Feeding the world in the twenty-first century

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The gains in food production provided by the Green Revolution have reached their ceiling while world population continues to rise. To ensure that the world's poorest people do not still go hungry in the twenty-first century, advances in plant biotechnology must be deployed for their benefit by a strong public-sector agricultural research effort.

The Green Revolution was one of the great technological success stories of the second half of the twentieth century. Because of the introduction of scientifically bred, higher-yielding varieties of rice, wheat and maize beginning in the 1960s, overall food production in the developing countries kept pace with population growth, with both more than doubling. The benefits of the Green Revolution reached many of the world's poorest people. Forty years ago there were a billion people in developing countries who did not get enough to eat, equivalent to 50 per cent of the population of these countries. If this proportion had remained unchanged, the hungry would now number over two billion — more than double the current estimate of around 800 million, or around 20 per cent of the present population of the developing world. Since the 1970s, world food prices have declined in real terms by over 70 per cent. Those who benefit most are the poor, who spend the highest proportion of their family income on food.

The Green Revolution brought benefits too for the industrialized world. The high-yielding varieties of staple crop plants bred by the international agricultural research centres of the CGIAR (the Consultative Group on International Agricultural Research) have been incorporated into the modern varieties grown in the United States and Europe. The additional wheat and rice produced in the United States alone from these improved varieties is estimated to have been worth over $3.4 billion from 1970 to 1993 (ref. 1).

Yet today, despite these demonstrable achievements, over 800 million people consume less than 2,000 calories a day, live a life of permanent or intermittent hunger and are chronically undernourished[2]. Most of the hungry are the women and young children of extremely poor families in developing countries. More than 180 million children under five years of age are severely underweight: that is, they are more than two standard deviations below the standard weight for their age. Seventeen million children under five die each year and malnourishment contributes to at least a third of these deaths.

As well as gross undernourishment, lack of protein, vitamins, minerals and other micronutrients in the diet is also widespread[3]. About 100 million children under five suffer from vitamin A deficiency, which can lead to eye damage. Half a million children become partly or totally blind each year, and many subsequently die. Recent research has shown that lack of vitamin A has an even more pervasive effect, weakening the protective barriers to infection put up by the skin, the mucous membranes and the immune system[4]. Iron deficiency is also common, leading to about 400 million women of childbearing age (15–49 years) being afflicted by anaemia. As a result they tend to produce stillborn or underweight children and are more likely to die in childbirth. Anaemia has been identified as a contributing factor in over 20 per cent of all maternal deaths after childbirth in Asia and Africa.

If nothing new is done, the number of the poor and hungry will grow. The populations of most developing countries are increasing rapidly and by the year 2020 there will be an additional 1.5 billion mouths to feed, mostly in the developing world. What is the likelihood that they will be fed?

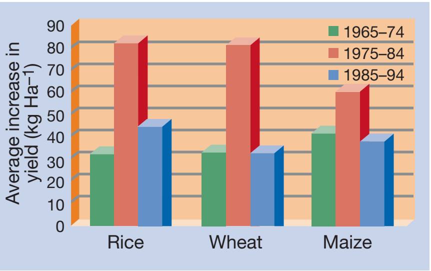

Figure 1 **Average annual increase in yields of rice, wheat and maize in developing countries by periods.**

The end of the Green Revolution

The prognosis is not good. As indicated in Fig. 1, there is widespread evidence of decline in the rate of increase of crop yields[5–7]. This slowdown is due to a combination of causes. On the best lands many farmers are now obtaining yields close to those produced on experimental stations, and there has been little or no increase in the maximum possible yields of rice and maize in recent years. A second factor is the cumulative effect of environmental degradation, partly caused by agriculture itself.

Simply exporting more food from the industrialized countries is not a solution. The world already produces more than enough food to feed everyone if the food were equally distributed, but it is not. Market economies are notoriously ineffective in achieving equitable distribution of benefits. There is no reason to believe that the poor who lack access to adequate food today will be any better served by future world markets. Food aid programmes are also no solution, except in cases of specific short-term emergency. They reach only a small portion of those suffering chronic hunger and, if prolonged, create dependency and have a negative impact on local food production.

About 130 million of the poorest 20 per cent of people in developing countries live in cities. For them, access to food means cheap food from any source. But 650 million of the poorest live in rural areas where agriculture is the primary economic activity, and as is the case in much of Africa, many live in regions where agricultural potential is low and natural resources are poor[8]. They are distant from markets and have limited purchasing power. For them, access means local production of food that generates employment and income, and is sufficient and dependable enough to meet local needs throughout the year, including years that are unfavourable for agriculture.

All these arguments point to the need for a second Green Revolution, yet one that does not simply reflect the successes, and mistakes, of the first. In effect, we require a 'Doubly Green Revolution', an agricultural revolution that is both more productive and more 'green' in terms of conserving natural resources and the environment than the first. We believe that this can be achieved by a combination of: ecological approaches to sustainable agriculture; greater participation by farmers in

Table 1 Biotechnology research useful in developing countries

Traits now in greenhouse or field tests	Traits now in laboratory tests
Input traits	*Input traits*
Resistance to insects, nematodes, viruses, bacteria and fungi in crops such as rice, maize, potato, papaya and sweet potato	Drought and salinity tolerance in cereals
Delayed senescence, dwarfing, reduced shade avoidance and early flowering in rice	Seedling vigour in rice
Tolerance of aluminium, submergence, chilling and freezing in cereals	Enhanced phosphorus and nitrogen uptake in rice and maize
Male sterility/restorer for hybrid seed production in rice, maize, oil-seed rape and wheat	Resistance to the parasitic weed *Striga* in maize, rice and sorghum, to viruses in cassava and banana, and to bacterial blight in cassava
New plant types for weed control and for increased yield potential in rice	Nematode resistance and resistance to the disease black sigatoka in banana
	Rice with the alternative C_4 photosynthetic pathway and the ability to carry out nitrogen fixation
Output traits	*Output traits*
Increased β-carotene in rice and oil-seed rape	Increased β-carotene, delayed post-harvest deterioration and reduced content of toxic cyanides in cassava
Lower phytates in maize and rice to increase bioavailable iron	Increased vitamin E in rice
Modified starch in rice, potato and maize and modified fatty-acid content in oil-seed rape	Apomixis (asexual seed production) in maize, rice, millet and cassava
Increased bioavailable protein, essential amino acids, seed weight and sugar content in maize	Delayed ripening in banana
Lowered lignin content of forage crops	Use of genetically engineered plants such as potato and banana as vehicles for production and delivery of recombinant vaccines to humans
	Improved amino-acid content of forage crops

agricultural analysis, design and research; and the application of modern biotechnology directed towards the needs of the poor in developing countries, which is the subject of the rest of this article.

The price of biotechnology

The application of advances in plant breeding — including tissue culture, marker-aided selection (which uses DNA technology to detect the transmission of a desired gene to a seedling arising from a cross) and genetic engineering — are going to be essential if farmers' yields and yield ceilings are to be raised, excessive pesticide use reduced, the nutrient value of basic foods increased and farmers on less favoured lands provided with varieties better able to tolerate drought, salinity and lack of soil nutrients.

In the industrialized countries the new life-science companies, notably the big six multinationals — Astra-Zeneca, Aventis, Dow, Dupont, Monsanto and Novartis — dominate the application of biotechnology to agriculture. In 1998, 'genetically modified (GM)' crops, more accurately referred to as transgenic or genetically engineered crops, mostly marketed by these companies or their subsidiaries, were grown on nearly 29 million hectares worldwide (excluding China)[9]. That year, 40 per cent of all cotton, 35 per cent of soya beans and 25 per cent of maize grown in the United States were GM varieties.

So far, the great majority of the commercial applications of plant genetic engineering have been for crops with single-gene alterations that confer agronomic benefits such as resistance to pests or to herbicides. These agronomic traits can reduce costs to the farmer by minimizing applications of insecticides and herbicides. However, as with many agricultural inputs, the benefits received by farmers vary from year to year.

Most of the GM crops currently being grown in developing countries are cash crops; Bt cotton, for example, has reportedly been taken up by over a million farmers in China. But despite claims to be 'feeding the world', the big life-science companies have little interest in poor farmers' food crops, because the returns are too low. National governments, the international research centres of the CGIAR, and a variety of western donors are, and will continue to be, the primary supporters of work that produces advances in biotechnology useful to poor farmers. New forms of public–private collaboration could help to ensure that all farmers and consumers benefit from the genetic revolution and, over time, this should increase the number of farmers who can afford to buy new seeds from the private sector.

The cost of accomplishing this will not be insignificant but it should not be excessive. For example, over the past 15 years, the Rockefeller Foundation has funded some US$100 million of rice biotechnology research and trained over 400 scientists from Asia, Africa and Latin America. In several places in Asia there is now a critical mass of talented scientists who are applying the new tools of biotechnology to rice improvement. To date, most of the new varieties are the result of tissue culture and marker-aided selection techniques. For example, scientists at the West Africa Rice Development Association have used anther culture to cross the high-yielding Asian rices with traditional African rices. The result is a new plant type that looks like African rice during its early stages of growth (it is able to shade out weeds, which are the most important constraint on crop production in Africa; Fig. 2a) but becomes more like Asian rice as it reaches maturity, thus giving higher yields with few inputs. Marker-aided selection is being used to breed rice containing two or more genes for resistance to the same pathogen, thereby increasing the durability of the resistance, and to accumulate several different genes contributing to drought tolerance.

Potential of genetic engineering

For some time to come, tissue culture and marker-aided selection are likely to be the most productive uses of biotechnology for cereal breeding. However, progress is being made in the production of transgenic crops for the developing countries. As in the industrialized countries, the focus has been largely on traits for disease and pest resistance, but genes that confer tolerance of high concentrations of aluminium (found in many tropical soils) have been added by Mexican scientists to rice and maize (Fig. 2c), and Indian scientists have added two genes to rice which may help the plant tolerate prolonged submergence. There is also the possibility of increasing yield ceilings, through more efficient photosynthesis, for example, or by improved control of water loss from leaves through regulation of stomatal opening and closing[10].

In addition to generating new traits that enable the plant to grow better (input traits), which are useful to poor farmers, GM technology can also generate plants with improved nutritional features (output traits) of benefit to poor consumers. One of the most exciting developments so far has been the introduction of genes into rice that result in the production of the vitamin A precursor β-carotene in the rice grain[11]. β-carotene is a pigment required for photosynthesis and is synthesized in the green tissues of all plants, including rice, but is not usually present in non-photosynthetic tissues such as those of seeds. Traditional plant breeding has given us some plants that produce β-carotene in non-photosynthetic tissue, such as the roots of carrots, but despite decades of searching no rice mutants had been found that produce β-carotene in the grain, so conventional breeding was not an option. To get the cells of the grain to produce β-carotene, genetic engineers added three genes for key enzymes for β-carotene biosynthesis to the rice genome. The grain of the transgenic rice has a light golden-yellow colour (Fig. 2b) and contains sufficient β-carotene to meet human vitamin A requirements from rice alone. This 'golden' rice offers an opportunity to complement vitamin A supplementation programmes, particularly in rural areas that are difficult to reach. These same scientists and others have also added genes to rice that increase the grain's nutritionally available iron content by more than threefold.

Over the next decade we are likely to see much greater progress in multiple gene introductions that focus on output traits or on difficult-to-achieve input characteristics (Table 1).

The potential benefits of plant biotechnology are considerable, but are unlikely to be realized unless seeds are provided free or at nominal cost. This will require heavy public investment by national governments and donors, at times in collaboration with the private sector, both in the research and in the subsequent distribution of seed and technical advice. Breeding programmes will also need to include crops such as cassava, upland rice, African maize, sorghum and millet, which are the food staples and provide employment for the 650 million rural poor who need greater stability and reliability of yield as much as increased yield.

The role of the public sector

None of this will happen through marketing by multinational seed companies, particularly if they decide to deploy gene-protection technologies, commonly referred to as terminator gene technologies, which will mean that farmers cannot save seed from the crop and sow it to get the next crop. In developing countries roughly 1.4 billion farmers still rely on saving seed for their planting materials and many gain access to new varieties through farmer-to-farmer trade. Much of the success of the Green Revolution was due to the true-breeding nature of the higher-yielding rice and wheat varieties.

While terminator technology is clearly designed to prevent rather than encourage such spread of proprietary varieties among poor farmers, some argue that it will do them no harm because they can still use and replant new varieties from the public sector. But if the companies tie up enabling technologies and DNA sequences of important genes with patents, and then use terminator technologies to control the distribution of proprietary seed and restrict its use for further breeding, the public sector will be severely constrained in using biotechnology to meet the needs of the poor.

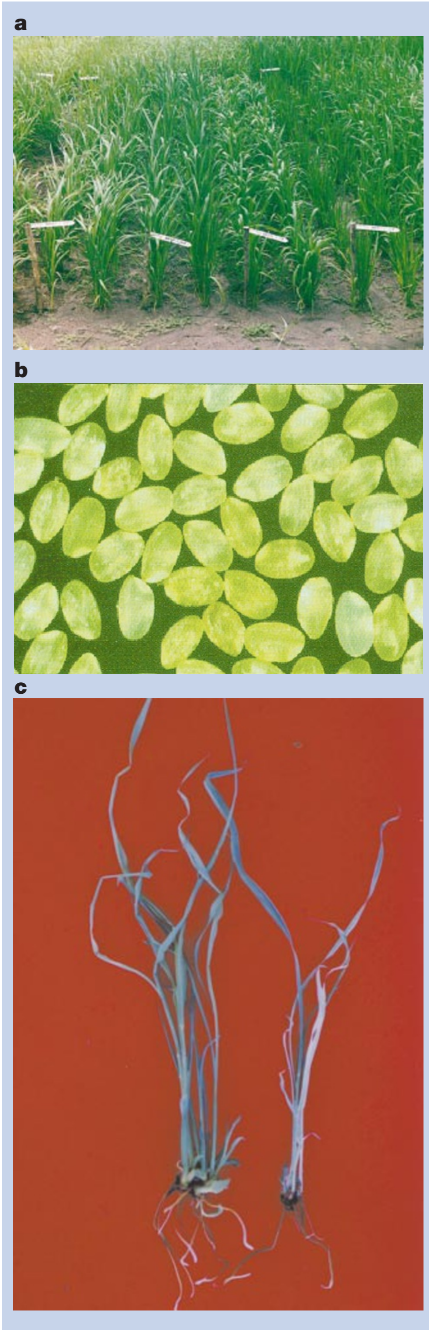

Figure 2 **Biotechnology products of value in developing countries.** a, **Interspecific progenies of Asian × African rice. Rows 3 and 4 from the right have vigorous growth with droopy lower leaves that suppress weeds. (Courtesy of M. Jones.)** b, **Transgenic rice grain containing β-carotene (provitamin A). (Courtesy of I. Potrykus and P. Beyer.)** c, **Transgenic rice (left) with increased citrate production and exudation by roots, tolerates aluminium (100 μM at pH 4.5) better than control. (Courtesy of L. Herrera Estrella.)**

Rather than using the terminator technology to protect their intellectual property in developing countries, it would be better if seed companies focused on producing hybrid seed combined with plant variety protection (PVP) to protect the commercial production of the seed. Hybrid plants do produce viable seed but it is not genetically identical to the original hybrid seed; it may lack some of the desirable characteristics. Hence, there is still an incentive (for example, increased yield) for farmers to purchase hybrid seed for each planting. However, if such purchase is not possible, farmers can still use a portion of their harvest as seed and obtain a reasonable crop. Such recycling of hybrids is not uncommon in developing countries and is an important element of food security. And with PVP, new varieties can be protected while also becoming a resource that both the private and public sectors can use in further breeding for the benefit of all farmers.

Intellectual property rights

Even assuming that terminator technologies are not used, there is cause for concern about the rights of developing countries to use their own genetic resources, the freedom of their plant breeders to use new technologies to develop locally adapted varieties, and the protection of poor farmers from exploitation. In part, these concerns result from the privatization of crop genetic improvement, the rapid expansion of corporate ownership of key technologies and genetic information and materials, and the competitive pressure on these companies to capture world market share as rapidly as possible

It is only recently that intellectual property rights (IPR) have become an important factor in plant breeding, primarily through the greater use of utility patents. Such patents have stimulated greater investment in crop improvement research in industrialized countries, but they are also creating major problems and potentially significant additional expense for the already financially constrained public-sector breeding programmes that produce seeds for poor farmers.

The success of the Green Revolution was based on international collaboration which included the free exchange of genetic diversity and information. Most of the 'added value' present in modern crops has been accumulated over the centuries by farmers themselves as they selected their best plants as the source of seed for the next planting. These 'land races' have traditionally been provided free of charge by developing countries to the world community. The CGIAR centres add value through selective breeding, and the superior varieties they generate are widely distributed without charge, benefiting both developing and developed countries.

Patents on biotechnology methods and materials, and even on plant varieties, are complicating and undermining these collaborative relationships. Public-sector research institutions in industrialized countries no longer fully share new information and technology. Rather, they patent and license and have special offices charged with maximizing their financial return from licensing. Commercial production of any genetically engineered crop variety requires dozens of patents and licenses. It is only the big companies that can afford to put together the IPR portfolios necessary to give them the freedom to operate. And now, under the TRIPS (Trade-Related Aspects of Intellectual Property Rights) agreement of the World Trade Organization, most developing countries are required to put in place their own IPR systems, including IPR for plants. Furthermore, all of this 'ownership' of plant genetic resources is causing developing countries to rethink their policies concerning access to the national biodiversity they control, and new restrictions are likely.

So far, international negotiations relevant to agricultural biotechnology and plant genetic resources have not been effectively coordinated. There are inconsistencies, and the interests of poor farmers in developing countries have not been well represented. The days of unencumbered free exchange of plant genetic materials are no doubt over, and agreements and procedures need to be formulated to ensure that public-sector institutions have access to the technological and genetic resources needed to produce improved crop varieties for farmers in developing countries who will not be well served by the for-profit sector. If the big life-science companies wish to find a receptive and growing market in developing countries, they will need to work with the public sector to make sure this happens.

Some solutions

While negotiations are underway, there are a number of things that should be done. With little competitive loss, seed companies could agree to use the PVP system (including provisions allowing seed saving and sharing by farmers) in developing countries in cooperation with public plant-breeding agencies, rather than using patents or terminator technologies to protect their varieties.

To speed the development of biotechnology capacity in developing countries, companies that have IPR claims over certain key techniques or materials might agree to license these for use in developing countries at no cost.

We would also like to see an agreement to share the financial rewards from IPR claims on crop varieties or crop traits of distinct national origin, such as South Asian Basmati rice or Thailand's Jasmine rice. The granting of free licenses to use such materials in breeding programmes in the country of origin of the trait might gain the appreciation of developing country researchers and governments.

Finally, the current opposition to GM crops and foods is likely to spread from Europe to the developing countries and maybe even to North America unless there is greater public reassurance. At the heart of the debate about the safety of GM crops and their food derivatives is the issue of relative benefits and risks. The debate is particularly impassioned in Europe. Some of it is motivated by anti-corporate or anti-American sentiment, but underlying the rhetoric are genuine concerns about lack of consumer benefits, about ethics, about the environment and about the potential impact on human health[12–16].

Much of the opposition tends to lump together the various risks — some real, some imaginary — and to assume there are generic hazards[17]. However, GM organisms are not all the same and each provides different potential benefits to different people and different environmental and health risks. Calls for general moratoria are not appropriate. Each new transgene and each new GM crop containing it needs to be considered in its own right. Well planned field tests are crucial, particularly in the developing countries where the risks of using, or not using, a GM crop may be quite different from those in industrialized countries.

The multinational companies could take a number of specific decisions in this area that would improve acceptance of plant biotechnology in both the developing and the industrialized world. First, consumers have a right to choose whether to eat GM foods or not and although there are serious logistic problems in separating crops all the way from field to retail sale, the agricultural seed industry should come out immediately and strongly in favour of labelling. Second, the industry should disavow use of the terminator technology in developing countries and, third, it should phase out the use of antibiotic-resistance genes as a means of selecting transgenic plants. Alternatives exist and should be used.

The Rockefeller Foundation and other donors have invested significant sums in helping developing countries put in place biosafety regulations and the facilities necessary for biosafety testing of new crops and foods, but much more needs to be done. The big life-science companies could join forces and establish a fellowship programme for training developing country scientists in crop biotechnology, biosafety, intellectual property rights and international negotiations administered by a neutral fellowship agency.

Most important of all, a new way of talking and reaching decisions is required. We believe a global public dialogue is needed which will involve everyone on an equal footing — the seed companies, consumer groups, environmental groups, independent scientists, and representatives of governments, particularly from the developing nations.

Agriculture in the twenty-first century will need to be more productive and less damaging to the environment than agriculture has been in the twentieth. An increased effort is needed to assure that the benefits of agricultural research reach the hundreds of millions of poor farmers who have benefited little from previous research. We believe that biotechnology has significant potential to help meet these objectives but that this potential is threatened by a polarized debate that grows increasingly acrimonious. We need to reverse this trend, to begin working together, to share our various concerns, and to assure the new technologies are applied to agriculture only when this can be done safely and effectively in helping to achieve future food security for our world.

Note added in proof: We commend the Monsanto Company's recent public commitment not to commercialize sterile seed technologies and encourage other companies to follow their lead.

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