Part I

AGRICULTURAL BIOTECHNOLOGY

Meeting the needs of the poor?

Part I

1. Can biotechnology meet the needs of the poor?

Introduction and overview

Biotechnology in food and agriculture, particularly genetic engineering, has become the focus of a "global war of rhetoric" (Stone, 2002). Supporters hail genetic engineering as essential to addressing food insecurity and malnutrition in developing countries and accuse opponents of "crimes against humanity" for delaying the regulatory approval of potentially life-saving innovations (Potrykus, 2003). Opponents claim that genetic engineering will wreak environmental catastrophe, worsen poverty and hunger, and lead to a corporate takeover of traditional agriculture and the global food supply. They accuse biotechnology supporters of "fooling the world" (Five Year Freeze, 2002). This issue of *The State of Food and Agriculture* surveys the current state of scientific and economic evidence regarding the potential of agricultural biotechnology, particularly genetic engineering, to meet the needs of the poor.

Agriculture in the twenty-first century is facing unprecedented challenges. An additional 2 billion people will have to be fed over the next 30 years from an increasingly fragile natural resource base. More than 842 million people are chronically hungry, most of them in rural areas of poor countries, and billions suffer from micronutrient deficiencies, an insidious form of malnutrition caused by the poor quality of, and lack of diversity in, their habitual diet. The Green Revolution taught us that technological innovation – higher-yielding seeds and the inputs required to make them grow – can bring enormous benefits to poor people through enhanced efficiency, higher incomes and lower food prices. This virtuous cycle of rising productivity, improving living standards and sustainable economic growth has lifted millions of people out of poverty (Evenson and Gollin, 2003). But many remain trapped in subsistence agriculture. Can the Gene Revolution reach those left behind?

At the same time, a rapidly urbanizing global population is demanding a wider range of quality attributes from agriculture, not just of the products themselves but of the methods used in their production. The agriculture sector will need to respond in ways beyond the traditional focus on higher yields, addressing the protection of environmental common goods, consumer concerns for food safety and quality, and the enhancement of rural livelihoods both in the South and in the North. Is the rhetoric of war deafening us to a more reasoned debate regarding the hazards and opportunities posed by biotechnology?

There is clear promise that biotechnology (Box 1) can contribute to meeting these challenges. Biotechnology can overcome production constraints that are more difficult or intractable with conventional breeding. It can speed up conventional breeding programmes and provide farmers with disease-free planting materials. It can create crops that resist pests and diseases,

BOX 1
Scope of the report

Agricultural biotechnology encompasses a range of research tools scientists use to understand and manipulate the genetic make-up of organisms for use in agriculture: crops, livestock, forestry and fisheries. Biotechnology is much broader than genetic engineering, including also genomics and bioinformatics, marker-assisted selection, micropropagation, tissue culture, cloning, artificial insemination, embryo transfer and other technologies. However, genetic engineering, particularly in the crop sector, is the area in which biotechnology is most directly affecting agriculture in developing countries and in which the most pressing public concerns and policy issues have arisen. It is also an area in which a body of economic evidence regarding the impact of biotechnology on the poor is beginning to emerge. Therefore, although this report touches on the full range of agricultural biotechnology tools and applications, particularly in Chapter 2, the focus is on transgenic crops and their impact on poor people in poor countries. Many of the challenges to securing the benefits of transgenic crops for the poor will be equally or more difficult for other biotechnology applications in livestock, fisheries and forestry. For more information on FAO's programme of work on agricultural biotechnology, see the FAO biotechnology Web site at http://www.fao.org/biotech/index.asp?lang=en.

replacing toxic chemicals that harm the environment and human health, and it can provide diagnostic tools and vaccines that help control devastating animal diseases. It can improve the nutritional quality of staple foods such as rice and cassava and create new products for health and industrial uses.

But biotechnology is not a panacea. It cannot overcome the gaps in infrastructure, markets, breeding capacity, input delivery systems and extension services that hinder all efforts to promote agricultural growth in poor, remote areas. Some of these challenges may be more difficult for biotechnology than for other agricultural technologies, but others may be less difficult. Technologies that are embodied in a seed, such as transgenic insect resistance, may be easier for small-scale, resource-poor farmers to use than more complicated crop technologies that require other inputs or complex management strategies. On the other hand, some biotechnology packages, particularly in the livestock and fisheries areas, require a certain institutional and managerial environment to function properly and thus may not be effective for resource-poor smallholders.

The safety and regulatory concerns associated with transgenic crops constitute a major hurdle for developing countries, because many lack the regulatory frameworks and technical capacity necessary to evaluate these crops and the conflicting claims surrounding them. Although the international scientific community has determined that foods derived from the transgenic crops currently on the market are safe to eat, it also acknowledges that some of the emerging transformations involving multiple transgenes may require additional food-safety risk-analysis procedures. There is less scientific consensus on the environmental hazards associated with transgenic crops, although there is general agreement that these products should be evaluated against the hazards associated with conventional agriculture. There is also wide consensus that transgenic crops should be evaluated on a case-by-case basis, as is the case with pharmaceuticals, taking into consideration the specific crop, trait and agro-ecological system. Because very few transgenic crops have been evaluated for their ecological impacts in tropical regions, a major research effort is required in this area.

Public- and private-sector transgenic crop research and development are being carried out on more than 40 crops worldwide and dozens of innovations are being studied, but there is clear evidence that the problems of the poor are being neglected. Barring a few initiatives here and there, there are no major public- or private-sector programmes to tackle the critical problems of the poor or targeting crops and animals that they rely on. Concerted international efforts are required to ensure that the technology needs of the poor are addressed and that barriers to access are overcome.

Capacity building for agricultural research and regulatory issues related to biotechnology should be a priority for the international community. FAO has proposed a major new programme to ensure that developing countries have the knowledge and skills necessary to make their own decisions about the use of biotechnology.

Key lessons from the report

Biotechnology – including genetic engineering – can benefit the poor when appropriate innovations are developed and when poor farmers in poor countries have access to them on profitable terms. Thus far, these conditions are only being met in a handful of developing countries.

Biotechnology should form part of an integrated and comprehensive agricultural research and development programme that gives priority to the problems of the poor. Biotechnology can complement but not substitute for research in other areas such as plant breeding, integrated pest and nutrient management, and livestock breeding, feeding and disease management systems.

The public sector – developing and developed countries, donors and the international research centres – should direct more resources to agricultural research, including biotechnology. Public-sector research is necessary to address the public goods that the private sector would naturally overlook and to provide competition in technology markets.

Governments should provide incentives, institutions and an enabling environment for public- and private-sector agricultural biotechnology research, development and deployment. Public–private partnerships and other innovative strategies to mobilize research and technology delivery for the poor should be encouraged.

Regulatory procedures should be strengthened and rationalized to ensure that the environment and public health are protected and that the process is transparent, predictable and science-based. Appropriate regulation is essential to command the trust of both consumers and producers, but duplicative or obstructionist regulation is costly and should be avoided.

Summary of the report

Chapter 2 explores the frontiers of agricultural biotechnology and places it in the broader context of the production, conservation and management goals that researchers are addressing. Most of the controversies surrounding biotechnology focus on transgenic crops, but these innovations represent only a tiny fraction of the technical possibilities offered by biotechnology in crops, livestock, forestry and fisheries. Genetic engineering is both a more precise extension of breeding tools that have been used for decades and a radical departure from conventional methods. It is the ability of genetic engineering to move genes across species barriers that gives it its tremendous power and that makes it so controversial.

Chapter 3 recalls the role of public-sector research at the national and international levels in generating the technologies that produced the Green Revolution. By contrast, most transgenic crop research is being performed by the private transnational sector. This has important implications for the kind of research that is being performed and the products that are being developed. Research trends and commercialization data confirm that the crops and traits of concern to the poor are being neglected. Six countries (Argentina, Brazil, Canada, China, South Africa and the United States of America), four crops (maize, soybean, canola/rapeseed and cotton) and two traits (insect resistance and herbicide tolerance) accounted for 99 percent of the global area planted in transgenic crops in 2003. These same crops and traits are the subject of most of the transgenic crop research under way in both developed and developing countries and in the public and private sectors. One of the key constraints developing countries face in adopting and adapting biotechnology innovations developed elsewhere is their own lack of national agricultural research capacity.

Chapter 4 reviews the evidence to date regarding the socio-economic impacts of transgenic crop adoption, particularly in developing countries. With the exception of those in China, all transgenic crops commercialized to date have been developed and distributed by private companies. Nevertheless, some of these crops, especially insect-resistant cotton, are yielding significant economic gains to small farmers as well as important social and environmental benefits through the changing use of agricultural chemicals. The evidence so far suggests that small farmers are just as likely as large farmers to benefit from the adoption of transgenic cotton. The evidence also suggests that, despite fears of corporate control of the sector, farmers and consumers so far are reaping a larger share of the economic benefits of transgenic crops than the companies that develop and market them. It must be considered, however, that this evidence is based on only two or three years of data for a relatively small number of farmers in just a few countries. These short-term gains may not be sustained as larger numbers of farmers adopt the technologies. Time and more carefully designed studies are required to determine what the level and distribution of benefits from transgenic crops will be.

Chapter 5 reviews the scientific concerns and evidence associated with transgenic crops and summarizes the international scientific consensus where it exists. Scientists have determined that the transgenic products currently on the market are safe to eat, although they recommend ongoing monitoring and concur that newer, more complex products may need additional food safety procedures. The potential environmental impacts of transgenic crops provoke greater disagreement among scientists. They generally agree on the types of hazard that exist, but they disagree on their likelihood and severity. Thus far, none of the major environmental hazards potentially associated with transgenic crops has developed in the field. Scientists agree that transgenic crops must be evaluated on a case-by-case basis taking into consideration the crop, the trait and the agro-ecosystem in which it is to be released. Scientists also agree that regulation should be science-based, but that judgement and dialogue are essential elements in any science-based regulatory framework. International harmonization through the Codex Alimentarius Commission (CAC) or the International Plant Protection Convention (IPPC), for example, can help ease international tensions in this area. Developing countries must enhance their national capacity to regulate these crops and comply with their national and international obligations.

Chapter 6 reviews global public opinion research on the use of biotechnology in food and agriculture. Whatever scientific or regulatory consensus emerges, genetic engineering in food and agriculture cannot succeed unless the public is convinced of its safety and usefulness. Views on these subjects vary widely both within and across countries, but a careful examination of the internationally comparable survey data reveals that people in all countries take a nuanced view of biotechnology, differentiating among technologies and applications according to their perceived usefulness and acceptability. Very few people take a doctrinaire position for or against all biotechnology. Labelling has been proposed as a way to bridge differences of opinion on the acceptability of transgenic foods by allowing the individual consumer to choose. Others argue that labelling is appropriate only if the product – not just the process used to produce it – differs from its conventional counterpart. Member governments of the CAC are debating the role of labelling for transgenic foods.

Chapter 7 looks at the kind of agricultural biotechnology research that is needed to address the needs of the poor, particularly poor farmers in poor countries. This includes research on the crops that provide the bulk of their food supply and livelihoods: rice and wheat, of course, but also a variety of so-called "orphan crops" such as sorghum, pearl millet, pigeon pea, chickpea and groundnut that are largely neglected in conventional or biotechnology research programmes. Traits of particular interest to the poor include resistance to production stresses such as drought, salinity, disease and pests, as well as nutritional enhancement. This chapter also explores a range of institutional options and incentives that could help promote public- and private-sector research on the problems of the poor.

Chapter 8 addresses the capacity-building needs of developing countries and countries with economies in transition. All countries need strong and dynamic capacity at the technical, institutional and management levels for the successful and sustainable application of biotechnology in food and agriculture. Several international initiatives to build capacity are reviewed, but a great deal more needs to be done if all countries are to be empowered to make their own decisions about these technologies for the benefit of their own people.

Chapter 9 draws together the essential conclusions from the report and recommends specific steps to ensure that biotechnology helps meet the needs of the poor.

2. What is agricultural biotechnology?

Broadly speaking, biotechnology is any technique that uses living organisms or substances from these organisms to make or modify a product for a practical purpose (Box 2). Biotechnology can be applied to all classes of organism – from viruses and bacteria to plants and animals – and it is becoming a major feature of modern medicine, agriculture and industry. Modern agricultural biotechnology includes a range of tools that scientists employ to understand and manipulate the genetic make-up of organisms for use in the production or processing of agricultural products.

Some applications of biotechnology, such as fermentation and brewing, have been used for millennia. Other applications are newer but also well established. For example, micro-organisms have been used for decades as living factories for the production of life-saving antibiotics including penicillin, from the fungus *Penicillium*, and streptomycin from the bacterium *Streptomyces*. Modern detergents rely on enzymes produced via biotechnology, hard cheese production largely relies on rennet produced by biotech yeast and human insulin for diabetics is now produced using biotechnology.

BOX 2
Defining agricultural biotechnology

The Convention on Biological Diversity (CBD) defines biotechnology as: "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products for specific use" (Secretariat of the Convention on Biological Diversity, 1992). This definition includes medical and industrial applications as well as many of the tools and techniques that are commonplace in agriculture and food production.

The Cartagena Protocol on Biosafety defines "modern biotechnology" more narrowly as the application of:

(a) *In vitro nucleic acid techniques, including recombinant deoxyribonucleic acid (DNA) and direct injection of nucleic acid into cells or organelles, or*

(b) *Fusion of cells beyond the taxonomic family, that overcome natural physiological reproductive or recombination barriers and that are not techniques used in traditional breeding and selection.*

(Secretariat of the Convention on Biological Diversity, 2000)

The FAO *Glossary of biotechnology* defines biotechnology broadly as in the CBD and narrowly as "a range of different molecular technologies such as gene manipulation and gene transfer, DNA typing and cloning of plants and animals" (FAO, 2001a).

Recombinant DNA techniques, also known as genetic engineering or (more familiarly but less accurately) genetic modification, refer to the modification of an organism's genetic make-up using transgenesis, in which DNA from one organism or cell (the transgene) is transferred to another without sexual reproduction. Genetically modified organisms (GMOs) are modified by the application of transgenesis or recombinant DNA technology, in which a transgene is incorporated into the host genome or a gene in the host is modified to change its level of expression. The terms "GMO", "transgenic organism" and "genetically engineered organism (GEO)" are often used interchangeably although they are not technically identical. For the purposes of this report they are used as synonyms.

Biotechnology is being used to address problems in all areas of agricultural production and processing. This includes plant breeding to raise and stabilize yields; to improve resistance to pests, diseases and abiotic stresses such as drought and cold; and to enhance the nutritional content of foods. Biotechnology is being used to develop low-cost disease-free planting materials for crops such as cassava, banana and potato and is creating new tools for the diagnosis and treatment of plant and animal diseases and for the measurement and conservation of genetic resources. Biotechnology is being used to speed up breeding programmes for plants, livestock and fish and to extend the range of traits that can be addressed. Animal feeds and feeding practices are being changed by biotechnology to improve animal nutrition and to reduce environmental waste. Biotechnology is used in disease diagnostics and for the production of vaccines against animal diseases.

Clearly, biotechnology is more than genetic engineering. Indeed, some of the least controversial aspects of agricultural biotechnology are potentially the most powerful and the most beneficial for the poor. Genomics, for example, is revolutionizing our understanding of the ways genes, cells, organisms and ecosystems function and is opening new horizons for marker-assisted breeding and genetic resource management. At the same time, genetic engineering is a very powerful tool whose role should be carefully evaluated. It is important to understand how biotechnology – particularly genetic engineering – complements and extends other approaches if sensible decisions are to be made about its use.

This chapter provides a brief description of current and emerging uses of biotechnology in crops, livestock, fisheries and forestry with a view to understanding the technologies themselves and the ways they complement and extend other approaches. It should be emphasized that the tools of biotechnology are just that: tools, not ends in themselves. As with any tool, they must be assessed within the context in which they are being used.

Understanding, characterizing and managing genetic resources

Farmers and pastoralists have manipulated the genetic make-up of plants and animals since agriculture began more than 10 000 years ago. Farmers managed the process of domestication over millennia, through many cycles of selection of the best adapted individuals. This exploitation of the natural variation in biological organisms has given us the crops, plantation trees, farm animals and farmed fish of today, which often differ radically from their early ancestors (see Table 1).

The aim of modern breeders is the same as that of early farmers – to produce superior crops or animals. Conventional breeding, relying on the application of classic genetic principles based on the phenotype or physical characteristics of the organism concerned, has been very successful in introducing desirable traits into crop cultivars or livestock breeds from domesticated or wild relatives or mutants (Box 3). In a conventional cross, whereby each parent donates half the genetic make-up of the progeny, undesirable traits may be passed on along with the desirable ones, and these undesirable traits may then have to be eliminated through successive generations of breeding. With each generation, the progeny must be tested for its growth characteristics as well as its nutritional and processing traits. Many generations may be required before the desired combination of traits is found, and time lags may be very long, especially for perennial crops such as trees and some species of livestock. Such phenotype-based selection is thus a slow, demanding process and is expensive in terms of both time and money. Biotechnology can make the application of conventional breeding methods more efficient.

Genomics

The most significant breakthroughs in agricultural biotechnology are coming from research into the structure of genomes and the genetic mechanisms behind economically important traits (Box 4). The rapidly progressing discipline of genomics is providing information on the identity, location, impact and function of genes affecting such traits – knowledge that

TABLE 1
An agricultural technology timeline

Technology	Era	Genetic interventions
Traditional	About 10 000 years BC	Civilizations harvested from natural biological diversity, domesticated crops and animals, began to select plant materials for propagation and animals for breeding
	About 3 000 years BC	Beer brewing, cheese making and wine fermentation
Conventional	Late nineteenth century	Identification of principles of inheritance by Gregor Mendel in 1865, laying the foundation for classical breeding methods
	1930s	Development of commercial hybrid crops
	1940s to 1960s	Use of mutagenesis, tissue culture, plant regeneration. Discovery of transformation and transduction. Discovery by Watson and Crick of the structure of DNA in 1953. Identification of genes that detach and move (transposons)
Modern	1970s	Advent of gene transfer through recombinant DNA techniques. Use of embryo rescue and protoplast fusion in plant breeding and artificial insemination in animal reproduction
	1980s	Insulin as first commercial product from gene transfer. Tissue culture for mass propagation in plants and embryo transfer in animal production
	1990s	Extensive genetic fingerprinting of a wide range of organisms. First field trials of genetically engineered plant varieties in 1990 followed by the first commercial release in 1992. Genetically engineered vaccines and hormones and cloning of animals
	2000s	Bioinformatics, genomics, proteomics, metabolomics

Source: Adapted from van der Walt (2000) and FAO (2002a).

BOX 3
Induced mutation-assisted breeding

Spontaneous mutations are the "natural" motor of evolution, and the resource into which breeders tap to domesticate crops and to "create" better varieties. Without mutations, there would be no rice, or maize or any other crop.

Starting in the 1970s, the International Atomic Energy Agency (IAEA) and FAO sponsored research on mutation induction to enhance genetic improvement of food and industrial crops for breeding new improved varieties. Induced mutations are brought about by treating plant parts with chemical or physical mutagens and then selecting for desirable changes – in effect, to mimic spontaneous mutations and artificially broaden genetic diversity. The precise nature of the mutations induced has generally not been a concern irrespective of whether the mutant lines were used directly or as sources of new variation in cross-breeding programmes.

Induced mutation to assist breeding has resulted in the introduction of new varieties of many crops such as rice, wheat, barley, apples, citrus, sugar cane and banana (the FAO/IAEA Mutant Varieties Database lists more than 2 300 officially released varieties[1]). The application of mutation induction to crop breeding has translated into a tremendous economic impact on agriculture and food production that is currently valued in billions of US dollars and millions of hectares of cultivated land. Recently, mutation techniques have undergone a renaissance, expanding beyond their direct use in breeding into novel applications such as gene discovery and reverse genetics.

[1] Available at http://www-infocris.iaea.org/MVD/.

BOX 4
DNA from the beginning

All living things are made up of cells that are programmed by genetic material called deoxyribonucleic acid (DNA). Only a small fraction of the DNA chain actually makes up genes, which in turn code for proteins, and the remaining share of the DNA represents non-coding sequences whose role is not yet clearly understood. The genetic material is organized into pairs of chromosomes. For example, there are five chromosome pairs in the much-studied mustard species *Arabidopsis thaliana*. An organism's entire set of chromosomes is called the genome. The Human Genome Sequencing Project has provided the agricultural research community not only with many spin-off technologies that can be applied across the board for all living organisms but also with a model for international collaboration in tackling large genome-sequencing projects for model plants such as *Arabidopsis* and rice.

For a refresher course in DNA, genetics and heredity, see the interactive Web site www.dnafromthebeginning.org developed by the Cold Spring Harbor Laboratory in the United States, where much of the pioneering work in genetics and genetic engineering has been performed.

will increasingly drive the application of biotechnology in all agricultural sectors. Genomics sets the foundation for post-genomics activities, including new disciplines such as proteomics and metabolomics to generate knowledge on gene and protein structure, as well as their functions and interactions. These disciplines seek to understand systematically the molecular biology of organisms for their practical use.

A vast range of new and rapidly advancing technologies and equipment has also been developed to generate and process information about the structure and function of biological systems. The use and organization of this information is called bioinformatics. Advances in bioinformatics may allow the prediction of gene function from gene sequence data: from a listing of an organism's genes, it will become possible to build a theoretical framework of its biology. The comparison across organisms of physical and genetic maps and DNA sequences will significantly reduce the time needed to identify and select potentially useful genes.

Through the production of genetic maps that provide the precise location and sequences of genes, it is apparent that even distantly related genomes share common features (Box 5). Comparative genomics assists in the understanding of many genomes based on the intensive study of just a few. For instance, the rice genome sequence is useful for studying the genomes of other cereals with which it shares features according to its degree of relatedness, and the mouse and malaria genomes provide models for livestock and some of the diseases that affect them. There are now model species for most types of crops, livestock and diseases and knowledge of their genomes is accumulating rapidly.

Molecular markers

Reliable information on the distribution of genetic variation is a prerequisite for sound selection, breeding and conservation programmes. Genetic variation of a species or population can be assessed in the field or by studying molecular and other markers in the laboratory. A combination of the two approaches is required for reliable results. Molecular markers are identifiable DNA sequences, found at specific locations of the genome and associated with the inheritance of a trait or linked gene. Molecular markers can be used for (a) marker-assisted breeding, (b) understanding and conserving genetic resources and (c) genotype verification. These activities are critical for the genetic improvement of crops, forest trees, livestock and fish.

Marker-assisted breeding

Genetic linkage maps can be used to locate and select for genes affecting traits of economic importance in plants or animals. The potential benefits of marker-assisted selection (MAS) are greatest for traits that are controlled by many genes, such as fruit yield, wood quality, disease resistance, milk and meat production, or body fat, and that are difficult, time-consuming or expensive to measure. Markers can also be used to increase the speed or efficiency of introducing new genes from one population to another, for example when wishing to introduce genes from wild relatives into modern plant varieties. When the desired trait is found within the same species (such as two varieties of millet – Box 6), it may be transferred with traditional breeding methods, with molecular markers being used to track the desired gene.

Measuring and conserving genetic diversity

The use of molecular markers to measure the extent of variation at the genetic level, within and among populations, is of value in guiding genetic conservation activities and in the development of breeding populations in crops, livestock, forestry and fisheries. Studies carried out using these technologies in fish and forest tree species have revealed high levels of genetic variation both among and within populations. Livestock species are characterized by a high degree of genetic variation within populations, whereas crops exhibit a higher degree of variation across species. Data from other approaches, for example field observation, often cannot provide such information or are extremely difficult to collect.

Molecular markers are increasingly used to study the distribution and patterns of genetic diversity. Global surveys indicate, for example, that 40 percent of the remaining

BOX 5
Synteny is life!

Mike Gale[1]

Synteny describes the conservation or consistency of gene content and gene order along the chromosomes of different plant genomes. Until well into the 1980s we imagined that each crop plant had its own genetic map. Only when we were able to make the first molecular maps, using a technique called “restriction fragment length polymorphism” (RFLP), did it begin to dawn on us that related species had remarkably similar gene maps. The early experiments demonstrated conservation over a few million years of evolution in syntenous relationships between potato and tomato in the broad-leafed plants and between the three genomes of bread wheat in the grasses. Later we were able to show that the same similarities held over the rice, wheat and maize genomes, which were separated by some 60 million years of evolution. The diagram summarizes this research and shows 70 percent of the world’s food linked in a single map. The 12 chromosomes of rice can be aligned with the ten chromosomes of maize and the basic seven chromosomes of wheat and barley in such a way that any radius drawn around the circles will pass through different versions, known as alleles, of the same genes.

The discovery of synteny has had an enormous impact on the way we think about plant genetics. There are obvious applications for evolutionary studies; for example, the white arrows on the wheat and maize circles describe evolutionary chromosomal translocations that describe *Pooideae* and *Panicoideae* groups of grasses. There are great opportunities to predict the presence and location of a gene in one species from what we know from another. Now that we have the complete DNA sequence of rice we are able to identify and isolate key genes from large genome intractable species such as wheat and barley by predicting that the same genes will be present in the same order as in rice. Key genes for disease resistance and tolerance to acid soils have recently been isolated from barley and rye in this way. For practical plant breeding, knowledge of synteny allows breeders access to all alleles in,

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domestic livestock breeds are at risk of extinction. Most of these breeds are found only in developing countries, and there is often little knowledge about them or of their potential for improvement. They may contain valuable genes that confer adaptation or resilience to stresses, such as heat tolerance or disease resistance, that may be of use for future generations. Modern biotechnologies can help to counteract trends of genetic erosion in all food and agriculture sectors.

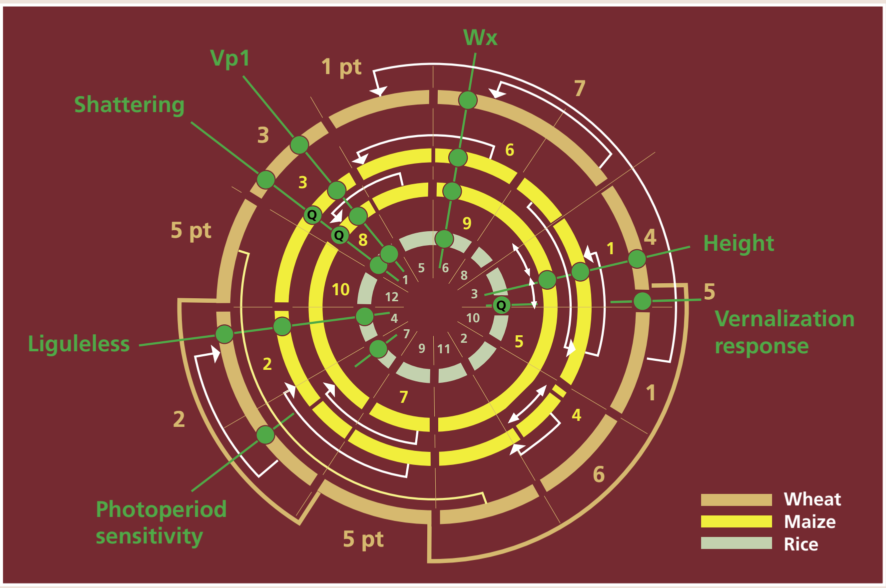
Genotype verification

Molecular markers have been widely used for identifying genotypes and for "genetic fingerprinting" of organisms. Genetic fingerprinting has been used in advanced tree-breeding programmes in which the correct identification of clones for large-scale propagation programmes is essential. Molecular markers have been used to identify endangered marine species that are either inadvertently captured in wild fisheries or that are purposefully taken illegally. Genotype verification is used intensively in parentage testing of domestic animals and for tracing livestock products in the food chain back to the farm and animal of origin.

Breeding and reproducing crops and trees

In addition to MAS, described above, a number of biotechnologies are used in breeding and reproducing crops and

for example, all cereals rather than just the species on which they are working. A key first example of this is the transfer to rice of the wheat dwarfing genes that made the Green Revolution possible. In these experiments the gene was located in rice by synteny and then isolated and engineered with the alteration in DNA sequence that characterized the wheat genes before replacing the engineered gene in rice. This approach can be applied to any gene in any cereal, including the so-called "orphan crops" that have not attracted the research dollars that the big three – wheat, rice and maize – have over the past century. The main significance is, however, that we can now pool our knowledge of biochemistry, physiology and genetics and transfer it between crops via synteny.



BOX 6
Molecular markers and marker-assisted selection for pearl millet in India

Tom Hash[1]

Pearl millet is a cereal grown for foodgrain and straw in the hottest, driest areas of Africa and Asia where rainfed and dryland agriculture are practised. It is similar to maize in its breeding behaviour. Traditional farmers' varieties are open-pollinated and out-breeding and thus continuously changing. Genetically uniform hybrid varieties have been developed that offer higher yield potential but are more vulnerable to a plant disease called downy mildew. In India, pearl millet is grown on about 9 million ha and more than 70 percent of this is sown to such hybrid cultivars. Since pearl millet hybrids first reached farmers' fields in India in the late 1960s, every variety that has become popular with farmers has ultimately succumbed to a downy mildew epidemic. Unfortunately, by the time the poorer farmers in a given region decide to adopt a particular variety, its days are usually numbered.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) wanted to reduce the risks associated with adoption of higher-yielding pearl millet hybrids and extend the useful economic life of these varieties, especially for poorer producers. Biotechnology helped us to achieve this. With tools from the John Innes Centre and support from the Plant Sciences Research Programme of the Department for International Development (DFID), we developed and applied molecular genetic tools for pearl millet. We mapped the genomic regions of pearl millet that control downy mildew resistance, straw yield potential, and grain and straw yield under drought stress conditions. Then our millet breeders used conventional breeding and marker-assisted selection (MAS) to transfer several genomic regions conferring improved downy mildew resistance to the two elite inbred parental lines of popular hybrid HHB 67. We then used MAS to derive two new varieties – ICMR 01004 and ICMR 01007 – with two different downy mildew resistance gene blocks.

These varieties have performed as well or better than their parent lines for grain and straw yield, and are markedly improved for downy mildew resistance. They also retain several favourable traits, including 1 000-grain mass, panicle length, plant height and rust resistance. Hybrids based on crosses involving ICMR 01004 and ICMR 01007 have recently advanced to trials in the Indian states of Gujarat, Rajasthan and Haryana under the All India Coordinated Pearl Millet Improvement Project. This follows their successful evaluation in 2002, in which they exhibited marginal grain yield superiority and substantially better downy mildew resistance than HHB 67, while maintaining the early maturity that contributes to its popularity.

At least one of these two hybrids could be released as a replacement for HHB 67 before the latter succumbs (as it surely will) to a downy mildew epidemic. Because HHB 67 is so widely grown by poor farmers in India, if its timely replacement could prevent such an epidemic for even one year, the losses avoided would exceed the total value of research-funding support by DFID for the development and application of the molecular genetic tool kit for pearl millet (£3.1 million to date). All future benefits from this research by ICRISAT, its DFID-supported partners in the United Kingdom, and collaborating national programme partners in India can then be considered profits to society.

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trees. Often these technologies are used in combination with each other and with conventional breeding approaches.

Cell and tissue culture and micropropagation

Micropropagation involves taking small sections of plant tissue, or entire structures such as buds, and culturing them under artificial conditions to regenerate complete plants. Micropropagation is particularly useful for maintaining valuable plants, breeding otherwise difficult-to-breed species (e.g. many trees), speeding up plant breeding and providing abundant plant material for research. For crop and horticultural species, micropropagation is now the basis of a large commercial industry involving hundreds of laboratories around the world. In addition to its rapid propagation advantages, micropropagation can also be used to generate disease-free planting material (Box 7), especially if combined with the use of disease-detection diagnostic kits. There have been some attempts to use micropropagation more widely in forestry. Compared with vegetative propagation through cuttings, the higher multiplication rates available through micropropagation offer a more rapid dissemination of planting stock, although limited availability of desirable clones is an impediment to its wider adoption in forestry.

In vitro selection

In vitro selection refers to the selection of germplasm by applying specific selection pressure to tissue culture under laboratory conditions. Many recent publications have reported useful correlations between *in vitro* responses and the expression of desirable field traits for crop plants, most commonly disease resistance. Positive results are available also for tolerance to herbicides, metals, salt and low temperatures. For the selection criteria of major general importance in forest trees (in particular vigour, stem form and wood quality), poor correlations with field responses still limit the usefulness of *in vitro* selection. However, this method may be of interest in forestry programmes for screening disease resistance and tolerance to salt, frost and drought.

Genetic engineering

When the desired trait is found in an organism that is not sexually compatible with the host, it may be transferred using genetic engineering. In plants, the most common method for genetic engineering uses the soil bacterium *Agrobacterium tumefasciens* as a vector. Researchers insert the desired gene or genes into the bacterium and then infect the host plant. The desired genes are transmitted to the host along with the infection. This method is used mainly with dicot species such as tomato and potato. Some crops,

BOX 7
Micropropagation of disease-free banana in Kenya

Banana is generally grown in developing countries where it is a source of employment, income and food. Banana production is in decline in many regions because of pest and disease problems that cannot be addressed successfully through agrochemical control for reasons of cost and negative environmental effects. The problem is exacerbated because banana is reproduced clonally; the use of diseased mother plants therefore gives rise to diseased offspring.

Micropropagation represents a means of regenerating disease-free banana plantlets from healthy tissue. In Kenya, banana shoot tips have been successfully tissue-cultured. An original shoot tip is heat-treated to destroy infective organisms and then used through many cycles of regeneration to produce daughter plants. A single section of tissue can be used to produce as many as 1 500 new plants through ten cycles of regeneration.

Micropropagation of banana has had a tremendous impact in Kenya, among many other countries, contributing to improved food security and income generation. It has all the advantages of being a relatively cheap and easily applied technology and one that brings significant environmental benefits.

particularly monocot species such as wheat and rye, are not naturally susceptible to transformation via *A. tumefasciens*, although the method has recently been successfully used to transform wheat and other cereals. In the most common transformation technique for these crops, the desired gene is coated on gold or tungsten particles and a "gene gun" is used literally to shoot the gene into the host at high velocity.

Three distinctive types of genetically modified crops exist: (a) "distant transfer", in which genes are transferred between organisms of different kingdoms (e.g. bacteria into plants); (b) "close transfer", in which genes are transferred from one species to another of the same kingdom (e.g. from one plant to another); and (c) "tweaking", in which genes already present in the organism's genome are manipulated to change the level or pattern of expression. Once the gene has been transferred, the crop must be tested to ensure that the gene is expressed properly and is stable over several generations of breeding. This screening can usually be performed more efficiently than for conventional crosses because the nature of the gene is known, molecular methods are available to determine its localization in the genome and fewer genetic changes are involved.

Most of the transgenic crops planted so

BOX 8

Agriculture on acid soils: improving aluminium tolerance in cereals

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Aluminium in acid soils limits plant growth on more than 30 percent of all arable land, primarily in developing countries. There are two approaches to increasing crop production on acid soils. Lime can be added to the soil to increase the pH, but this is a costly, temporary measure. Alternatively, genetically improved cultivars, tolerant to aluminium, can be developed. Existing wheat cultivars do not contain significant genetic variation for increasing aluminium tolerance. Improved tolerance will have to be introduced into wheat from the gene pools of related, more tolerant species. A genetic linkage map of wheat was developed using available markers for the existing aluminium-tolerance gene.

Rye exhibits a fourfold increase in aluminium tolerance over wheat. Therefore, a rye gene controlling aluminium tolerance was characterized. Markers from wheat, barley and rice were used to establish a tight linkage, flanking the rye gene, and to construct a high-resolution genetic map. A potential candidate gene was used for root-gene-expression, time-course studies that showed expression in rye roots only under aluminium stress.

Targeting the aluminium tolerance gene is one example of using problem-based approaches to integrate molecular and breeding tools to improve wheat production. Using the genetic relationship (synteny) among the cereals to supply markers to identify and characterize value-added traits, complementary approaches for improved wheat production emerge. Breeders can use the markers flanking the rye gene in marker-assisted breeding programmes in areas where GMOs cannot be grown or where only conventional breeding tools are available. In addition, these markers can be used for map-based cloning to isolate the gene in question for transgenic approaches to wheat improvement. Finally, the use of syntenous relationships offers the technology to manipulate many value-added traits for crop improvement in other species.

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far have incorporated only a very limited number of genes aimed at conferring insect resistance and/or herbicide tolerance (see Chapter 3 for more information regarding the transgenic crops that are currently being researched and grown commercially). However, some transgenic crops and traits of greater potential interest for developing countries have been developed but have not yet been released commercially. Box 8 describes one research project to improve the tolerance of wheat to aluminium, a problem that affects acid soils in much of Africa and Latin America. Similar work is being performed to improve the tolerance of plants to other stresses such as drought, saline soils and temperature extremes.

Nutritionally enhanced crops could make a significant contribution to the reduction of micronutrient malnutrition in developing countries. Biofortification (the development of nutritionally enhanced foods) can be advanced through the application of several biotechnologies in combination. Genomic analysis and genetic linkage mapping are needed to identify the genes responsible for natural variation in nutrient levels of common foods (Table 2). These genes can then be transferred into familiar cultivars through conventional breeding and MAS or, if sufficient natural variation does not occur within a single species, through genetic engineering. Non-transgenic approaches are being used, for example, to enhance the protein content in maize, iron in rice, and carotene in sweet potato and cassava.

Genetic engineering can be used when insufficient natural variation in the desired nutrient exists within a species. Box 9 describes the debate surrounding a project to enhance the protein content of potato using genetic engineering. The well-known transgenic Golden Rice contains three foreign genes – two from the daffodil and one from a bacterium – that produce provitamin A (see Box 13 on page 42). Scientists are well on their way to developing transgenic "nutritionally optimized"' rice that would contain genes producing provitamin A, iron and more protein (Potrykus, 2003). Other nutritionally enhanced foods are under development, such as oils with reduced levels of undesirable fatty acids. In addition, foods that are commonly allergenic (shrimp, peanuts, soybean, rice, etc.) are being modified to contain lower levels of allergenic compounds.

A major technical factor limiting the application of genetic modification to forest trees is the current low level of knowledge regarding the molecular control of traits that are of most interest. One of the first reported trials with genetically modified forest trees was initiated in Belgium in 1988 using poplars. Since then, there have been more

TABLE 2
Genetic variation in concentrations of iron, zinc, beta-carotene and ascorbic acid found in germplasm of five staple foods, dry weight basis

	(mg/kg)			
	Iron	Zinc	Beta-carotene[1]	Ascorbic acid
RICE				
Brown	6–25	14–59	0–1	–
Milled	1–14	14–38	0	–
CASSAVA				
Root	4–76	3–38	1–24[2]	0–380[2]
Leaves	39–236	15–109	180–960[2]	17–4200[2]
BEAN	34–111[1]	21–54	0	–
MAIZE	10–63	12–58	0–10	–
WHEAT	10–99[3]	8–177[2]	0–20	–

[1] Range for total carotenoids is much greater.
[2] Fresh weight basis.
[3] Including wild relatives.
Source: International Center for Tropical Agriculture (CIAT), 2002.

BOX 9
The "protato": help for the poor or a Trojan horse?

Researchers at Jawaharlal Nehru University in India have developed a genetically engineered potato that produces about one-third to one-half more protein than usual, including substantial amounts of all the essential amino acids such as lysine and methionine. Protein deficiency is widespread in India and potato is the staple food of the poorest people.

The "protato" was developed by a coalition of Indian charities, scientists, government institutes and industry as part of a 15-year campaign against childhood mortality. The campaign aims to eliminate childhood mortality by providing children with clean water, better food and vaccines.

The protato includes a gene from the amaranth plant, a high-protein grain that is native to South America and widely sold in Western health-food stores. The protato has passed preliminary field trials and tests for allergens and toxins. Final approval from the Indian Government is probably at least five years away.

Supporters such as Govindarajan Padmanaban, a biochemist at the Indian Institute of Science, argue that the protato can provide an important nutritional boost to children with little danger of allergy because potatoes and amaranth are both already widely consumed. There is also little threat to the environment because neither potatoes nor amaranth have wild relatives in India, and the protato does not involve any change in normal potato production practices. Furthermore, because the protato was developed by public-sector scientists in India, there are no concerns about foreign corporate control of the technology. Given these benefits, Padmanaban commented: "I think it would be morally indefensible to oppose it" (Coghlan, 2003).

Opponents such as Charlie Kronick of Greenpeace argue that potatoes are naturally quite low in protein (about 2 percent), so even a doubling of the protein content would make only a minute contribution to India's malnutrition problem. He claims that the effort to develop the protato was aimed more at gaining public acceptance of genetic engineering than at addressing the problem of malnutrition: "The cause of hunger isn't lack of food. It's lack of cash and of access to the food. Creating these GM crops is something to make them look attractive when actually the utility of eating them is very, very low. It's very difficult to see how this on its own will change the face of poverty" (Charles, 2003).

than 100 reported trials involving at least 24 tree species, primarily timber-producing species. Traits for which genetic modification has been contemplated for forest trees include insect and virus resistance, herbicide tolerance and lignin content. Reduction of lignin is a valuable objective for species producing pulp for the paper industry because it would enable a reduction in the use of chemicals in the process.

Breeding and reproducing livestock and fish

Biotechnology has long been a source of innovation in livestock and aquaculture production and processing and has had a profound impact on both sectors. Rapid advances in molecular biology and further developments in reproductive biology provide new and powerful tools for further innovation. Technologies such as genomics and molecular markers, as described above, are valuable in understanding, characterizing and managing genetic resources in livestock and fisheries as well as in crops and forestry (Box 10). Genetic engineering is also relevant in livestock and fisheries, although the techniques differ, and additional reproductive technologies are available in these sectors. This section describes the reproductive biotechnologies that are specific to the livestock and fisheries sectors.

BOX 10
State of the World's Animal Genetic Resources

FAO has been requested by its member countries to develop and implement the Global Strategy for the Management of Farm Animal Genetic Resources. As part of this country-driven strategy for the management of farm animal genetic resources, FAO invited 188 countries to participate in preparing the First Report on the State of the World's Animal Genetic Resources, to be completed before 2006. To date, 145 countries have agreed to submit country reports and 30 country reports have been received and analysed (Cardellino, Hoffmann and Templeman, 2003). It is clear from these reports that artificial insemination (AI) is the most common biotechnology used by developing countries in the livestock sector. Many countries have requested training for the expansion of AI use, while expressing concerns that it has often been introduced without proper planning and may pose a potential threat to the conservation of local breeds. Although the use of multiple ovulation followed by embryo transfer (MOET) is mentioned and the desire for its introduction or expansion expressed, no clear objectives for this technique are mentioned. All countries have expressed the wish to introduce and develop molecular techniques, often as a complement to phenotypic breed characterization. Cryoconservation was identified as a priority by all countries and gene banks were recommended, but funding remains a major constraint. When animal GMOs are mentioned it is mainly to express the lack of proper regulations and guidelines for their eventual production, use and exchange. Some countries have expressed concerns that biotechnologies in the livestock sector should be, but are not always, pursued as an integral part of an overall genetic improvement strategy.

The main objective of reproductive biotechnologies for livestock is to increase reproductive efficiency and rates of animal genetic improvement. The genetic improvement of locally adapted breeds will be important in realizing sustainable production systems within the broad spectrum of developing country production environments, and will probably best be realized by the strategic use of both non-genetic and genetic interventions. Reproductive biotechnology in fisheries presents opportunities to increase growth rates and improve the management of farmed species and to limit the reproductive potential of genetically engineered species.

Artificial insemination and multiple ovulation/embryo transfer

Advances in artificial insemination (AI) and multiple ovulation followed by embryo transfer (MOET) have already had a major impact on livestock improvement programmes in developed countries and many developing countries because they speed up the process of genetic improvement, reduce the risk of disease transmission and expand the number of animals that can be bred from a superior parent – the male in the case of AI and the female in the case of MOET. They also increase the incentives for private research in animal breeding and significantly expand the market for improved parent stock.

The number of AIs performed globally during 1998 was over 100 million in cattle (primarily dairy cattle, including buffalo), 40 million in pigs, 3.3 million in sheep and 0.5 million in goats. These figures illustrate both the higher economic returns in dairy cattle and the fact that cattle semen is much easier to deep-freeze than semen from other animals. Although over 60 million cattle AIs were performed in South and Southeast Asia, fewer than 1 million were performed in Africa.

AI is only effective when the farm sector has access to considerably greater technical and institutional and other organizational capacity than when male animals are used directly for breeding purposes. On the positive side, farmers employing AI do not have to face the costs or hazards of rearing breeding males and can have access to semen from any part of the world.

Despite the widespread use of AI in developed countries and in many developing countries, including within more advanced smallholder systems, it is applied only on farms that practise intensive livestock management with high-value animals. This is clearly not because of technical problems with semen production and storage, as most procedures are now fully standardized and proven to be effective under tropical developing-country conditions. Rather, it is because of the many organizational, logistical and farmer-training constraints that influence the quality and efficiency of the technology.

MOET takes AI one step further, both in terms of genetic gains possible and level of technical capacity and organization required. MOET is one of the basic technologies for the application of more advanced reproductive biotechnologies such as cloning and transgenics. During 2001 the number of embryos transferred globally was 450 000, mainly in dairy cattle, with North America and Europe accounting for 62 percent, followed by South America (16 percent) and Asia (11 percent). About 80 percent of the bulls used in AI are derived from MOET. The main potential advantage of MOET for developing countries will be in the possibility of importing frozen embryos instead of live animals, for example in the establishment of nucleus breeding stocks of locally adapted genetic resources, with the related lower sanitary risks.

Chromosome-set manipulation and sex reversal in fish

Controlling the sex and reproductive capacity of fish can be important for commercial and environmental reasons. One sex is often more desirable than the other; for example, only female sturgeon produce caviar and male tilapia grow faster than females. Sterility may be desirable when reproduction affects the taste of the product (e.g. oysters) or when farmed species (transgenic or not) might breed with wild populations. Chromosome-set manipulation and sex reversal are well-established techniques to control these factors. In chromosome-set manipulation, temperature, chemical and pressure shocks applied to fish eggs can be used to produce individuals that have three sets of chromosomes rather than the usual two. These triploid organisms generally do not channel energy into reproduction and thus are functionally sterile. Sex reversal can be accomplished by several methods including administering appropriate hormones. For example, genetically male tilapia can be turned into females through oestrogen treatments. These genetic males, when mated with normal males, produce a group of all-male tilapia.

Genetic engineering in livestock and fish

Genetic engineering in animals can be used to introduce foreign genes into the animal genome or, alternatively, to "knock-out" selected genes. The method most used at present involves direct microinjection of DNA into the pronuclei of fertilized eggs, but progress is being made with new approaches such as nuclear transfer and the use of lentiviruses as DNA vectors.

In the first genetic engineering experiments with farm animals, genes responsible for growth were introduced into pigs to increase growth and improve carcass quality. Current research efforts include engineering resistance to animal diseases, such as Marek's disease in poultry, scrapie in sheep and mastitis in cattle, and diseases that affect human health such as *Salmonella* in poultry. Other examples include increasing the casein content of milk and inducing the production of pharmaceutical or industrial chemicals in the milk or semen of animals. Although conceptually simple, the methods used to genetically engineer livestock require special equipment and considerable dexterity, and no agricultural applications have proved commercially successful thus far. Applications in the near future therefore seem to be limited to the production of transgenic animals for use in the production of industrial or pharmaceutical products.

Genetic engineering is an active area of research and development in aquaculture. The large size and hardy nature of many fish eggs allow them to be manipulated easily and facilitate gene transfer by direct injection of a foreign gene or by electroporation, in which an electric field assists gene transfer. Gene transfer in fish has usually involved genes that produce growth hormone and has been shown to increase growth rates dramatically in carp, salmon, tilapia and other species. In addition, a gene from the winter flounder that produces an antifreeze protein was put into salmon in the hope of extending the farming range of the fish. The gene did not produce enough of the protein to extend the salmon's range into colder waters, but it did allow the salmon to continue growing during cold months when non-transgenic salmon would not grow. These applications are still in the research and development stage, and no transgenic aquatic animals are currently available to the consumer.

Other biotechnologies

Diagnostics and epidemiology

Plant and animal diseases are difficult to diagnose because the signs may be misleading or even entirely absent until serious damage has occurred. Advanced biotechnology-based diagnostic tests make it possible to identify disease-causing agents and to monitor the impact of disease control programmes to a degree of precision not previously possible. Molecular epidemiology characterizes pathogens (viruses, bacteria, parasites and fungi) by nucleotide sequencing, which enables their origin to be traced. This is particularly important for epidemic diseases, in which the possibility of pinpointing the source of infection can significantly contribute to improved disease control. For example, the molecular analysis of rinderpest viruses has been vital for determining the lineages circulating in the world and instrumental in aiding the Global Rinderpest Eradication Programme (GREP) (Box 11). Enzyme-linked immunosorbent assay (ELISA) tests have become the standard methodology for the diagnosis and surveillance of many animal and fish diseases worldwide, and the polymerase chain reaction (PCR) technique is especially useful in diagnosing plant diseases and is proving increasingly so also for livestock and fish diseases. The effectiveness of plant and animal health programmes is also being considerably enhanced by the development of genetic probes that allow specific pathogens to be distinguished and detected in tissue, whole animals and even in water and soil samples.

Vaccine development

Genetically engineered vaccines are being developed to protect fish and livestock against pathogens and parasites. Although vaccines developed using traditional approaches have had a major impact on the control of foot-and-mouth and tick-borne diseases, rinderpest and other diseases affecting livestock, recombinant vaccines can offer various advantages over conventional vaccines in terms of safety, specificity and stability. Importantly, such vaccines, coupled with the appropriate diagnostic test, allow the distinction between vaccinated and naturally infected animals. This is important in disease control programmes as it enables continued vaccination even when the shift from the control to the eradication stage is contemplated.

Today, quality improved vaccines are available for, for example, Newcastle disease, classical swine fever and rinderpest. In addition to the technical improvements, advances in biotechnology will make vaccine production cheaper, and therefore improve supply and availability for smallholders.

Animal nutrition

Biotechnologies have already resulted in animal nutrition aids such as enzymes, probiotics, single-cell proteins and antibiotic feed additives that are already widely used in intensive production systems worldwide to improve the availability of nutrients from feeds and the productivity of livestock and aquaculture. Gene-based technologies are being increasingly employed to improve animal nutrition, either through modifying the feeds to make them more digestible or through modifying the digestive and metabolic systems of animals to enable them to make better use of the available feeds. Although progress in the latter approach is likely to be slow because of gaps in our current understanding of the underlying genetics, physiology and biochemistry, one example of commercial success in high-input, intensively managed systems is the use of

BOX 11
Biotechnology: ridding the world of rinderpest

Rinderpest, one of the world's most devastating livestock diseases, is a serious threat to millions of small-scale farmers and pastoralists who depend on cattle for their food and livelihoods. This viral disease, which affects cattle including buffalo, yak and related wildlife species, destroyed nearly 90 percent of all cattle in sub-Saharan Africa in the 1890s. An epidemic between 1979 and 1983 killed more than 100 million head of cattle in Africa – more than 500 000 in Nigeria alone – causing estimated losses of $1.9 billion. Asia and the Near East have also been badly affected by this disease.

Today, the world is almost free of rinderpest: Asia and the Near East are believed to be free of the virus and strenuous efforts are being made to ensure that it does not break out of its last possible focus – believed to be the Somali pastoral ecosystem that encompasses northeastern Kenya and southern Somalia. The goal of complete freedom from rinderpest is within our grasp. Rinderpest would be only the second disease to be eradicated worldwide, after smallpox.

The progress seen so far has been a remarkable triumph for veterinary science, and a powerful example of what can be achieved when the international community and individual countries, their veterinary services and farming communities, cooperate to develop and implement results-based policies and strategies for seeing them through. The Pan African Rinderpest Eradication Campaign (PARC), overseen by the African Union, and the Global Rinderpest Eradication Programme (GREP), overseen by FAO, are the key coordinating institutions in the battle against rinderpest.

Biotechnology is at the heart of this effort. First, it enabled the development and large-scale production of the vaccines used to protect many millions of animals through national mass vaccination campaigns. The initial vaccine, which was developed by Dr Walter Plowright and colleagues in Kenya with support from the United Kingdom, was based on a virus that was attenuated by successive passages in tissue culture. Dr Plowright was awarded the World Food Prize in 1999 for this work. Although highly effective and safe, this vaccine lost some of its potency when exposed to heat. Further research was therefore directed at developing a thermostable vaccine for use in remote areas. Success was achieved through research in Ethiopia by Dr Jeffery Mariner supported by the United States Agency for International Development (USAID).

Secondly, biotechnology provided the technological platform (ELISA,

recombinant somatotropin, a hormone that results in increased milk production in dairy cows and accelerated growth and leaner carcasses in meat animals.

Conclusions

Biotechnology is a complement – not a substitute – for many areas of conventional agricultural research. It offers a range of tools to improve our understanding and management of genetic resources for food and agriculture. These tools are already making a contribution to breeding and conservation programmes and to facilitating the diagnosis, treatment and prevention of plant and animal diseases. The application of biotechnology provides the researcher with new knowledge and tools that make the job more efficient and effective. In this way, biotechnology-based research programmes can be seen as a more precise extension of conventional approaches (Dreher *et al*., 2000). At the same time, genetic engineering can be seen as a dramatic departure from conventional breeding because it gives scientists the power to move genetic material between organisms that could not be bred through classical means.

chromatographic pen-side systems and molecular tests) to detect and identify viruses and monitor the effectiveness of vaccination campaigns. Before these techniques and the necessary sampling and testing strategies, which were developed by FAO and the International Atomic Energy Agency (IAEA) with support from the Swedish International Development Cooperation Agency (SIDA), vaccinated animals could not be distinguished from infected ones, so countries could not demonstrate that they were free of rinderpest. As a result, they had to conduct costly annual vaccination programmes indefinitely while they continued to suffer from restrictions on animal movement and trade that were imposed to avoid the spread of the disease.

The economic impact of these efforts is already clearly apparent. Although the cost of vaccination and blood sampling and testing has been high for both developing and developed nations, the effectiveness of national campaigns and regional and global coordination is demonstrated by the fact that there is only one small focus of disease outbreaks still occurring around the world. By contrast, in 1987, for example, the disease was present in 14 African countries as well as in Pakistan and some countries in the Near East.

Although costs and benefits vary considerably from country to country, the figures for Africa illustrate the cost-effectiveness of PARC and GREP. Major outbreaks of rinderpest normally last for five years and result in a total mortality of 30 percent. With a total cattle population of 120 million in sub-Saharan Africa, this represents about 8 million head of cattle per year. At an estimated value per head of $120, the cost of another major rinderpest outbreak would be around $960 million. Under PARC, about 45 million head of cattle were vaccinated each year at a cost of $36 million, and the costs of serological monitoring and surveillance were around $2 million. This gives an annual cost–benefit ratio of around 22 : 1 and a net annual economic benefit to the region of at least $920 million.

PARC and GREP have also provided other significant benefits. Not least of these is that through the policies, strategies and institutional arrangements put in place to tackle rinderpest, and that have enabled effective linkages to be established among farmers, field and laboratory personnel and national authorities, they have opened up opportunities for countries to move on and tackle the challenges of controlling or eradicating other diseases affecting livestock and food security in the world.

Agricultural biotechnology is cross-sectoral and interdisciplinary. Most of the molecular techniques and their applications are common across all sectors of food and agriculture, but biotechnology cannot stand on its own. Genetic engineering in crops, for example, cannot proceed without knowledge derived from genomics and it is of little practical use in the absence of an effective plant-breeding programme. Any single research objective requires mastery of a bundle of technological elements. Biotechnology should be part of a comprehensive, integrated agricultural research programme that takes advantage of work in other sectoral, disciplinary and national programmes. This has broad implications for developing countries and their development partners as they design and implement national research policies, institutions and capacity-building programmes (see Chapter 8).

Agricultural biotechnology is international. Although most of the basic research in molecular biology is taking place in developed countries (see Chapter 3), this research can be beneficial for developing countries because it provides insight into the physiology of all plants and animals. The findings of the human and the mice genome projects provide direct benefits for farm animals, and vice versa, whereas studies of maize and rice can provide parallels for applications in subsistence crops such as sorghum and tef. However, specific work is needed on the breeds and species of importance in developing countries. Developing countries are host to the greatest array of agricultural biodiversity in the world, but little work has been done on characterizing these plant and animal species at the molecular level to assess their production potential and their ability to resist disease and environmental stresses or to ensure their long-term conservation.

The application of new molecular biotechnologies and new breeding strategies to the crops and livestock breeds of specific relevance to smallholder production systems in developing countries will probably be constrained in the near future for a number of reasons (see Chapters 3 and 7). These include lack of reliable longer-term research funding, inadequate technical and operational capacity, the low commercial value of the crops and breeds, lack of adequate conventional breeding programmes and the need to select in the relevant production environments. Nevertheless, developing countries are already faced with the need to evaluate genetically modified (GM) crops (see Chapters 4–6) and they will one day also need to evaluate the possible use of GM trees, livestock and fish. These innovations may offer opportunities for increased production, productivity, product quality and adaptive fitness, but they will certainly create challenges for the research and regulatory capacity of developing countries.

3. From the Green Revolution to the Gene Revolution

The Green Revolution brought high-yielding semi-dwarf wheat and rice varieties, developed with conventional breeding methods, to millions of small-scale farmers, initially in Asia and Latin America, but later in Africa as well. The gains achieved during the early decades of the Green Revolution were extended in the 1980s and 1990s to other crops and to less favoured regions (Evenson and Gollin, 2003). In comparison with the research that drove the Green Revolution, the majority of agricultural biotechnology research and almost all of the commercialization is being carried out by private firms based in industrialized countries.

This is a dramatic departure from the Green Revolution, in which the public sector played a strong role in research and technology diffusion. This paradigm shift has important implications for the kind of research that is performed, the types of technologies that are developed and the way these technologies are disseminated. The dominance of the private sector in agricultural biotechnology raises concerns that farmers in developing countries, particularly poor farmers, may not benefit – either because appropriate innovations are not available or are too expensive.

Public-sector research was responsible for creating the high-yielding varieties of wheat and rice that launched the Green Revolution. International and national public-sector researchers bred dwarfing genes into elite wheat and rice cultivars, causing them to produce more grain and have shorter stems and enabling them to respond to higher levels of fertilizer and water. These semi-dwarf cultivars were made freely available to plant breeders from developing countries who further adapted them to meet local production conditions. Private firms were involved in the development and commercialization of locally adapted varieties in some countries, but the improved germplasm was provided by the public sector and disseminated freely as a public good (Pingali and Raney, 2003).

The countries that were able to make the most of the opportunities presented by the Green Revolution were those that had, or quickly developed, strong national capacity in agricultural research. Researchers in these countries were able to make the necessary local adaptations to ensure that the improved varieties suited the needs of their farmers and consumers. National agricultural research capacity was a critical determinant of the availability and accessibility of Green Revolution agricultural technologies, and this remains true today for new biotechnologies. National research capacity increases the ability of a country to import and adapt agricultural technologies developed elsewhere, to develop applications that address local needs (e.g. "orphan crops") and to regulate new technologies appropriately.

The biotechnology revolution, by contrast, is being driven largely by the private sector. Public-sector research has contributed to the basic science underpinning agricultural biotechnology, but the private sector is responsible for most applied research and almost all commercial development. Three interrelated forces are transforming the system for providing improved agricultural technologies to the world's farmers. The first is the strengthening environment for protecting intellectual property in plant innovations. The second is the rapid pace of discovery and the growing importance of molecular biology and genetic engineering. Finally, agricultural input and output trade is becoming more open in nearly all countries, enlarging the potential market for new technologies and older related technologies. These developments have created powerful new incentives for private research, and are altering the structure of the public/private agricultural research endeavour, particularly with respect to crop improvement (Pingali and Traxler, 2002).

SPECIAL CONTRIBUTION 1

Feeding 10 billion people – our twenty-first century challenge

Norman E. Borlaug[1]

During the past 35 years, cereal production has more than doubled, expanding faster than world population growth. Rapid adoption of modern varieties, a threefold increase in chemical fertilizer consumption and a doubling in irrigated area were key factors driving this Green Revolution. By increasing yields on the lands best suited to agriculture, world farmers have been able to leave untouched vast areas of land for other purposes.

The world population may reach 10 billion by the middle of this century. Over the next 20 years, world cereal demand will increase by 50 percent, driven by rapidly growing animal feed use and meat consumption. With the exception of acid-soil areas in Africa and South America, the potential for expanding global crop area is limited. Future expansions in food output must come largely from land already in use. The productivity of this land must be sustained and improved.

Most of the world's 842 million hungry people live in marginal lands and depend upon agriculture for their livelihoods. Food-insecure households in these higher-risk rural areas face frequent droughts, degraded lands, remoteness from markets and poor market institutions. For many of these people, food security will only come through increased agricultural production and income. Investments in science, infrastructure and resource conservation are needed to increase productivity and lower risks in marginal lands. Some of the problems in such environments will be too formidable to overcome. However, significant improvements should be possible. Biotechnology will play an important role in developing new germplasm with greater tolerance to abiotic and biotic stresses and with higher nutritional content. Continued genetic improvement of food crops – using conventional research tools and biotechnology – is needed to shift the yield frontier higher and to increase stability of yield.

Neolithic man – or much more likely woman – domesticated virtually all of our food and livestock species over a relatively short period, 10 000–15 000 years ago. Subsequently, several hundred generations of farmers were responsible for making enormous genetic modifications in all of our major crop and animal species. Thanks to the development of science over the past 150 years, we now have the insights into plant genetics and breeding to do purposefully what Nature did in the past by chance or design. Genetic modification of crops is not some kind of witchcraft; rather, it is the progressive harnessing of the forces of nature to the benefit of feeding the human race. Indeed, genetic engineering – plant breeding at the molecular level – is just another step in humankind's deepening scientific journey into living genomes. It is not a replacement for conventional breeding but a complementary research tool to identify desirable traits from remotely related taxonomic groups and transfer them more quickly and precisely into high-yielding, high-quality crop species.

The world has the technology – already available or well advanced in the research pipeline – to feed on a sustainable basis a population of 10 billion people. However, access to such technology is not assured. The range of potential barriers includes issues related to intellectual property rights, technology acceptance by civil society and governments, and financial and educational barriers that keep poor farmers marginalized and unable to adopt new technology.

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With the growing importance of the private transnational sector, developing countries are facing increasing transaction costs in access to and use of technologies. Existing public-sector international networks for sharing technologies across countries and thereby maximizing spillover benefits are becoming increasingly threatened. The urgent need today is for a system of technology flows that preserves the incentives for private-sector innovation while at the same time meeting the needs of poor farmers in the developing world.

The first section of this chapter presents an overview of the organization and impacts of agricultural research and technology flows in the period 1960–90, when the Green Revolution paradigm of international, public-sector research held sway. The second section discusses the movement towards the increased privatization of agricultural research and development and its consequences for developing country access to technologies as revealed in recent global trends in biotechnology research, development and commercialization. The concluding section raises a number of questions regarding the potential of the Gene Revolution to benefit the poor. These questions are taken up in the subsequent chapters of the report.

The Green Revolution: research, development, access and impact

The Green Revolution was responsible for an extraordinary period of growth in food crop productivity in the developing world over the last 40 years (Evenson and Gollin, 2003). A combination of high rates of investment in crop research, infrastructure and market development, and appropriate policy support fuelled this progress. These elements of the Green Revolution strategy improved productivity growth despite increasing land scarcity and high land values (Pingali and Heisey, 2001).

Public-sector research and international technology transfer

The Green Revolution defied the conventional wisdom that agricultural technology does not travel well because it is either agroclimatically specific, as in the case of biological technology, or sensitive to relative factor prices, as with mechanical technology (Byerlee and Traxler, 2002). The Green Revolution strategy for food-crop productivity growth was explicitly based on the premise that, given appropriate institutional mechanisms, technology spillovers across political and agroclimatic boundaries could be created. Hence the Consultative Group on International Agricultural Research (CGIAR) was established specifically to generate technology spillovers, particularly for countries that are unable to capture all the benefits of their research investments. What happens to the spillover benefits from agricultural research and development in an increasingly global integration of food supply systems?

The major breakthroughs in yield potential that kick-started the Green Revolution in the late 1960s came from conventional plant-breeding approaches that initially focused on raising yield potential for the major cereal crops. The yield potential for the major cereals has continued to rise at a steady rate after the initial dramatic shifts in the 1960s for rice and wheat. For example, yield potential in irrigated wheat has been rising at the rate of 1 percent per year over the past three decades, an increase of around 100 kg/ha/year (Pingali and Rajaram, 1999). Essentially, no research or elite germplasm was available for many of the crops grown by poor farmers in less favourable agro-ecological zones (such as sorghum, millet, barley, cassava and pulses) during the early decades of the Green Revolution, but since the 1980s modern varieties have been developed for these crops and their yield potential has risen (Evenson and Gollin, 2003). In addition to their work on shifting the yield frontier of cereal crops, plant breeders continue to have successes in the less glamorous but no less important areas of applied research. These include development of plants with durable resistance to a wide spectrum of insects and diseases, plants that are better able to tolerate a variety of physical stresses, crops that require a significantly lower number of days of cultivation, and cereal grain with enhanced taste and nutritional qualities.

Prior to 1960, there was no formal system in place that provided plant breeders with

SPECIAL CONTRIBUTION 2
Towards an evergreen revolution

M.S. Swaminathan[1]

In August 1968, the Government of India issued a stamp entitled "Wheat Revolution" to generate public awareness of the revolutionary pathway India had entered in relation to increasing wheat production. Even while highlighting the yield breakthrough in wheat, the Government had also launched a massive programme to develop and spread high-yielding varieties for rice, maize, sorghum and pearl millet. These programmes were the drivers of the "Green Revolution" in India, which permitted striking advances in production and productivity without increasing cultivated area.

Because these high-yielding varieties require inputs such as fertilizer and irrigation water, social scientists criticized the Green Revolution technologies for not being resource neutral. Environmentalists attacked the Green Revolution because of potential damage to long-term productivity as a result of excessive use of pesticides and fertilizers and monocropping. Despite the success of the Green Revolution in raising millions of people out of misery, the incidence of poverty, endemic hunger, communicable diseases, infant and maternal mortality rates, low birth-weight children, stunting and illiteracy remain high.

The concerns of social scientists and ecologists and the remaining urgent problems of poverty and hunger led to my developing the concept of an "evergreen revolution" to stress the need for enhancing crop productivity in perpetuity without associated ecological or social harm. An evergreen revolution can be achieved only if we pay attention to pathways that can help to achieve revolutionary progress in enhancing productivity, quality and value-addition under conditions of diminishing per capita arable land and irrigation water availability, expanding biotic and abiotic stresses, and fast-changing consumer and market preferences. This will require mobilizing the best in both traditional wisdom and technologies and frontier

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access to germplasm available beyond their borders. Since then, the international public sector (the CGIAR system) has been the predominant source of supply of improved germplasm developed from conventional breeding approaches, especially for self-pollinating crops such as rice and wheat and for open-pollinated maize. These CGIAR-managed networks evolved in the 1970s and 1980s, when financial resources for public agricultural research were expanding and plant intellectual property laws were weak or non-existent. The exchange of germplasm is based on a system of informal exchange among plant breeders that is generally open and without charge. Breeders can contribute any of their material to the nursery and take pride in its adoption elsewhere in the world, while at the same time they are free to pick material from the trials for their own use.

The international flow of germplasm has had a large impact on the speed and the cost of crop development programmes of national agricultural research systems (NARS), thereby generating enormous efficiency gains (Evenson and Gollin, 2003). Traxler and Pingali (1999) argued that the existence of a free and uninhibited system of germplasm exchange that attracts the best of international materials allows countries to make strategic decisions on the extent to which they need to invest in plant-breeding capacity. Even NARS with advanced crop research programmes, such as in Brazil, China and India, rely heavily on cultivars taken from these nurseries for their prebreeding material and for finished science. Among the frontier technologies relevant to the next stage in our agricultural revolution, the foremost is biotechnology.

The apprehensions relating to molecular genetics and genetic engineering fall under the following broad categories: the science itself, the control of the science, access to the science, environmental concerns, and human and animal health. A disaggregated approach to the study of these issues will be important for a rigorous analysis of risks and benefits. Dealing with these issues in a composite manner for all applications of genetic engineering will result in inappropriately broad conclusions, such as the general condemnation of GMOs expressed by non-governmental organizations (NGOs) at the World Food Summit: *five years later* held in Rome in 2002.

The benefits of molecular breeding techniques such as the use of molecular markers and undertaking precision breeding for specific characters through recombinant DNA technology are immense. The work already performed in India has revealed the potential for breeding new GM varieties possessing tolerance to salinity, drought and some major pests and diseases, together with improved nutritive quality. A new era of integrated Mendelian and molecular breeding has begun. An evergreen revolution will blend these frontier technologies with the ecological prudence of traditional communities to create technologies that are based on integrated natural resource management and that are location specific because they are developed through participatory experimentation with farm families.

This is the only way we can face the challenges of the future, particularly in the context of the growing water scarcity and the urgent need to step up productivity in semi-arid and dry farming areas. Accelerated agricultural progress is the best safety net against hunger and poverty, because in most developing countries over 70 percent of the population depend on agriculture for their livelihood. Denying ourselves the power of the new genetics will be doing a great disservice both to resource-poor farming families and to the building of a sustainable national food and nutrition system.

varieties (Evenson and Gollin, 2003). Small countries behaving rationally choose to free-ride on the international system rather than invest in large crop-breeding infrastructure of their own (Maredia, Byerlee and Eicher, 1994).

Evenson and Gollin (2003) report that, even in the 1990s, the CGIAR content of modern varieties was high for most food crops; 35 percent of all varietal releases were based on CGIAR crosses, and an additional 22 percent had a CGIAR-crossed parent or other ancestor. Evenson and Gollin suggest that germplasm contributions from international centres enabled developing countries to capture the spillover benefits of investments in crop improvement made outside their borders and achieve productivity gains that would have been more costly or even impossible had they been forced to work only with the genetic resources that were available at the beginning of the period.

Impacts of food-crop improvement technology

Substantial empirical evidence exists on the production, productivity, income and human welfare impacts of modern agricultural science and the international flow of modern varieties of food crops. Evenson and Gollin (2003) provide detailed information on the extent of adoption and impact of modern variety use for all the major food crops. The adoption of modern varieties (averaged across all crops) increased rapidly during the two decades of the Green Revolution, and even more rapidly in the following decades, from 9 percent in 1970 to 29 percent in 1980, 46 percent in 1990 and 63 percent by 1998. Moreover, in many areas and in many crops, first-generation modern varieties have been replaced by second- and third-generation modern varieties (Evenson and Gollin, 2003).

Much of the increase in agricultural output over the past 40 years has come from an increase in yield per hectare rather than an expansion of area under cultivation. For instance, FAO data indicate that for all developing countries, wheat yields rose 208 percent from 1960 to 2000; rice yields rose 109 percent; maize yields rose 157 percent; potato yields rose 78 percent and cassava yields rose 36 percent (FAO, 2003). Trends in total factor productivity are consistent with partial productivity measures, such as rate of yield growth (Pingali and Heisey, 2001).

The returns to investments in high-yielding modern germplasm have been measured in great detail by several economists over the last few decades. Several recent reports have reviewed and analysed the data from hundreds of studies conducted over the last 30 years that calculated the social rates of return to investments in agricultural research. These studies examined investments by national and international public-sector institutions in Africa, Asia, Latin America and the Organisation for Economic Co-operation and Development (OECD) countries as well as by the private sector (Alston *et al*., 2000; Evenson and Gollin, 2003). Although these studies were carried out using a variety of different methods, they showed considerable consistency. The average social rate of return to public investment in agricultural research reported in these studies is in the region of 40–50 percent. Private-sector research was also found to generate similar rates of social returns.

The primary effect of agricultural research on the non-farm poor, as well as on the rural poor who are net purchasers of food, is through lower food prices. The wide-spread adoption of modern seed-fertilizer technology led to a significant shift in the food supply function, increasing output and contributing to a fall in real food prices:

> *The effect of agricultural research on improving the purchasing power of the poor – both by raising their incomes and by lowering the prices of staple food products – is probably the major source of nutritional gains associated with agricultural research. Only the poor go hungry. Because a relatively high proportion of any income gains made by the poor is spent on food, the income effects of research-induced supply shifts can have major nutritional implications, particularly if those shifts result from technologies aimed at the poorest producers.*
>
> (Alston, Norton and Pardey, 1995: 85)

Studies by economists have provided empirical support for the proposition that growth in the agriculture sector has economy-wide effects. Hayami *et al*. (1978) illustrated at the village level that rapid growth in rice production stimulated demand and prices for land, labour and non-agricultural goods and services. For sector-level validation of the proposition that agriculture does indeed act as an engine of overall economic growth, see Hazell and Haggblade (1993); Delgado, Hopkins and Kelly (1998); and Fan, Hazell and Thorat (1998).

Once modern varieties have been adopted, the next set of technologies that makes a significant difference in reducing production costs includes machinery, land management practices (often in association with herbicide use), fertilizer use, integrated pest management and (most recently) improved water management practices. Although many Green Revolution technologies were developed and extended in package form (e.g. new plant varieties plus recommended fertilizer, pesticide and herbicide rates, along with water control measures), many components of these technologies were taken up in a piecemeal, often stepwise manner (Byerlee and Hesse de Polanco, 1986). The sequence of adoption is determined by factor scarcities and the potential cost savings achieved. Herdt (1987) provided a detailed assessment of the sequential adoption of crop management technologies for rice in the Philippines. Traxler and Byerlee (1992) provided similar evidence on the sequential adoption of crop management technologies for wheat in Sonora, northwestern Mexico.

Although the favourable, high-potential environments gained the most from the Green Revolution in terms of productivity growth, the less favourable environments also benefited through technology spillovers and through labour migration to more productive environments. According to David and Otsuka (1994), wage equalization across favourable and unfavourable environments was one of the primary means of redistributing the gains of technological change. Renkow (1993) found similar results for wheat grown in high- and low-potential environments in Pakistan. Byerlee and Moya (1993), in their global assessment of the adoption of modern varieties of wheat, found that over time the adoption of modern varieties in unfavourable environments caught up with those in more favourable environments, particularly when germplasm developed for high-potential environments was further adapted to the more marginal environments. In the case of wheat, the rate of growth in yield potential in drought-prone environments was around 2.5 percent per year during the 1980s and 1990s (Lantican and Pingali, 2003). Initially, the growth in yield potential for the marginal environments came from technological spillovers as varieties bred for the high-potential environments were adapted to the marginal environments. During the 1990s, however, further gains in yield potential came from breeding efforts targeted specifically at the marginal environments.

The Gene Revolution: a changing paradigm for agricultural R&D

In the 1960s, 1970s and 1980s, private-sector investment in plant improvement research was limited, particularly in the developing world, owing to the lack of effective mechanisms for proprietary protection of the improved products (Box 12). This situation changed in the 1990s with the emergence of hybrids for cross-pollinated crops such as maize. The economic viability of hybrids led to a budding seed industry in the developing world, started by transnational companies from the developed world and followed by the development of national companies (Morris, 1998). Despite the rapid growth of the seed industry in developing countries, its activity has been limited to date, leaving many markets underserved.

The incentives for private-sector agricultural research increased further when the United States and other industrialized countries permitted the patenting of artificially constructed genes and genetically modified plants. These national protections were strengthened by the 1995 Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS) of the World Trade Organization (WTO), which obliges WTO members to provide patent protection for biotechnology inventions (products or processes) and protection for plant varieties either through patents or a *sui generis* system. These proprietary protections provided the incentives for private sector entry in agricultural biotechnology research (Box 12).

The large transnational agrochemical companies were the early investors in the development of transgenic crops, although much of the basic scientific research that paved the way was conducted by the public sector and made available to private companies through exclusive licences. One of the reasons why agrochemical companies moved into transgenic crop research and development was that they foresaw a declining market for pesticides and were looking for new products (Conway, 2000).

The chemical companies moved quickly into plant improvement by purchasing existing seed companies, first in industrialized countries and then in the developing world. These mergers between national seed companies and multinational corporations made economic sense because the two specialize in different aspects of the seed variety development and delivery process (Pingali and Traxler, 2002). This process is a continuum that starts upstream with generating knowledge on useful genes (genomics) and engineering transgenic plants and then moves downstream to the more adaptive process of backcrossing the transgenes into commercial lines and delivering the seed to farmers. The products from upstream activities have worldwide applicability across several crops and agro-ecological environments. By contrast, genetically modified crops and varieties are typically applicable to specific agro-ecological niches. In other words, spillover benefits and scale economies decline in the move to the more adaptive end of the continuum. Similarly, research costs and research sophistication decline in the

BOX 12
Public goods and intellectual property rights

Public goods are those that generate benefits for society beyond the private returns that can be captured by the person who created them. These benefits are sometimes called spillovers. Public goods are non-rival and non-excludable. Non-rivalry implies that the good is equally available to all, i.e. consumption by one person does not reduce the amount that is available for others to consume. Non-excludability means that people who do not pay for the product cannot be prevented from using it. These characteristics mean that private innovators cannot capture the full social benefit of their creation unless some means can be found to prevent unauthorized use. Because private firms cannot profit fully from research that produces public goods, they will not invest in a socially optimal level of research (Ruttan, 2001).

Much of the output of agricultural research, including biotechnology research, has one or both of the characteristics of a public good. For example, any scientist can use knowledge about the structure of the rice genome without reducing the amount of knowledge available to other scientists, and once that knowledge is published in an academic journal or on the Web, it is difficult to exclude other people from using it. A transgenic plant variety, on the other hand, may have public good characteristics to some degree (e.g. it is difficult to exclude unauthorized users completely) but it is not a pure public good because seeds can be used up and unauthorized use can be at least partially prevented.

There are two ways to prevent the unauthorized use of plant varieties – biological and legal. Hybrid seeds can be saved, reproduced and replanted but only at a significant loss in yield and quality, so hybridization provides a biological protection for the breeder's innovation. Genetic use-restriction technologies are another form of biological intellectual property protection that has been proposed for transgenic crops. These technologies would produce sterile seeds or seeds that require the application of a special chemical to activate the innovative trait. Public opposition to the sterile-seed approach has led the private company Monsanto to abandon its development. Legal protection such as patents, trademarks and contracts can also be used to protect intellectual property, but these methods usually provide incomplete protection.

progression towards downstream activities. Thus, a clear division of responsibilities in the development and delivery of biotechnology products has emerged, with the transnational firm providing the upstream biotechnology research and the local firm providing crop varieties with commercially desirable agronomic backgrounds (Pingali and Traxler, 2002).

The options available for capturing the spillovers from global corporations are less clear for public research systems. Public-sector research programmes are generally established to conform to state or national political boundaries, and direct country-to-country transfer of technologies has been limited (Pingali and Traxler, 2002). Strict adherence to political domains severely curtails spillover benefits of technological innovations across similar agroclimatic zones. The operation of the CGIAR germplasm exchange system has mitigated the problem for several important crops, but it is not clear whether the system will work for biotechnology products and transgenic crops, given the proprietary nature of the technology.

Biotechnology research investments

To understand the magnitude of private-sector investment in agricultural biotechnology research today, one need only look at its annual research budget relative to public research targeted at developing country agriculture (Pray and Naseem, 2003a). The world's top ten transnational

TABLE 3
Estimated crop biotechnology research expenditures

	(Million $/year)	*(Percentage)*
	Biotechnology R&D	Biotechnology as share of sector R&D
INDUSTRIALIZED COUNTRIES	**1 900–2 500**	
Private sector[1]	1 000–1 500	40
Public sector	900–1 000	16
DEVELOPING COUNTRIES	**165–250**	
Public (own resources)	100–150	5–10
Public (foreign aid)	40–50	…
CGIAR centres	25–50	8
Private sector	…	…
WORLD TOTAL	**2 065–2 730**	

[1] Includes an unknown amount of R&D for developing countries.
Source: Byerlee and Fischer, 2001.

bioscience corporations' collective annual expenditure on agricultural biotechnology research and development is nearly $3 billion. By comparison, the CGIAR, which is the largest international public-sector supplier of agricultural technologies, has a total annual budget of less than $300 million for plant improvement research and development. The largest public-sector agricultural research programmes in the developing world – those of Brazil, China and India – have annual budgets of less than half a billion dollars each (Byerlee and Fischer, 2002).

Looking at agricultural biotechnology research expenditures reveals a sharp dichotomy between developed and developing countries (Table 3). Developed countries spend four times as much as developing countries on public-sector biotechnology research, even when all sources of public funds – national, donor and CGIAR centres – are counted for developing countries. Few developing countries or international public-sector institutions have the resources to create an independent source of biotechnology innovations (Byerlee and Fischer, 2002).

Comprehensive data on private-sector biotechnology research in developing countries are not available, although most research appears to be carried out by transnational companies conducting trials of their transgenic varieties. Some work is being done by local research institutes (e.g. local private sugar-cane research institutes have fairly large biotechnology research programmes in Brazil and South Africa), whereas in India several local seed companies (notably the Maharashtra Hybrid Seed Company [Mahyco]) have biotechnology research programmes. The total investment of these private efforts is unknown but it is undoubtedly less than the public sector is investing in biotechnology research in developing countries (Pray and Naseem, 2003a).

Transgenic crop research measured by field trials

Although total biotechnology research expenditures are fairly evenly divided between the public and private sectors, the production of new technologies is almost entirely in the hands of the private sector.[1] The private sector has developed all the genetically transformed crops that have been commercialized in the world to date, with the exception of those in China (see Chapter 4). The dominance of the private sector in developing GM varieties suggests

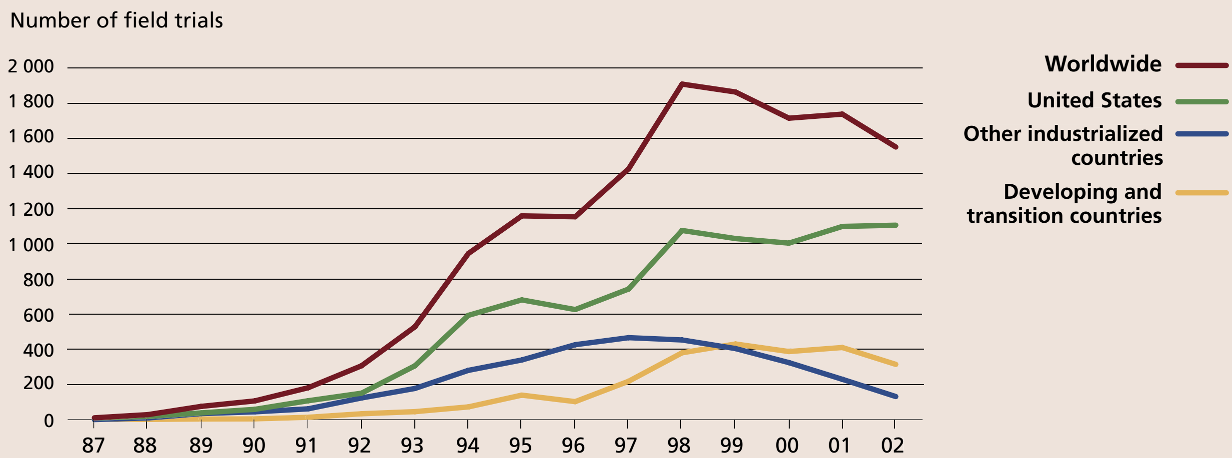
[1] Comprehensive data on field tests of all agricultural biotechnologies are not available. This section refers to transgenic crop trials only.

TABLE 4
Field trials by crop and region

	Maize	Canola	Potato	Soybean	Cotton	Tomato	Sugar beet	Tobacco	Wheat	Rice	Other	Totals
TOTAL NUMBER OF TRIALS	**3 881**	**1 242**	**1 088**	**782**	**723**	**654**	**394**	**308**	**232**	**189**	**1 610**	**11 105**
United States and Canada	2 749	826	770	552	407	494	118	194	190	102	1 087	7 489
Europe/ New Zealand/ Australia/Japan	452	366	227	20	72	89	237	61	23	36	316	1 901
Transitional economies	61	17	27	7	2	2	33	6	1	0	9	1 550
Developing countries	619	33	64	203	242	69	6	47	18	51	198	1 550
PERCENTAGE OF ALL CROPS	**35**	**11**	**10**	**7**	**7**	**6**	**4**	**3**	**2**	**2**	**14**	**100**
United States and Canada	37	11	10	7	5	7	2	3	3	1	15	100
Europe/ New Zealand/ Australia/Japan	24	19	12	1	4	5	13	3	1	2	17	100
Transitional economies	37	10	16	4	1	1	20	4	1	0	6	100
Developing countries	40	2	4	13	16	5	0	3	1	3	13	100

Source: Pray, Courtmanche and Govindasamy, 2002.

FIGURE 1
Transgenic crop field trials, by country group

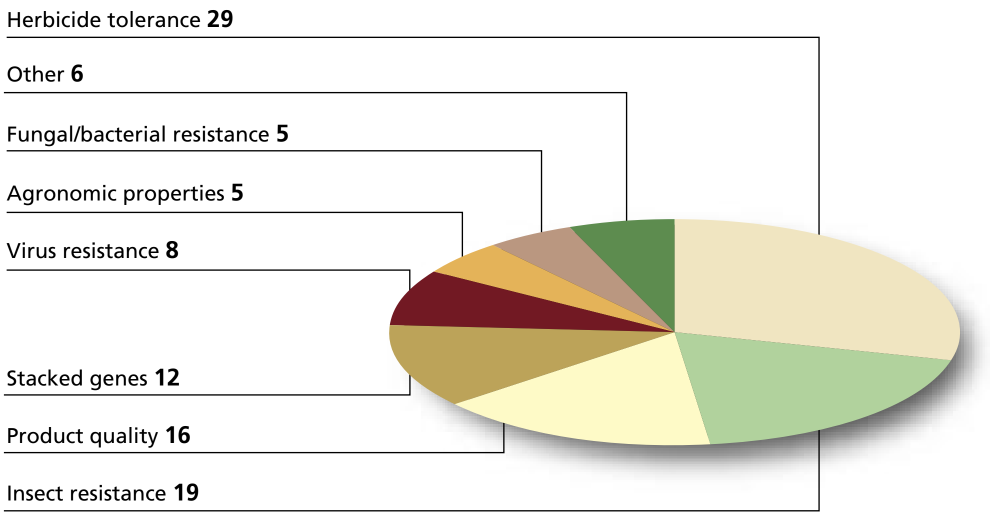


Source: Pray, Courtmanche and Govindasamy, 2002.

that the crops and production constraints of particular importance to the poor may be neglected because the markets for these seeds are probably quite small.

More than 11 000 field trials of 81 different transgenic crops have been performed since 1987 when the first trials were approved (Figure 1 and Table 4), but only 15 percent

FIGURE 2
GM crop traits tested in industrialized countries, 1987–2000 (percent)



Source: Pray, Courtmanche and Govindasamy, 2002.

have taken place in developing or transition countries.[2] This reflects the perceived lack of commercial potential in these markets and the difficulties their governments have had in establishing a regulatory system for biosafety. The number of trials in developed and transition countries has increased in recent years and at least 58 countries had reported field trials for transgenic crops by 2000 (Pray, Courtmanche and Govindasamy, 2002). Some countries have stopped field trials in certain years while re-evaluating their biosafety system.

The concern that the crops and traits of importance to developing countries could be neglected is validated by the data on field trials (Table 4, Figures 2 and 3). Staple food crops have been the subject of very little applied biotechnology research, although field trials for wheat and rice, the most important food crops in developing countries, have increased in recent years and a transgenic cassava variety was tested for the first time in 2000. Other staple food crops such as bananas, sweet potatoes, lentils and lupins have all been approved for field testing in one or more countries.

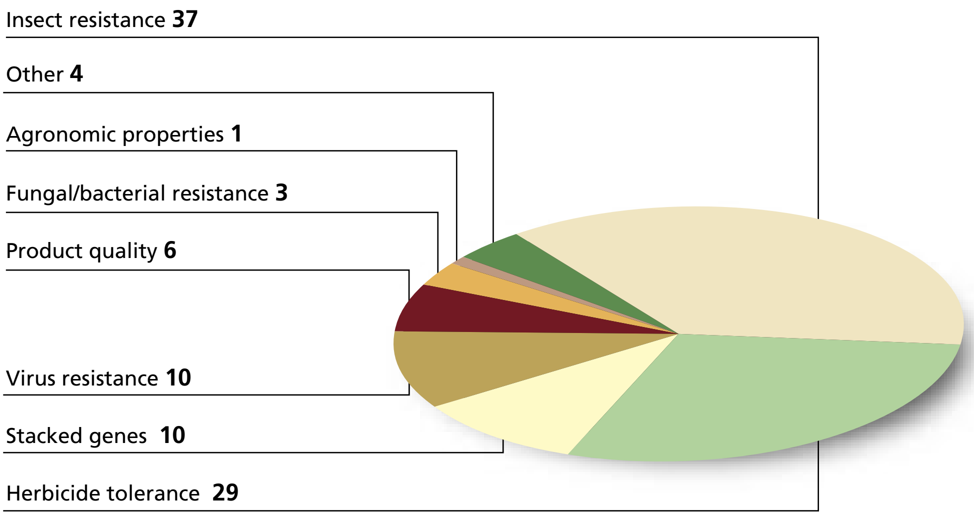
Almost two-thirds of the field trials in industrialized countries and three-quarters of those in developing countries focus on two traits: herbicide tolerance and insect resistance or a combination of the two traits together (Figures 2 and 3). Although insect resistance is an important trait for developing countries, herbicide resistance may be less relevant in areas where farm labour is abundant. By contrast, agronomic traits of particular importance to developing countries and marginal production areas, such as potential yields and abiotic stress tolerance (e.g. drought and salinity), are the subject of very few field trials in industrialized countries and even fewer in developing countries.

Transgenic crop commercialization

Transgenic crops were grown commercially in 18 countries on a total of 67.7 million ha in 2003, an increase from 2.8 million ha in 1996 (Figure 4). Although this overall rate of technology diffusion is impressive, it has been very uneven. Just six countries, four crops and two traits account for 99 percent

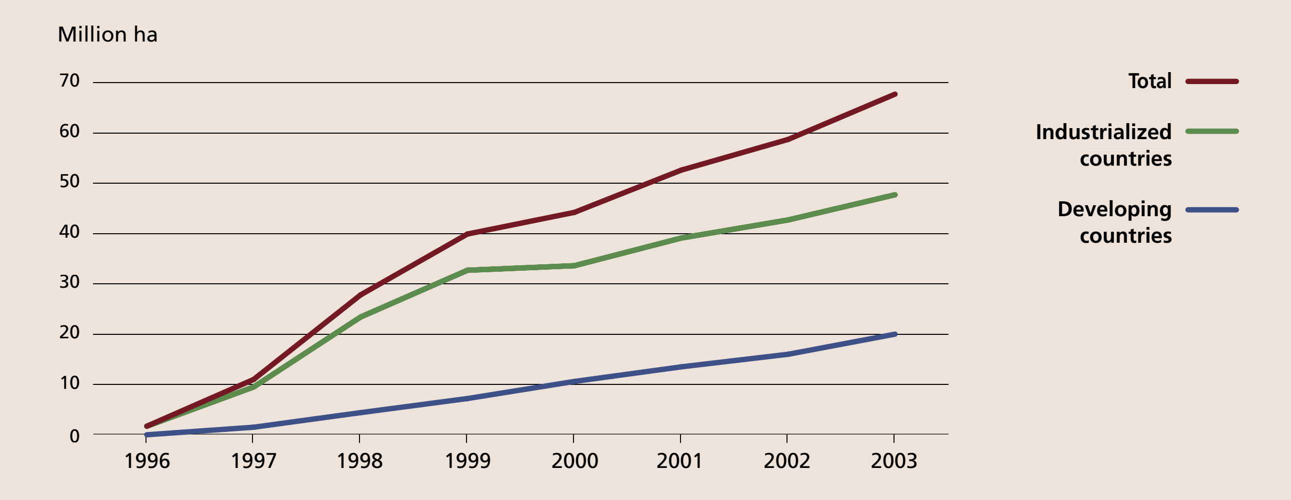
[2] This data source counts each individual test plot as a separate trial, so the same GM event may have multiple trials in a given country.

FIGURE 3
GM crop traits tested in less-developed countries, 1987–2000 (percent)



Source: Pray, Courtmanche and Govindasamy, 2002.

FIGURE 4
Global area of transgenic crops



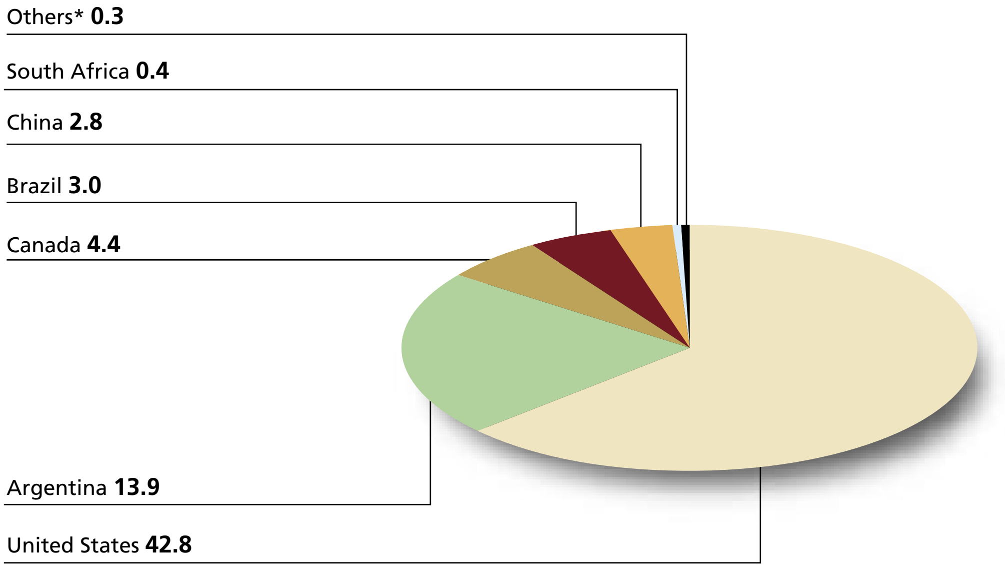
Source: James, 2003.

of global transgenic crop production (Figures 5–7) (James, 2003).

The United States plants almost two-thirds of the transgenic crops grown worldwide. Although transgenic crop area in the United States continues to expand, its share of global transgenic area has fallen rapidly as Argentina, Brazil, Canada, China and South Africa have increased their plantings. The other 12 countries where transgenic crops were grown in 2003 have a combined share of less than 1 percent of the global total.

The most widely grown transgenic crops are soybeans, maize, cotton and canola.

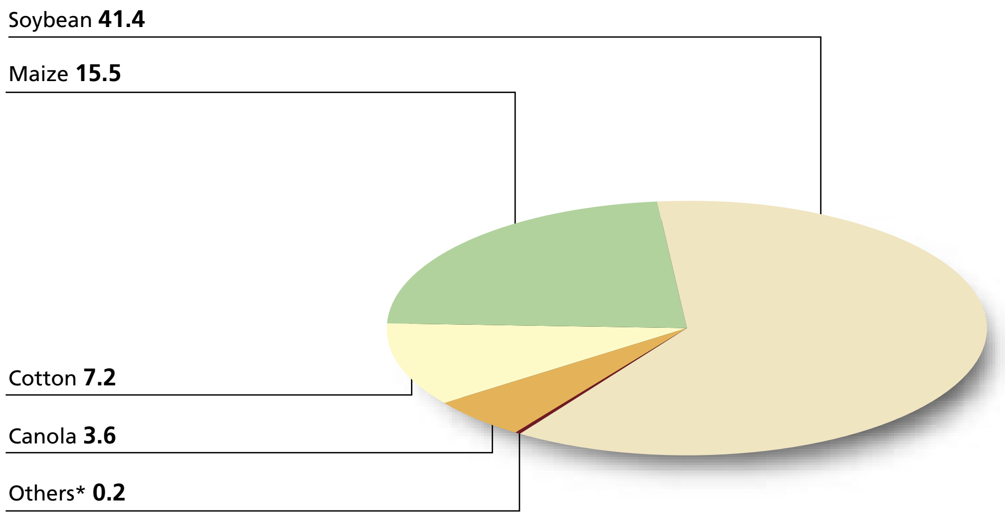
FIGURE 5
Global area of transgenic crops in 2003, by country (million ha)



* Australia, Bulgaria, Colombia, Germany, Honduras, India, Indonesia, Mexico, Philippines, Romania, Spain and Uruguay.

Source: James, 2003.

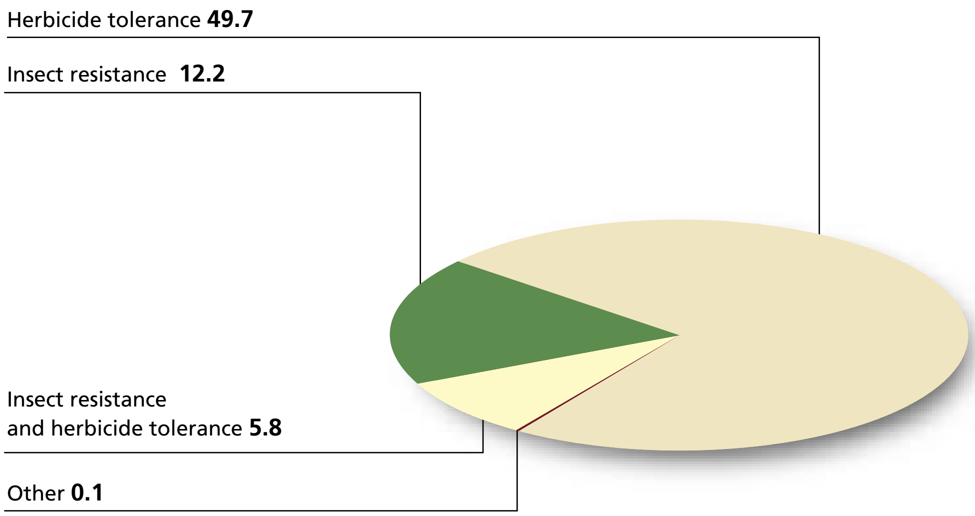
FIGURE 6
Global area of transgenic crops in 2003, by crop (million ha)



*Includes squash and papaya.

Source: James, 2003.

FIGURE 7
Global area of transgenic crops in 2003, by trait (million ha)



Source: James, 2003.

Herbicide tolerance and insect resistance are the most common traits. Herbicide-tolerant soybeans now comprise 55 percent of the global soybeans production area, and herbicide-tolerant canola comprises 16 percent of the global canola area. The transgenic cotton and maize varieties currently being grown commercially include traits for insect resistance, herbicide tolerance or both, and transgenic varieties now make up 21 percent and 11 percent, respectively, of the total area sown to those crops (James, 2003). The other transgenic crops being cultivated commercially include very small quantities of virus-resistant papaya and squash. Neither of the major food grains – wheat and rice – currently have transgenic varieties in commercial production anywhere in the world.

Conclusions

The changing locus of agricultural research from the public sector to the private transnational sector has had important implications for the types of products that are being developed and commercialized. Private-sector research naturally focuses on the crops and traits of commercial interest to farmers in higher-income countries where markets for agricultural inputs are robust and profitable. Agricultural public goods, including crops and traits of importance to subsistence farmers in marginal production environments, are of little interest to large transnational companies. Will farmers in developing countries be able to capture economic spillover benefits from the transgenic crops developed and commercialized by the private sector? What research priorities could more directly benefit the poor?

One of the lessons of the Green Revolution was that agricultural technology could be transferred internationally, especially to countries that had sufficient national agricultural research capacity to adapt the imported high-yielding cultivars to suit local production environments. What kind of research capacity do developing countries need to take advantage of the Gene Revolution? Given the dwindling resources available to public-sector research, how can more resources be mobilized for research for the poor? How can public–private partnerships be structured to capitalize on the strengths of each sector?

Unlike the high-yielding varieties disseminated in the Green Revolution, the products of the Gene Revolution are raising public concerns and encountering significant regulatory and market barriers. How do these issues influence the international transfer of new technologies? What policy measures are needed to facilitate the safe international movement of transgenic technologies?

The improved varieties that were responsible for the Green Revolution were disseminated freely as international public goods. Many of the innovations of the Gene Revolution, by contrast, are held under patents or exclusive licences. Although these intellectual property protections have greatly stimulated private-sector research in developed countries, they can restrict access to research tools for other researchers. What institutional mechanisms are needed to promote the sharing of intellectual property for public goods research?

The following section takes up these questions, examining the evidence so far regarding the economic (Chapter 4) and scientific (Chapter 5) issues surrounding transgenic crops and public concerns regarding their use (Chapter 6). The final section looks at the way forward in making biotechnology work for the poor.