This was also true in India. The areas where the wheat revolution began, such as the Punjab, Haryana, and Western Uttar Pradesh, also became the centers of origin for rice, potato (*Solanum tuberosum* L.), milk, and other forms of agricultural production. The radiating impact of the wheat revolution, which began with the breeding of semidwarf strains, has been immense, since improved genetic strains triggered a farm management revolution.

To quote Dr. Normal Borlaug, "there is no time to relax." It is projected that global demand for wheat will increase by 40% by the year 2020. Also, 67% of the world's wheat consumption will be in developing countries. Between 1961 and 1990, yield increases accounted for 92% of the additional cereal production in developing countries. In the years ahead, there is no option except to produce more from less per capita land and water resources. Can we sustain the yield revolution in wheat? It will be useful to consider this issue in the context of the genetic pathways that led to the wheat revolution of the 20th century.

Progress in Yield Improvement

Wheat is a crop of great antiquity. The ancestry of the cultivated bread wheat, *T. aestivum* ($2n = 6x = 42$) has been studied in detail. Synthetic hexaploids have also been produced by crossing *Triticum turgidum* ($2n = 4x = 28$) and *Triticum tauschii* ($2n = 2x = 14$) (Chen et al., 1997). Wheat is the first major cereal for which extensive cytogenetic analysis by several scientists (E.R. Sears, Ralph Riley, Hitoshi Kihara, Otto Frankel, and James McKey) led to important advances in crop improvement. The development of a complete set of monosomics in 'Chinese Spring' wheat by E. R. Sears and his colleagues helped breeders to plan their work based on the location of genes in different chromosomes. Analysis of induced mutations further helped to understand genetic relationships among *Triticum* species (Swaminathan, 1965).

We can identify at least four major phases in the evolution of wheat breeding during the 20th century.

Phase I (1900–1930): Early Days of Mendelian Genetics. Soon after the rediscovery of Mendel's laws of genetics in 1900, systematic work on the genetics of resistance to stem, leaf, and stripe rusts started. Selection from naturally occurring genetic variability also began. For example, in India an improved wheat cultivar, NP 4, originated through simple selection. Soon thereafter, hybridization work started, involving the use of land races. In recent years, the contribution of land races to the pedigrees of successful cultivars has continued to increase.

According to scientists at CIMMYT, the more widely used land races include Yaroslav Emmer (an emmer wheat from the former Soviet Union), Turkey (a land race grown in the Crimea by Turkish Farmers), Fife (believed to have originated in Poland), Daruma (source of dwarfing genes and believed to have originated in Korea), Rieti (an early maturing Italian land race), and Zeeuwse White (a Dutch land race). Some of the frequently used landraces from developing countries are Hard Red Calcutta, Etawah, Indian G (all from India), and Alfredo Chaves and Polyssu (from Brazil).

During the early part of the 20th century, the major breeding challenges were in the areas of resistance to rusts and grain quality improvement. A study of the yield improvement achieved from 1900 to 1930 in the USA shows only limited progress (Fig. 2). The emphasis was more on stability of production through disease resistance than on achieving quantum jumps in yield.

Phase II (1930–1960): Enlarging the base of theory and its application. This period was marked by the introduction of cytogenetic knowledge and tools in wheat improvement. The search for genes for yield improvement started. The first breakthrough came when Japanese scientists developed the Norin 10 semidwarf wheat, with Daruma as the donor of the semidwarf character (Fig. 3). The Norin semidwarf wheats brought into the USA from Japan by Dr. S. D. Salmon led to the breeding of the semidwarf winter wheat cultivar Gaines by

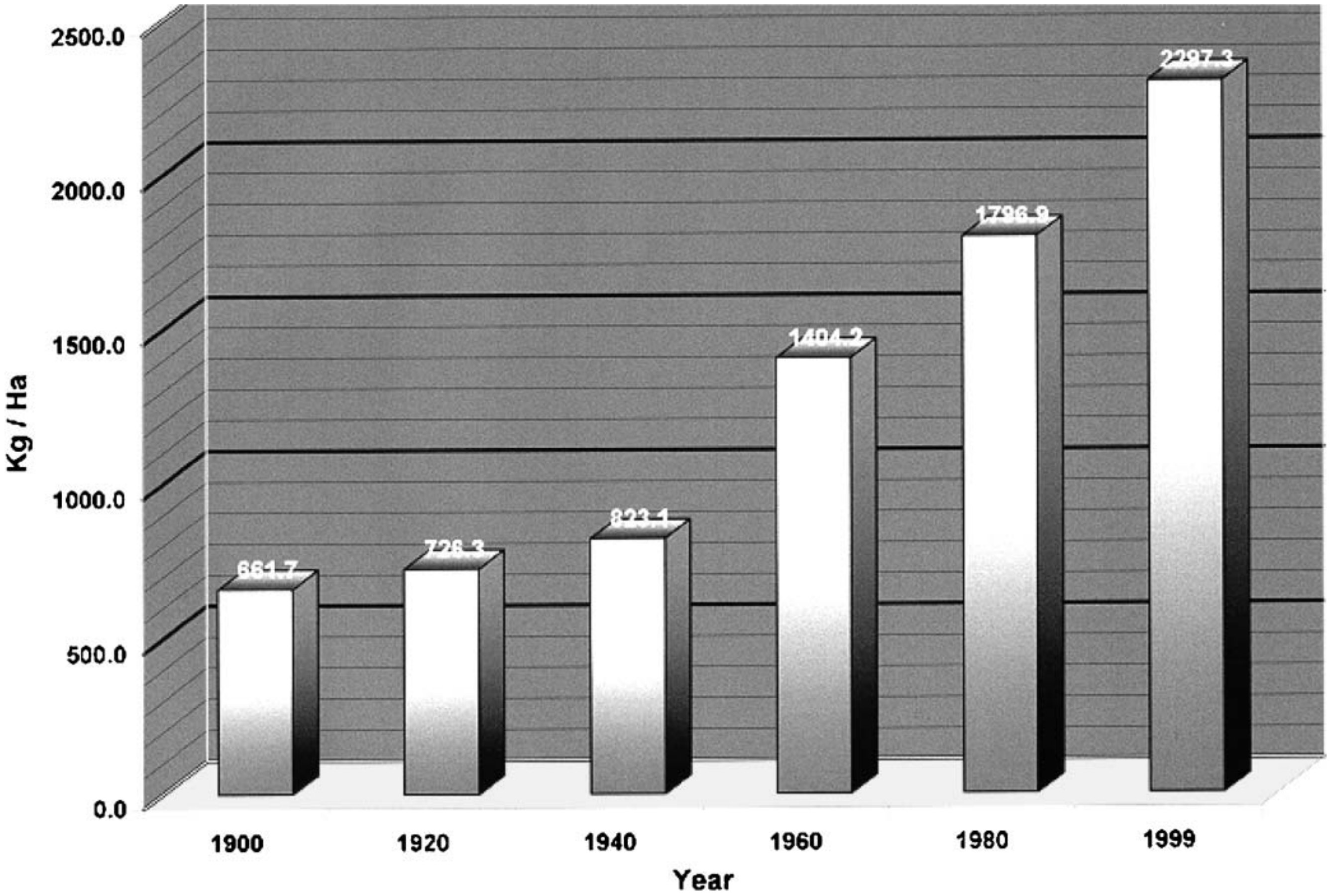

Fig. 2. Yield of wheat grain in the USA 1900 to 1999.

Dr. Orville Vogel in the late fifties. The same material was used by Dr. Norman Borlaug in Mexico to develop semidwarf spring wheat (Borlaug, 1989). Other important concepts introduced during this period were shuttle breeding and international testing nurseries. The shuttle breeding program developed by Dr. N.E. Borlaug in Mexico involved growing alternate generations under two diverse environments. The Yaqui Valley location is located at 27° N latitude and 49 m elevation in the state of Sonora in northwest Mexico. Toluca is located at 18° N latitude and 2600 m elevation in the state of Mexico. These locations differed in soil type, temperature, rainfall, and photoperiod. The shuttle breeding procedure led to the selection of strains possessing relative insensitivity to photoperiod as well as broad spectrum resistance to stem rust. In addition, it helped to reduce considerably the time needed to breed a new cultivar.

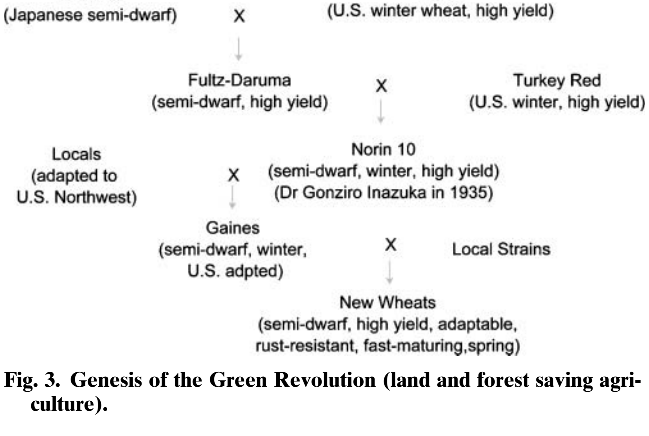

Fig. 3. Genesis of the Green Revolution (land and forest saving agriculture).

Another important feature of this era was accelerated breeding and testing for resistance to rusts and other diseases. As early as in the 1890s, Farrer (1898) in Australia recognized the importance of general resistance to rust in wheat. With the discovery of physiological specialization in rust by Stakman et al. (1962) and the clarification of the genetic basis of resistance (Biffen, 1905; Flor, 1956), the hypersensitive type of resistance was incorporated in many wheat cultivars. Van der Plank (1963) defined clearly the theoretical basis of genetic resistance to rusts. Thus, this phase of wheat improvement was characterized by widening the gene pool used by breeders, incorporation of genes for the semidwarf plant type, shuttle breeding, and breeding to meet the challenge of physiological specialization in pathogens.

Phase III (1960–1980): The Green Revolution phase. This phase is also generally referred to as the Green Revolution era. It was characterized by revolutionary progress in improving wheat production and productivity in several developing countries, including India and Pakistan. The introduction of the semidwarf plant type enabled the wheat plant to yield well under conditions of good soil fertility and irrigation water manage-

Fig. 4. India now occupies the second position in the world in wheat production.

ment (Fig. 4). Farmers who were used to harvesting 1 to 2 Mg ha^{-1} of wheat started harvesting >5 Mg ha^{-1}. The various steps involved in this revolution in India have been chronicled (Swaminathan, 1993). In view of the widespread interest in this remarkable transformation in India's agricultural destiny, it will be useful to summarize some of the highlights.

The Food and Agriculture Organization (FAO) of the United Nations was established even before the end of World War II, since combating food insecurity was recognized as a major challenge of the post World War II era. During 1942 to 1943, the Indian subcontinent witnessed a severe famine in Bengal, resulting in the death of nearly three million children, women, and men. This prompted Jawaharlal Nehru, the first Prime Minister of Independent India, to remark in 1948, "everything else can wait, but not agriculture." Priority to agriculture was reflected in the form of land reform, expansion of irrigation facilities, and greater support for research, extension, and the production of inputs, particularly seeds and fertilizer. Fertilizer trials with cultivars of wheat and rice in the 1950s revealed that the cultivated types lodged even when applying approximately 20 kg ha^{-1} of nitrogen.

The quest for the breeding of crop cultivars capable of responding to higher levels of plant nutrition started in 1952 when, at the insistence of the late Dr. K. Ramiah, a program for incorporating genes for fertilizer response from *japonica* rice cultivars into *indica* strains was initiated at the Central Rice Research Institute. This research was conducted under the sponsorship of FAO and the Indian Council of Agricultural Research. The major aim of this project was to select, from segregating populations of *indica* × *japonica* crosses, lines that showed the ability to utilize effectively about 100 kg ha^{-1} of N. With this quantity of nutrient supplied, about five Mg ha^{-1} of rice can be produced. This program led to cultivars such as ADT 27 in Tamil Nadu and Mashuri in Malaysia. Several genetic problems arose, including semisterility, rendering the speedy selection of high-yielding rice cultivars from *indica* × *japonica* crosses difficult. With the advent of semidwarf, nonlodging, relatively photoinsensitive cultivars based on the Dee-gee-woo-gen dwarfing gene identified in China in the early 1960s, interest in transferring genes for fertilizer response from *japonica* cultivars waned. Semidwarf *indica* rice cultivars (e.g., Taichung Native-1, IR 8, and Jaya) provided the initial material to breed a wide range of high yielding rice cultivars.

When I joined the Indian Agricultural Research Institute (IARI), New Delhi, in late 1954, I started a research program for developing nonlodging and fertilizer-responsive cultivars of wheat. I used the approach adopted in a hybridization program in which I was earlier involved at the Central Rice Research Institute, Cuttack. At that time, the research strategy adopted had three components. First, crosses were made between cultivated bread wheat cultivars and the semidwarf, stiff straw *compactum* and *sphaerococcum* subspecies of *T. aestivum*, as well as with the naturally occurring dwarf, Tom Thumb. Second, attempts were made to induce *erectoides* mutants in commercial wheat cultivars through the use of radiation and chemical mutagens. Third, studies on the potential for increasing straw stiffness through different chemical treatments were initiated. Unfortunately, in all these three approaches, short and stiff straw was always associated with short panicles with fewer grains. Straw stiffness became such an essential prerequisite for favorable response to water and fertilizer due to the tendency among the cultivated tall wheat cultivars to lodge when mineral fertilizer was applied. Also, such lodging made it difficult to give irrigation during the grain development phase, when the crop would benefit much from water availability. Thus, with the earlier tall cultivars, it was difficult to get economic response to the application of mineral fertilizers and adequate irrigation water. Average yield stagnated at <1 Mg ha^{-1}. This is why the breeding of nonlodging cultivars was accorded such high priority during the 1950s, when India had taken to the path of expanding the area under irrigation and manufacturing mineral fertilizers (Swaminathan, 1993).

During the late 1950s, Dr. Orville Vogel at Washington State University published on the transfer of dwarfing genes from the Norin 10 wheat cultivar to North American winter wheats. When requested, Dr. Vogel was kind enough to make available seeds of Gaines, a semidwarf winter wheat cultivar with red grains. He further indicated that Dr. Borlaug in Mexico had semidwarf cultivars in a spring wheat background, which will grow better under the short-day conditions prevailing in India during winter months. I hence wrote to Dr. Borlaug seeking his help.

In March 1962, a few dwarf spring wheat strains entered by Dr. Borlaug in the International Wheat Rust Nursery and sent by the USDA were grown in the fields of IARI. Their phenotype was most impressive. They had reduced height and long panicles, unlike the earlier hybrids between *T. aestivum*, subsp. *compactum*, and supsp. *sphaerococcum*, and the induced *erectoides* mutants, which had short height and small panicles. In 1963, Dr. Borlaug visited India and sent a wide range of semidwarf material that provided the initial material for achieving an accelerated advance in wheat productivity and production.

In 1964, a National Demonstration Program was started in farmers' fields, both to verify the results obtained in research plots and to introduce farmers to the new opportunities introduced by semidwarf cultivars for improving the productivity of wheat. When small farmers, who with the help of scientists organized the National Demonstration Program, harvested >5 Mg ha^{-1} of wheat, its impact on the minds of other farmers was electric. The clamor for seeds began and the area under high-yielding cultivars of wheat rose from 4 ha in 1963–1964 to >4 million ha in 1971–1972. A small government program became a mass movement. The rest of the history is recorded in a book on the wheat revolution (Swaminathan, 1993).

The remarkable speed with which the high-yielding cultivars were identified from the initial Mexican material and later developed within the country was the result of the multilocation testing and interdisciplinary research organized under the All India Co-Ordinated Wheat Research Project of the Indian Council of Agricultural Research. Wheat production in India rose from 10 million Mg in 1964 to 17 million Mg in 1968. In 2005, Indian farmers harvested about 75 million Mg of wheat, taking India to the second position in the world in wheat production.

Rajaram and Hettel (1995) have chronicled the various steps taken at CIMMYT during the Green Revolution period to internationalize wheat breeding. Some of the significant steps were (i) exploitation of the spring × winter gene pool through a cooperative venture between CIMMYT and Oregon State University in the USA; (ii) Septoria leaf spot (caused by *Septoria* spp.) resistance in semidwarf wheats through a cooperative venture between CIMMYT, Tel Aviv University in Israel, and IPO, Wageningen, the Netherlands; (iii) slow rusting genes to leaf rust were identified, quantified, and bred with initial guidance from Dr Caldwell at Purdue University, USA; (iv) industrial quality characters were emphasized; (v) breeding for resistance to aluminium toxicity was initiated through a cooperative venture between CIMMYT and several Brazilian Agricultural Research Institutes; (vi) breeding programs for durum wheat and triticale were initiated; and (vii) germplasm dissemination through formalized International Nurseries for bread wheat, durum wheat, and triticale were established.

Emphasis on productivity improvement was coupled with attention to stability of production. Breeding for slow rusting received particular attention (Fig. 5). Also, the diversity of resistance sources was maintained. This helped in developing effective gene deployment strategies to ensure that widespread epidemics do not occur. For example, a high degree of stability of performance in relation to leaf rust (*Puccinia recondita* f. sp. *tritici*) was achieved through introduction of genes from the Brazilian cultivar Frontana.

In the case of stem rust (*Puccinia graminis* f. sp. *tritici*), the cultivar Hope has been the mainstay. The Sr-2 gene complex actually consists of Sr.2, plus 8 to 10 genes pyramided in three to four gene combinations (Rajaram and Hettel, 1995). Sr-2, referred to as the backbone gene in stem rust resistance breeding, demonstrates slow rust development and has conferred in wheat cultivars an impressive level of durability of resistance.

For resistance to stripe rust (*Puccinia striiformis*), more than eight genes have been identified and gene pyramiding has been the major pathway in resistance breeding. During the Green Revolution era, karnal bunt, caused by *Tilletia indica*, assumed importance. Several winter × spring wheat crosses showed wide adaptation and stability. A major factor for such wide adaptation was the 1 BL/1RS translocation. The 1B/IR translocation carried several resistance genes, such as Lr 26, Sr 31, Yr 9, and Pm 8 (McIntosh, 1983).

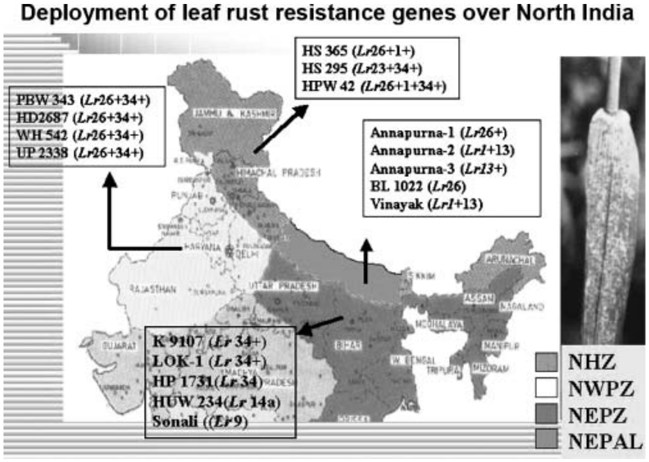

Fig. 5. The need for gene pyramiding.

During this period, crosses with *Secale cereale*, *Triticum dicoccoides*, *T. tauschi*, and other alien species transfers were intensified. A very valuable service was provided by CIMMYT in spreading diverse genetic material through international screening nurseries and trials (Rajaram and Hettel, 1995).

Thus, during the period from 1900 to 1980, the Mendelian methods of selection from segregating populations, recombination through intervarietal and interspecific crosses, and induced mutations, helped to breed both durum and *T. aestivum* wheat cultivars, adapted to different photoperiods and climatic conditions. Wheat productivity and production increased worldwide.

Greater interdisciplinary collaboration among breeders, plant pathologists, agronomists, physiologists, soil scientists, entomologists, nemotalogists, economists, and other social scientists, climatologists, and policymakers was the principal factor responsible for the success of the Green Revolution. The Green Revolution era can also be called the golden age in interdisciplinary and international collaboration in wheat improvement for sustainable food security. The concept of shuttle breeding transcended continental boundaries and a global college of wheat scientists emerged. Above all, the Green Revolution showed how to generate synergy between technology and public policy.

Phase IV (1980–2000): Transition from Mendelian to Molecular Breeding. The last part of the 20th century witnessed great progress in using sophisticated approaches to wheat breeding. Hybrid wheat has approached large-scale commercial cultivation. The use of genetic-cytoplasmic male sterility and of chemical hybridizing agents (CBA) is responsible for progress in the commercial exploitation of hybrid wheat. Different management practices such as lower seed rate, raised bed planting, split nitrogen application, and different row width are being tried to enhance the expression of hybrid superiority. The cultivation of hybrid wheat is slowly gaining in momentum in South Africa, Australia (New South Wales), China, Argentina, and France. The use of wild relatives in genetic engineering is growing (Khush and Baenziger, 1998). The global average yield of wheat is 2.5 Mg ha^{-1}; this low average yield of wheat is because large areas of wheat are under rainfed conditions. Progress in improving yield is, however, steady. Some of the critical issues in yield improvement in wheat have recently been discussed in a book edited by Satorre and Slafer (1999). The explosive progress being witnessed in the areas of functional genomics and molecular manipulation will influence future trends in wheat breeding in the 21st century (Briggs, 1998; McCouch, 1998). Several thousand restriction fragment length polymorphism (RFLP) markers, in addition to amplified fragment length polymorphisms (AFLP), single sequence repeats (SSR), and morphological and isozyme markers have been mapped. Nearly 100 quantitative trait loci (QTL) have been identified. This should help to accelerate the pace of breeding for increased grain yield. So far, yield increases have been associated with increases in harvest index (i.e., grain–straw ratio). Further advances will depend on greater biomass production and not merely on partitioning the photosynthates.

RICE

Rice occupies, and will continue to occupy, a pivotal place in global food and livelihood security systems. Of the annual world production of 596.485 million Mg from 155.128 million ha, Asia produces 540.621 million Mg from 138.563 million ha. Average rice yield in Asia is 3.9 Mg ha^{-1}, compared with 3.8 Mg ha^{-1} in the world, 6.4 Mg ha^{-1} in Japan, 6.3 Mg ha^{-1} in China, 2.1 Mg ha^{-1} in India, and 10.1 Mg ha^{-1} in Australia (www.riceweb.org, IRRI, Metro Manila, the Philippines; verified 9 Mar. 2006). Per capita consumption of rice in Asia ranges from 132 to 449 g per day. The world population will reach seven billion near the year 2010, eight billion near 2020, where 82% will live in developing countries (Evans, 1998, p. 247). The UN forecasts that the world population will reach 9.4 billion by 2050. It is projected that there will be only 1.2 billion people in the more developed regions of the world, compared with 8.2 billion in the currently less developed countries, with 5.5 billion of them in Asia and 2 billion in Africa. The world must develop the capacity to feed 10 billion within the next 40 to 50 yr, predominantly within Asia and Africa.

More than 90% of rice is produced and consumed in Asia. However, it is also a staple food crop for 40% of the world population. In most developing countries, agriculture occupies an important place in national livelihood. In spite of a steady drop in the share of agriculture in GDP, the share of agriculture in the workforce remains high. The situation is different in industrialized countries (Gardner and Halwell, 2000). In many countries where agriculture is a major source of employment, the income is low, resulting in inadequate purchasing power. This is the primary cause of food insecurity at the household level. Therefore, agricultural intensification, diversification, and value-addition are essential for providing opportunities for skilled jobs in the farm sector. Importing food rather than improving productivity will only reduce employment in predominantly agricultural countries.

A quantum jump in rice yield was possible using semidwarf cultivars that responded to increased use of fertilizers, pesticides, herbicides, and a host of other chemicals, along with water. Rice production increased by 2.3% per year from 1968 to 2001 after the release of IR 8 (Hossain and Narciso, 2002). In India, rice production grew at 1.11% from 1994 to 2001 (Venkataramani, 2002). The slowdown in productivity growth of irrigated rice is due to a decline in the N-supplying capacity of intensively cultivated wetland soils (about 30%) during a 20-yr period at all N levels. Two other macronutrients demanded by rice are P and K. Their deficiencies are becoming widespread across Asia in areas not considered deficient. Balanced use of N, P, and K, along with slow release fertilizers, should be encouraged as they improve fertilizer use efficiency over time.

The biological pathways for raising the ceiling to yield included both an increase in total biomass and higher harvest index. It is essential that the capacity of the plant to produce higher biomass per day is enhanced, because the scope for yield improvement through the harvest index pathway has been practically exhausted. Such a trend in yield improvement is continuing, with the commercial exploitation of hybrid vigor providing added opportunities for raising the ceiling to yield further in indica rice (Peng et al., 1999; Swaminathan, 1996). In addition to the morphological and physiological attributes, tolerance or resistance to a wide range of biotic and abiotic stresses will also be necessary. Several donors from tropical germplasm are available in cultivars with good genetic backgrounds. This will call for pyramiding of genes from diverse genetic material. Several useful traits from wild rice were identified and transferred to cultivated rice using various biotechnological approaches (Khush, 2003).

Pyramiding major genes is possible due to the identification of QTL for several traits. The pyramided lines that were developed with two or more genes showed a wider spectrum and a higher level of resistance than lines with only a single gene (Khush, 2003). Sanchez et al. (2000) used sequence-tagged site (STS) markers to pyramid three genes for bacterial blight resistance in an elite breeding line of rice. The pyramided lines, having three or four genes in combination, showed an increased and wider spectrum of resistance to bacterial blight than those having a single resistance gene. Singh et al. (2001) also used MAS to pyramid genes for bacterial blight resistance into a high-yielding indica rice cultivar PR 106, which is susceptible to bacterial blight. The MAS approach was also employed to pyramid genes for resistance to blast [caused by the fungus *Pyricularia grisea* (Cooke) Sacc.; Hittalmani et al., 2000] and gall midge (*Orseolia oryzae* Wood-Mason; Katiyar and Bennett, 2001). The greatest source of rice improvement research is the availability of a wide range of germplasm in the

International Rice Gene Bank at IRRI as well as in the ex situ gene banks of several countries like India, China, and Japan. With the advent of molecular breeding technologies, it is also becoming possible to transfer genes from wild *Oryza* species.

In a book titled *Asian Rice Bowls: The Returning Crisis?*, Pingali et al. (1997) have described in detail the steps needed to increase rice production in Asia to meet future needs. If global warming and the associated changes in temperature, precipitation, and sea level do occur, the position of rice in national and global food security systems will increase, since rice has the ability to grow under very diverse environmental conditions. Rice is by far the best adapted crop to lowland soils that are prone to flooding during the wet season. They draw attention to the following challenges facing rice research and development agencies: (i) productivity gains from the exploitation of Green Revolution Technologies are close to exhaustion; (ii) in the absence of further technical change, Asian farmers face increasing costs per Mg of rice produced; (iii) adverse agricultural externalities are increasing due to a lack of the holistic perspective of the farm resource base management; (iv) despite an anticipated decline in per capita rice consumption, aggregate Asian demand for rice is expected to increase by 50 to 60% during the 1990 to 2025 periods both due to population increase and poverty reduction; (v) economic growth and the commercialization of agricultural systems could reduce the competitiveness of rice relative to other crops and other farm enterprises; and (vi) an upward shift in rice yield frontier is necessary to meet future rice requirements and to sustain farm-level profits.

Compounding these problems, there are potential dangers arising from the diminishing investment in research in institutions devoted entirely to national and international public good and the expanding intellectual property rights (IPR) regime. The question now is how much more improvement can we bring about in productivity without ecological harm? This is where the new tools of molecular genetics assume importance.

INCREASING PRODUCTION AND PRODUCTIVITY

Bridging the Yield Gap

Maximum reported rice yields range from 11 to 13 Mg ha^{-1} in India and at IRRI. However, the average climate-adjusted yield potential is about 8 Mg ha^{-1} for inbred cultivars and 8.8 Mg ha^{-1} for hybrids in the intensive double cropping area. The gap between potential and actual yields is higher in most rice farming systems. The present average yield is just 40% of what can be achieved even with technologies currently on the shelf. This is because of imperfect adaptation to local environments, insufficient provision of nutrients and water, and incomplete control of pests, diseases, and weeds. There is considerable scope for further investment in land improvement through drainage, terracing, and control of acidification, where these have not already been introduced. While irrigated areas are making good progress, there is need for more intensive research and development attention in rainfed lowland and upland areas. Therefore, a massive effort should be made to launch a productivity revolution in farming. An integrated approach is necessary to remove the technological infrastructure and social and policy constraints responsible for the productivity gap and, in some cases, productivity decline. Reducing the cost of production through ecotechnologies and improving income through efficient production and postharvest technologies will help to enhance opportunities for both skilled employment and farm income. Public policies should not only pay attention to agrarian reform and input and output pricing, but also to reaching the unreached in technology dissemination through training, techno infrastructure, and trade. Public policy research should receive as much attention as agronomic research. Hence, mutually reinforcing packages of technology, services, and public policies will be needed. Future agricultural production programs will have to be based on a three-pronged strategy designed to foster an Evergreen Revolution. These strategies include defending the gains already achieved, extending the gains, and making new gains.

Defending the Gains Already Achieved

There is a need for stepping up maintenance research for ensuring that new strains of pests and pathogens do not cause crop losses and for preventing the introduction of invasive alien species. Water harvesting, watershed development, and economic and efficient water use can help to enhance productivity and income considerably. Where water is scarce, high value but low water requirements should be promoted. As pulses and oilseeds are important income-earning and soil-enriching crops, they should be included in rice farming systems. In areas such as the Red River delta in Vietnam, where seven crops of rice are grown in 2 yr, pulses should be promoted in the crop rotation for soil enrichment.

Extending the Gains

This needs to be done in rainfed and semiarid, hill and island areas, which have so far been bypassed by modern yield enhancement technologies. Regional imbalances in agricultural development are growing based largely on the availability of assured irrigation on the one hand, and assured and remunerative marketing opportunities on the other. The introduction of ecoregional technology missions, aimed to provide appropriate packages of technology, technoinfrastructure, services, and input and output pricing and marketing policies will help to include the excluded in agricultural progress. Technologies for elevating and stabilizing yields are available for semiarid and dry farming areas (Ryan and Spencer, 2001). Therefore, the emphasis should be on farming systems that can optimize the benefits of natural resources in a sustainable manner and not merely on cropping systems. Dry farming areas are also ideal for the cultivation of low water requiring, but high value, pulses and oilseeds.

Making New Gains

Farming system intensification, diversification, and value-addition should be promoted. Watershed and wasteland atlases should be used to develop improved farming systems, which can provide more income and jobs. Value addition to primary products should be done at the village itself. This will call for appropriate institutional structures that can provide key centralized services to small and marginal farm families and to provide them with the power of scale in ecofarming (i.e., integrated pest management, integrated nutrient supply, scientific water management, precision farming, etc.) as well as in marketing. A quantum leap in sophistication of management of all production factors will be required to sustain yield gains (Swaminathan, 2001) from the present levels to the commercially feasible threshold of about 80% yield potential.

Yield of commercial rice hybrids has been shown to be 10 to 15% greater than pure line cultivars. There is the need to identify new sources of male sterility and restorers, as about 95% of the male sterile lines used in commercial production in China and other countries have wild abortive cytoplasm. The newly developed cytoplasmic male sterile (CMS) line from *Oryza perennis* is different from that of WA. The search for new, stable sources of sterile cytoplasm, as in *O. glumaepatula*, and for restorers of these CMS sources, should continue. Search for linkage between the genes for resistance to biotic and abiotic stresses and molecular markers should continue, as markers facilitate selection for resistance during the transfer of resistance to elite, yet susceptible, breeding lines of rice.

PHOTOSYNTHETIC EFFICIENCY IMPROVEMENT

Stimulation of photosynthesis, reduction in photorespiration and enhancing source–sink relationships need to be explored, as they are major yield-determining factors. Increased sink size is the most important trait for increasing rice yield potential. Promising avenues under investigation include incorporating genes that confer C_4 photosynthesis into the rice genome and improve lodging resistance. The latter will facilitate high N fertilizer application, thereby leading to improved radiation use efficiency during the most rapid crop growth periods. Modifying plant architecture for better light interception and assimilate partitioning and utilization of solar energy, nutrients, and water more efficiently is necessary to improve rice yield.

To improve photosynthetic efficiency of the rice plant, transfer of C_4 traits into C_3 rice is being explored. Ku et al. (1999) used *Agrobacterium*-mediated transformation and introduced into rice a gene for phosphoenolpyruvate carboxylase (PEPC) from maize, which catalyzes the initial fixation of atmospheric CO_2 in C_4 plants. The level of expression of the maize PEPC in transgenic rice plants is correlated with the amount of transcript and the copy number of the inserted maize gene. Transgenic rice plants exhibited reduced O_2 inhibition of photosynthesis and higher photosynthetic rates compared with those of untransformed plants. These findings demonstrate a successful strategy for introducing the key biochemical component of the C_4 pathway of photosynthesis into rice.

The most important among the internal threats is the damage to the ecological foundations (i.e., land, water, forests, and biodiversity) essential for sustaining agricultural advancements. The external threats include the unequal trade bargain inherent in the WTO agreement of 1994, the rapid expansion of proprietary science, and potential adverse changes in temperature, precipitation, sea level rise, and ultraviolet B. Hence, farmers have to achieve revolutionary progress in productivity, quality, and value addition (Swaminathan, 2002). As an immediate measure for strengthening food security at the level of individuals and households, there is no better option than initiating a systematic effort in each agroclimatic zone to identify and remove the constraints responsible for the prevailing yield gaps. Community-based institutions or other forms of local bodies should be fully involved both in identifying constraints that limit production and in removing them.

PRODUCING MORE SUSTAINABLY: SHIFTING TO AN ERA OF PRECISION FARMING

Precision Farming

Researchers and farmers must move speedily to an era of precision farming, which helps to reduce the cost of production and improve productivity on an ecologically sustainable basis. They should launch a movement for achieving an Evergreen Revolution in rice farming systems based on ecologically sustainable and location-specific precision farming technologies. Precision farming methods, which can help to enhance income and yield per drop of water and per units of land and time, need to be standardized, demonstrated, and popularized speedily, if a reduction in the cost of production is to be achieved without reduction in yield. A responsive, field-specific management approach will require farmers to monitor crop growth stage, N status, and pest pressure to precisely identify when N top dressing, insecticide, or fungicide applications are required. Farmers need to monitor crop growth and N status and have access to predictions of growth stage, crop stage, and yield potential from crop simulation models that use real-time weather data and weather projections. This information is crucial for estimating the N fertilizer requirement and the proper timing of N topdressings and prophylactic treatment against endemic diseases when weather conditions are conducive to disease progression. The revolution in information technology should make it feasible for smallholder rice farmers in Asia to access needed information. Without access to this information, it will not be possible to sustain the rate of yield gain needed to meet rice demand. A precise match of genotype to environment is needed while utilizing field-specific tactics to ensure that input requirements are met without deficiency or excess in time and space.

Small Farm Management

Institutional structures, which will confer on farm families with smallholdings the advantages of scale at both the production and postharvest phases of agriculture, are urgently needed. For example, thanks to the cooperative method of organization of milk processing and marketing, India now occupies the first position in the world in milk production. Strategic partnerships with the private sector will help farmers' organizations to have access to assured and remunerative marketing opportunities.

There are great opportunities for achieving higher yields per units of land, water, and time, provided rice farmers are empowered to shift to precision farming methods. The five vital areas of research, development, and extension, which need attention from the point of view of achieving environmentally sustainable advances in rice productivity, are (i) soil health and fertility management; (ii) water management; (iii) integrated plant health management; (iv) energy management; (v) postharvest management; and (vi) soil health and fertility management.

Several studies have shown that the recovery of applied urea in lowland rice can be as low as 20% during the main growing season. Also, about one-third of applied N is immobilized in the soil. All over South Asia, about one-third to one-half of fertilizer N applied to rice crop is lost by leaching, ammonia volatilization, denitrification, and surface runoff. In the USA, Global Positioning Satellites are being used to measure soil health properties such as soil salinity. Use of the chlorophyll meter in the management of nitrogen is becoming more widespread. The Silsoe Research Institute in the UK has developed *plant-scale husbandry*. This technology involves the use of a high-tech tractor to operate nozzles, which can release precise doses of herbicides, pesticides, and fertilizers to plants. Silsoe Researchers feel that this method could help to cut down the use of chemicals by 90%.

A responsive, field-specific management approach will require farmers to monitor crop growth stage, N status, and pest pressure to precisely identify when N topdressing, insecticide, or fungicide applications are required. They should have access to predictions of growth stage, crop stage, and yield potential from crop simulation models that use real-time weather data and weather projections. This information is crucial for estimating the N fertilizer requirement and the proper timing of N topdressings and prophylactic treatment against endemic diseases when weather conditions are conducive to disease progression. A revolution in information technology should make it feasible for farmers to access needed information.

ORGANIZATION OF AN INTERNATIONAL RESEARCH NETWORK FOR AN EVERGREEN AGRICULTURAL REVOLUTION

There is an urgent need for an international research network which can facilitate knowledge and technology sharing in the area of improving farming systems productivity on an environmentally sustainable basis. Such a network, which may comprise partners in the major farming systems and agroecological regions of the world, could undertake studies on the following topics: (i) integrated gene management; (ii) higher factor productivity, with particular reference to water and nutrients; (iii) precision farming and development of the biological software essential for sustainable agriculture; (iv) bioorganic agriculture combining relevant features of organic farming and biotechnology; (v) biomass utilization for adding economic value to every part of the biomass; and (vi) knowledge connectivity through internet-aided rural knowledge centers.

It will be appropriate if ASA-CSSA-SSSA could help to organize such a Research Network in collaboration with the Inter-Academy Council and appropriate multilateral and bilateral donors.

Finally, the 21st Century enigma lies in the persistence of hunger in the midst of impressive technological capacity to grow more food. The Hunger Task Force cochaired by Pedro Sanchez and me (Sanchez and Swaminathan, 2005) has addressed this issue and offered suggestions on methods of ending this sad irony. Ultimately, science can only show the way—it is only synergy between science and public policy that can help to make hunger history.

REFERENCES

Biffen, R.H. 1905. Mendel's laws of inheritance and wheat breeding. J. Agric. Sci. 1:4–48.

Borlaug, N.E. 1989. Feeding the world during the next doubling of the world population. p. 523–555. *In* M.S. Swaminathan and S.L. Kochhar (ed.) Plants and society. Macmillan, London.

Briggs, S.P. 1998. Plant genomics: More than food for thought. Proc. Natl. Acad. Sci. USA 95:1986–1988.

Chen, P., D. Liu, and W. Sun. 1997. New countermeasures of breeding wheat for scab resistance. p. 59–65. *In* H.J. Dubin et al. (ed.) Fusarium head scab: Global status and future prospects. CIMMYT, Mexico.

Evans, L.T. 1998. Feeding the ten billion: Plants and population growth. Cambridge Univ. Press, U.K.

Farrer, W. 1898. The making and improvement of wheats for Australian conditions. Agric. Gaz. New South Wales 9:131–168.

Flor, H.H. 1956. The complementary genetic systems in flax and flax rust. Adv. Genet. 8:29–54.

Gardner, G., and B. Halwell. 2000. Overfed and underfed: The global epidemic of malnutrition. Paper 150. World Watch Inst., Washington, DC.

Hittalmani, S., A. Parco, T.W. Mew, R.S. Zeigler, and N. Huang. 2000. Fine mapping and DNA marker-assisted pyramiding of the three major genes for blast resistance in rice. Theor. Appl. Genet. 100:1121–1128.

Hossain, M., and J. Narciso. 2002. Global rice market: Trends and perspectives. Special lecture delivered in the annual conference of the Indian Society of agricultural economics, New Delhi, India. 19–21 Dec. 2002.

Katiyar, S.K., and J. Bennett. 2001. Biotechnology for gall midge resistance from molecular tagging to gene pyramiding. p. 369–378. *In* S. Peng and B. Hardy (ed.) Rice research for food security and poverty alleviation. IRRI, Manila, the Philippines.

Khush, G.S. 2003. Rice biotechnology. Paper presented at the Interdisciplinary dialogue on *The legacy of Watson and Crick: 50 years later*. 9–12 Jan. 2003. M.S. Swaminathan Research Foundation, Chennai, India.

Khush, G.S., and P.S. Baenziger. 1998. Crop improvement: Emerging trends in rice and wheat. p. 113–125. *In* V.L. Chopra et al. (ed.) Crop productivity and sustainability—Shaping the future. Proc. 2nd Int. Crop Sci. Congr. Oxford and IBH Publ., New Delhi, India.

Ku, M.S., B.S. Agarie, M. Nomura, H. Fukuyama, H. Tsuchida, K. Ono, S. Hirose, S. Toki, M. Miyao, and M. Matsuoka. 1999. High-level expression of maize phosphoenolpyruvate carboxylase in transgenic rice plants. Nat. Biotechnol. 17:76–80.

McCouch, S.R. 1998. Toward a plant genomics initiative: Thoughts on the value of cross-species and cross-genera comparisons in the grasses. Proc. Natl. Acad. Sci. USA 95:1983–1985.

McIntosh, R.A. 1983. A catalogue of gene symbols for wheat. p. 1197–1255. *In* S. Sakamoto (ed.) Proc. VI Int. Wheat Genet. Symp., Kyoto, Japan.

Muller, H.J. 1935. Out of the night. Vanguard Press, New York.

Peng, S., K.G. Cassman, S.S. Virmani, J. Sheehy, and G.S. Khush. 1999. Yield potential trends of tropical rice since the release of IR 8 and the challenge of increasing rice yield potential. Crop Sci. 39: 1552–1559.

Pingali, P.L., H. Hossain, and R.V. Gerpacio. 1997. Asian rice bowls: The returning crisis? CAB International, Wallingford, Oxford, U.K., and IRRI, Manila, the Philippines.

Rajaram, S., and G.P. Hettel. 1995. Wheat breeding at CIMMYT: Commemorating 50 years of research in Mexico for global wheat improvement. Ciudad Obregon, Sonora, Mexico.

Ryan, J.G., and D.C. Spencer. 2001. Future challenges and opportunities for agricultural R&D in the semi-arid tropics. ICRISAT, Patancheru, Andhra Pradesh, India.

Sanchez, A.C., D.S. Brar, N. Huang, Z. Li, and G.S. Khush. 2000. Sequenced tagged site marker-assisted selection for three bacterial blight resistance genes in rice. Crop Sci. 40:792–797.

Sanchez, P.A., and M.S. Swaminathan. 2005. Hunger in Africa: The link between unhealthy people and unhealthy soils. Lancet 265:442–444.

Satorre, E.H., and G.A. Slafer. 1999. Wheat: Ecology and physiology of yield determination. The Haworth Press, New York.

Singh, S., J.S. Sidhu, N. Huang, Y. Vikal, Z. Li, D.S. Brar, H.S. Dhaliwal, and G.S. Khush. 2001. Pyramiding three bacterial blight resistance genes (xa5, xa13 and Xa21) using marker-assisted selection into indica rice cultivar PR106. Theor. Appl. Genet. 102:1011–1015.

Stakman, E.C., D.M. Stewart, and W.Q. Loegering. 1962. Identification of physiologic races of *Puccinia graminis* var. tritici. USDA-ARS Bull. E-617. U.S. Gov. Print. Office, Washington, DC.

Swaminathan, M.S. 1965. Artificial trans-mutation of the gene. J. Sci. Ind. Res. (India) 24:217–220.

Swaminathan, M.S. 1968. The age of algeny, genetic destruction of yield barriers and agricultural transformation. Presidential Address, Agricultural Science Section, 55th Indian Science Congr., Jan. 1968. Proc. Indian Science Congr., Varanasi, India.

Swaminathan, M.S. (ed.) 1993. Wheat revolution: A dialogue. Macmillan, Bangalore, India.

Swaminathan, M.S. 1996. Sustainable agriculture: Towards an Evergreen Revolution. Konark Publ., Delhi, India.

Swaminathan, M.S. 2001. Food security and sustainable development. Curr. Sci. 81:948–954.

Swaminathan, M.S. 2002. Building a national nutrition security system. Paper presented at India–ASEAN Eminent Persons Lecture Series, 11 Jan. 2002. FAO, Bangkok, Thailand.

Van der Plank, J.E. 1963. Plant diseases: Epidemics and control. Academic Press, New York.

Venkataramani, G. 2002. Policies need to be farmer-friendly. p. 5–7. *In* Survey of Indian agriculture. The Hindu, Tamil Nadu, India.

Wilson, E.O. 2002. The future of life. Knopf, New York.