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Plenary Lecture

Challenges for meeting the global food and nutrient needs in the new millennium

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Major advances have occurred in food production during the last 30 years as a result of the adoption of 'green revolution' technology. The price of rice and wheat is 40 % lower than it was in the 1950s. This lower price has helped the poorer sections of society, who spend 50–60 % of their income on food. The proportion of the population in the developing world that is malnourished fell from 46·5 % in the early 1960s to 31 % in 1995. However, there are still 1·3 billion of the population who go to bed hungry every day. Deficiencies of micronutrients such as Fe, Zn and vitamin A affect millions of the population in the developing world. The world population is increasing at the rate of 1·4 %, or an increase of eighty million per year. It is estimated that we will have to produce 50 % more food grains by 2025. Various strategies for meeting this challenge exist, including the development of cereal varieties with a higher yield potential and yield stability, and farmer-friendly public policies. In order to tackle hidden hunger, efforts are underway to develop crop varieties with higher concentrations of Fe and Zn. Recently, a breakthrough has occurred in the introduction of the genes for the pathway leading to the biosynthesis of β-carotene, a precursor of vitamin A, in rice. Various conventional approaches and modern tools of biotechnology are being employed in the development of crop varieties with higher yields and higher levels of micronutrients.

Malnutrition: Hidden hunger: Micronutrient deficiencies: Food security

The 1960s was a decade of despair with regard to the world's ability to cope with the food–population balance, particularly in the tropics. The cultivated land frontier was closing in most Asian countries, while population growth rates were accelerating, owing to rapidly-declining mortality rates resulting from advancements in modern medicine and health care. International organisations and concerned professionals were busy organising seminars and conferences to raise awareness regarding the threatening food crisis and to mobilise global resources to tackle the problem on an emergency basis. In a famous book entitled *Times of Famine* Paddock & Paddock (1967) predicted that 'Ten years from now, parts of the underdeveloped world will be suffering from famines. In 15 years, the famines will be catastrophic and revolutions and social turmoil and economic upheavals will sweep areas of Asia, Africa and Latin America.'

Thanks to the widespread adoption of 'green revolution' technology, large-scale famines and economic upheavals were averted. Between 1966 and 1990 the population of densely-populated low-income countries grew by 80 %, but food production more than doubled. In 1997 the average *per capita* food availability was 18 % higher than that in 1966.

The technological advance that led to the dramatic achievements in world food production over the last 30 years was the development of high-yielding varieties of cereals. The adoption of 'green revolution' technology was facilitated by: (1) development of irrigation facilities; (2) availability of inorganic fertilizers; (3) benign government policies.

The gradual replacement of traditional varieties of wheat and rice by improved ones, together with the associated improvement in farm management practices, has had a dramatic effect on the growth of rice and wheat output, particularly in Asia (Table 1). Farmers produce 5–7 t

Abbreviations: Bt, *Bacillus thuringiensis*; IPM, integrated pest management.
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Table 1. Total area planted, coverage of high-yielding varieties (HYV) and increase in rice production in selected Asian countries

Country	Total area planted ($\times 10^6$ ha) 1966	Total area planted ($\times 10^6$ ha) 1996	Area planted to HYV (%)	Production ($\times 10^6$ tons)* 1966	Production ($\times 10^6$ tons)* 1996	Increase in production (%)
Bangladesh	9·1	10·3	46	14·3	28·0	96
China	31·3	31·4	100	98·5	190·1	93
India	35·2	42·7	75	45·6	120·0	163
Indonesia	7·7	11·3	77	13·6	51·2	276
Myanmar	4·5	6·5	58	6·6	20·9	217
Pakistan	1·4	2·3	41	2·0	5·6	180
Philippines	3·1	4·0	94	4·1	11·3	176
Sri Lanka	0·5	0·8	94	1·0	2·2	120
Thailand	7·3	9·2	13	13·5	21·8	61
Vietnam	4·7	7·3	80	8·5	26·3	209

* 1 ton (short, 2000 lb) is 907·2 kg.

unmilled rice/ha from high-yielding varieties compared with 1–3 t/ha from conventional varieties. Since 1966, when the first high-yielding variety of rice was released, the area harvested has increased only marginally, from 126 to 148×10^6 ha (17 %), while the average rice yield has increased from 2·1 to 3·6 t/ha (71 %). The total rice production doubled in a 25-year period from 257×10^6 t in 1966 to 520×10^6 t in 1990 (Khush, 1999). Similarly, world wheat production increased from 308×10^6 t in 1966 to 541×10^6 t in 1990. In Asia wheat production increased from 33×10^6 t in 1966 to 225×10^6 t in 1995 or a sixfold increase.

In many Asian countries the growth in rice production has outstripped the rise in the population, leading to a substantial increase in cereal consumption and energy intake *per capita*. During 1965–90 the daily energy supply in relation to requirements improved from 81 % to 120 % in Indonesia, from 86 % to 110 % in China, from 82 % to 99 % in the Philippines, and from 89 % to 94 % in India (United Nations Development Program, 1994). Overall, the *per capita* availability of food for direct human consumption is currently about 16 % higher than it was 30 years ago. The percentage of the population in the developing world that is malnourished fell from 46·5 to 31 in 1995 (Smith & Haddad, 2000).

The increase in the *per capita* availability of rice and a decline in the cost of production per ton output contributed to a decline in the real price of rice and wheat, both in international and domestic markets. The unit cost of production is about 20–30 % lower for high-yielding varieties than for traditional varieties of rice (Yap, 1991) and of wheat. In fact, the price of rice adjusted for inflation was 40 % lower in 1992 than it was in the mid 1960s (Fig. 1). The decline in food prices has benefited the urban poor and the rural landless, who spend more than half their income on food grains.

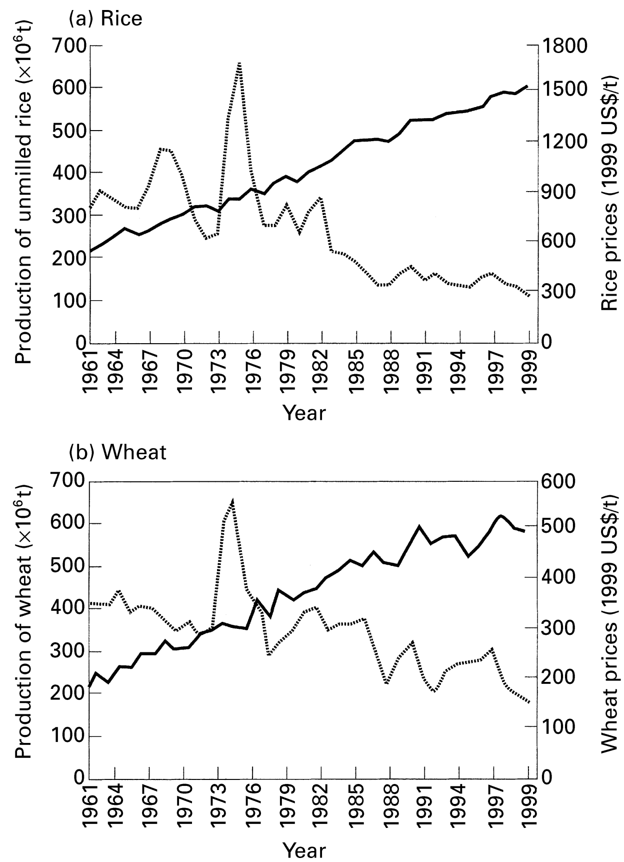

Fig. 1. Trends in world rice (a) and wheat (b) production (—) and price (---) in 1961–99. Production values were obtained from the FAOSTAT statistical database (Food and Agriculture Organization, 2000). Rice prices relate to Thai rice 5 %-broken deflated by G-5 MUV index deflator (World Bank, 1999).

The population–food scenario at the turn of the century

The world's capacity to sustain a favourable food–population balance has again come under the spotlight in view of continued population growth, a drastic slowdown in the growth of cereal production since 1990 (Brown, 1996, 1997) and changing food habits.

Population

Estimates of future numbers are based on the latest UN population projections, using their medium-level figures (Fig. 2). Under this scenario, the world's population will grow from 6·1 billion in 2000 to eight billion in 2025 and to 9·4 billion in 2050. Most of the increase (93 %) will take place in the developing world, whose share of the global population is projected to increase from 78 % in 1995 to

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83 % in 2020. The annual rate of the world's population growth reached its historical high in 1964 at 2·2 %. Since then, it has been slowly declining, dropping to 1·4 % in 1998. Despite the falling rate of growth, the annual increase in the world's population was seventy-two million in 1964, reaching an all-time high of eighty-seven million in 1990. Since then, the annual increase has also declined, falling to eighty million in 1997, where it is expected to remain for the next two decades, before starting to decline (US Bureau of Census, 1998).

The population projections for individual countries vary more widely than at any time in history. At mid-century populations were growing everywhere, but currently they have stabilized in about thirty-two countries, while they continue to expand in some countries at ≥3 %/year. With the exception of Japan, all the nations in the first group are in Europe and all are industrial countries. The populations of some countries, including Russia, Japan and Germany, are actually projected to decline over the next 50 years. In another thirty-nine countries fertility has dropped to replacement levels or below. Among the countries in this category are China and USA, which together contain 26 % of the world's population (Brown *et al*. 1998).

In contrast to this group, some countries are projected to triple their populations by 2050 (Table 2). For example, Ethiopia's current population of sixty-two million will more than triple by 2050. Pakistan's population is projected to go from 148 million to 357 million, surpassing that of the USA before 2050. Nigeria, meanwhile, is projected to go from 122 million currently to 339 million, giving it a higher population in 2050 than that for the whole of Africa in 1950.

The amount of land under grain production *per capita* has been shrinking since mid-century, but the drop projected for the next 50 years means the world will have less land under grain production *per capita* than India has currently. Future population growth is likely to reduce this key number in many countries to the point where they will no longer be able to feed themselves (Brown *et al*. 1998). The challenge to governments presented by continuing rapid population growth is not limited to food. It also includes education, housing and employment.

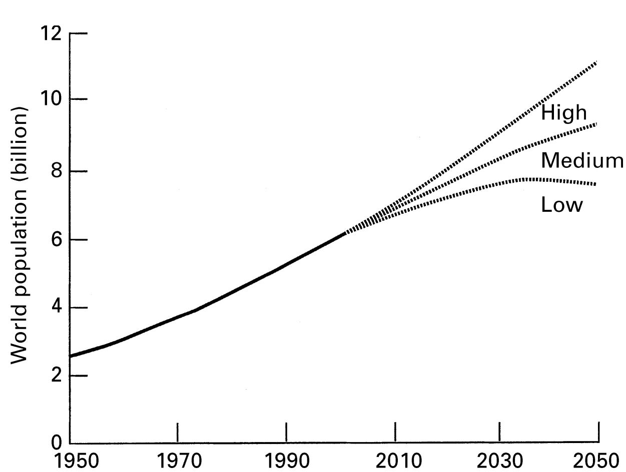

Fig. 2. World population projections under three variants, 1950–2050.

Cereal production

The relationship between growth in the world's population and grain production has shifted over the last half century, neatly dividing this period into two distinct eras. From 1960–85, the growth in the grain harvest easily exceeded that of the population, raising the harvest *per capita* from 279 kg in 1960 to 343 kg in 1985. During the next 10 years the growth in the grain harvest fell behind that of the population growth, dropping output *per capita* to 293 kg (Table 3). The slower growth in the world's grain harvest since 1985 is due to a lack of new land under cultivation and

Table 2. The twenty largest countries ranked according to population size in 1998, with projections to 2050 (United Nations, 1996)

	1998		2050	
Rank	Country	Population (million)	Country	Population (million)
1	China	1255	India	1533
2	India	976	China	1517
3	USA	274	Pakistan	357
4	Indonesia	207	USA	348
5	Brazil	165	Nigeria	339
6	Pakistan	148	Indonesia	318
7	Russia	147	Brazil	243
8	Japan	126	Bangladesh	218
9	Bangladesh	124	Ethiopia	213
10	Nigeria	122	Iran	170
11	Mexico	96	The Congo	165
12	Germany	82	Mexico	154
13	Vietnam	78	Philippines	131
14	Iran	73	Vietnam	130
15	Philippines	72	Egypt	115
16	Egypt	66	Russia	114
17	Turkey	64	Japan	110
18	Ethiopia	62	Turkey	98
19	Thailand	60	South Africa	91
20	France	59	Tanzania	89

Table 3. World grain production 1960–95 and *per capita* grain availability (data from Brown, 1996)

Year	Total grain ($\times 10^6$ t)	Grain production *per capita* (kg)
1960	847	279
1970	1096	296
1980	1447	325
1985	1664	343
1986	1683	341
1987	1612	321
1988	1564	306
1989	1685	324
1990	1780	336
1991	1696	315
1992	1776	316
1993	1703	307
1994	1745	309
1995	1680	293

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to slower growth in irrigation and fertilizer use. The irrigated area *per capita*, after expanding by 30 % between 1950 and 1978, has declined by 4 %. Since then, growth in irrigated areas has fallen behind that of the population (Postal, 1997). The increase in world fertilizer use has slowed dramatically since 1990, as diminishing returns following the application of additional fertilizer have stabilized use in the USA, Western Europe and Japan, and slowed annual growth in world fertilizer use from 6 % between 1950 and 1990 to only 2 % in recent years (Soh & Isherwood, 1997)

After rising at 2·5 %/year from 1960 to 1990, the annual increase in the productivity of land under grain production dropped to about 1 % from 1990 to 1997. The challenge for the world's farmers is to reverse this trend at a time when the area cropped *per capita* is shrinking, the amount of irrigation water *per capita* is dropping and the crop yield response to additional fertilizer use is falling.

Changing food habits

The most important factor that influences *per capita* consumption of staple grains is the level of income of the consumer. At low levels of income, meeting energy needs is the most basic concern for an individual. Staple foods such as starchy roots, rice, wheat and coarse grains provide the cheapest source of energy. Low-income consumers spend most of their income on this type of food. As income increases, the consumer shifts from low-quality to better-quality products. For example, rice is the most preferred food staple in Asia where 90 % of the world's rice is produced. At low levels of income, rice is considered a luxury commodity. At times of scarcity when incomes are very low, consumers are often satisfied with coarse grains and sweet potatoes, which are the cheapest source of energy. As incomes grow, *per capita* rice consumption increases, with consumers substituting rice for coarse grains and root crops. However, as income increases beyond a threshold, consumers can afford to have a high-value balanced diet containing foods that provide more proteins and vitamins, such as vegetables, fruits, fish and livestock products. Thus, *per capita* rice consumption starts to decline. This pattern of changes in food consumption with economic growth is amply demonstrated by the experience of Japan and Korea, which made a transition from a low- to a high-income level within a short period of time. The rice consumption in Japan increased with economic growth after the Second World War, reached a peak of about 120 kg *per capita* per year in the early 1960s and then started to decline. By the late 1980s the *per capita* rice consumption was 40 % lower than that in the early 1960s (Hossain & Sombilla, 1999). It is only 68 kg *per capita* per year at present.

In South Korea the *per capita* consumption of cereals increased from the mid 1960s when it was a low-income country, up to 1979 when it reached middle-income level. Since then *per capita* consumption has been declining. The changes in *per capita* food intake in South Korea over the last two decades can be seen in Table 4. There has been a substantial reduction in the consumption of cereals and root crops, but a surge in the demand for livestock products, fish, fruits and vegetables. We can expect these changes to occur in other countries as they move along the path of economic development.

Table 4. Changes in food consumption pattern (g *per capita* per d) in South Korea, 1974–6 to 1992–4 (from Food and Agriculture Organization, 1996)

Food item	1974–6	1992–4	Change
Cereal	686	513	–173
Roots	101	43	–58
Vegetables	373	511	138
Fruits	63	229	166
Sugar	23	88	65
Oils and fats	11	35	24
Fish	132	181	49
Meat and eggs	32	124	92
Milk	12	58	46
Total	1433	1782	349

In many countries in East and Southeast Asia, incomes have reached a level where we can expect the *per capita* cereal consumption to decline in the future. The Food and Agriculture Organization (1996) data show that among Asian countries *per capita* cereal consumption has declined substantially in Japan, Taiwan, South Korea, Malaysia and Thailand, all middle- and high-income industrialized countries that have passed the income threshold mentioned earlier. China and Indonesia, two giant Asian countries which account for over one-third of the global cereal consumption, are approaching the threshold of peak consumption, from where we may expect a declining trend to set in soon. However, in South Asia, the Philippines and Vietnam in Southeast Asia 30–50 % of the population still live in poverty and do not have an income which is adequate to have access to the food required for a healthy productive life. With economic growth and a reduction in poverty, *per capita* consumption is expected to further increase in these countries. The rate of change in *per capita* consumption of cereals in Asia will then depend on the relative strength of the upward pressure for the low-income countries and the downward pressure for the middle- and high-income countries.

Indirect demand for cereals for livestock production

The other important factor that we must take into consideration in projecting the growth in demand for cereals is their indirect demand as livestock feed (Alexandratos, 1995). Between 1965 and 1995 demand for meat in the world increased more than fourfold, from $2{\cdot}6 \times 10^6$ t in 1965 to about $10{\cdot}7 \times 10^6$ t in 1995 (Food and Agriculture Organization, 1997). Asia as a whole has emerged as a major importer of meat, with its share of global meat imports reaching about 28 % in 1995. It takes 2, 4 and 8 kg grain to produce 1 kg poultry, pork and beef respectively. The increase in the demand for livestock products implies a fast growth in the demand for cereal grains as livestock feed.

Recent projections show that world demand for meat will grow at a rate of 1·8 %/year between 1993 and 2020. Most of this demand will be accounted for by the developing

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Table 5. Projected growth (%) in demand for livestock products, 1993–2020 (from Rosegrant *et al.* 1995)

	Meat	Eggs	Milk
World	1·82	1·6	1·06
Developed	0·46	0·4	1·08
Developing	2·93	2·31	2·38
Latin America	2·15	1·86	1·21
Sub-Saharan Africa	3·39	2·96	1·51
WANA	2·67	2·24	1·14
Asia	3·17	2·39	3·20

WANA, West Asia and North Africa.

nations (Table 5). Growth in demand in the developed countries will continue to slow down because of stabilized populations and as the population consume less meat as they become more health conscious. The demand of Asian countries for meat products will grow at 3·2 %/year and will thus account for most of the global demand (Hossain & Sombilla, 1999).

Status of food security

Access to food depends on income. Currently, more than 1·3 billion of the population are absolutely poor, with incomes of ≤ 1 US$/d *per capita*, while another two billion are marginally better off (World Bank, 1997). Projections of food production and consumption in 2020 offer some sign of progress, but prospects of a food-secure world (a world in which each and every individual is assured of access at all times to the food required to lead a healthy and productive life) remain bleak. The International Food Policy Research Institute's latest global model for Policy Analysis Commodities and Trade projects the future world food situation according to several scenarios (Rosegrant *et al.* 1995). Under the most likely or baseline scenario, 150 million children under the age of 6 years will be malnourished in 2020, just 20 % fewer than that in 1993 (Fig. 3). Child malnutrition is expected to decline in all major developing regions except Sub-Saharan Africa, where the number of malnourished children could increase by 45 % between 1993 and 2020 to reach forty million. In South Asia, home to half the world's malnourished children, the number is expected to decline by more than thirty million between 1993 and 2020 (Fig. 3). With more than 70 % of the world's malnourished children, Sub-Saharan Africa and South Asia are expected to remain 'black spots' of child malnutrition in 2020. According to Smith & Haddad (2000) *per capita* availability of food is not the only determinant of child malnutrition. Other factors such as women's education and status in the society, the health environment and political stability play an important role.

Projections by the FAO on the size of the food-insecure population paint a similarly mixed picture. FAO projects that 680 million of the world's population (12 % of the developing world's population) could be food insecure in 2010, a reduction from 840 million in 1990–2 (Fig. 4).

Food insecurity is expected to diminish rapidly in East Asia and to a lesser extent in South Asia and Latin America, but it could accelerate substantially in Sub-Saharan Africa,

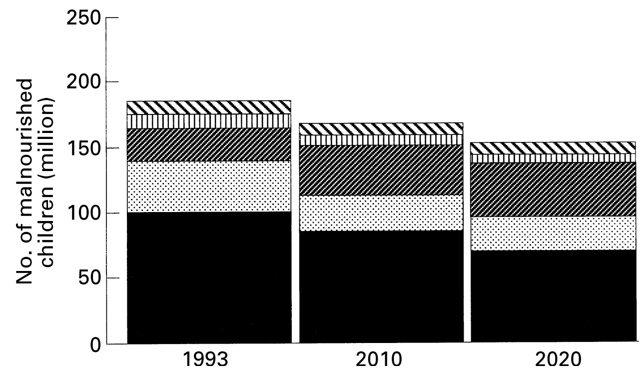

Fig. 3. The number of malnourished children in 1993, 2010 and 2020 in South Asia (▬), China and Southeast Asia (▭), Sub-Saharan Africa (▨), Latin America (▥) and West Asia and North Africa (▧). (From Pinstrup-Anderson *et al.* 1997.)

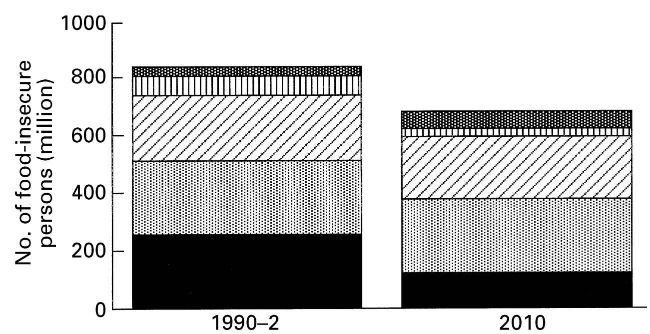

Fig. 4. The number of food-insecure persons in 1990–2 and 2020 in East Asia (▬), South Asia (▭), Sub-Saharan Africa (▨), Latin America (▥) and West Asia and North Africa (▩).

West Asia and North Africa. Sub-Saharan Africa and South Asia, home to a projected 70 % of the world's food-insecure population in 2010 will be the loci of hunger in the developing world. By 2010, every third person in Sub-Saharan Africa is likely to be food-insecure compared with every ninth person in South Asia and every twentieth person in East Asia. These disturbing figures reflect widespread poverty and poor health in some parts of the world (Pinstrup-Anderson *et al.* 1997).

Poverty rather than food shortage is frequently the underlying cause of hunger. Indeed, about 80 % of all malnourished children in the developing world live in countries that boasted food surpluses. The more important feature common to those countries is pervasive poverty, which limits an individual's access to food. As an example, India was exporting $3–4 \times 10^6$ t rice/year during the 1990s, yet 200 million of its population go to bed hungry every day because they lack purchasing power. Poverty also means poor access to non-food services, including health care, education and a clean living environment, which increases the likelihood of hunger. Conditions like diarrhoea, for instance, usually the result of an unclean water supply, prevent a child from absorbing available nutrients, while a poor education often means poor job prospects, with adverse consequences for income and in turn for nutrition.

Meeting the challenge

To feed a world population of eight billion by 2025 we have to act now and develop strategies for meeting the challenge. Various strategies for increasing food production include: (1) genetic improvement of crops; (2) improved management of crops, pests, water, nutrients and soil resources; (3) agriculture-friendly government policies.

Genetic improvement of crop cultivars

Genetic improvement strategies should aim at developing crop cultivars with a higher yield potential, higher yield stability and greater production efficiency.

Improving the yield potential. Crop cultivars with a higher yield potential are the key to increased productivity. Several approaches are useful in raising the yield potential.

Conventional hybridization and selection is the time-tested strategy for developing crop cultivars with higher yield potential. This process involves the creation of variability by hybridization and selection of desirable recombinants. It has been estimated that on average an increase of about 1 %/year has occurred in the yield potential of major crops. For example, the yield potential of wheats developed at the International Center for the Improvement of Wheat and Maize (since the development of dwarf wheats) increased by 0·83 %/year over the last 30 years (Fischer, 1994). There is no reason why further increases cannot be attained.

Another approach which led to a dramatic increase in the yield potential of cereals was the modification of plant types. To increase the genetic yield potential of rice from the present level of 10 t/ha to 12 t/ha, a new plant type was conceptualized. Modern high-yielding rice varieties have a harvest index (grain:straw) of 0·5. The new plant type was conceptualized to raise the harvest index to 0·6. The suggested modifications to plant structure included a reduction in tiller number, and an increase in the number of grains per panicle and straw stiffness (Khush, 1995). Numerous breeding lines with desired characteristics have been developed and are being evaluated in replicated yield trials. Wheat breeders at the International Center for the Improvement of Wheat and Maize are similarly developing wheat germplasm with a modified plant structure.

Yield improvement in maize has been associated with hybrid development. Yields in the USA were basically unchanged from the mid 19th century until the 1930s, and accelerated greatly after the introduction of double-cross hybrids. The subsequent replacement of double-cross hybrids by single-cross hybrids in the 1960s led to a second acceleration in maize yield (Fig. 5). The average yield advantage of hybrids *v.* cultivars is approximately 15 % (Tollenaar, 1994). Heterosis (first-generation hybrid vigour) has also been exploited to increase the yield potential of sorghum and pearl millet, and more recently of rice. Rice hybrids with a yield advantage of 10–15 % were introduced in China in the 1970s, and are now planted in about 50 % of the land under rice production in that country. Rice hybrids suitable for planting in the tropics and subtropics are being developed at the International Rice Research Institute and under national programmes. When adopted widely, hybrids will affect the rice production in tropical and subtropical Asia (Yuan *et al.* 1989).

Crop gene pools can be widened through hybridization of crop cultivars with wild species, weedy races as well as intraspecific crosses between diverse germplasm groups. Such gene pools are exploited for improving many traits, including yield. Lawrence & Frey (1976) reported that one-quarter of the lines from BC_2-BC_4 segregants from the *Avena sativa* × *Avena sterilis* (oats) matings were significantly higher in grain yield than the recurrent parent. Nine lines were tested over years and sites. They were very similar to the recurrent parent, but had a 10–29 % higher grain yield. Recently quantitative trait loci for higher yield potential were tagged with molecular markers in a cross involving *Oryza rufipogon*, a wild species of *Oryza*, and a variety of cultivated rice, *Oryza sativa* (Xiao *et al.* 1996).

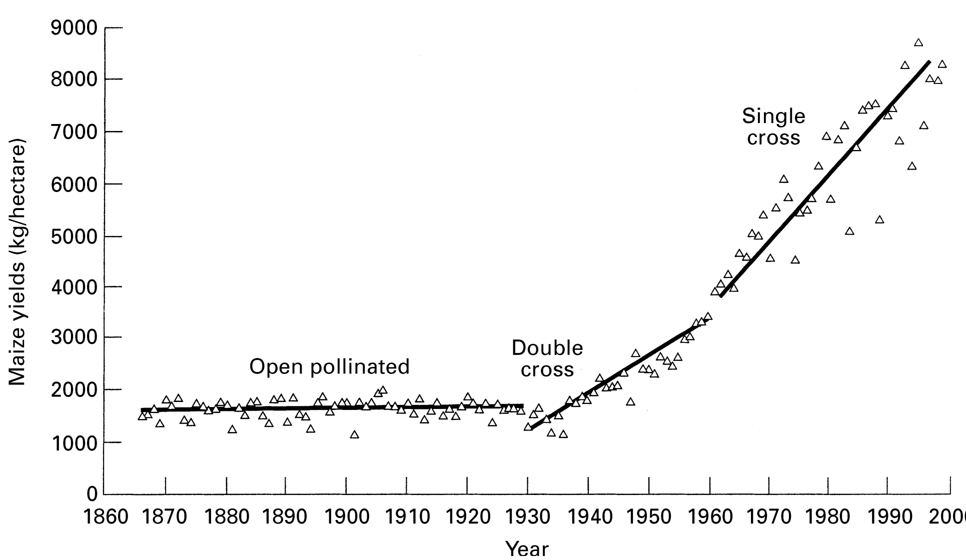

Fig. 5. Average US maize yields and types of maize, Civil War to 1998. (Adapted from Troyer, 1999.)

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Several biotechnological approaches for increasing the crop yield potential are being investigated. These approaches include the introduction of cloned novel genes through transformation, and the use of molecular marker technology. Starch biosynthesis plays a pivotal role in plant metabolism, both as a transient storage metabolite of leaf tissue and as an important energy and C reserve for storage organs such as seeds, roots, tubers and fruit. Several enzymic steps are involved in starch biosynthesis in plants. ADP-glucose pyrophosphorylase is a critical enzyme in the regulation of starch biosynthesis in plant tissues. Even in storage organs with high levels of ADP-glucose pyrophosphorylase, its activity is still limiting. It should be possible to positively affect starch production in storage tissues by up regulating expression of the gene encoding this enzyme (Kishore, 1994). Starch levels and DM accumulation were enhanced in potato tubers of plants transformed with the $glgC^{16}$ gene from *Escherichia coli* encoding ADP-glucose pyrophosphorylase (Stark *et al*. 1992). The transformed potato plants had tubers with higher DM and starch contents, under both growth-chamber and field conditions. The $glgC^{16}$ gene, when introduced into cereals through transformation, may help increase the yield potential.

Increasing the yield stability. The full yield potential of our crops is not realised, because of the toll taken by the attack of diseases and insects which have been estimated to cause a yield loss of up to 25 % annually in cereal crops. Similarly, crop yields are reduced and fluctuate greatly as a result of abiotic stresses such as drought, excess water, mineral deficiencies and toxicities, and abnormal temperatures. The genetic improvement of crops to withstand these biotic and abiotic stresses can impart yield stability and will contribute to increased food security.

Host-plant resistance is the logical approach for minimizing the crop losses from pest attack. As mentioned earlier, numerous cereal crop varieties with multiple resistance have been developed. Recent breakthroughs in cellular and molecular biology have opened new vistas for the development of crop cultivars with durable resistance. It is now possible to introduce novel genes for pest resistance from unrelated plants, animals and micro-organisms into crop cultivars. Protocols for the transformation of most of the important food crops have now been developed (Uchimiya *et al*. 1989), and novel genes are being successfully incorporated into crop species. The δ endoprotein produced by the bacterium *Bacillus thuringiensis* (*Bt*) is lethal to caterpillars of lepidopteran insects. When cloned *Bt* gene, after proper modifications, is transferred into crop plants through genetic engineering, plants produce their own biocides. *Bt* gene has been incorporated into maize and rice. *Bt*-containing maize strains were planted in millions of hectares in the USA in 1997, and the transgenic plants exhibit high levels of resistance to maize insect pests. *Bt*-containing rice plants show a high level of resistance to rice stem borers (Ghareyazie *et al*. 1997). Many other genes for host-plant resistance, such as protease inhibitors, chitinases and gluconases, are being incorporated into crop plants.

The progress in developing crop cultivars with tolerance to abiotic stresses has been slow because of a lack of knowledge of the mechanisms of tolerance, poor understanding of the inheritance of tolerance, low heritability and lack of efficient techniques for screening the germplasm and breeding materials. Genetic engineering techniques hold great promise in developing crop cultivars with higher levels of tolerance to abiotic stresses. Accumulation of sugar alcohols is a widespread response that may protect the plants against environmental stress through osmoregulation. Mannitol is one of the sugar alcohols commonly found in plants. Tobacco (*Nicotiana* spp.) plants lacking mannitol were transformed with a bacterial gene *mtlD* encoding mannitol (Tarczynski *et al*. 1992). Mannitol concentrations exceeded 6 μmol/g (fresh weight) in the leaves and in the roots of some transformants, whereas this sugar alcohol was not detected in these organs of wild-type tobacco plants. Growth of plants from control and mannitol-containing lines in the absence and presence of added NaCl was analysed. Plants containing mannitol had an increased ability to tolerate salinity. After 30 d of exposure to concentrations of 250 mM-NaCl culture solution, transformed plants increased their height by a mean of 80 %, whereas control plants increased by only a mean of 22 % in height over the same interval.

Management strategies

To achieve sustainable increases in crop productivity it is important to improve the efficiency of all production inputs (e.g. nutrients and water) and minimize the losses caused by pests and weeds, and during post-harvest handling.

Integrated nutrient management. Fertilizers are the most important input in crop production, yet the area-specific or regional fertilizer recommendations are based on short-term trials which do not necessarily reflect the long-term impact of fertilizer use on resource base, environmental quality and human health. Moreover, blanket recommendations are static and cannot accommodate variability in soil nutrient status, crop demand and crop management. Practical and easy-to-use diagnostic methods are necessary to determine requirements for major nutrients (N, P and K), soil nutrient supply and variable fertilizer needs of crops (A Dobermann, KG Cassman, SB Peng, PS Tan, CV Phung, PC Santa Cruz, JB Bajita, MAA Adviento and DC Olk, unpublished results).

Water management. Water is currently the most limiting resource for crop production, and is recognized as the most critical resource for future agricultural development. Efficient management of water resources and investment in their improvement, with regard to both availability and quality, will be critical for the sustainability, productivity and dependability of crop production in decades ahead. According to FAO estimates, 600×10^6 hectares of potentially-arable land is unused because of limited water availability (Alexandratos, 1988). Thus, there is an urgent need to conserve water resources and maximize efficiency of water use. Water-use efficiency can be improved through the introduction of short-duration and drought-tolerant cultivars, mulching to reduce evaporation, land levelling to reduce water requirement and optimum irrigation regimens.

Soil management. Vast areas of land are unsuitable for crop production or have poor productivity due to the high levels of toxic substances, e.g. high salinity, high alkalinity or high levels of Fe or Al. Various amendments can improve the productivity of such soils. Gypsum has been used for many years as a soil conditioner and ameliorant for sodic (alkaline) soils, and as a nutrient source of soil Ca. Gypsum can also be used to improve infertile acidic soils, and to reduce surface crusting and subsurface hard layers. Gypsum applications also result in substantial improvements in crop rooting patterns and water infiltration into soils, resulting in decreased run-off and erosion, and improved yields (Summer, 1993).

Integrated pest management. Integrated pest management (IPM) is an economically-benign system of crop protection which combines several techniques, such as host-plant resistance, cultural, mechanical and biological control, and judicious but need-based use of insecticides, to sustain productivity with the minimum adverse effects on the environment. It has been defined as a 'pest management system which in the context of the associated environment and population dynamics of pest species, utilizes all suitable techniques in as compatible a manner as possible to maintain the pest population at levels below those causing economic injury.' (Ovdejans, 1991).

Appalled at the continued misuse of insecticides, the FAO launched the IPM programme to attempt to manage the pest problems in rice. The first phase of the FAO programme (1980–6) focused on developing and testing the technical aspects of the IPM concept using the knowledge generated by the International Rice Research Institute and national programmes in the region. More recently, the project has been directed towards enhancing adoption of IPM by farmers. Preserving conditions that favour natural pest control has been the basis of rice IPM. It depends on farmers' ability to recognize beneficial organisms and their willingness to rationalize pesticide use. Reducing or eliminating insecticide applications and allowing time for populations of natural enemies to build up is a proven technique for insect pest management (PE Kenmore, unpublished results). There is much knowledge on parasitism and predation on insects, and one of the long-term goals of the International Rice Research Institute has been to develop action thresholds which also take into account the number of beneficial organisms present. Restricting the type, timing and volume of pesticide applications conserves the natural enemies of rice pests which provide effective biological control in the majority of rice fields. IPM for rice has been adopted as a national policy by most of the nations in Asia. Similar programmes for the other crops should help reduce the yield losses and contribute to environmental sustainability.

Government policies

The importance of government policies in increasing food production and food security can hardly be overemphasized. Investment in infrastructure such as roads, markets, rural electrification, land levelling, irrigation and land reform are essential for increasing crop productivity. Sound national agricultural policies, such as access to inputs (fertilizers, quality seeds and farm machinery) and fair and predictable prices for farm produce, are harbingers of higher crop yields. Investments in national agricultural expansion, training and research, including agricultural universities, must continue to receive priority.

In addition to improvements in *per capita* food availability, the education of women, the promotion of the status of women relative to men, and provision of a healthy environment offer the best hope for the future reductions in child malnutrition. To maintain the necessary resource base and the political will for these investments, improvements in national income growth and democratic development must be accelerated as well (Smith & Haddad, 2000).

Tackling the hidden hunger

In addition to protein–energy malnutrition, deficiencies of minerals and vitamins affect a high proportion of the world's population, particularly in the developing world. Thus, human nutrition organizations such as WHO, and more recently the Consultative Group on International Agricultural Research, have made fighting this 'hidden hunger' (i.e. micronutrient deficiencies) a high priority (World Health Organization, 1992; Bouis *et al*. 2000). The micronutrients Fe, Zn, I and vitamin A have been targeted for intervention due to the immense magnitude of the problem of deficiencies of these micronutrients amongst the world's poor. Estimates are that two billion of the world's population are Fe deficient, with consequent diminished work performance, impaired body temperature regulation, impaired psychomotor development and intellectual performance, detrimental behavioural changes (e.g. significantly decreased responsiveness and activity, and increased body tension and fearfulness), decreased resistance to infection and increased susceptibility to Pb poisoning (Dallman, 1990). Women and children are particularly at risk of Fe deficiency because of their elevated requirements for child-bearing and growth respectively. An estimated 58 % of the pregnant women in developing countries are anaemic, and their infants are more likely to be born with a low birth weight. WHO estimates 31 % of these children under 5 years old are also anaemic.

At least 400 million of the world's population have vitamin A deficiency, and of that number more than 100 million are young children. As many as three million children die annually as a result of vitamin A deficiency. Fourteen million children suffer from clinical eye problems, and increased risk of respiratory diseases and diarrhoea (Sommer, 1990).

One billion of the world's population reside in I-deficient regions, with numerous inhabitants of these areas suffering from I-deficiency disorders, including goitre, cretinism, lower intelligence quotients and increased prenatal mortality (Hetzel, 1990). Zn deficiency, thought to be widespread, can lead to retarded growth, depressed immune function, anorexia, dermatitis, skeletal abnormalities, diarrhoea, alopecia and increased complications, and mortality during childhood if it is prolonged (International Life Sciences Institute, 1990). Furthermore, Zn deficiency in man has been linked to vitamin A underutilization. Even in the developed countries micronutrient deficiencies affect a significant number of the population. Taken together, micronutrient deficiencies affect a far greater number of the world's population than protein–energy malnutrition (Chandra, 1990).

Intervention programmes, including supplementation, food fortification and education, have been successful in reducing malnutrition in specific situations, and will be needed in the future. For example, dietary I supplementation programmes, through the use of iodized salt, have proved to be effective in many countries. The programmes are inexpensive and reach many of the populations most at risk (Hetzel, 1990). However, for the micronutrients Fe, Zn and vitamin A such programmes are expensive, incur ongoing annual expenditures and are unlikely to reach all of those at risk. Moreover, these intervention programmes have often been suspended for economic, political and logistical reasons (Gibson, 1994).

Nutritionists agree that part of the solution to micronutrient deficiencies is convincing the population to make their diets more nutritious. So far, however, attempts to change eating behaviour have been unsuccessful. It is often difficult to make dietary changes using local foods if you are poor. One project designed to increase vitamin A consumption among the poor in Northeast Thailand showed positive results. The project promoted vitamin-rich foods as something used by loving and caring mothers, focusing on a locally-grown vegetable, ivy gourd (*Coccinia grandis*), which is rich in vitamin A and they could cultivate themselves. Most projects seeking to change diets, however, end with participants returning to their old ways. Such approaches have worked only in limited settings. They require a lot of input, constant follow-up and education. When they are scaled up they rarely work, so they tend not to be sustainable. Under these limitations, breeding for trace-mineral-dense seeds has been considered most effective for tackling micronutrient deficiencies. Crop varieties with mineral-dense seeds are not only useful for alleviation of hidden hunger, but also suitable for growing on trace-mineral-deficient soils. Results from Australia and elsewhere show that where the soil is deficient in a particular micronutrient, seeds containing more of that nutrient have better germination, better seedling vigour, and more resistance to infection during the vulnerable seedling stage. These benefits to crop establishment can, in turn, result in higher grain yields. Thus, priorities for human and plant nutrition may often coincide (Graham & Welch, 1996).

Putting micronutrients into staple crops

The new strategy for supplying micronutrients to the poor in developing countries involves making the staple foods they eat more nutritious by using conventional plant breeding and biotechnology. This strategy is low cost and sustainable, and it does not require a change in eating habits and does not impose the recurring costs that accompany fortification and supplements. The greatest potential for improving nutritional status on a large scale involves rice, which is the staple of billions of the poor population of Asia.

Iron and zinc. A research project to develop improved rice varieties with high Fe and Zn contents was initiated at the International Rice Research Institute in 1992, with screening of germplasm to identify donors.

Up to now, about 7000 entries have been analysed in cooperation with the Department of Plant Science, University of Adelaide, Adelaide, NSW, Australia. A lot of variation was observed in the rice germplasm for both Fe and Zn contents in the grain. Among a subset of 1138 samples analysed, Fe concentrations ranged from 6·3 to 24·4 mg/kg, with a mean value of 12·2 mg/kg. For Zn, the range was 15·3–58·4 mg/kg (Table 6). A comparison of the Fe and Zn contents of selected varieties with those of widely-grown varieties IR36 and IR64 is shown on Table 7. Traditional varieties Jalmagna and Zuchen contained almost twice as much Fe and 50 % more Zn compared with IR36 and IR64. A number of aromatic rice varieties such as Basmati 370 from India and Pakistan, and Azucena from the Philippines also showed consistently higher Fe as well as Zn contents (Gregorio *et al.* 2000). Ortiz-Monasterio (1998) found a four- or fivefold variation between the lowest and the highest Fe and Zn concentrations in grain among several hundred wheat accessions. The highest concentrations were twice those of the popular modern cultivars.

Rice varieties with high Fe and Zn contents are tall, traditional and low-yielding, and hence not suitable for modern agriculture. Efforts are underway to develop improved breeding lines with elevated levels of Fe and Zn. Crosses between these traditional varieties and high-yielding varieties have produced progenies with both high yield and high levels of these micronutrients. For example, an improved breeding line with short stature, IR68144-3B-2-2-3, from crossing a high-yielding variety IR72 with the tall traditional variety Zawa Bonday from India has a high concentration of Fe in the grain (about 21 mg/kg in brown

Table 6. Iron and zinc contents of brown (unmilled) rice of varieties and breeding lines grown under similar conditions (data from Gregorio *et al.* 2000)
(Mean values with their standard errors and ranges)

Variety set	No. of samples	Fe (mg/kg)			Zn (mg/kg)		
		Mean	SE	Range	Mean	SE	Range
Traditional and improved varieties	140	13·2	2·9	7·8–24·4	24·2	4·6	13·5–41·6
IR breeding lines	350	10·7	1·6	7·5–16·8	25·0	7·6	15·9–58·4
Tropical japonicas	250	12·9	1·5	8·7–23·9	26·3	3·8	15·0–40·1
Popular varieties and donors	199	13·0	2·5	7·7–19·2	25·7	4·6	15·3–37·3
Promising lines	83	8·8	1·3	6·3–14·5	25·4	4·2	17·0–38·0
New plant types	44	16·7	2·1	11·5–24·0	29·6	3·2	23·0–36·0
Wild rice and derivatives	21	15·6	2·3	11·8–21·0	37·9	8·6	23·0–52·0
Aromatic rices	51	14·6	3·2	10·8–23·2	31·9	6·0	23·0–50·0

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Table 7. Iron and zinc contents of brown (unmilled) rice of selected varieties (from Gregorio *et al.* 2000)
(Mean values with their standard errors)

	Fe (mg/kg)		Zn (mg/kg)	
Variety	Mean	SE	Mean	SE
Jalmagna	22·0	1·4	31·8	7·7
Zuchen	20·2	1·8	34·2	5·0
Xua Bue Nuo	18·8	0·8	24·3	0·7
Madhukar	14·4	0·5	34·7	2·8
IR64	11·8	0·5	23·2	1·4
IR36	11·8	0·9	20·9	1·4

(i.e. unmilled) rice). Its yield potential is comparable with that of improved rice varieties. Milled rice of this variety is being used in human feeding trials to determine the bio-availability of the Fe (Gregorio *et al.* 2000).

Effect of milling on the iron content of the grain. Rice is consumed in the milled form after removal of the bran. It is important, therefore, to determine what proportion of Fe is lost during milling. Normally, rice is milled for about 15 min. Fig. 6 shows the Fe content of the grain of five varieties after different durations of milling. In the popular variety IR64 the Fe content dropped by 35 % after polishing for 15 min. Thereafter, there was almost no reduction. Loss of Fe after 15 min milling of Jalmagna and Tong Lan Mo Mi was even higher and the Fe content decreased drastically as polishing time increased. These observations confirm reports that in rice grain, Fe and other micronutrients are deposited in higher concentrations in the outer layers. However, genotypic differences do exist with regard to the distribution of micronutrients in different layers of rice grain. As shown in Fig. 6, the reduction in the Fe content of Xua Bue Nuo, a traditional high-Fe rice from China, and IR68144-3B-2-2 was much lower than that of other varieties (Gregorio *et al.* 2000).

It also appears possible to raise the micronutrient content of cereals through genetic engineering. For example, Goto *et al.* (1999) transferred the soyabean *ferritin* gene into the rice variety Kita-ake through *Agrobacterium*-mediated transformation. The promoter for the rice-seed storage protein glutelin GluB-1 was used to localise the expression of the soyabean gene specifically in the endosperm. The Fe content of the transgenic seeds was as much as threefold greater than that of untransformed controls.

Another genetic engineering approach for increasing the bioavailability of Fe in rice diets is the elimination of phytate. This sugar-like molecule binds a high proportion of dietary Fe, so that the human body is unable to absorb the Fe. A Swiss team led by Ingo Potrykus (personal communication) introduced a fungal gene for the enzyme phytase which breaks down phytate, thus improving the bioavailability of Fe in rice diets.

Rasmussen & Hatzack (1998) isolated Na_2O-induced mutants of barley with a low phytate content. The level of free phosphate was higher in these mutants. The results indicate the possibility of improving the nutritional value of crops through mutation breeding.

Vitamin A. Rice grains do not contain β-carotene, the precursor to vitamin A. However, they do contain geranylgeranyl pyrophosphate which can be converted to β-carotene by a sequence of four enzymes in the vitamin A biosynthetic pathway. The four genes for these enzymes, two from the daffodil (*Narcissus pseudonarcissus*) and two from the bacterium *Erwinia uredovora*, were introduced into the rice variety Taipei 309 through *Agrobacterium tumefacien*-mediated transformation. One to three transgene copies were found in transformed plants. Ten plants harbouring all four introduced genes showed the normal

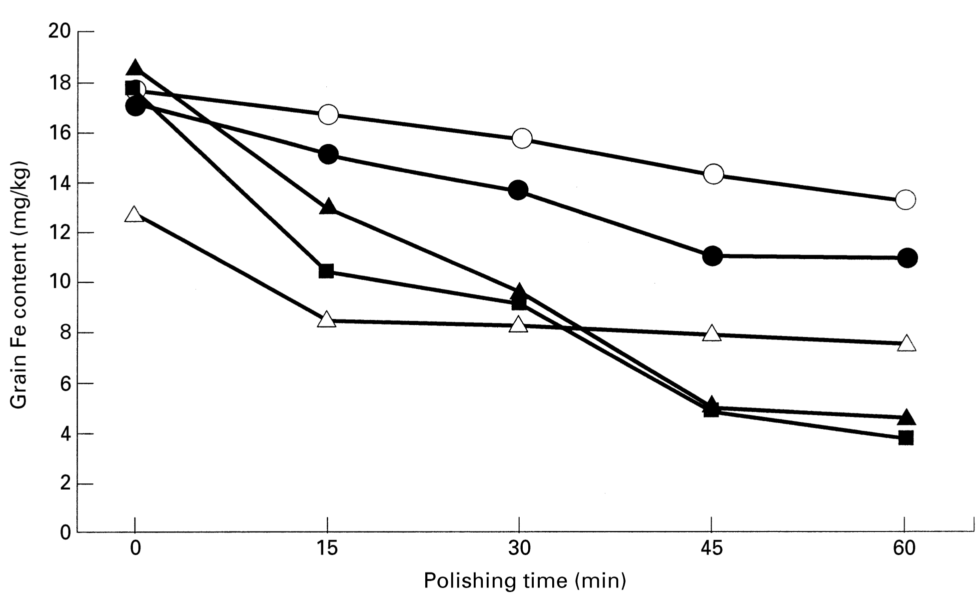

Fig. 6. Iron content of the grain from some selected rice varieties after different periods of polishing (rice for consumption is normally polished for 15 min). (○), Xua Bue Nuo; (●), IR68144; (△) IR64; (▲), Tong Lan Mo Mi; (■), Jalmagna.

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vegetative phenotype, were fully fertile, and had a yellow endosperm indicating carotenoid formation. Extracts from the coloured grains were analysed and the goal of providing at least 2 µg provitamin A/g seems to be realistic (Ye *et al*. 2000). The rice variety Taipei 309 was used to introduce the β-carotene biosynthetic pathway, as it is easy to transform. However, it is no longer cultivated. The International Rice Research Institute has started a project with the aim of introducing the genes into widely-grown improved cultivars through transformation, as well as through conventional hybridization techniques between transformed Taipei 309 and elite rice cultivars. It is anticipated that elite rice cultivars containing β-carotene will become available for large-scale cultivation during the next 3–4 years.

Strong carotenoid pigmentation was present in older bread-wheat varieties. However, during this century market demand has driven wheat breeding to be focused on the production of wheat for white flour. These types could be brought back into breeding programmes if desired. Similarly, in maize there are high-carotene types (yellow maize) that are high yielding, but again in several cultures consumers prefer white maize which lacks carotenoid and is thus nutritionally inferior. Variation in carotenoid content also occurs in cassava (*Manihot* spp.) and sweet potato (*Ipomoea batatas*). There are accessions in the Brazilian collection of cassava with yellow and even orange-coloured storage roots. Thus, conscious efforts are needed to introduce crops containing β-carotene to help alleviate vitamin A deficiency in regions inhabited by the world's poor. An action research project was recently implemented by the Kenya Agricultural Research Institute (Nairobi, Kenya) in collaboration with the International Potato Center (Lima, Peru). Orange-fleshed varieties of sweet potatoes, both high-yielding and rich in β-carotene, were introduced to women farmers. The result was that orange-fleshed sweet potatoes, both eaten alone and as ingredients in processed foods, were highly acceptable to both producers and consumers. Using standard methods of analysis, it was demonstrated that their increased consumption did in fact contribute to the alleviation of vitamin A deficiency in case-study households (Hageniwana, 2000).

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