CHAPTER 1

CURRENT STATUS AND OPTIONS FOR CROP BIOTECHNOLOGIES IN DEVELOPING COUNTRIES

SUMMARY

In developing countries, there is a need for continued focus on optimizing agricultural output in conjunction with conserving the natural resources base via improved crops and crop management systems. The implications of climate change make it necessary to integrate considerations regarding adaptation, uncertainty, vulnerability and resilience into agricultural research programmes and strategies. The various biotechnologies available have the potential to play a significant role in achieving these aims.

Crop biotechnologies have developed incrementally over the past century, but progress has accelerated greatly over the last two decades leading to many important scientific achievements and impressive technological advances. A wide range of crop biotechnologies is available and some are increasingly used in developing countries, especially tissue culture-based techniques (such as micropropagation), mutagenesis, interspecific or intergeneric hybridization, genetic modification, marker-assisted selection (MAS), disease diagnostics and bioprotection, and biofertilization.

As with other maturing technologies, there have been mixed experiences with crop biotechnologies in developing countries. Genetic modification has had limited but real success in modifying a few simple input traits in a small number of commercial commodity crops, adopted also in some developing countries. The wider application of genetic modification has been slowed down by severe limitations on the kinds of traits available, complex intellectual property rights regimes and regulatory issues, and the often negative public perception. While there have been significant successes in the adoption by farmers of a few first-generation transgenic varieties, there have also been unexpected market setbacks as farmers sought to avoid high seed costs and other restrictions.

The major breeding and crop management applications to date have come from non-transgenic biotechnologies encompassing the full range of agronomic traits and practices relevant to developing countries' farmers. For example, mutagenesis is widely used in developing countries and more than 2 700 mutation-derived crop varieties have been obtained worldwide in the last sixty years, mainly in developing countries. Interspecific hybridization allows the combination of favourable traits from different species and has been used successfully in, for instance, the development of interspecific disease-resistant Asian rice and New Rice for Africa (NERICA) varieties. However, interspecific hybridization programmes can be slow and require a great deal of scientific expertise and skilled labour.

MAS is still at a relatively early stage in its application for key subsistence crops in many developing countries, although it has begun to produce some significant results such as the development of a pearl millet hybrid with resistance to downy mildew disease in India. The costs and technical sophistication required for MAS, however, remain major challenges for developing countries. Micropropagation is used for the mass clonal propagation of elite lines or disease-free planting material. Many developing countries have significant crop micropropagation programmes and are applying it to a wide range of subsistence crops.

Biotechnology also offers important tools for the diagnosis of plant diseases of both viral and bacterial origin, and immuno-diagnostic techniques as well as DNA-based methods are commercially applied for this purpose in many developing countries. Biofertilizers are also being used in developing countries both to augment the nutritional status of crops and as alternatives to chemical supplements.

Biotechnologies such as cryopreservation, artificial seed production, somatic embryogenesis, and other forms of *in vitro* cell or tissue culture are also extensively used for the conservation of genetic resources for food and agriculture in developing countries.

The uptake of biotechnologies in developing countries is increasing gradually but remains patchy. Many biotechnological advances were made in industrialized countries in the private sector, leading to development of proprietary technologies that are often unavailable to scientists in developing countries. Farmers in developing countries, especially small farmers, cultivate crops and face problems that are particular to their cultural and environmental conditions, and have often limited purchasing power to access proprietary technologies. The spillover of research results obtained in industrialized countries by the private sector has therefore had only a limited impact on the livelihoods of subsistence farmers in developing countries. In fact, the most enduring successes to date have come from indigenous public-sector crop research programmes addressing farmer-relevant problems.

Even when there has been strong development of biotechnologies within the public sector in developing countries, they have not always been directed towards – or made available for – improving smallholder livelihoods. In fact, an inclusive process of decision-making about the allocation of resources for the development of appropriate crop biotechnologies was rarely adopted, undermining the successful development of crop biotechnologies. In some cases, even though the technology was sound and the products were potentially beneficial to farmers, there was limited or no adoption due to often-predictable infrastructure or market deficiencies. A promising approach to address such problems is farmer participatory research but this must be coupled with measures to address a wide range of cross-sectoral issues from extension services to seed multiplication programmes.

Biotechnology programmes have been effective where they complemented well-structured conventional plant breeding and agronomy research and development (R&D) programmes. Key factors in the successful development of crop biotechnologies in developing countries have been: appropriate policy development, strengthened research and extension institutions, and enhanced capacities for researchers and technicians. The establishment of cross-sectoral regulatory measures has also been important.

1.1 INTRODUCTION

Despite great advances in agricultural productivity and economic well-being in much of the world over the past 50 years, food insecurity and poverty continue to be serious issues in many regions (FAO, 2008a; 2009a). Moreover, in 2008, the world entered a period of deepening uncertainty and economic downturn that impacted significantly on the future security of food production and distribution systems (Nellemann *et al.*, 2009). The current economic downturn plus the effects of climate change both reinforce the need to extend the effectiveness of crop improvement and management programmes. The key role of crop improvement in increasing food production and in minimizing agricultural land use in developing countries is shown by estimates that, in the 1990s alone, yield gains saved about 80 Mha (million hectares) of land (Nelson and Maredia, 2007). However, if current food production per capita is to be maintained in the face of population growth and climatic uncertainty, 120 Mha (or 12 percent) of additional land might be needed by 2050, mainly in sub-Saharan Africa and Latin America (FAO, 2009b).

Clearly, in developing countries there is a need for continued focus on optimizing agricultural output, together with preserving the natural resources base through improved crops and management systems. The various biotechnologies available will play a part in this process, but there are difficult choices to be made concerning which methods to use for a particular crop or trait in a particular country or region. So, what are the best options for using biotechnological approaches to address global food security? There is no simple one-size-fits-all answer to this question. In many developing countries, staple crops have only recently started to benefit from the scientific plant breeding methods practised in industrialized countries for almost a century. In other cases, some developing country crops are already being improved using newer technologies such as MAS and genetic modification. Thus, there is no straightforward recipe for the use of a particular group of breeding or management methods for a particular crop or within a particular region. Moreover, the rapid pace of scientific progress is making some hitherto relatively complex and expensive technologies both cheaper and easier to access, even for some of the relatively resource-limited breeding and management programmes involving subsistence crops.

Several removable constraints still impede the uptake of modern crop breeding and management by developing countries. These include the privatization of agricultural R&D in developed countries which restricts access to proprietary technologies and limits the possibility of capturing research spillovers (IAASTD, 2009). While constraints relating to intellectual property rights (IPR) are relatively new and apply mainly to advanced biotechnologies, financial, institutional, socio-economical and political barriers have been concerns for many decades. They include basic measures, such as seed supply, bank loans, transport links and market regulations, and their combined effects can negate even the most impressive technology gains (King and Byerlee, 1978; Limao and Venables, 2001). For example, inadequate market infrastructure has limited fertilizer adoption by African smallholders, leading to persistently poor crop yields, low profitability, and chronic food insecurity (Nkonya *et al.*, 2005).

The purpose of this Chapter is to examine options from crop biotechnologies to address food insecurity in developing countries, particularly in the context of deepening economic and environmental uncertainty. Its primary focus is on sector-specific issues relating to biotechnology and their impact on crop breeding, management and genetic resources, but it also considers relevant cross-sectoral aspects such as socio-economic, regulatory, and public-good concerns.

The Chapter is divided into two main Sections – "Stocktaking: Learning from the Past" and "Looking Forward: Preparing for the Future". Under "Stocktaking", Part 1.2 provides a brief definition of the biotechnologies covered here; Part 1.3 documents the current status of application of crop biotechnologies, both traditional and new, in developing countries; Part 1.4 provides an analysis of the reasons for successes/failures of application of crop biotechnologies in developing countries; and Part 1.5 presents some relevant case studies. The conclusions of the stocktaking exercise and a summary of lessons learned are presented in Part 1.6. The "Looking forward" Section comprises three parts. Part 1.7 deals with key, unsolved problems in the sector where the use of biotechnologies could be useful. Part 1.8 identifies a number of specific options to assist developing countries make informed decisions regarding adoption of biotechnologies, while Part 1.9 proposes a set of priorities for action for the international community (FAO, UN organizations, non-governmental organizations [NGOs], donors and development agencies).

A. STOCKTAKING: LEARNING FROM THE PAST

1.2 DEFINING BIOTECHNOLOGIES

One of the challenges in discussing biotechnology is the lack of a consistent definition of the term itself. In this document, the following definition from the Convention on Biological Diversity (CBD) is used: "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use".

A distinction is sometimes made between "traditional" and "modern" biotechnologies, and while this may be valid in areas such as fermentation, it is less useful in the field of crop improvement and management. Scientific plant breeding has developed incrementally over the past century by harnessing advances in plant biology, supplemented at times by traditional empirical knowledge (lore), and informed by the principles of Mendelian, and later molecular, genetics. The impact of such biological approaches has been greatly extended by the deployment of a series of increasingly sophisticated biotechnologies, ranging from induced mutagenesis and tissue culture to robotized and fully automated trait selection based on molecular analyses. As described below, some older biotechnologies such as induced mutagenesis and wide crosses which originally dated from the 1920s have now been updated to new and more powerful forms. In the 21st century, biotechnologies are so pervasive in crop improvement programmes worldwide that it is no longer useful to delimit categories like "conventional" and "modern" when discussing crop breeding or management (OECD, 2009). Though a sharp category distinction between non-transgenic and transgenic approaches might be somewhat contrived in breeding terms, and may not be recognized by all crop scientists, such a distinction is nevertheless quite real in terms of legislation and the perception of many policy-makers and consumers.

1.3 CROP BIOTECHNOLOGIES AND THEIR CURRENT STATUS IN DEVELOPING COUNTRIES

Plant biotechnology is a rapidly evolving area encompassing basic and strategic research and its application in agriculture. While new methods and approaches are constantly being developed, an equally important feature is the improvement of existing biotechnologies that makes them cheaper and easier to use. This is especially relevant to developing countries where hitherto expensive and complex techniques, such as MAS or transgenesis, are becoming increasingly accessible. In this Chapter, the technologies are divided into three groups that reflect the three stages of crop development, namely: (i) creation of new genetic variation;

(ii) screening and selection of favourable variants; and (iii) production/management systems for crops or their derivatives. The last category includes plant propagation, nutrition, protection, and genetic resource management/conservation.

For the past 10 000 years, crop productivity has been improved via the processes of breeding and management. Breeding involves the selection by humans of certain genetic variants of a few chosen plant species according to their suitability for exploitation, whether as edible or non-edible resources. The two key prerequisites to both breeding and evolution are variation and selection. Novel genetic variations in wild populations arise from a relatively slow process of naturally-occurring mutation, plus the mixing of genomes that occurs with sexual reproduction. In contrast, science-based breeding as practised over the past century is based on the creation of genetic variation via processes such as induced mutagenesis, hybridization, controlled introgression of traits from diverse populations of the same or different species, and transgenesis. This is followed by the highly regulated reproduction or propagation of selected variants designed to minimize variation in favoured progeny and hence to create a relatively uniform population that is then managed (i.e. cultivated, harvested and processed) for human exploitation.

While so-called "traditional" methods of enhancing variation, e.g. the use of crop landraces, still have great and often untapped potential, the use of newer biotechnologies to create even wider genetic diversity has given breeders unprecedented opportunities for additional crop improvement. This greatly increased potential to create additional genetic variation has been matched in recent years by a revolution in the screening, identification and selection of potentially useful variants using methods such as biochemical and genomic screening, plus molecular MAS. Thanks to continued advances in basic plant research and in genomic and related technologies, there is great scope for further progress in plant breeding, especially in developing countries, during the coming years (Jauhar, 2007; Moose and Mumm, 2008). The major impacts of biotechnologies relate both to breeding new crop varieties and to areas of crop cultivation and management such as the production of propagation materials especially in vegetatively propagated crops (FAO, 2009c); aspects of plant nutrition such as the production and use of biofertilizers (Odame, 2002; FAO, 2005a); the use of symbiotic nitrogen-fixing bacteria and mycorrhizal fungi (Kohler *et al.*, 2008; FAO, 2009c; Yang, Kloepper and Ryu, 2009); aspects of plant protection, including diagnostics and biopesticides (Carpenter *et al.*, 2002; FAO, 2005a; Pender, 2007); and, finally, the conservation and management of crop genetic resources, both *in situ* and *ex situ* (FAO, 2006a).

Here follows a survey of crop biotechnologies, many of which were initially developed in industrialized countries but are now being adapted and increasingly used in developing countries where they are used mainly for commercial crops – though in a few cases they are also being applied to some subsistence crops.

1.3.1 Creation of new genetic variation

The ability of plant breeders to create new genetic variation was enormously increased in the mid-twentieth century by the invention of tissue culture and use of growth regulators (Thomas, Murphy and Murray, 2003). The creation of new genetic variation includes wide crossing with the assistance of methods such as embryo rescue, asymmetric cell fusion, nuclear implanting and somatic embryogenesis. Attempts at wide crossing between distantly related species are frequently frustrated by the incompatibility of their genomes.

Chromosome doubling: This is one of the most important technologies for the creation of fertile interspecific hybrids. Wide-hybrid plants are often sterile so their seeds cannot be propagated. This is due to differences between chromosome sets inherited from genetically divergent parental species, which prevent stable chromosome pairing during meiosis. However, if the chromosome number is artificially doubled, the hybrid may be able to produce functional pollen and eggs and therefore be fertile. Colchicine has been used for chromosome doubling in plants since the 1940s and applied to more than 50 plant species, including the most important annual crops. It has also been used to create seedless fruits and to produce wide crosses and somatic hybrids. More recently, other chromosome doubling agents, all of which act as inhibitors of mitotic cell division, have been used successfully in plant breeding programmes. In some plant species, tissue culture techniques have been used to induce chromosome doubling (Sonnino, Iwanaga and Henestroza, 1988; Cardi, Carputo and Frusciante, 1992). As well as making much wider genetic crosses possible, chromosome doubling has enabled the use of powerful methods such as somatic hybridization and haploid breeding, which have been especially useful in developing countries. To date, dozens of important crops have been improved and hundreds of new varieties produced around the world thanks to chromosome doubling technology.

Tissue culture-based technologies

Tissue culture has been widely used for over 50 years and is now employed to improve many of the most important developing country crops including major staples such as rice and potato, as well as endangered native species (AboEl-Nil, 1996). A brief survey of tissue culture based technologies now follows.

Somatic hybridization: Somatic hybridization is another way of enhancing variation in crop species by importing genes or even whole chromosomes from other species that are not closely enough related for normal sexual crossing (Arcioni and Pupilli, 2004). Although similar in its aims to conventional hybridization, somatic hybridization involves a more radical technological approach. The development of sophisticated microinjection and cell fusion techniques in the 1960s and 1970s allowed researchers to fuse whole cells or parts of cells to create composite cells from unrelated species. The resultant hybrid cells can either be treated with colchicine to induce chromosome doubling, or they spontaneously double the chromosome number during the *in vitro* regeneration process, hence stabilizing the new genome. Finally, the hybrid cells are induced to divide and differentiate into new hybrid plants. Somatic hybridization was introduced into crop breeding programmes in the early 1980s and has been attempted with several developing country crops (Murphy, 2007a).

The main technical hurdle at present is the instability of the new genome combinations from two dissimilar species. To a great extent, somatic hybridization has been replaced over the past decade by transgenesis, which has greater precision, fewer problems with genome instability and a higher overall success rate. However, transgenesis is only of use when there is a known useful gene (or genes) to be transferred. Many useful traits are controlled by as yet unknown sets of genes and can only be transferred into a crop by adding an entire donor genome, or at least a substantial portion thereof. In recent years, breeders have started to return in greater numbers to explore the potential of somatic hybridization, especially in some fruit crops. The reasons for this are threefold. First, transgenesis is not always a quick and easy option for enhancing variation in crops. Second, tissue culture and molecular marker techniques have improved considerably over the past decade, which has increased the rate of success in regenerating genetically stable progeny from such hybridizations. Third, unlike transgenesis, somatic hybridization is not regarded by regulatory authorities as genetic modification. Therefore, varieties produced by this technology are not subject to the same regulatory testing and approval requirements as transgenic varieties, which has created new commercial opportunities for breeders. Although somatic hybridization has not yet been used to a great extent for public-good purposes in developing country crops, this often-overlooked technology has considerable potential and should be kept in mind for the future.

Haploids and doubled haploids: Haploid plants can be produced using anther culture which involves the *in vitro* culture of immature anthers (i.e. the pollen-producing structures of the plant). As the pollen grains are haploid, the resulting pollen-derived plants are also haploid (FAO, 2009c). Doubled haploid plants were first produced in the 1960s using colchicine and today several treatments can be used, including thermal shock or mannitol incubation (Kasha *et al.*, 2001). Doubled haploids may also be produced from ovule culture. Breeders value doubled haploid plants because they are 100 percent homozygous and any recessive genes are therefore readily apparent. The time required after a conventional hybridization to select pure lines carrying the required recombination of characters is consequently drastically reduced (Smith *et al.*, 2008). The application of this technique to plant breeding is hindered by the investments in facilities and human resources necessary to produce and to test large populations of doubled haploids. The need to test large numbers of lines can add significantly to the skilled labour requirement and hence lead to increased costs. In the developing world, a major centre of such breeding work is China, where numerous doubled haploid crops have been released and many more are being developed (FAO, 1995). By 2003, China was cultivating over 2 Mha of doubled haploid varieties, the most important of which were rice, wheat, tobacco and peppers (Maluszynski *et al.*, 2003). Improved varieties of durum and bread wheat have also been obtained by applying anther culture techniques in Tunisia and Morocco, respectively (FAO, 2005a).

Sterile plant varieties: Manipulations by plant breeders frequently result in sterile varieties that cannot readily be propagated. Sometimes this is a useful trait and is deliberately engineered by breeders, e.g. in watermelon and citrus crops where consumers demand seedless fruits. Seed sterility is analogous to F_1 or F_2 hybrids or other non-propagable plant types in its utility to commercial seed companies because the farmer cannot use saved seed and therefore needs to repurchase it each year for replanting. One of the most rapid and cost-effective approaches for inducing sterility in a plant is to create polyploids, especially triploids. In most cases, triploid plants will grow and develop normally except for their inability to set seed and therefore cannot be reproduced or propagated, except by the company that owns the parent lines through the use of embryo culture. Alternatively, triploid plants can be regenerated from endosperm tissue, which is naturally triploid. This method has been used to create triploid varieties of numerous fruit crops including most of the citrus fruits, acacias, kiwifruit (*Actinidia chinensis*), loquat (*Eriobotrya japonica*), passionflower (*Passiflora incarnata*) and pawpaw (*Asimina triloba*) (Lee, 1988).

Mutagenesis

This involves the use of mutagenic agents such as chemicals or radiation to modify DNA and hence create novel phenotypes (Donini and Sonnino, 1998). It includes somatic mutagenesis whereby tissue or cell cultures may undergo useful epigenetic modifications provided the resultant traits are stable in future generations. Induced mutagenesis has been practised with great success in crop breeding programmes in developing countries since the 1930s (Ahloowalia, Maluszynski and Nichterlein, 2004), but its scope and utility have recently been greatly enhanced and extended by the new molecular-based technology of targeting induced local lesions in genomes (TILLING, see below). An apparent limitation of mutagenesis versus wide crossing or transgenesis methods is that breeders can manipulate only genes already present in the genome. No new genes can be added by this method. Furthermore, nearly all mutations result in a loss of gene function, meaning that mutagenesis is concerned more with reducing the effects of unwanted genes than increasing the expression of desirable genes. At first sight, this might seem like a serious limitation to the creation of useful new agronomic traits. However, recent genomic studies reveal the surprising fact that during the 10 000-year history of agriculture, loss-of-function alleles were associated with nine out of 19 key episodes in crop improvement and/or varietal divergence (Doebley, Gaut and Smith, 2006; Burger, Chapman and Burke, 2008). Therefore, the past and future potency of mutagenesis for crop improvement cannot be underestimated.

Somaclonal mutagenesis is caused by changes in DNA induced during *in vitro* culture (Durrant, 1962). Somaclonal variation is normally regarded as an undesirable by-product of the stresses imposed on a plant by subjecting it to tissue culture. These stresses include abiotic factors, such as cold, water deficiency, or high salt concentrations; excess or dearth of nutrients; the effects of chemical growth regulators; and infections by pathogens. The stresses of tissue culture can result in single-gene mutations; the deletion or transposition of larger lengths of DNA, including chromosome segments; methylation or de-methylation of genes; and even the duplication or loss of entire chromosomes. Provided they are carefully controlled, somaclonal changes in cultured plant cells can potentially provide a powerful new tool to generate variation for crop breeders (Sala and Labra, 2003). Somaclonal mutagenesis has been used to manipulate traits such as disease resistance, insect resistance, nutritional value, drought and salt tolerance in crops ranging from sugar cane to banana.

Mutagenesis is currently one of the few biotechnologies used much more in developing countries than elsewhere. Both radiation and chemical mutagenesis have been used for crop improvement since the 1930s. During the 1950s, FAO began working with the International Atomic Energy Agency (IAEA) to make irradiation technology more widely available to developing countries in a collaboration that is now known as the Atoms for Food global partnership (FAO and IAEA, 2008). More than 2 700 mutation-derived varieties have been obtained world-wide, generating benefits worth billions of dollars, mainly in developing countries (Ahloowalia, Maluszynski and Nichterlein, 2004; FAO and IAEA, 2008).

TILLING can be viewed as an updated high-tech version of mutation breeding (McCallum *et al.*, 2000a; 2000b). First, mutagenic agents such as alkylating agents or radiation are used as normal to create a population of thousands of mutagenized plants. Next, the second (or M_2) generation of these mutants is screened using a semiautomated high-throughput DNA-based method to detect mutations in genes of interest. Screening involves use of the polymerase chain reaction (PCR) to amplify gene fragments of interest, plus rapid identification of any mutation-induced lesions by looking for mismatches in duplexes with non-mutagenized DNA sequences. The third step is to evaluate the phenotypes of a limited number of selected mutant plants. TILLING is also amenable to automation including high-throughput robotic screening systems, making it especially suitable for large and complex polyploid genomes found in several major crops. As well as screening mutagenized populations, TILLING can be used to screen variation in natural populations in what has been termed EcoTILLING (Henikoff, Till and Comai, 2004).

As with other technologies, TILLING will eventually get cheaper and more accessible, so it can be applied more readily by developing countries. However, the wider applications of this and other new biotechnologies depend critically on how and where they have been developed. For example, chemical/radiation mutagenesis was pioneered in the public sector and was subsequently disseminated around the world. In contrast, other biotechnologies such as maize F_1 hybrids and transgenesis were commercialized by the private sector and, outside the arena of globally traded commodity crops, they have spread more slowly and less widely. In the case of TILLING, it will be important to maintain a balance between protecting the legitimate commercial interests and research investments of the exploiting companies while making the technology available for non-profit, public-good applications in developing countries.

Genetic modification

This is the use of exogenous DNA or RNA sequences to create transgenic organisms that express novel and useful traits in agriculture. It may involve the insertion of copies of endogenously derived DNA or RNA sequences into the same species, e.g. as part of gene amplification or RNA interference (RNAi) based manipulation of gene expression. Unlike other methods for creating variation, there is no limit to the source of the added DNA or RNA; this can be derived from animals, viruses, bacteria, or even from totally man-made sequences. In transgenesis, DNA for stable, inherited transformation is normally added to cells by biolistics or biological vectors (Slater, Scott and Fowler, 2008). In biolistics, DNA is attached to small particles that are propelled into plant tissues. This technique is useful because it can be applied to any plant species, but is relatively inefficient and does not always result in the incorporation of the transgenes into the plant genome (Kikkert, Vidal and Reisch, 2005). Alternatively, DNA can be added in a more controlled fashion by means of vectors such as *Agrobacterium tumefaciens* which are able to insert DNA directly into the genome of a plant cell (Chilton, 1988). Exogenous genes can also be delivered for transient expression using viral vectors, which is faster but less versatile than stable transformation (Marillonnet *et al.*, 2005).

Despite their limitations, each of these methods of DNA transfer can sometimes be more efficient in delivering genes into crops than the non-transgenic biotechnologies such as induced mutations or wide crosses. Tissue culture methods have also been vital in enabling transgenesis. Indeed, even today, more than 25 years after the first transgenic plants were produced, the efficiency of gene transfer in many species (and especially some of the less well studied developing country crops) is still often limited more by the capacity of a plant species/genotype to be cultured and regenerated *in vitro* than by the ability to transfer exogenous genes *per se*.

In some respects, transgenesis is simply a more precise form of wide crossing. The major difference is that the transferred DNA can be derived from a multiplicity of sources. One disadvantage of transgenesis is that for complex multigenic traits, such as drought or salinity tolerance, the genes involved (of which there may be many) have yet to be conclusively identified. This means that breeders currently have relatively few candidate genes available for transfer, although the list of potential genes will continue to grow with further advances in genomics. A further limitation for transgenesis in crop breeding is the current IPR system, whereby several key underpinning technologies are owned by a few commercial companies. As discussed below, this can inhibit the wider development of transgenic crops and is a particular disincentive to their deployment in developing countries (Murphy, 2007a). Additional limitations to the wider adoption of transgenesis include complex and still-unresolved regulatory regimes for the release of transgenic crops plus uncertain public responses in developing countries and/or in potential customer countries (Stein and Rodríguez-Cerezo, 2009; Ramessar *et al.*, 2009).

In response to the problem of restricted ownership of IPR relating to first-generation transgenic crops, there are numerous local initiatives for developing countries to develop their own proprietary biotechnologies, many of which emanate from public-private partnerships (PPPs). For example, in 2009, EMBRAPA, the Brazilian agricultural research organization, applied for final regulatory approval of transgenic herbicide-tolerant soybean varieties, as an alternative to the Roundup Ready® technology owned by Monsanto. In this PPP with the BASF Corporation, EMBRAPA developed locally adapted soybean varieties which are planned for release to farmers in 2011. In addition to its longstanding and successful non-transgenic breeding programmes, the Malaysian Palm Oil Board has a number of partnership programmes, including PPPs, where some of the objectives include the development of transgenic oil palm varieties expressing traits such as improved oil quality and yield, and pest resistance (Murphy, 2007b; Sambanthamurthi *et al.*, 2009). In India, locally-bred transgenic eggplant (*Solanum melongena*) varieties carrying the Bt trait – i.e. containing genes derived from the soil bacterium *Bacillus thuringiensis* (Bt) coding for proteins that are toxic to insect pests – are nearing the final stages of development (Choudhary and Gaur, 2009). The original Bt hybrid stock was donated by its developer, Maharashtra Hybrid Seeds Company, to public research institutes in India, Bangladesh, and the Philippines for use in smallholder targeted breeding programmes in a PPP and North-South partnership (NSP) with Cornell University.

Transgenic crops were first grown on a fully commercial scale in the mid 1990s. The "first-generation" transgenic crops which were grown on an estimated 125 Mha in 2008, are almost exclusively private-sector goods developed in industrialized countries (James, 2008) and tailored to satisfy the needs of their farmers. For over a decade, large-scale commercial transgenesis has been effectively restricted to four commodity crops (maize, soybean, canola/rapeseed and cotton) that collectively accounted for over 99.5 percent of transgenic crop production in 2008. These four crops expressed two transgenic trait classes, i.e. herbicide tolerance (63 percent of genetically modified [GM] crops planted in 2008) or insect resistance (15 percent), while 22 percent had both traits (James, 2008). Although the very narrow range of existing transgenic crops and traits was developed by the private sector primarily for commercial use in industrialized countries, some of them have also been adopted by developing country farmers including many smallholders (Glover, 2007, 2008). For example, the vast majority of soybean output in South America is transgenic and is grown on commercial farms while Bt cotton is grown by an estimated 12 million small and resource-poor farmers in India and China (James, 2008).

One factor that should be taken into consideration with transgenic varieties is that while their transgenic status is normally due to the presence of one or a few exogenous genes, the background genotype is still the product of non-transgenic biotechnologies. For example, the background genotype of Bt cotton grown in India was created by conventional hybridization and backcrossing; and Roundup Ready® soybeans grown in South America have improved yield and quality traits thanks to decades of mutagenesis and wide-crossing programmes. In some cases, such as soybean in Argentina and hybrid maize in South Africa, farmers will be using these varieties not just because of their transgenic traits, but equally (or possibly more) because the varieties also contain other useful agronomic features such as disease resistance or heterosis that were incorporated using non-transgenic breeding methods (Burke, 2004). In other cases, such as Bt cotton in India, the transgenic trait is probably the primary reason for farmer interest in the varieties (Pender, 2007).

Both soybean and cotton are cash crops, and despite their higher prices, transgenic varieties have been widely cultivated in some developing countries. In India, the price of Bt hybrid cottonseed was initially almost triple that of non-transgenic counterparts (Qaim, 2003), but it was nevertheless popular with farmers. However, the high prices led to increased demand for transgenic seed that had been illicitly crossed with local Indian varieties and was available to farmers on the black market. Illicit Bt cotton hybrids were already being sold on the black market across significant areas of the Indian cotton belt for several seasons before the officially approved hybrids were commercialized in 2002 (Scoones, 2005). By 2005, there were reports of black market seeds capturing over 70 percent of Bt cotton sales thanks in part to their being 15–40 percent cheaper than official varieties (Herring, 2006, 2007). Several years later, there were an estimated 200 unofficial Bt cotton varieties, but these were losing popularity due to steep falls in seed prices for official Bt seed (Herring, 2009). Similarly, in China, fully IPR-protected Bt cottonseed imported from the United States initially commanded a price premium of 333 percent in 2001. By 2006, however, non-enforcement of IPR and illicit seed marketing had eroded the price premium to virtually nil (Tripp, Louwaars and Eaton, 2007). Finally, in Argentina, Qaim and de Janvry (2003) report that Bt cotton initially cost from upwards of four to six times more than non-transgenic varieties, resulting in an adoption rate of only 5.4 percent. Within a few years, black market seed was available at one third the official price and these IPR had become virtually unenforceable in Argentina (Qaim and Traxler, 2005).

Therefore, while these examples underscore the popularity of some first generation transgenic crops in developing countries, they also highlight serious problems associated with near-monopoly ownership, anti-competitive IPR regulations and the enforced payment of licence fees (Qaim and Traxler, 2005; Murphy, 2007a). High price differentials and/or licence fees can drive farmers to black-market seed (Qaim and de Janvry, 2003; Perrin and Fulginiti, 2008), or to refuse fee payments as happened with herbicide tolerant soybean in South America (Murphy, 2007a). A possible solution is for developing countries to develop indigenous proprietary biotechnologies which can be made available to farmers at lower cost (Cohen, 2005). Another possibility is for developing countries to invest in the infrastructure to develop extension and seed distribution systems that can provide objective, independent information to farmers regarding the "on-farm" economic benefits and drawbacks from these and other agricultural technologies originating in developed countries and, if farmers are interested, explain how they can gain legal access to such innovations.

Following over a decade of first generation transgenesis which has been restricted to virtually four globally traded commodity crops, the emerging second-generation of transgenic crops includes several examples aimed specifically at subsistence farmers in developing countries. In sub-Saharan Africa, despite relatively low capacity for the indigenous development of transgenesis, several such crops are currently being trialled in joint ventures such as PPPs and/or NSPs (Hartwich, Janssen and Tola, 2003; Smale, Edmeades and De Groote, 2006; Anandajayasekeram *et al.*, 2007). For example, banana is primarily a subsistence crop in rural areas in Uganda, providing some seven million people with food and income. The highest yielding varieties are susceptible to diseases, but since they are sterile, there is limited potential for crossbreeding. In a recent NSP, the National Agricultural Research Organization of Uganda imported transgenic disease-resistant sweet banana plants from the University of Leuven, Belgium (Kikulwe, Wesseler and Falck-Zepeda, 2008). The plants are being field trialled at the Kawanda Agricultural Research Institute for resistance to bacterial wilt and black sigatoka fungal disease. While initial results are promising, the ultimate success of this and similar ventures depends critically on the response of local growers and consumers (Smale, Edmeades and De Groote, 2006).

Other transgenic varieties are at even earlier stages of research and face many years of further development and complex regulatory hurdles before they can be even considered for release. For example, in South Africa the replication-associated protein gene of the severe pathogen maize streak virus (MSV) was used to transform maize plants. Transgenic plants displayed a significant delay in symptom development, a decrease in symptom severity and higher survival rates than non-transgenic plants after MSV challenge (Shepherd *et al*., 2007). Also, a United States based group funded partially by the Rockefeller Foundation and the Centro Internacional de Agricultura Tropical (CIAT) is developing transgenic cassava containing a bacterial ADP-glucose pyrophosphorylase gene for enhanced starch production (Ihemere *et al*., 2006). Other examples currently in the pipeline include: maize for insect resistance and improved protein content; potatoes for viral disease and pest resistance; and rice for disease and pest resistance.

Interspecific hybridization

Wide crossing, or interspecific hybridization, involves hybridizing a crop variety with a distantly related plant from outside its normal sexually compatible gene pool. The usual purpose of wide crossing is not to produce true hybrids, i.e. progeny containing significant parts of both parental genomes, but rather to obtain a plant that is virtually identical to the original crop except for a few genes contributed by the distant relative. In some cases, it may even be possible to use wide crossing to obtain a plant that is almost identical to an elite variety of a crop except for the presence of a single new trait or gene transferred from a different species. The strategy of obtaining useful genes from other species via wide crosses was greatly enhanced by advances in plant tissue culture. A particular challenge was to circumvent the biological mechanisms that normally prevent interspecific and intergenus crosses. The spontaneous rejection of hybrid embryos is normally an important mechanism to ensure the reproductive isolation of populations and to avoid non-viable or debilitated hybrid progeny. Therefore, a high proportion of wide hybrid seeds either does not develop to maturity, or does not contain a viable embryo. To avoid spontaneous abortion, the breeder removes embryos from the ovule at the earliest possible stage and places them into culture *in vitro* (Chi, 2003). Mortality rates can be high, but enough embryos normally survive the rigours of removal, transfer, tissue culture, and regeneration to produce adult hybrid plants for testing and further crossing.

First generation, wide hybrid plants are rarely suitable for cultivation because they have only received half of their genes from the crop parent. From the other (non-crop) parent they will have received not only the few desirable genes sought by the breeder but also thousands of undesirable genes that must be removed by further manipulation. This is achieved by re-crossing the hybrid with the original crop plant, plus another round of embryo rescue, to grow up the new hybrids. This “backcrossing” process is repeated for about six generations (sometimes more) until the breeder ends up with a plant that is 99.9 percent identical to the original crop parent except that it now contains the desirable gene from the donor parent plant. Particularly useful for gene and quantitative trait locus

(QTL) discovery and breeding are the so-called introgression libraries, namely collections of backcrossed families each carrying an introgressed segment (about 10-20 cM) from the donor parent and covering, as a collection, the entire genome (Zamir, 2001). Wide crossing programmes can take more than a decade to complete although MAS and anther culture can also be used to speed up the process. They involve thousands of plants, a great deal of scientific expertise and skilled labour, and success is never guaranteed. Nevertheless, wide crosses have been largely successful in enabling breeders to access genetic variation beyond the normal reproductive barriers of their crops. Some case studies of successes with interspecific crops, including disease-resistant Asian rice and New Rice for Africa (NERICA) varieties are discussed in Part 1.5.

One concern for the future of wide crossing is that many potentially beneficial donor species or local populations of wild plants are being destroyed every year by habitat degradation, industrialization and agricultural expansion. This illustrates the need for an inventory and/or the improved conservation of wild plants that could possibly contribute useful genes to major crops such as those influencing disease resistance. Threats to potentially useful wild relatives of the major Asian crops are particularly serious. Gurdev Khush, former principal breeder at the International Rice Research Institute (IRRI), developer of wide crosses of rice, and 1996 World Food Prize laureate, has described wild relatives as "truly priceless seeds" (Barclay, 2004). Using wide crosses, IRRI has produced new rice varieties that are resistant to the grassy stunt virus, bacterial blight, and blast and tungro diseases. Wide crossing with the wild species *Oryza officinalis* has produced four new rice varieties, each carrying resistance to the brown planthopper which is a particularly serious pest (as well as being a viral vector) in Vietnam (Murphy, 2007a). The new rice varieties reduce pesticide use and also contain resistance to the grassy stunt virus.

The use of the hybrid-plant technologies listed above has been one of the cornerstones of modern crop breeding and is set to benefit further from advances in plant biotechnology. For example, new chromosome engineering techniques are being translated into a greatly improved capacity to effect wide hybridization and hence enable the recruitment of important agronomic traits from wild species into developing country crops (Gupta and Tsuchiya, 1991; Jauhar, 2003; Ceoloni *et al.*, 2005; Singh, 2007). Like TILLING, chromosome engineering can be viewed as a modern high-tech form of an earlier biotechnology. It will be important for developing countries to be in a position to participate in and capitalize on such research advances in the future. This is a good argument for much greater investments in human and physical resources. Indeed, even in a major agricultural research centre like China, there have been recent concerns that insufficient resources are being channelled into R&D to underpin future advances in crop breeding (Chinese Academy of Sciences, 2008).

1.3.2 Screening and selection

In addition to creating new genetic variation, breeders need effective and efficient methods to identify, select and propagate useful variants, and there has been striking recent progress in this area. Examples include the many improvements in efficiency and accuracy in screening and selecting the huge numbers of genetic variants, often numbered in the tens of thousands, created by technologies such as hybridization or mutagenesis. From tandem gas chromatography/mass spectroscopy to automated sequencing and robotized PCR, a host of new analytical and screening technologies can enable breeders to progress from the laborious processing of a few dozen samples per day to routine, rapid, automated, round-the-clock, in-depth analyses of the detailed molecular characteristics of many thousands of plants. Genomics, and genome sequencing/annotation in particular, is a core technology group that is already underpinning improvement in an increasing range of species, including rice, sorghum and oil palm (Kovach and McCouch, 2008; Sakamoto and Matsuoka, 2008; Bolot *et al.*, 2009; Skamnioti and Gurr, 2009).

Marker-assisted selection (MAS)

MAS is a comparatively new screening method with the potential to revolutionize aspects of crop breeding via the use of DNA-derived molecular markers (for a detailed review of MAS in rice, see Collard *et al.*, 2008, and Jena and Mackill, 2008; for cereals in general, see Goff and Salmeron, 2004; and for more comprehensive overviews see FAO, 2007a, Varshney and Tuberosa, 2007a and 2007b, and Xu and Crouch, 2008). MAS can be employed to support any form of crop breeding programme including crossing of traditional land races or within participatory plant breeding programmes with smallholders. Molecular markers are also being used as highly effective research tools to uncover the genetic basis of complex agronomic traits such as drought or salt tolerance and pest/disease resistance (Bernardo, 2008; Cai, Bai and Zhang, 2008; Collins, Tardieu and Tuberosa, 2008). In addition to their increasingly prominent role in the genetic improvement of crops, molecular markers are useful for a host of other agriculturally related applications such as characterizing crop genetic resources, plant gene bank management, and diagnosis of diseases (FAO, 2006a). Using molecular markers, breeders can screen many more plants at a very early stage and thereby save several years of laborious work in the development of a new crop variety. In the case of wheat breeding, for example, it has been estimated that MAS may result in an overall cost saving of 40 percent relative to conventional phenotypic selection, in addition to improved genetic gains (Kuchel *et al.*, 2005).

Hitherto, the use of MAS in crop breeding was largely restricted to a few economically important temperate crops, but the list is now expanding. Public sector initiatives and PPPs have developed cheaper and easier MAS breeding systems (Koebner and Summers, 2003).

MAS technologies have also benefited from more efficient screening methods including PCR, DNA/DNA hybridization, and DNA sequencing (Varshney and Tuberosa, 2007a). Today, most MAS technologies use PCR-based methods, such as sequence-tagged microsatellites and single-nucleotide polymorphisms (SNPs). Molecular marker technology is now being applied to an increasing range of crops and even to domesticating entirely new crops. As well as annual crops such as cereals and legumes (Garzón, Ligarreto and Blair, 2008), MAS has been useful in perennial crops, including subsistence and cash crops in developing countries. Examples include oil palm, coconut, coffee, tea, cocoa, and many tropical fruit trees such as bananas and mangoes. By using DNA markers in conjunction with other new breeding technologies such as clonal propagation, it should be possible to make rapid strides in the creation and cultivation of greatly improved varieties of many of these important tropical crops.

In the medium term, MAS could well evolve into what has been termed "genomics-assisted breeding" (Varshney, Graner and Sorrells, 2005; Varshney and Tuberosa, 2007b). Here bioinformatics-supported genomic and metabolomic resources are key parts of breeding programmes. For example, the immediate wild ancestor of rice, *Oryza rufipongon*, is a genetically diverse species containing alleles that confer agronomically useful unexpected (transgressive) variation when crossed with elite cultivars of *O. sativa.* However, there is currently no way of predicting where to look for such wild alleles. The integration of whole-genome mapping and marker analyses coupled with QTL cloning and EcoTILLING would greatly facilitate a targeted use of wild relatives in breeding (Kovach and McCouch, 2008). Of course, this assumes that such resources and infrastructure are available for the crop in question, which is complex enough in the case of rice despite its small and much studied genome, but may be even more challenging for more genetically complex and less well studied subsistence crops such as cassava or millet.

Despite improvements over the past decade, a major challenge in developing MAS is still the cost and technical sophistication of the initial investment. For each crop, mapping populations must be created, genomic markers assembled, and genetic maps compiled. A cost/benefit analysis by the International Maize and Wheat Improvement Center (CIMMYT) on using MAS in resource-limited public breeding programmes has concluded that each case for developing MAS technology needs to be assessed separately and depends critically on: the nature of the crop including its genomic organization; the availability of requisite technical infrastructure and know-how; and the availability of capital for set-up costs (FAO, 2007b). Such calculations are especially important when developing countries are deciding whether to invest scarce resources in such technologies. Although MAS is becoming progressively cheaper, it is still often relatively expensive compared with alternative approaches for many developing country crops. Prospects for MAS in African breeding programmes have been reviewed by Stafford (2009).

Marker-assisted selection is beginning to produce significant results in the relatively few crop breeding programmes in which it has been deployed, and future prospects here are very good. One example is the development using MAS of “HHB 67 Improved”, a pearl millet hybrid with resistance to downy mildew disease, which was approved for release in India in 2005. In 2008, F_1 hybrid seed was produced to sow at least 300 000 ha with HHB 67 Improved, while the 2009 area could exceed 500 000 ha if sowing conditions are favourable (Hash, 2009). Other examples where MAS has been used in the development of new products for farmers include new rice varieties with resistance to bacterial blight in India (Gupta, 2009) and with submergence tolerance in the Philippines (Rigor, 2009). Although most crop research centres of the Consultative Group on International Agricultural Research (CGIAR) and many national organizations are increasingly using MAS in crop improvement programmes, it is still at a relatively early stage in its rollout for key subsistence crops in many developing countries (FAO, 2007c).

1.3.3 Production and management systems

Many developing country crops including cassava, potato, banana, sweet potato and oil palm are mainly vegetatively propagated and tissue culture based micropropagation systems have become especially important for their improvement. Additional production/management-related biotechnologies include the use of biofertilizers and bioinsecticides, plus the use of tools such as molecular markers and cryopreservation for the management and conservation of plant genetic resources. While there are several existing examples of applying these biotechnologies in various developing countries, their true potential for the improvement of food production and reducing chemical inputs has barely been tapped.

Micropropagation

In crops where sexual reproduction is problematic or impractical, vegetative propagation has been used for a long time. More recently, biotechnologies have been developed for mass clonal propagation of elite lines or disease-free planting material by culturing *in vitro* explants such as shoot tips, tuber sections or other cuttings. The regenerated plantlets are subcultured, often on a massive scale, until thousands or millions have been produced for transfer to the field. In this way, cuttings from a single elite tree or disease-free plant can be used for rapid large-scale cultivation. These methods are especially useful for subsistence root and tuber crops such as cassava, potato, and sweet potato as well as for fruit tree crops such as banana and oil palm because they facilitate the production of healthy planting materials at reasonable costs (FAO, 2009c). In the past few decades, the technique of mass propagation has become increasingly useful in breeding programmes, especially for tree crops most of which are too long-lived to be amenable to the approaches developed for annual crops. Mass clonal propagation can be a fast and cheap method for multiplying the best genetic stock in such perennial species.

Today, *in vitro* propagation including micropropagation and somatic embryogenesis, is widely used in a range of developing country subsistence crops, including banana, cassava, yam, potato, sweet potato (*Ipomoea batatas*), frafra potato (*Solenostemon rotundifolius*) and cocoyam; commercial plantation crops, such as cocoa, coffee, oil palm, sugarcane and tea; niche crops, such as artichoke, cardamom, garlic, ginger, and vanilla; and fruit trees, such as almond, cactus, citrus, coconut, date palm, ensete, granadilla, grape, lemon tree, mango, olive, pistachio, pineapple, and plantain (Sharma, 2001; Blakesley and Marks, 2003; Pender, 2007; Smale and Tushemereirwe, 2007; FAO, 2009c). Some of the many countries with significant crop micropropagation programmes include Argentina, Gabon, India, Indonesia, Kenya, Nigeria, the Philippines, Uganda and Vietnam.

Micropropagation is especially useful for vegetatively propagated root crops and it is here that the greatest successes have been demonstrated. For example, disease-free sweet potatoes based on tissue culture have been adopted on 0.5 Mha in Shandong Province in China, with yield gains of 30–40 percent (Fuglie *et al.*, 1999). By 1998, more than 80 percent of local farmers had adopted the technology, generating productivity increases of US$145 million and increasing agricultural income for the seven million sweet potato growers by 3.6 and 1.6 percent, in relatively poor and better-off districts respectively. In India, a scheme enabled potato breeders to integrate micropropagation and virus detection into the initial stages of seed production, leading to an estimated two- to three-fold increase in seed health, and generating more than US$4 million in revenues (Naik and Karihaloo, 2007).

In Kenya, micropropagated disease-free bananas were adopted by more than 500 000 farmers over a 10-year period (Wambugu, 2004). It had been predicted that these new varieties would offer higher financial returns in Kenya than traditional bananas (Qaim, 1999), and this was later empirically verified (Mbogoh, Wambugu and Wakhusama, 2003). In the late 1990s, the Uganda National Banana Research Programme sought to address the decline of cooking banana production in Bamunanika subcounty by introducing micropropagated, high-yielding cultivars. The new cultivars generated socio-economic benefits for the adopters. However, notwithstanding the use of a participatory farmer-to-farmer extension approach, the relatively high capital and recurrent costs of these new cultivars have prevented less endowed households from benefiting (FAO, 2009c).

The use of micropropagated planting materials in Hwedza District (Zimbabwe) enhanced crop yield and economic returns of sweet potato compared with traditionally propagated planting materials (Mutandwa, 2008). In this case the innovation was adopted by 97 percent of the farmers, including both the worst-off and better-off farmers, and contributed to household food security and produced cash surplus (FAO, 2009c). In Vietnam, farmers participated in the micropropagation of new high yielding late-blight resistant potatoes, resulting in a doubling of yields from 10 to 20 T/ha. By producing their own plantlets, farmers have increased yield and incomes, and have set up rural microenterprises specializing in the commercial production of disease-free seed (Uyen *et al.*, 1996).

Disease diagnostics and bioprotection

Biotechnology offers important tools to diagnose plant diseases of both viral and bacterial origin. These tools are of particular value when identification of the causal agent is difficult (e.g. many viral diseases exhibit similar symptoms) and when knowledge of the nature of the pathogen is necessary to develop and apply proper management measures. Immunodiagnostic techniques including enzyme-linked immunosorbent assay (ELISA) and monoclonal antibodies are commercially applied in many developing countries, as well as DNA-based methods (FAO, 2005a). Additionally, diagnostic techniques are routinely used for quarantine systems and the production of seeds and other propagation materials in developing countries.

Bioprotection involves biologically based crop protection systems against biotic threats such as pests and diseases. One example is biological control, which has been defined as: "the use of living organisms to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be" (Eilenberg, Hajek and Lomer, 2001). Microbial agents are a form of bioprotection and constitute one of the commonest forms used in developing countries. Often these agents have the additional benefit of substituting chemical pesticides that might be unaffordable and/or environmentally undesirable for use in cash-poor, labour-intensive farming systems. There is a small but growing use of microbial pesticides such as the crystalline (cry) proteins produced by the Bt bacterium and biocontrol agents such as pheromones, growth regulators and hormones. There is also an increasing acceptance of alternative pest control agents via the various forms of integrated pest management (IPM) (FAO, 2005a). For example, Bt sprays are being used in Malaysia to control insect pests of oil palm such as the bagworm group (including *Mahasena corbetti* Tams, *Metisa plana* Wlk and *Cremastopsyche pendula* Joannis) and the rhinoceros beetle (*Oryctes rhinoceros*), and large-scale Bt production facilities have been set up. In India, Bt sprays have also been used successfully at village level in Andhra Pradesh (Puente-Rodríguez, 2007).

Fungi are increasingly used as highly target-specific pest management agents that can often replace chemical pesticides. One example is the desert locust, a sporadic pest that can have a severe impact on food production over wide areas of North Africa. Between 2003 and 2005, conventional control using chemical sprays required 42 million litres of mainly organophosphate pesticides over about 13 Mha. While there were no reported instances of serious animal or human health problems, the cost of safety measures was high and there was significant environmental damage (FAO, 2007d). For these reasons, FAO and other partners have been developing alternative bio-based control strategies. These have involved a combination of *Metarhizium* fungi which are existing pathogens of locusts and grasshoppers, plus the biocontrol agent phenyacetonitrile which is a hormone that affects the swarming behaviour of locusts. One particular isolate of *Metarhizium anisopliae* has been formulated as the proprietary agent Green Muscle® and is produced commercially by a South African company. Recent assessments of these biopesticides underlined the kinds of challenges that also confront the wider deployment of many other biotechnologies (FAO, 2007d and 2007e). These include further R&D to improve product formulation and efficacy in the field; improved production and quality assurance methods; accelerated registration for environmental release; improved awareness, capacity building and training for all stakeholders; and formal incorporation into crop protection strategies. *Metarhizium* strains have been used also as effective control agents against rhinoceros beetle and the Metarhizium Technology Centre in Malaysia has produced nearly 0.5 tonnes of pure *Metarhizium* spores for future crop treatments (Moslim *et al.*, 2006).

Plant nutrition

This category includes the production and use of biofertilizers and the use of nitrogen-fixing bacteria and/or mycorrhizal fungi to improve plant performance. Recent studies have shown that there are numerous plant growth-promoting rhizobacteria that not only enhance nutrient uptake by crops but also induce systemic tolerance to other abiotic stresses such as drought and salinity (Yang, Kloepper and Ryu, 2009). As with biopesticides, the use of bionutrition strategies carries the double benefit of reducing input costs for farmers and preventing nitrate and phosphate accumulation within soils and run-off into sensitive watercourses.

There are numerous examples of the use of these strategies in developing countries both to augment the nutritional status of crops and as alternatives to chemical supplements. For example, it was shown in Thailand that rhizobial inoculants can effectively replace chemical fertilizers for the production of soybean, groundnut and mung bean crops (Boonkerd, 2002). The use of *Rhizobia* in Thai soybean, groundnut and mung bean production between 1980 and 1993 produced estimated accumulated benefits of US$100, US$17 and US$4 million, respectively, for crop producers. However, the performance of inoculants can vary with micronutrient conditions in the field and according to the persistence of bacterial populations in different soils. Some studies have revealed the widely differing effects of inoculants in different locations, even within small areas, and significant variations in their performance over time (Hall and Clark, 1995). Therefore, in addition to agronomic factors, the knowledge and experience of local farmers is important in ensuring the effective application of biofertilizers. In Kenya, the UNESCO Microbiological Resources Centre (MIRCEN) developed a *Rhizobium* inoculant known as Biofix for sorghum crops that has been in use since 1981 (Odame, 2002). Elsewhere in Africa, biofertilizers are being developed for cowpea, groundnut, bambara groundnut and rice (FAO, 2005a).

In Mexico, a *Rhizobium*-based biofertilizer developed by the National University of Mexico for the common bean (Peralta *et al*., 2004) was commercialized in 2003 under the name of Rhizofer. It is sold either on its own or together with spores of the mycorrhizal fungus *Glomus intraradices*, to help the plant acquire soil nutrients and to solubilize phosphates. This commercial package also includes printed material and technical assistance. The biofertilizer has been used mainly in the central and northern regions of Mexico. To date, 20 000 ha from a total of 2 million sown in the country have been biofertilized with reportedly very satisfactory results. The use of this biofertilizer offers important savings in the cultivation of the common bean, and costs significantly less than chemical fertilization. Moreover, it improves soil biodiversity and promotes soil biological activity (Peralta, 2009).

The nutritional status of the soil can also be enhanced by using fungal inoculants to accelerate the breakdown of organic fertilizer. In the Philippines, inoculation of rice straw with the fungus *Trichoderma* reduced composting time to as little as 21–45 days depending on the type of plant residue used (FAO, 2009c). Following the success of this "rapid composting technology" (RCT), the Philippines government set up production units for the fungal agent and actively promoted the production and use of organic fertilizer by farmers' cooperatives, private enterprises and NGOs. An impact study concluded that rice and sugarcane farmers adopting RCT used significantly less chemical fertilizer and had higher yields and higher net incomes (Rola and Chupungco, 1996). For example, rice farmers using both organic fertilizer made via RCT and chemical fertilizer produced 15 percent more than farmers using chemical fertilizer only. Net income gains per ha were about US$171. The main advantages of the substitution of chemical with organic fertilizer were the positive effect on soil nutrient content as well as on soil tilth and texture, making organic fertilizer superior to the chemical fertilizers (Cuevas, 1997).

Genetic resource conservation and management

The need to conserve crop genetic resources is now widely accepted and generally justified for one or more of several reasons such as their importance as raw material for plant breeding to face future changes in market needs, production and environmental/climatic conditions, and their importance as a source of material for scientific research and future germplasm development. They are also part of our cultural and historical heritage, passed down from previous generations. In addition, the characterization of genetic resources goes hand-in-hand with conservation because it is fundamental both to our understanding of what is being conserved and to choosing which genetic resources should be conserved. Characterization can also play an important role regarding issues of ownership as well as access to and the benefit-sharing of agricultural genetic resources.

The key role of biotechnologies in the acquisition, management, conservation, protection, characterization and exchange of plant genetic resources is becoming ever more apparent (Karp, 2002; Peacock and Chaudhury, 2002; FAO, 2006a). Many biotechnologies already discussed here are being employed for germplasm management in the widespread network of public sector seed banks and resource centres across the world (Engels *et al*., 2002; FAO, 2005a; Hunter and Taylor, 2007; Murphy, 2007a). For example, relatively well established technologies such as cryopreservation, artificial seed production, somatic embryogenesis, and other forms of *in vitro* cell or tissue culture are extensively used for the conservation of genetic resources for food and agriculture in developing countries, especially for vegetatively propagated plants which can easily get contaminated with pathogenic micro-organisms. Whereas phenotypes (e.g. yield, growth rate) and morphological traits (coat colour, seed shape) are influenced by both genetic and environmental factors, the use of molecular markers and genomics reveals differences at the DNA level that are not influenced by the environment. These molecular tools are having an increasing impact on the study and management of genetic resources.

1.4 ANALYSIS OF EXPERIENCES WITH BIOTECHNOLOGIES IN DEVELOPING COUNTRIES OVER THE PAST 20 YEARS

As with other maturing technologies and as described in Section 1.3, experiences with crop biotechnologies have been mixed. Although transgenesis is being increasingly deployed, the vast majority of new biotech-derived crop varieties remain non-transgenic. Transgenesis is lagging significantly behind owing to severe limitations on the kinds of traits available, complex IPR and regulatory issues, and often negative public perceptions (Stein and Rodríguez-Cerezo, 2009; Ramessar *et al*., 2009). On the other hand, major successes encompassing the whole range of desirable agronomic traits have been achieved via non-transgenic technologies. In the future, breeders will have the additional benefit of genomic and metabolomic technologies which will contribute to all forms of crop improvement. While there have been significant successes in farmer adoption of a few first generation transgenic varieties, there have also been unexpected market setbacks as farmers seek to avoid high seed costs and other restrictions. In some cases, although the technology was sound and the products were potentially beneficial to farmers, there was little or no adoption due to often predictable infrastructure or market deficiencies. A promising approach to addressing such problems is farmer participatory research (FPR), but this must be coupled with measures to address a wide range of cross-sectoral issues from extension services to civil society programmes. The uptake of biotechnologies is therefore gradually improving but remains patchy.

Some of the main factors affecting the use of biotechnologies in developing countries in the past are highlighted below.

1.4.1 Focus on smallholders

Even where there is strong development of biotechnologies within the public sector, they are not always directed towards improving smallholder crops (Kiers *et al.*, 2008). There have been concerns among some policy-makers in industrialized countries and among others in both the private and public sectors that assisting developing country smallholders with crop biotechnologies might not always address overall poverty reduction (Tschirley and Benfica, 2001; Collier, 2008). However, this thesis has been increasingly challenged and the case for supporting smallholder development as a major mechanism for reducing poverty and food insecurity remains robust (Peacock *et al*., 2004; Lipton, 2006; Hazell *et al*., 2007; FAC, 2009). Indeed, recent data from Vietnam, Africa and elsewhere show that small-scale agriculture can act as an important engine of national economic growth and help generate relative affluence from the bottom up in a society (Gollin, Parente and Rogerson, 2002; Murphy, 2007a; Jama and Pizarro, 2008). In India and South America, transgenic crops such as Bt cotton and herbicide tolerant soybean have also had a positive impact on millions of small farmers (FAO, 2004; Trigo and Cap, 2006; Gruère, Mehta-Bhatt and Sengupta, 2008). Smallholders are responsible for an important share of developing country food production and can play a key role in poverty reduction especially in rural communities. But smallholders cannot be always assisted by biotechnology-driven crop improvements in isolation, so wider cross-sectoral challenges must also be addressed at the same time. For example, it is well known that hunger and food insecurity have much deeper and more complex roots than mere crop yields (Pereira, 2008).

Most new biotechnologies have originated outside developing countries, so improved North-South links to facilitate capacity building and technology flow are especially crucial. Unfortunately, efforts to build enduring links between public sector crop research institutions in industrialized and developing countries have been erratic and only partially effective.

1.4.2 Investments in biotechnological R&D

Investment patterns in biotechnology R&D are highly uneven in developing countries. Care should therefore be exercised when discussing all such countries together (as in this Chapter). For example, China recently invested US$500 million in biotechnologies and is now an acknowledged global leader in agriculturally applied plant genomics (USDA, 2008). Indeed, much of the spectacular economic growth of modern China has been underpinned by huge gains in agricultural productivity that enabled the country to remain self-sufficient in many major crops despite steady increases both in population and in per capita food consumption (IAASTD, 2008). Brazil and India each spend less than one tenth of the Chinese agricultural biotechnology budget, but vastly out-spend the whole of sub-Saharan Africa (e.g. for India, see Sharma, Charak and Ramanaiah, 2003). China, India and Brazil are now recognized as significant global centres of emerging excellence in biotechnology that will soon be on a par with the United States and the European Union (Dutton, 2009). A note of concern here comes from a recent downward revision in estimates of global agriculture R&D spending, especially in developing countries (Beintema and Stads, 2008).

The lack of adequate and sustained investments remains a major limiting factor in most developing countries (IAASTD, 2009). This situation may be exacerbated by the consequences of the current economic downturn.

1.4.3 Biotechnology capacities

Insufficient and unstable investments in R&D are only a part of the problem. A further constraint in developing countries is the limitation of capacity to generate, adapt or utilize potentially beneficial biotechnologies due to limitations in agricultural research systems. Such limitations include:

- absent or inadequate policies for agricultural R&D at government and institutional level (Spielman, Hartwich and von Grebmer, 2007);
- poor scientific, political and public awareness of the opportunities and risks of different crop biotechnologies (Gressel *et al.*, 2004; Cohen, 2005; Pender, 2007);
- inconsistent policy and regulatory regimes regarding issues such as IPR enforcement, the protection of plant and animal health, biosafety, food safety and bioethics (Diao *et al*., 2008; Stein and Rodríguez-Cerezo, 2009);
- deficiencies in economic and physical infrastructures (including trade markets) that impede farmer ability to capitalize on new biotechnologies (Murphy, 2007a; Diao *et al.*, 2008);
- the weaknesses of research institutions that do not allow efficient implementation of research projects;
- insufficiently educated/trained human resources and the lack of appropriate incentive schemes for capacity building, the retention and motivation of staff through competitive career development opportunities.

1.4.4 IPR and other regulatory issues

The status of agricultural IPR in different countries and trade blocks is inconsistent and uncertain (Murphy, 2007a; Gold *et al.,* 2008; Smith, 2008, Yamanaka, 2008). Linked to these IPR problems is the fact that many technology leaders and products (e.g. new crop varieties) are part of private sector bodies with no explicit public good missions. A major challenge is to find ways to facilitate the uptake of agricultural R&D discoveries into developing countries and non-commercial crop staples without compromising the innovative processes that often produce such discoveries. In some cases, this requires balancing the ability to innovate, driven largely by the assurances that IPR provides, with ensuring that access to these innovative technologies is provided to those who need it most.

Many crop biotechnologies originate from discoveries in the public sector but require significant private sector involvement for effective reduction to practice (Hartwich, Janssen and Tola, 2003). Moreover, several aspects of crop biotechnologies, including some key plant transformation and regeneration steps, are subject to private sector IPR, which can significantly limit the freedom to operate of public bodies wishing to develop new crop varieties. This has led to the establishment of a range of PPPs with the broad objective of making the products of existing biotechnologies available to smallholders in developing countries, normally in areas where the private sector has little commercial interest. The private and public sectors should establish a more inclusive intellectual property landscape that recognizes the special needs of subsistence and commercial farmers alike in developing countries.

The rollout of GM crops has at times been inhibited by high transaction costs and complex, inconsistent regulatory requirements (Stein and Rodríguez-Cerezo, 2009), sometimes leading to IPR avoidance and piracy of traits. This could be regarded as a qualified market failure. A comprehensive analysis of IPR and regulation is beyond the scope of this document, and these aspects are covered in much greater detail in Chapters 8 and 9.

1.4.5 Link between biotechnology R&D and plant breeding programmes

It is important to underline that biotechnology can assist and expand, but not substitute, traditional plant breeding programmes. The presence of skilled personnel and adequate facilities for the identification of appropriate parents and segregating materials, as well as the selection of improved lines for their stabilization and agronomic assessment, are essential. Even countries that decide to rely on research results obtained abroad, for instance in neighbouring countries with similar ecological conditions, need capacities for the evaluation, adaptation and adoption of improved lines developed elsewhere. Investments in biotechnology infrastructures and human capacities cannot therefore be made at the expense of conventional breeding or agronomic research and strong breeding programmes must remain at the core of crop improvement.

1.4.6 Farmer involvement in research and breeding

The relevance and uptake of biotechnology advances in crop improvement by smallholders can be improved using participatory research approaches. Participatory approaches to research can lead to more relevant, site-adapted and socially acceptable solutions to real-world problems and technological constraints in agriculture and natural resource management. Research participatory approaches are used in problem identification, planning, implementation and research transfer and/or evaluation. Experiences using FPR for the improvement of crop production have been made in the area of plant breeding and are known as participatory plant breeding (PPB) (Murphy, 2007a), and in IPM, often using farmer field schools.

Recent evaluations of the effectiveness of FPR and PPB have been encouraging (Ashby and Lilja, 2004; Scoones and Thompson, 2009). Small farmers often produce in marginal areas with limited access to knowledge, improved technologies and inputs. Conventional breeding has focused heavily on "broad adaptability" and major traits, resulting in high yielding varieties with pest and disease resistance that produce well when input levels are high, but poorly in the marginal conditions under which cash-poor farmers often operate (Murphy, 2007a). Traits such as resilience to adverse conditions (e.g. water scarcity), ease of harvest and storage, taste and cooking qualities, speed of crop maturation, and the suitability of crop residues as livestock feed, can be of high relevance to small farmers. Involving them in the breeding process from the beginning will help to develop new crop varieties and agricultural practices that are better adapted to the areas where they produce and more relevant to their farming conditions and needs. Examples of participatory approaches in plant breeding are described by Ceccarelli *et al*. (1997 and 2000), Toomey (1999), Almekinders and Elings (2001), Vernooy (2003), and Morris and Bellon (2004).

While participatory research can generate a range of direct and indirect benefits for participants, careful attention needs to be paid to achieving equitable impacts. Participatory approaches must consider power sharing and participant selection, or risk missing important contributions from women and other marginalized groups (Johnson *et al*., 2004). Gender issues can play an important role in many aspects of agriculture (Boserup, 1970), and have been shown to be relevant also for plant breeding/management/processing and the uptake of new technologies (Wambugu *et al.*, 2000; Nguthi, 2007; Smale and Tushemereirwe, 2007; CGIAR, 2008). For example, many traits relevant for the harvesting, threshing, milling and cooking of grains can be more or less invisible even to the men in the local community, and may be overlooked by scientist-breeders. However, these processing-related traits may be of paramount concern to the women who actually carry out such tasks as they prepare food from the crops on a daily basis. The importance of women in the outcome of breeding projects has been shown in several case studies in Côte d'Ivoire, where the selection of inappropriate traits by poorly-informed scientific breeders led to the rejection of new varieties by women farmers (Lilja and Dalton, 1997; Dalton and Guei, 2003; Dalton, 2004).

Modern biotechnologies successfully applied in conventional plant breeding programmes have recently also been introduced using participatory approaches. MAS has been used as part of a PPB approach for developing rice with improved stress tolerance (Steele *et al.*, 2002 and 2004; Witcombe, Joshi and Goyal, 2003), for developing higher yielding maize (Virk *et al.*, 2003) and in small-scale potato crop systems in the Bolivian Andes (Puente-Rodríguez, 2008). Participatory approaches have been used for varietal selection of NERICA rice (see Part 1.5), and for the adaptation and diffusion of NERICA technologies for rice-based production systems in Africa (Somado, Guei and Keya, 2008). Similar schemes are being piloted for other crops and together with more effective extension services, should be considered integral to the process of crop improvement (World Bank, 2007). FPR approaches have also been applied to the production of micropropagated planting materials in many countries including Colombia and Bolivia, and to the production of biofertilizers and biopesticides in Colombia, Ecuador and Peru among other countries, leading to the establishment of micropropagation laboratories managed by farmers.

1.4.7 Technology uptake

Crop varieties and management systems developed by even the most sophisticated new technologies will have little impact on improving food security in developing countries unless they are effectively taken up by farmers on a sustained, long-term basis (Tripp, 2001). Indeed, while modern breeding and crop management technologies can easily take a decade or more to make improved materials available to farmers, it is a telling but often overlooked fact that the widespread on-farm adoption of such technologies can take much longer (FAO, 2007f). Technology uptake, or lack thereof, is an abiding concern for the improvement of food security at small farmer level. For example, it is estimated that simply by applying existing recommended practices of crop management, Ghanaian farmers could double or treble average yields of most staple crops (Al-Hassan and Diao, 2007).

Seed systems

One of the major hurdles to the wide-scale use of improved varieties obtained though biotechnological approaches in developing countries is the weakness of the local seed systems. In many developing countries, the vast majority of seeds used in agriculture are supplied by informal seed systems which include farm-saved seeds, seed exchanges between farmers and seeds purchased from local markets. The informal seed system can, in some instances, play an important role in the conservation of local landraces and other precious genetic resources, and satisfies the demand of low-cost inputs, but the seed supplies often do not meet acceptable quality standards. Seeds of improved varieties obtained by biotechnological means combined with conventional breeding approaches such as MAS-derived varieties, are usually multiplied and distributed through formal seed production and distribution schemes which offer high-standard propagation materials but which often lack the capacity to meet the seed demand for these new varieties and to reach vast numbers of small-scale farmers.

For example, the current demand for seeds of NERICA varieties in West Africa exceeds their supply. Also, the seeds offered by the formal production and distribution systems are frequently more expensive and cannot be accessed by farmers with low purchasing power. In addition to infrastructure, government support within developing countries may consider providing financial incentives to farmers to plant higher yielding varieties that will ultimately bring increased revenue back to the farmer.

Extension services

In a recent report on seed delivery systems in Africa, Guei, Somado and Larinde (2008) stated that: "Most extension services are characterized by a lack of information, technical capacity and logistics for timely delivery of advice to farmers. They have inadequate capacity in terms of personnel and are unable to formulate and implement good and sound technology transfer approaches". Even in comparatively well developed and resourced cropping systems such as oil palm in Malaysia, the effectiveness of extension services to smallholders has come in for criticism (Jalani *et al.*, 2002). Extension services are fundamental to the success of agricultural development, including advice to farmers and local seed production and distribution. Because they are an end-of-pipeline function, extension services are frequently overlooked by researchers, policy-makers and in government budget allocations. Importantly, the linkages between agriculture researchers, extensionists and producers are quite weak, resulting in the poor uptake of innovations, research that fails to reflect smallholder needs, and the delivery of the wrong type of extension education programmes (FAO, 2001). And yet, without a good extension service the introduction of even the best new crop varieties may be delayed or prevented (World Bank, 2007). Some of the problems with extension services include poor human resources, inadequate operational and transportation support, and inappropriate orientation and methodological approaches. Extension agents also have a particularly difficult and often isolated role that may be hampered by poor or inappropriate training, insufficient technical support, lack of motivational incentives, unrealized expectations of farmers and external pressures from third parties such as private seed merchants or NGO representatives.

A report from 39 African countries indicated that nine of them had no extension services at all, while ten more relied on overseas development agencies (Guei, Somado and Larinde, 2008). Even where extension services exist in a country, they are not always able to respond to new crop introductions. For example, when Bt cotton was introduced to India, there was a complete lack of government provision of such services and farmers relied solely upon private seed companies for knowledge dissemination and advice (Solution Exchange, 2007; Gruère, Mehta-Bhatt and Sengupta, 2008). This is clearly unsatisfactory and in the case of Bt cotton in India it contributed to public scepticism about the technology. Clearly, there is a significant structural problem if so many countries do not oversee the provision of national or local extension services to farmers. The case for a qualitative improvement in the status and local management of extension services as an integral aspect of crop development should be emphasized more strongly to governments and policy-makers. The potential for better designed technologies and better technology uptake via well managed and better linked research-extension-producer networks to lead directly to increased food production is demonstrated by the case of potatoes in China. Following a change in government policy in the 1980s, potato cultivation was encouraged in the country. Advanced breeding materials were obtained from the International Potato Center (CIP) in Peru and developed by the Crop Research Institute in Yunnan Province into locally adapted varieties such as Cooperation 88 which greatly outperformed existing varieties. A combination of vigorous extension services and expanding consumer markets led to an increase in the potato-growing area from 2.45 to 4.7 Mha, and in yields from 9.7 to 16 T/ha between 1982 and 2002 (Reader, 2009). This made China the largest potato producer in the world with output reaching 72 Mt or one quarter of the entire global output by 2007 (FAO, 2009d). Improved seed and extension services able to respond to market demand have been cited as factors in the positive economic impact of sweet potatoes at village level in China (Fuglie *et al.*, 1999).

1.5 CASE STUDIES OF EXPERIENCES WITH CROP BIOTECHNOLOGIES

This Part includes several brief case studies of experiences with biotechnologies in developing country crops. In reality, most of them cannot be labelled as full successes or failures because each case may present positive and negative consequences at the same time. Nevertheless, some experiences have brought improved food security to large numbers of people in developing countries such as the African-Asian rice hybrids (NERICA), rice interspecific hybrids in Asia, and mutation breeding. The study of socio-economic impacts of biotechnological innovations in developing countries is still very patchy or limited and few reports are solid and scientifically sound (FAO, 2009c). In most cases it is therefore impossible to draw clear conclusions. In many instances even the more negative experiences can be most accurately described as temporary halts in progress rather than permanent setbacks.

1.5.1 Wide crossing to improve African rice – NERICA

There is little doubt that one of the outstanding recent success stories of African agriculture is the development of a new interspecific form of rice, NERICA. The original NERICA varieties were developed in the 1990s by a team of breeders at the Africa Rice Center, Côte d'Ivoire (Jones *et al.*, 1997a and 1997b; Jones, 1999a and 1999b). NERICA varieties have led to yield increases of up to 50 percent in upland rice crops. These replaced low-yielding, lodging and shattering-prone *O. glaberrima*. While rice tends to be a cash crop for small-to-medium-scale farmers in East and Southern Africa, it is very much a subsistence crop in West Africa where the majority of African rice is produced.

The NERICA lines were created by crossing *O. glaberrima* and *O. sativa*. As these two species do not naturally interbreed, it was necessary to use a range of advanced tissue culture technologies to enable the hybrid plants to survive. In particular, embryo rescue and anther culture methods ensured that crosses survived to produce plantlets to grow on to full maturity. As with many other hybrids of two relatively inbred lines, NERICA varieties display very good degrees of heterosis. For example, they grow faster, yield more, and/or resist stresses better than either parent. Some features of NERICA varieties include: an increase in grain head size from 75–100 grains to 400 grains per head; yield gains from 1 T/ha to 2.5 T/ha and up to 6–7 T/ha with fertilizer application; 2 percent more protein than their African or Asian parents; plus better pest and weed resistance and more tolerance of drought and infertile soils than Asian rice. During the 1990s, about 3 000 lines were developed, many of which have been released and are already being grown by farmers in West African countries. The high-yielding new rice varieties are drought and pest resistant. Their unique adaptation to the growing conditions in West Africa has helped increase yields and has the potential to benefit 20 million farmers (Sarla and Mallikarjuna Swamy, 2005; Kijima, Sserunkuuma and Otsuka, 2006).

The Africa Rice Center has reported the release of NERICA varieties in 30 African countries, and these are now planted in about 0.2 Mha, mainly in Côte d'Ivoire, Guinea, Nigeria and Uganda. Uptake is likely to expand as more varieties are released. In sub-Saharan Africa, over 100 upland varieties are being field tested by the Africa Rice Center in 30 countries and 60 lowland/irrigated varieties are being field tested in 20 countries (FAO, 2009c). Many NERICA varieties are particularly suitable for use in the rainfed upland agrisystems where smallholders lack the means to irrigate or to apply chemical fertilizers or pesticides (Somado, Guei and Keya, 2008). In addition to benefiting rural economies, NERICA has the potential to assist cash-strapped national economies by reducing the cost of food imports. It has been estimated that the introduction of NERICA in Guinea alone led to import savings of US$13 million in 2003 (Harsch, 2004). An evaluation by Obilana and Okumu (2005) discussed the livelihood impacts of NERICA in Benin, Guinea and Mali and concluded: "NERICA rice impacts the whole spectrum of human life problems in the areas of health, nutrition, education, female empowerment, environmental protection, and improved collaboration and partnerships for enhanced development. The impacts in all the three countries are hence the same although they vary in magnitude". By the 2008 season, NERICA varieties were playing a key role in the record rice harvests being enjoyed across Africa (FAO, 2009e).

1.5.2 Wide crossing to improve Asian rice

In Asian rice, wide crosses have been especially effective in addressing serious viral diseases such as the grassy stunt virus to which cultivated rice has little genetic resistance. The virus is transmitted to the plant by a leaf-dwelling brown planthopper, *Nilaparvata lugens.* By the 1960s and 1970s, grassy stunt virus had become endemic in rice crops throughout Asia and threatened food supplies. During a collecting expedition, scientists from IRRI found a tiny population of a wild rice relative from India, *Oryza nirvara*, resistant to the virus. Normally, it would be impossible to cross these two rather different *Oryza* species, but IRRI breeders used tissue culture to produce a crude wide hybrid of this wild Indian plant and Asian rice. Eventually, after many years of repeatedly backcrossing this hybrid with local rice varieties, three new virus-resistant varieties of Asian rice were released in 1974 to subsistence farmers (Barclay, 2004). Despite repeated searching, the original Indian population of virus-resistant *O. nirvara* was never found again and may well have been lost forever. Luckily, some of the useful *Oryza nirvara* genes have been saved by the IRRI scientists, although these genes are now located in the genomes of the three new varieties of Asian rice, *O. sativa*.

1.5.3 Soil bio-inoculants in Kenya

The importance of extension services and overall infrastructure in biotechnology uptake is highlighted by the case of the rhizobial inoculant Biofix in Kenya. Although Biofix has been marketed since 1981 and its effectiveness was clearly demonstrated in field trials within the country, national adoption rates remain relatively low. Explanations include poor distribution systems, lack of product information, insufficiency of extension services, poor access to credit, unsuitable package size, and other constraints (Odame, 1999). The public image of Biofix may also have been tarnished by reports of mixed performance, possibly due to similar factors to those discussed earlier for *Rhizobia* in Thailand (Part 1.3.3). One of these site-specific factors is the need for simultaneous phosphorus provision for certain soil types. Having been identified, this particular problem is now being addressed by the manufacturers with an improved product that contains rock phosphate to counter phosphorus deficiency. In contrast, the uptake rate of Biofix was much higher among smallholders in the Nyeri district of Kenya. Here, there are organized groups of farmers who have ready access to and clear information about the product (Odame, 2002). One factor in the success of Biofix in Nyeri may be peer group encouragement because successful implementation of the technology by neighbours within a local social network is highly visible. Similar peer group-based strategies, such as farmer clubs or societies based on common access to the crop/technology in question are increasingly being used by extension services.

1.5.4 Mutation-bred crop varieties

Public agencies, including the Joint FAO/IAEA Division and universities have been effective proponents of mutagenesis technology and there are essentially no IPR barriers to its deployment for public good crop breeding. Hence, many mutagenized crop varieties have been produced by and for developing countries. More than 2 700 varieties of mutation-bred crop varieties have been released worldwide, mainly in developing countries (FAO and IAEA, 2008). They include all the major staple species (Ahloowalia, Maluszynski and Nichterlein, 2004) and have been cultivated in at least 59 developing countries, mostly in Asia. The largest mutation breeding programmes are in China and India but dozens of other countries are also using the technology (Maluszynski, Szarejko and Maluszynska, 2003; for review see Kodym and Afza, 2003). Widely used mutagenized crops include: Soghat bread wheat in Pakistan, Zhefu rice in Thailand, Shwewartun rice in Myanmar, and Bajra pearl millet in India. In Vietnam, three new varieties of rice with improved food quality and salt tolerance have been developed since 1996. Since their release in the Mekong Delta region, they have increased smallholder incomes by US$350/farmer/year and include some of the top export varieties (FAO and IAEA, 2008).

1.5.5 Bt cotton in India

Cotton is an important commodity crop in India, growing in most agroclimatic zones and providing a livelihood for more than 60 million people working in agriculture, processing, and textiles. According to averaged production statistics between 1997 and 2006, India was the third largest global producer of cotton, but yields were only ranked 70th among the producing countries. This strikingly low-yield performance was caused by factors such as persistent pest problems and lack of irrigation facilities and by issues inherent in small-scale, non-mechanized and resource-poor farming systems. In an effort to increase cotton yields, the Indian government authorized the introduction of transgenic cotton varieties with the Bt insect-resistant trait in 2002, potentially enabling the crop to withstand pests such as the bollworm as well as reducing pesticide requirements (USDA, 2005). Between 2002 and 2008, India rapidly increased its cotton production to over 9 Mha, becoming a major exporter, and in 2007/08 it passed the United States in output to become the second largest global producer of cotton after China. According to the Indian Cotton Advisory Board, Bt cotton was the major factor behind the increased production of cotton from 15.8 million bales in 2001/02 to 24.4 million bales in 2005/06 (ISAAA, 2006). There has also been a significant increase in cotton yields from 300 kg/ha in 1997 to 400 kg/ha in 2003/04, and more than 500 kg/ha in 2006/07 (Gruère, Mehta-Bhatt and Sengupta, 2008).

The uptake of Bt cotton in India has continued to rise as more varieties, both official and illicit, appear on the market. In July 2007, Indian government agencies approved 73 new commercial varieties of hybrid Bt cotton. At that time, a total of 135 hybrid Bt cotton varieties were available on the market plus numerous unofficial varieties (SABP, 2007). It is noteworthy that despite its undoubted commercial success in most states, Bt cotton in India has been surrounded by controversy since its introduction in 2002 (Gruère, Mehta-Bhatt and Sengupta, 2008). Various groups have contested its effectiveness, reporting that farmers have lost income due to lower yields and higher than expected pesticide use, while some groups reported (albeit not in scientific journals and despite contradictory evidence) alleged toxic effects of Bt cotton on livestock health. Others have objected to the high prices for Bt cottonseed charged by seed companies and this has led to widespread unofficial seed trading. It is also the case that the introduction of Bt cotton in India was mediated by company advisors rather than government extension agents, which leaves room to question the partiality of advice received. This has led to assertions of so-called "agricultural de-skilling" as farmers followed their neighbours as part of a "fad" to buy Bt cottonseed (Stone, 2007). However, as discussed above in case study 1.5.3 from Kenya, the follow-my-neighbour strategy is regularly used by extension services in attempts to disseminate new seed or agronomic methods among farmers.

According to other reports, Bt cotton has also been associated with allegations of increased rates of farmer suicide. Although these reports seem to have been disproved, with Gruère, Mehta-Bhatt and Sengupta (2008) concluding that "our analysis clearly shows that Bt cotton is neither a necessary nor a sufficient condition for the occurrence of farmer suicides", the association between farmer suicide and Bt cotton is still widely believed in many quarters. Indeed, the whole topic of the performance and social context of Bt cotton in India is characterized by polarized viewpoints and a dearth of unequivocally reliable evidence. There appears to have been a tendency for supporters of Bt cotton to overstate its benefits and for its many critics to exaggerate its shortcomings, whereas numerous articles instead report a more complex and mixed situation (Qaim and Zilberman, 2003; Bambawale *et al.*, 2004; Rao, 2004; Morse, Bennett and Ismael, 2005; Shah 2005, 2008; Smale, Zambrano and Cartel, 2006; Smale *et al.*, 2006, 2009; Herring, 2007, 2008; Stone, 2007; Glover, 2009).

For example, there is little doubt that the performance of Bt cotton has varied significantly in different regions of this vast country. Average national cotton yield improvements and farmer revenue gains from the use of Bt varieties were in the region of 30–40 percent, and such values were found in the states of Maharashtra and Tamil Nadu. However, there was a decline of 3 percent in both yield and revenue gains in Andhra Pradesh, while farmers in Karnataka reported increases of 70 percent (Raney, 2006). In some cases, these wide variations were due to climatic effects. For example, the initially negative performance of the varieties in Andhra Pradesh was mainly due to severe drought conditions to which the Bt hybrids were not optimally adapted (Qaim *et al*., 2006). An important indicator that does not necessarily correlate with yield/revenue gains is overall profit margins, where the national average increase was 69 percent, but Tamil Nadu reported 229 percent while Andhra Pradesh suffered a decline of 40 percent. To quote Herring (2007): "Bt cottons have been in the field too short a time for definitive assessment of either biological or economic success across so varied an agro-ecology as India; results vary with seasonal variations of pests, weather and local agronomics".

On balance, the limited available evidence supports Bt cotton as a qualified success in most, but not all, parts of India. In several states, it has been very successful and has greatly increased overall national cotton yields and farmer/processor incomes. Moreover, as of 2008 more than 270 Bt cotton varieties were available in India including lines specifically adapted to all the major cotton-growing regions of the country (James, 2008). On the negative side, it has polarized some sections of Indian society and contributed to a somewhat tarnished image of aspects of GM technology. Also, its high technology fees have led to IPR transgressions that might adversely affect the future development of other commercial crops. The wider negative image of Bt cotton in some circles in India might be associated with the provenance of the technology, i.e. it comes from an overseas private-sector source in contrast to many previous, less controversial, crop improvement biotechnologies that have often come from indigenous public-sector sources (Murphy, 2007a). This contrasts with the less controversial locally developed Bt cotton in China. The situation is less clear in South Africa, where modest yield and profit gains were reported from a two-year survey of smallholders (Thirtle *et al.*, 2003), but a later study showed a more complex picture (Shankar and Thirtle, 2005). More recent studies of Bt and herbicide-tolerant maize performance in the KwaZulu Natal region of South Africa over the 2006/07 growing season also revealed a complex picture (Gouse *et al.*, 2009). Some farmers of the GM varieties had substantially higher yields but both GM technologies had very little impact on efficiency, and it was concluded that the tillage system was a key determinant of efficiency levels. As stated by the authors: "The results mostly serve to show how dangerous it is to make any inferences from small sample surveys in one production season".

1.5.6 Micropropagation of oil palm

A risk with mass clonal propagation by micropropagation is the creation of abnormalities during the tissue culture process itself. In the 1980s, a commercial scheme to mass propagate millions of oil palm plantlets from superior breeding lines in Malaysia foundered when the maturing trees were found to have a serious abnormality in their floral development (Corley, 2000). This so-called "mantling" phenotype led to a failure of fruit formation and the trees were effectively useless (Corley and Tinker, 2003). In the case of oil palm, the problem was compounded by the fact that fruits do not normally appear on the plant for about five years. This meant that the abnormalities were not discovered until the trees were already established in mature plantations that had been expensively maintained for several years. At the time, this was a significant setback for Malaysian oil palm development and the desired increases in production were only maintained by an expansion of plantation area. Varietal development and yield gains were also impeded by the slower rates of alternative propagation methods.

More recently, prospects for mass clonal propagation of oil palm have improved significantly. Several private and public sector research programmes have investigated the causes of the mantling phenotype which appears to be due to genotype-dependent epigenetic changes induced by altered patterns of DNA methylation that occur during tissue culture (Tanurdzic *et al.*, 2008). Thanks to this improved understanding of tissue culture/epigenetic interactions, clonal propagation of oil palm has now resumed in some plantations (Wong, Tan and Soh, 1997). Flowering abnormalities still occur, but can often be detected and removed at an early stage leading to much higher success rates in the production of fertile trees. While this technology was primarily developed for commercial plantations, over one third of oil palm yield is generated by smallholders (Vermeulen and Goad, 2006). Globally, there are more than two million independent smallholders cultivating 5 Mha who also stand to benefit directly from such improved clonal lines. The Malaysian example illustrates some of the problems that can arise from tissue culture when manipulations used for plant regeneration cause developmental abnormalities. Despite these setbacks, tissue culture and mass propagation remain immensely valuable for agriculture in developing countries. It should also be stressed that apart from micropropagation, oil palm breeding is showing impressive gains via other biotechnologies. For instance, novel germplasm from Africa and South America is being integrated into Asian breeding lines with the assistance of gene discoveries showing monogenic inheritance for shell thickness, while advanced genomic and MAS methods are now being deployed to address the full range of agronomic traits (Sambanthamurthi *et al.*, 2009).

1.5.7 Biopesticides for control of migratory locusts

Several different biopesticides are available for controlling locusts. Among them, the most tested both in laboratory and in semi-field conditions and used for large-scale field trials (mainly in Africa) as well as in operational conditions (in Australia and China), is a mycopesticide formulated with the spores of the fungus *Metarhizium anisopliae* var. *acridum*. As biopesticides have a slower rate of action compared with conventional chemicals, they are usually sprayed if crops are not under immediate threat or when the environment is particularly sensitive.

For many years FAO has supported environmentally friendly alternatives to chemical pesticides for controlling locusts and has contributed to several field trials. In 2007, the first FAO locust campaign ever carried out using a biopesticide was successfully undertaken in

Timor-Leste (FAO, 2009f). A migratory locust outbreak which had developed since the beginning of the year was threatening maize and rice crops in a huge, inaccessible (only a few roads and no airstrip) and highly sensitive (many water bodies and rivers) area. Upon the recommendation of FAO, the Ministry of Agriculture, Forestry and Fisheries (MAFP) of Timor-Leste agreed to use the biopesticide formulated with the spores of *Metarhizium anisopliae* var. *acridum* (trade name Green Guard®) in aerial and ground spraying operations. Under the framework of an emergency project funded by the Central Emergency Response Fund and implemented by FAO, the *Metarhizium* biopesticide was provided by FAO for aerial spraying operations in May 2007 against in-flight swarms of the migratory locust in the western part of Timor-Leste. They were supplemented in June by localized ground spraying operations against smaller infestations.

The operations were successful and resulted in the quick control of the outbreak, with no further spread of the locust populations (the locust adults were killed before egg laying) and no damage to the rice crops. There were no side-effects on human health or on the very sensitive environment of the Maliana area. It is also important to note that MAFP and FAO carried out a public awareness campaign prior to the aerial spraying operations, providing information about the locust situation and the use of a helicopter and a biopesticide to control the locust populations. More recently, in 2009, similar biopesticides were deployed as part of an international red locust emergency campaign in Eastern and Southern Africa. This was the first time that biopesticides were used against locusts on a large scale in Africa and a massive outbreak in Tanzania was successfully contained. This intervention is estimated to have averted potentially serious damage to the food crops of over 15 million people in the region (FAO, 2009g).

1.5.8 Hybrid sorghum in Africa

Sorghum is one of the most important crops in Africa where two of the main challenges it faces are periodic drought and competition from the often devastating plant parasite Striga or witchweed. Research at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in the Sudan resulted in the first hybrid varieties of sorghum for Africa that were both drought tolerant and high yielding. An early variety, Hageen Dura-1, produced 50–100 percent greater yield than traditional varieties and laid the foundations of a commercial seed industry in Sudan. Newer drought tolerant hybrid varieties in Niger have yielded 4–5 times the national average. In an unusual example of South-to-North technology transfer, African breeder Gabisa Ejeta used germplasm he had produced in the Niger and the Sudan to develop elite inbred lines of sorghum at Purdue University to generate commercial sorghum hybrids for the United States and international markets.

However, perhaps the most important sorghum hybrids were the Striga tolerant forms developed in the 1990s and widely disseminated in Africa after 2002–2003. It is estimated that Striga affects 40 percent of arable savannah land and the livelihoods of over 100 million people in Africa (Gressel *et al*., 2004). Ejeta and colleagues used a broad-based research approach involving molecular genetics, biochemistry and agronomy to identify genes for Striga resistance which were then introgressed into both locally adapted and more modern sorghum varieties (Ejeta, 2007). The new sorghum lines were thus broadly adapted to different African ecologies and farming systems and are now grown from Sudan to Zimbabwe. Finally, an integrated Striga management system was developed that has further increased sorghum productivity through a combination of weed resistance, soil fertility enhancement, and water conservation (Ejeta and Gressel, 2007). Meanwhile future research is focusing on identifying other yield-related genes such as early-season cold tolerance (Knoll, Gunaratna and Ejeta, 2008; Knoll and Ejeta, 2008). In 2009, the World Food Prize was awarded to Gabisa Ejeta in recognition of his achievements in improving the prospects of African sorghum farmers (World Food Prize, 2009).

1.6 CONCLUSIONS: LESSONS LEARNED

The preceding parts of this document have provided an overview of the current and past experiences of applying biotechnologies in the crop sector in developing countries. Based on these, a number of lessons can be learned that are summarized below.

Documentation of development, adoption and impact

Assessing the value of biotechnologies for rural development is quite difficult as the information related to their application and socio-economic impact in developing countries is very scant and sometimes inconsistent. Impact studies are often limited to the analysis of the production equation, and fail to pay due attention to the socio-economic effects of the newly introduced technologies.

Investments in biotechnology R&D

- Crop biotechnologies in general have developed incrementally over the past century although progress has accelerated greatly over the last two decades.
- Many crop biotechnologies have been used for the benefit of agriculture in developing countries and all have significant potential for future improvement.
- The most enduring successes to date have come from long-term public-sector crop improvement programmes addressing farmer-relevant problems.
- Farmers in developing countries, especially small farmers, cultivate crops and face problems that are particular to their cultural and environmental conditions and often have limited purchasing power to access proprietary technologies. The spillover from

private sector research in industrialized countries has therefore had limited impact on the livelihoods of subsistence farmers in developing countries.

- An analysis of the past shows that a wide range of existing and emerging problems related to food security can be tackled using crop biotechnologies in combination with other technologies.

Linkages between biotechnology and other agricultural R&D

- The major breeding and crop management successes to date have come from non-transgenic biotechnologies encompassing the full range of agronomic traits and practices relevant to farmers in developing countries.
- Transgenesis has had limited but real success in modifying a few simple input traits in a small number of commercial commodity crops which have also been adopted by some farmers in developing countries.
- Biotechnology programmes were effective when they complemented conventional plant breeding and agronomy R&D programmes and were intimately linked to strong extension programmes.

Policy development and priority-setting

- Even where there was strong development of biotechnologies within the public sector in developing countries, these were not always directed towards or made available to smallholders.
- An inclusive process of decision-making about appropriate crop biotechnologies in the context of scarce resource allocations was rarely adopted in developing countries, undermining the successful development of crop biotechnologies.

Capacity development

Key factors in the successful development of crop biotechnologies in developing countries are: appropriate policy development; strengthened research and extension institutions; and enhanced capacities of researchers and breeders.

Regulation of biotechnology use

- The rollout of biotechnologies was successful when complemented by the full range of cross-sectoral measures to ensure their efficient uptake by smallholders and effective downstream use in well-regulated and fair markets, both local and global.
- The lack of coherent national and international regulatory systems has created uncertainty and possibly reduced investments in biotechnology. This, in turn, has discouraged its adoption and use in developing countries.

Uptake of biotechnologies

- Experience has demonstrated that the uptake of improved varieties or technologies by smallholder farmers does not depend on their performance only, but also on equitable access, adequate infrastructures, appropriate extension capacities and the involvement of all relevant stakeholders.
- There are indications that farmer participatory research, including participatory plant breeding, is a useful approach for connecting high-tech scientists with the most disadvantaged subsistence farmers in developing countries.

Shared access to technologies

- Many resources, technologies and skills relevant for biotechnology development are either currently held by the private sector or are scarcely available to scientists in developing countries.
- A few developing countries have established solid plant biotechnology programmes sustained by substantial investments and have achieved remarkable progress in biotechnology development and adoption.

B. LOOKING FORWARD: PREPARING FOR THE FUTURE

1.7 KEY UNSOLVED PROBLEMS WHERE BIOTECHNOLOGIES CAN HELP

One of the major concerns for the future is the potential impact of climate change on agriculture. Changing temperatures and precipitation patterns will clearly affect the range of crops that can be grown in different regions and their manner of cultivation. In some cases, existing crops might continue to be grown but new varieties would be needed to cope with the changed conditions. Examples might include heat, cold, salt, or drought tolerant varieties of existing crop staples. In other cases, alternative crops may need to be grown or entirely new species domesticated in order to adapt to changed environmental conditions. The occurrence and severity of biotic stresses such as weeds, pests, and diseases will be altered. Once again, breeders will need to develop new stress tolerant varieties, possibly at relatively short notice. Related problems might arise from human impacts, and in some cases these will have similar solutions to those caused by climate change. For example, the lack of water in a region could be due to either drought or diversion by other people, and increased soil salinity could be caused either by climate-related inundation by seawater or by inappropriate irrigation practices.

In this Section, two principal topics are addressed: first, to identify a range of potentially problematic issues that will be important in the future and, second, to examine the role that different kinds of biotechnologies might play in dealing with them. Perhaps equally important is the availability of such biotechnologies and the local capacity for their development and/or exploitation in a particular country or region.

1.7.1 Biotic stresses

Existing diseases, pests and weeds

Historically, breeders have been successful in selecting resistance traits in many of the major crops but such achievements can be offset by the sporadic nature of some important disease and pest threats and the eventual breakdown of resistance, especially during heavy infestations. Many effective chemical treatments and agronomic practices are available to help farmers control fungi and nematodes, but there are no equivalent virus-control agents. The production of virus-free plantlets is effective for avoiding secondary infections (infections transmitted to the next generation crop by the planting materials), but is totally inefficient against primary infections. Therefore, combating viral diseases normally relies on endogenous resistance within the plant itself. In the absence of resistance, viral infections can be particularly devastating to a crop. This has stimulated efforts to engineer viral resistance into transgenic crops. The commercial cultivation of transgenic squash and papaya varieties with virus-resistance genes has already been approved in some tropical regions of developed countries and may soon be extended to some developing countries. In the medium term, the use of transgenesis and MAS to produce virus resistance in crops is a highly promising area, and is one case where this approach may well be the best option for combating this class of crop diseases.

As discussed previously, there are several effective biological strategies to replace or complement the chemical control of bacterial, fungal and nematode pathogens. Examples include IPM and biocontrol, and these approaches will benefit from new advances in biotechnology. In many developing countries, and indeed elsewhere, there are increasing financial, safety, and environmental advantages to such strategies especially given the widespread need for increased sustainability in agricultural practices. Another future option that could carry a similar range of benefits is the development of endogenous resistance to pests and pathogens through genetic modification (Gressel *et al.*, 2004) or conventional breeding, possibly assisted by molecular genetics. Technically speaking, and although several promising approaches have been demonstrated, this has been much more problematic to address than viral or insect resistance where single-gene resistance traits are more common. The broader question of engineering plants with increased disease resistance, regarding both what genes to use and how to ensure that they are expressed in the right place at the right time, has been examined by Gurr and Rushton (2005a, 2005b). The severe agronomic impact of pathogens and the limitations of chemical control have stimulated a wide variety of approaches to engineering resistance in crops. For example, in China, the *Xa21* bacterial blight resistance gene has been transferred to five rice varieties (Zhai *et al.*, 2000). In India, molecular MAS was successfully used in a backcross breeding programme to introgress three genes (*Xa21*, *xa13*, and *xa5*) for bacterial blight resistance into a local susceptible rice variety (Sundaram *et al.*, 2009). Antifungal agents such as phytoalexins and chitinases have also been expressed in plants (Shah, Rommens and Beachy, 1995). However, in developing fungal resistance within crops it is difficult to produce broad-spectrum durable resistance without transferring huge numbers of genes. In fact, fungi often evolve spontaneously in the field, overcoming the resistance. It is possible that in the longer term, additional transgenic crops resistant to bacterial, fungal and nematode pathogens will be developed but, at present, non-transgenic approaches may often be the more pragmatic option.

As far as resistance to pest insects is concerned, current approaches focus on genes conferring antibiosis or properties that adversely affect insect physiology. This type of resistance may become futile in the long run because insects can develop mechanisms to overcome the resistance. Another possible drawback of antibiosis-based pest resistance is that it can affect target and non-target organisms, damaging the crop-associated diversity. A promising research area is the development of pest resistance based on antixenosis, or plant properties that deter or prevent pest colonization by interfering with their behaviour (van Emden, 2002). Although generally under multigenic control and thus more difficult to manipulate genetically, antixenosis mechanisms are more specific and more environmentally benign. Antixenosis genes have been recently identified and mapped in several plant species, for instance in wheat (Castro *et al*., 2005), but the pathway to practical applications seems quite long.

Newly emerging threats

New crop pests and diseases are constantly emerging and with global transportation and trade can spread rapidly across the world. Some biotechnologies can be used both in surveillance and in breeding programmes to detect and then combat such threats. For example, one of the most serious crop diseases to emerge in recent years is a highly virulent strain of the wheat black stem rust, *Puccinia graminis* (Ayliffe, Singh and Lagudah, 2008; FAO, 2008b). Termed Ug99, the rust first emerged in Uganda in 1998–99, spread around East Africa in the early 2000s, and has now been detected in the Arabian Peninsula and Iran, with a high likelihood of further spread to major wheat growing areas of the Indian subcontinent (Hodson, Singh and Dixon, 2005). This disease has already overcome most of the rust resistance genes bred into wheat over the past 50 years since the early days of the Green Revolution. The US Department of Agriculture's Agricultural Research Service (USDA-ARS) has recently reported the presence of a new variant of the pathogen in Kenya (Comis, 2007). Over one billion people live in potentially affected areas and almost 120 MT of annual wheat production is threatened. The serious threats to food security posed by Ug99 and other emerging crop pathogens will only be satisfactorily addressed by an international effort using all available methodologies. In the case of Ug99, the threat is now being tackled by the Borlaug Global Rust Initiative, a multinational programme whose members include CIMMYT, the International Center for Agricultural Research in the Dry Areas (ICARDA), the Gates Foundation, FAO and USDA-ARS (Kaplan, 2009).

Two key areas where biotechnologies can quickly contribute to combating newly emerging threats are surveillance/detection and breeding for resistance. It has been alleged that the initial detection of the Ug99 outbreak was delayed due to a (perhaps understandable) reduction in the disease monitoring work by CIMMYT after a period of 40 years without rust outbreaks (Stokstad, 2007). In the future, improved molecular kits such as microarray-based systems might enable surveillance to be carried out more cost effectively and extensively, possibly by larger teams of non-experts supervised by smaller numbers of experts. By their nature, new threats are unknown, but the more the relationships between crops and pests/disease organisms in general are understood, the better are the prospects to mount rapid and effective responses. Rapid identification of new pathogens and especially their genome sequences will facilitate the development of control strategies based on previous experience with related disease organisms. Such measures have already been of immense benefit in the case of new human and animal pathogens such as the coronavirus that causes severe acute respiratory syndrome and the virulent influenza A-type viruses. For example, within days of the April 2009 outbreak of influenza A (H1N1) in Mexico, the entire genome sequence of the virus was publicly available online (NIH, 2009).

1.7.2 Abiotic stresses

Abiotic stresses are a particular concern in regions such as the Middle East and parts of Africa where climate change and increasing soil salinization are threatening crop yields in more than 170 Mha of farmland (Ashraf, Ozturk and Athar, 2009). Drought and salinization are already significant threats to agricultural productivity and among the most common causes of sporadic famine in arid and semi-arid regions. Extended episodes of aridity, normally caused by changes in rainfall patterns, were associated with the collapse of numerous civilizations around the world during the past 8 000 years (Murphy, 2007c). The increasing scarcity of water resources and fertile soils is likely to cause human conflicts at local and international levels that will exacerbate food shortages in the affected regions still further. Although abiotic stress is often regarded as a primarily external (i.e. environmental) factor in crop performance, there is also a great deal of untapped genetic variation in responses to such stresses in all the major crop groups (Boyer, 1982; Ribaut and Betrán, 1999; Forster *et al.*, 2000; Ribaut *et al.*, 2000; Harris, 2005; Bänziger *et al.*, 2006). In particular, genetic diversity within crop groups whether in the form of wild relatives or conserved landraces or other genetic resources can be a powerful source of useful variation for abiotic stress tolerance (Singh, Ocampo and Robertson, 1998; Almekinders and Struik, 2000; Langridge, Paltridge and Fincher, 2006). Biotechnology can play a major role here, by enabling the exploration of large germplasm collections without expensive testing against adverse environmental conditions. For example, an international effort to identify genetic loci associated with drought tolerance has recently started under the auspices of the Generation Challenge Programme.

Another potential component of abiotic stress tolerance in crops that has been much neglected by researchers and breeders is the rhizosphere, the soil region around the plant roots. While the structural and inorganic components of the rhizosphere have been well studied, very little work has been done on biological communities such as rhizosphere flora (FAO, 2008c), which can both promote plant growth and reduce the impact of stresses such as drought (Figueiredo *et al.*, 2008), salinity (Zhang *et al.*, 2008), and poor soil nutrition (Shaharoona *et al.*, 2008). While this approach is still in its infancy and has yet to be applied in developing countries directly, it carries the promise of addressing stress tolerance in the context of lower input nutrient management systems that would be highly relevant to such regions (Adesemoye, Torbert and Kloepper, 2008; Yang, Kloepper and Ryu, 2009).

It has been claimed that there is significant potential for transgenesis in modifying stress related traits (Wang, Vinocur and Altman, 2003). However, as researchers in the field have pointed out, our limited knowledge of stress associated metabolism in plants still constitutes a major handicap to effect such manipulations in practice (Vinocur and Altman, 2005). Another problem that farmers and breeders have long been aware of is the synergistic effect of different stresses on crop performance. It is often the combination of such stresses that is so deleterious to the crop in the field, rather than the effect of a single category of stress. However, molecular biologists have tended to focus (for understandable reasons) on single stresses applied in highly controlled environments. Unfortunately for this piecemeal approach, recent studies have shown that the simultaneous application of several stresses gives rise to unique responses that cannot be predicted by extrapolating from effects of stresses given individually (Mittler, 2005). The simultaneous presence of multiple stresses is the norm in open environments, so the success of molecular approaches in addressing them in crops will probably require broader and more holistic approaches than the somewhat reductive strategies employed until now.

Salinity

Salt and nutrient stresses together affect over 100 Mha of farmland, resulting in low outputs, poor human nutrition and reduced educational and employment opportunities (Ashraf, Ozturk and Athar, 2009). Salt tolerance was one of the earliest traits selected by breeders in intensive farming systems. Indeed, in ancient Mesopotamia about 4 200 years ago, Sumerian farm managers switched from emmer wheat to intensive cultivation of more salt tolerant forms of barley in an effort to combat increasing salinization and aridity (Murphy, 2007c). Efforts to select salt tolerant crop varieties, while partially successful, have been hampered by the complexity of the trait and the number of minor genes involved. One problem facing breeders is that crop improvement is often negated by a lack of effective germplasm evaluation during the full growth cycle of the plant (Munns, 2002, 2005; Munns and Tester, 2008). It can also be difficult to ascertain which mechanism of salt adaptation is being expressed in a particular species or developmental stage. Ashraf *et al.* (2008) have listed the following reasons for limited success in tackling salt tolerance: 1) breeding is time consuming and labour intensive, 2) deleterious genes are often transferred alongside desirable traits, and 3) reproductive barriers obstruct the transfer of favourable alleles from wide crosses. In the future, breeding technologies such as MAS and assisted wide crosses will enable breeders to address these challenges with more success than previously. A concerted R&D focus on breeding for salinity traits should be a priority during the next decade.

Salt tolerance has been a particular focus of claims for significant results from transgenic approaches. One of the key prerequisites for success in a transgenic strategy to develop salt tolerance is that it should be regulated as a simple genetic trait, i.e. one involving a very small number of genes. Although such apparently simple genetic regulation has been reported in some laboratory studies (Yamaguchi-Shinozaki and Shinozaki, 2001), it seems more likely that salt tolerance in most crops in the field is a rather complex multigene trait that has evolved differently in several plant groups (Flowers, 2004; Rozema and Flowers, 2008). However, there have been some promising successes in developing salt tolerance in model plants in the laboratory. For example, transgenic tobacco engineered to accumulate elevated levels of mannitol was able to withstand high salinity (Tarczynski, Jensen and Bonhert, 1992). Laboratory and small-scale field studies have shown that the accumulation of compounds, such as betaine or trehalose in transgenic plants may also enhance salt tolerance (Nuccio *et al.*, 1999). Rapeseed plants expressing an *Arabidopsis* vacuolar transport protein tolerated as much as 250 mM sodium chloride (about half the concentration of sea water and enough to kill most crops) without significant impact on seed yield or composition (Zhang *et al.*, 2001). A project to conserve mangrove genetic resources in India is studying and characterizing the genes involved in salinity tolerance from these plants and their associated species which are capable of surviving in highly saline environments. The genes thus isolated were transferred to crops such as rice and initial laboratory analyses have been promising (FAO, 2006b).

Despite these encouraging reports, it is not clear whether such relatively simple modifications will lead to a sustained effect on crop yields in more complex real world cropping systems where osmotic stress is often linked with a combination of other factors such as periodic aridity, mineral/salt buildup and/or erosion. This means that the jury is still very much out on the amenability of salt tolerance in the field to modification by transgenesis (Yamaguchi and Blumwald, 2005). It is known that salt tolerance must be an especially complex physiological trait because there are so many tolerance mechanisms in salt adapted plants in the wild. This should lead to some caution about claims in published studies that the transfer of one or a few genes can increase the tolerance of a wide range of field crops to saline conditions. As stated by Flowers (2004): "It is surprising that, in spite of the complexity of salt tolerance, there are commonly claims in the literature that the transfer of a single or a few genes can increase the tolerance of plants to saline conditions.... After ten years of research using transgenic plants to alter salt tolerance, the value of this approach has yet to be established in the field".

The way forward here is to investigate as many realistic strategies as possible. Nevertheless, given the present state of knowledge it is probably more appropriate to focus limited breeding resources on non-transgenic approaches while supporting research into the physiology and molecular genetics of salt tolerance for potential future application.

Drought tolerance

Like salt tolerance, drought tolerance appears to be controlled by a complex set of traits that may have evolved on numerous occasions as separate mechanisms in different plants and according to the dynamics (i.e. timing and intensity) of water shortages. In the near future, it is likely that aridity will increase in several parts of the world with FAO estimating that by 2025, 1.8 billion people will be living in regions of water scarcity (FAO, 2009h). This will be caused by factors such as localized lower rainfall due to climate change and the diversion of upstream water supplies from rivers, e.g. for dams or irrigation, thus depriving farmers in downstream regions. In the case of rice alone, over 70 Mha are already affected by drought stress (Ashraf, Ozturk and Athar, 2009). Given the predicted increase in long-term aridity, it is surprising that until relatively recently there have been few well resourced attempts to produce drought tolerant crops, even by publicly funded organizations. Such research is complicated by the sporadic nature and hugely varying intensity of drought or aridity episodes in the affected cropping systems. This also highlights the importance of the concept of genotype x environment x management, which is a crucial but highly complex multifactorial relationship that affects all efforts to select for drought tolerance and other abiotic stress traits. An integrated approach taking into consideration several aspects is therefore advisable (FAO, 2008c).

Meanwhile, basic research using reverse genetics and other genomic approaches is beginning to give a few clues about some aspects of drought tolerance mechanisms. For example, it was recently reported that the *erecta* gene, involved in transpiration efficiency, might regulate some of the genetic variation for drought tolerance in the model plant, *Arabidopsis* (Masle, Gilmore and Farquhar, 2005). Although the data are still very preliminary in this case and do not directly relate to major crop systems, the general approach merits further attention. However, as with salt tolerance it may turn out that in a practical field situation many other genes are involved in addition to *erecta* or its equivalents in other plant families.

As with salinity, advanced non-transgenic breeding methods are available to improve the agronomic performance of existing drought tolerant crops in arid regions. Of such crops, one of the most important is pearl millet which is grown on more than 40 Mha in Africa. The similarity in gene order, or synteny, between the pearl millet genome and that of the other major cereals (Moore *et al.*, 1995; Bolot *et al.*, 2009) means that once their loci are identified, drought tolerance traits could potentially be introduced into local varieties via MAS. Another option is to use wide crossing and tissue culture methods to cross millet with one of the other high yielding cereal crop species to create a new drought tolerant, high yielding hybrid species. Breeders have already used such a strategy to create the drought adapted rye/wheat hybrid, triticale, which is a completely new man-made plant species. Further breeding of triticale is now underway to extend its agronomic performance and drought tolerance especially in arid regions (FAO, 2005b). A combination of breeding approaches by ICRISAT and national organizations has generated significant varietal improvements for pearl millet and sorghum. For example, in southern Africa these new varieties occupy 34 percent of the millet area and 23 percent of the sorghum area (CGIAR, 2005). In some cases, farmer participation has been a key element in varietal improvement. One example is the early maturing millets that can enable dryland communities to get through the "hungry season" just prior to the main harvest when the previous year's grain has already been exhausted. Here, Namibian farmers selected a variety that matured 4–6 weeks earlier than traditional millets. Within a few years, the new variety covered half the millet area of Namibia. From an initial R&D investment of US$3 million, a sustainable annual return of US$1.5 million in yield benefits has been achieved (CGIAR, 2005).

At present, the major transgenic work on drought tolerance is being done in the private sector. In some cases, genes are being transferred from other species but companies are reportedly using multipronged approaches involving both conventional breeding and biotechnology. The resulting varieties are likely to carry very specific trait combinations such as enhanced root growth for maize grown under high input conditions (Castiglioni *et al.*, 2008; Edgerton, 2009). These approaches may well highlight possible future breeding strategies or target traits in developing country staples but may not be directly applicable to some of the less intensively managed crops. Also, such approaches are not always realistic in the less well funded context of public sector, public good orientated crop improvement, especially in developing countries. One exception here might be the PPP between Monsanto, the African Agricultural Technology Foundation and CIMMYT, which includes funding from the Gates Foundation and is aimed at developing drought tolerant maize varieties in Africa (Water Efficient Maize for Africa). Other approaches to drought tolerant maize development at CIMMYT are focusing on using genomics and MAS to identify and introgress drought related traits in existing germplasm.

1.7.3 Yield

Maximizing crop yield is probably the most desired aim of any farmer. By increasing yield per ha, more people can be fed from the same area of land. Higher yields also mean that less land is required for crop production, relieving pressure to develop pristine and often environmentally sensitive habitats such as rain forests or species-rich wetlands. It is a telling fact that the great majority of increased crop production over human history has occurred due to the expansion of arable cultivation rather than increased yield per ha. For example, prior to the introduction of scientific breeding techniques in the early twentieth century, grain yields across the world rarely exceeded 2 T/ha, even in the most favourable environments (Ruttan, 1999). The application of Mendelian genetics was an important step forward in realizing yield gains, but some of the most spectacular progress came from new hybrid technologies especially as applied to maize. Following the almost universal adoption of hybrid varieties, US maize yields increased from 1.8 T/ha in the 1920s to 7.8 T/ha in the 1990s (Murphy, 2007c). It has been estimated that at least 60 percent of the increase in maize yields was attributable to advances in breeding with the remaining 40 percent resulting from improved crop management including more effective inputs and mechanization (Duvick, 1997).

These relatively recent biologically-attributable yield gains in commercial grain crops should stimulate greater investment aimed at applying a combination of modern breeding and management technologies to the broad range of developing country crops where yields still remain well below their physiological limits. As noted by Ruttan (1999): "In most developing countries, yields are still so far below existing biological ceilings that substantial gains can be realized from a strategy emphasizing traditional crop breeding combined with higher levels of technical inputs, better soil and crop management, and first generation biotechnology crop protection technology".

Yield traits are increasingly becoming priority targets in developing countries as breeders improve their understanding of the genetics of indigenous crops, and hence their capacity to manipulate these often complex characters. Yield gains of major temperate crops have levelled off in recent years and genetic modification has so far made a limited contribution to the increase in intrinsic yields and to the yield capacity of plants in standard conditions (Gurian-Sherman, 2009). In contrast, the capacity for dramatic yield improvements of many developing countries' crops, especially "orphan" crops, remains largely unrealized (Qaim and Zilberman, 2003). Semi-dwarf cereals were the basis of the Green Revolution of the 1960s and 1970s. However, the identification of these key traits involved the selection of serendipitous variants with little understanding of the developmental processes underlying the traits. Thanks to emerging knowledge of plant development and genomics it is now becoming increasingly feasible to consider the rational redesign of crops (Sinclair, Purcell and Sneller, 2004). For example, gibberellins are important regulators of plant height and hence mutations or gene deletions that either reduce the activity of known gibberellin biosynthetic enzymes or compromise signal transduction pathways involving gibberellins can be confidently predicted to result in the kind of dwarf phenotype seen in modern cereals (Hedden and Kamiya, 1997; Sasaki *et al.*, 2002).

The new understanding of the genetic basis of domestication syndrome traits in many crops, coupled with detailed genomic sequence data and genome synteny in major plant groups, will allow breeders to move key traits between crops or to domesticate new species (Motamayor and Lanaud, 2002; Murphy, 2007c; Weeden, 2007; Burger, Chapman and Burke, 2008; Sang, 2009).

There is a great deal of basic research in industrialized countries of possible relevance to future yield improvements, although robust mechanisms for the application of such research are often lacking, especially in developing countries. Two basic approaches to yield improvements of particular promise are the manipulation of seed development and the manipulation of plant architecture. Crop yields can be increased by developing larger seeds or by manipulating seeds to accumulate more of the desired edible products (e.g. starch or oil) and less of the unwanted products.

Alternatively, plant architecture can be manipulated to maximize yield-bearing structures such as seeds and fruits, and reduce non-productive structures such as excessive branching, thick seed coats, or tall, slender stems. In principle, plant architecture could be redesigned to give higher yielding wheat-like maize plants or dwarf banana, oil palm, or coconut palm trees (Lev-Yadun, Abbo and Doebley, 2002). In order to exploit likely developments in these and other areas of basic plant science for practical crop improvement it will be crucial for research capacities to be built up further in developing countries, and for greater use to be made of molecular markers especially among public sector crop researchers in industrialized countries.

1.7.4 Nutritional quality

Quality traits such as increased nutritional content have been selected by farmers for over ten millennia (Murphy, 2007c). In principle, varieties can be selected/engineered to produce edible parts that contain specified amounts of macronutrients (starch, protein, and oil) and/or micronutrients (vitamins and minerals). The type of starch, protein, or oil in seeds and fruits can also be modified to some extent by both transgenic and non-transgenic methods (Korth, 2008; Newell-McGloughlin, 2008; Slater, Scott and Fowler, 2008). However, more precise manipulations may be possible in the future to produce so-called “designer crops” (Murphy, 2002). For example, there are several cases where the amount or potential nutritional value of seed or tuber protein has been improved by transgenesis although no new crop varieties have yet been commercially released (Chakraborty, Chakraborty and Datta, 2000; Lee *et al.*, 2003; Wang *et al.*, 2003; Popelka, Terryn and Higgins, 2004).

The manipulation of fatty acid composition of oil crops can add to their nutritional and commercial value, and transgenic approaches are extending the range of fatty acids in future crops to include long-chain omega-3 polyunsaturates that cannot normally be synthesized by higher plants (Murphy, 2006). Many, but not all, of these manipulations will involve transgenesis and most of them lie in the medium-to-long-term future rather than being immediate practical options for developing country crop improvement.

Biofortification

Almost all global crop staples are nutritionally deficient in some respect (Murphy, 2007c). This means that when populations are forced to rely on a narrow range of food crops they can suffer from varying degrees of malnutrition, with young children invariably faring the worst. While an ideal solution to this problem is to reduce poverty, hence enabling farmers to purchase a wider range of foods, another approach is to improve the nutritional value of existing subsistence crops. The examples below illustrate some of the methods that are beginning to be used by breeders to increase levels of key nutrients such as vitamins and minerals, in a strategy known as biofortification (Nestel *et al.*, 2006; Gilani and Nasim, 2007; Hirschi, 2008; Mayer, Pfeiffer and Beyer, 2008; Stomph, Jiang and Struik, 2009). Several vitamin-enhanced fruit varieties for Asia and Africa, including a high-carotene tomato for adaptation to semi-arid areas of West Africa are being developed (AVRDC, 2009).

The HarvestPlus consortium focuses on the three dietary micronutrients recognized by the World Health Organization (WHO) as particularly limiting in many subsistence populations in developing countries, namely iron, zinc and vitamin A. HarvestPlus has breeding programmes utilizing all available biotechnologies including MAS and genomics for six of the most important staple food crops, i.e. rice, wheat, maize, cassava, sweet potato and common beans (Cakmak, Graham and Welch, 2004). In addition to enhancing micronutrient levels in selected crops, its objectives are to assess the bioavailability of micronutrients in foods actually consumed by the population to facilitate farmer uptake of the varieties and measure their long-term nutritional impacts (HarvestPlus, 2007). The Vitamin A for Africa (VITAA) programme is focused on vitamin A in the sweet potato (CIP-VITAA, 2008).

Sweet potato is the fifth most important global crop on a fresh weight basis and is especially important in Africa. Traditional white varieties have little vitamin A and over 3 million children in the region suffer from vitamin A-related blindness. Vitamin A deficiency is also a leading cause of early childhood death and a major risk factor for pregnant women. New orange-fleshed varieties with high vitamin A levels obtained through conventional plant breeding schemes could potentially replace white sweet potato varieties that had previously been favoured by farmers throughout Africa (Low, Walker and Hijmans, 2001; Tumwegamire *et al.*, 2004). One future challenge is to provide enough planting material (normally as bundles of vine cuttings) to meet the high levels of farmer demand. Micropropagation can assist in this respect. Other targets are to improve post-harvest handling and food-preparation methods at community level to ensure retention of beta-carotene (provitamin-A) levels, and to assess the impact of orange-fleshed sweet potatoes on the health status of HIV/AIDS-affected communities.

The best known transgenic approach to biofortification is "golden rice", developed in the 1990s by a Swiss/German public-sector group (Ye *et al.*, 2000). This rice variety has yellow rather than white grains due to the accumulation of beta-carotene, which is normally absent from polished rice grains. More recently, an improved version of golden rice has been developed with a reported 23-fold increase in provitamin-A levels (Paine *et al.*, 2005). The development of laboratory versions of golden rice was just the start of a lengthy process of backcrossing into local varieties and field tests that has already lasted a decade. In 2005–07, the original golden rice trait was crossed into the popular IR64 variety at IRRI, and outdoor field trials of 20 potential breeding lines started in 2008. Field trials of the improved golden rice variety show five times more provitamin-A than the original lines (IRRI, 2008). A further challenge will be to ensure that newly expressed provitamin-A can withstand processing, storage, and cooking, while remaining bioavailable after consumption.

1.7.5 Narrow genetic basis of crop production

Since the beginning of agriculture, more than 7 000 species of plants have been cultivated or collected. Many remain important to local communities where exploiting their potential is crucial to achieving food security, but nowadays it is estimated that only 30 crops provide 95 percent of human food energy needs and just four of them – rice, wheat, maize and potatoes – provide more than 60 percent. The domestication of new crops by advanced breeding methods is an exciting prospect for broadening the genetic base of crop production and extending the potential of agriculture to provide food and other materials in the climatically uncertain times that lie ahead. Recent advances in genomics and the manipulation of complex traits have clear applications in the domestication of new crops (Varshney, Graner and Sorrells, 2005; Varshney and Tuberosa, 2007b). Emerging understanding of the genetic basis of domestication traits will aid their manipulation via advanced methods such as MAS (Murphy, 2007c). This will accelerate breeding programmes aimed at improving agronomic performance and enable the faster and more reliable multiplication of seeds or plantlets for dissemination to growers. For example, Bioversity International has recommended that partially domesticated or undomesticated tropical fruits are used as alternative sources of vitamins.

In a recent survey of southeast Asian fruits, ten candidate species with high vitamin A levels were found, including durians (*Durio* spp.), milk apple (*Syzygium malaccense*), rose apple (*S. jambos*), and button mangosteen (*Garcinia prainiana*) (Khoo *et al.*, 2008). Some of these fruits could be grown as cash crops. Their further improvement, and that of other newly domesticated plants with great potential in developing countries, would be greatly facilitated by biotechnologies such as MAS (Murphy, 2007a). From records of indigenous cultures, at least 1 650 tropical forest species are potential horticultural crops. Many of these plants are already adapted to areas unsuitable for existing crops and could therefore extend local food-producing capacity without interfering with existing crops.

1.7.6 Sustainable and environmentally friendly crop production

Intensive agriculture using primarily human and animal inputs has been practised in various regions of the world for well over four millennia. Examples include irrigated barley/wheat production in ancient Mesopotamia, paddy rice in East Asia, and the milpa system in the Americas (Murphy, 2007c). Over the past century, however, the availability of cheap energy and raw materials has facilitated a massive expansion of intensive farming across the globe that does not depend on biological inputs. In particular, the introduction of inorganic fertilizers and new crop varieties bred for efficient fertilizer response have been the cornerstone of the Green Revolution which largely alleviated the crisis in food security in developing countries during the 1960s and 1970s (Murphy, 2007a). During the past century, intensive arable farming has spread globally as more and more land has been brought into cultivation. It is now generally agreed that humankind is approaching limits both in the amount of land available for future agricultural expansion and in the sustainability of intensive, high input, fossil fuel dependent farming systems. But there remains a fundamental tension between understandable concerns for the long-term sustainability of crop production with the lowest feasible environmental footprint and the undoubted requirement for higher yields to feed expanding and increasingly urbanized populations, especially with the added uncertainties of climate change and a possible consequent reduction in usable arable land. This complex and interrelated set of challenges can be addressed, at least in part, by biotechnologies in combination with other approaches.

In the recent past, environmental and sustainability concerns about cropping systems have frequently been the drivers for technology-based solutions. Examples already discussed include IPM or biocontrol to replace pesticide inputs, and biofertilizers or legume intercropping to replace inorganic nitrogen inputs. Such methods are widely used in developing countries but there remains great scope for their refinement and extension to a wider range of crop types.

The replacement of inorganic inputs by biological agents can have multiple benefits such as reduced energy use, enhanced environmental credentials (e.g. the reduction or elimination of input residues), lower costs and improved safety for farmers who would no longer need to purchase or handle so many chemical inputs. The use of advanced breeding technologies to create significant yield gains, especially if these can be achieved without greatly increasing inputs, has clear environmental implications because it reduces pressure to bring more land into cultivation. Clearly, many of these developments remain aspirational at present but the fact remains that biotechnologies can play a greater role in enhancing the sustainability and mitigating the environmental impact of farming. One emerging area that will become increasingly important in the future is that of agro-ecological system dynamics as applied to breeding strategies and technological interventions. This area relates especially to the implications of climate change and the manner in which adaptation, uncertainty, vulnerability and resilience are viewed. A useful critical discussion of this area with a commentary on biotechnology-based strategies is provided by Thompson and Scoones (2009).

Decisions about introducing more sustainable and/or environmentally friendly crop production methods have sometimes thrown up both threats and opportunities that can be addressed via biotechnology. For example, the voluntary implementation in Malaysia of a no-burn policy when replacing ageing oil palm trees led to an increase in infestation rates by the virulent fungal pathogen, *Ganoderma boninense*, which causes basal stem rot (Bridge *et al.*, 2000).

Public sector researchers in Malaysia and Indonesia responded by developing new molecular technologies for the early detection of this problematic disease and innovative microbial agents for its effective treatment (Flood, Bridge and Holderness, 2000; Soepena, Purba and Pawirosukarto, 2000; Panchal and Bridge, 2005; Bréton *et al.*, 2006; Paterson, 2007; Sundram *et al.*, 2008).

1.7.7 Conclusions

- There is a wide range of existing and emerging problems related to food security that can be tackled by crop biotechnologies in combination with other technologies.
- Key areas include pest/disease control, salt/drought tolerance, crop yield/quality, and the sustainability and environmental impact of crop production.
- The knowledge gained from basic plant research will underpin future crop improvements but effective and robust mechanisms for the rapid and effective translation of research discoveries into public good agriculture remain to be developed.
- Maximum benefit will be derived if robust plant breeding and crop management programmes have ready access to all the modern crop biotechnologies, both transgenic and non-transgenic, to address food security issues. This will require additional investments in capacity building for R&D in developing countries.
- Technology implementation alone is not sufficient to address such complex questions as food security. Biotechnologies will make new options available but their uptake and effective exploitation will rely on an intricate web of cross-sectoral factors.

1.8 IDENTIFYING OPTIONS FOR DEVELOPING COUNTRIES

Based on the overview and previous analyses contained in this Chapter, a number of specific options can be identified to assist developing countries make informed decisions regarding the adoption of biotechnologies in the future, such as when and if they should employ one or more crop biotechnologies and, if they decide to use them, how to ensure the successful application of the chosen biotechnologies to enhance food security in the future. The options identified are grouped under the same eight headings as the lessons learned from the past (Part 1.6).

Documentation of development, adoption and impact

Developing countries should undertake national-level documentation and analysis of the adoption and socio-economic impacts of biotechnological innovations for crops to advise policy-makers on the cost/benefit implications of biotechnology applications. This includes the collection of data, studies, etc.

Investments in biotechnology R&D

- Developing countries, possibly working in regional groups, should build up indigenous research, development, and advisory capacities for the generation, assessment and adoption of appropriate biotechnologies.
- Adequate, consistent, stable investments should be ensured from indigenous resources to public sector biotechnology R&D.

Linkages between biotechnology and other agricultural R&D

- Investments in biotechnology R&D cannot be made at the expense of current spending in other research fields.
- Biotechnological research should be linked more effectively to strong and well resourced R&D programmes on crop breeding.

Policy development and priority-setting

- Countries should develop expertise to ensure they can make sovereign decisions about adopting biotechnologies and carry out their own independent, broad- based risk/benefit analyses.
- Countries should prioritize research activities to address the greatest food security needs, with special reference to the needs of smallholders.
- Countries should ensure the appropriate involvement of relevant stakeholders in decision-making processes.

- Decisions on crop biotechnology tools to address the problems of smallholders should reflect the appropriateness and socio-economic impacts of the tools.
- Independent public sector organizations should engage and communicate more effectively with society at large about the role of all crop improvement/management biotechnologies for food security.

Capacity development

Countries should develop the biotechnology capacities of national agricultural research systems in their three dimensions (policy development, institutional set-up and human capacities).

Regulation of biotechnology use

- All countries should be encouraged to establish consistent and transparent, evidence-based decision-making processes to regulate crop biotechnology R&D and its application.
- Biotechnology-related regulations should be developed in harmony with other national regulations, especially those relating to plant and animal health and food safety. For this purpose, the adoption of the biosecurity[1] approach is strongly encouraged.
- While it is essential that decisions on adopting biotechnologies are ultimately based on verifiable scientific evidence, public participation should, where appropriate, form part of the decision-making process.
- Developing countries can often act more effectively in regional groups when engaging with international trade and conventions.

Uptake of biotechnologies

- Biotechnology development strategies should be strongly linked with strategies for its widespread dissemination.
- Stronger extension services, with expertise in modern agronomy and linked with participatory crop improvement programmes, should be an integral part of national/regional agricultural support structures.
- Seed production and distribution systems should be enhanced.

Shared access to technologies

- Effective and equitable mechanisms for PPP should be established where appropriate.
- Developing countries should consider, where appropriate, sharing technologies, skills and knowledge with each other by means of South-South collaboration platforms or mechanisms.

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[1] A cross-sectoral national approach to the management of biological risks associated with food and agriculture, including plant and animal health, food safety and biosafety of GMOs.

1.9 IDENTIFYING PRIORITIES FOR ACTION FOR THE INTERNATIONAL COMMUNITY

The international community, including FAO and other UN organizations as well as NGOs, donors and development agencies, can play a key role in supporting developing countries by providing a framework for international cooperation and funding support for the generation, adaptation and adoption of appropriate biotechnologies. Below is a set of Priorities for Action that will assist the international community in playing this role, grouped under the same eight main headings as parts 1.6 and 1.8.

Documentation of development, adoption and impact

International agencies should systematically collect and systematize documentation on development and adoption of crop biotechnologies and analyze their socio-economic impacts in developing countries. This includes compiling statistics, establishing and maintaining biotechnology application databases, studies, etc

Investments in biotechnology R&D

Donors and international funding agencies are encouraged to dedicate an appropriate share of their assistance projects to promoting and strengthening public biotechnology R&D in developing countries.

Linkages between biotechnology and other agricultural R&D

- Technical assistance in biotechnology R&D cannot be done to the detriment of present spending in other research fields.
- Technical assistance in biotechnology R&D should always support effective and intimate links to strong plant breeding, agronomic research and extension programmes.

Policy development and priority-setting

- The international community should assist developing countries in strengthening capacities for biotechnology policy development and long-term planning.
- The international community should assist developing countries to enhance the capacities of national agricultural research systems to involve relevant stakeholders in decision-making processes.
- International organizations should inform more effectively society at large about the role that biotechnologies for crop improvement/management have in food security.
- International R&D organizations should develop innovative approaches for the appropriate inclusion of the public in decision-making processes in developing countries.

Capacity development

The international community should help developing countries enhance the biotechnology capacities of national agricultural research systems in their three dimensions (policy development, institutional set-up and human capacities).

Regulation of biotechnology use

- The international community should continue its efforts to assist developing countries in establishing robust national regulatory frameworks in areas such as biosafety, food safety, plant health protection, the protection of intellectual property and the protection of traditional knowledge.
- The international community should promote the adoption of the biosecurity approach to assist in the framing of holistic and integrated biotechnology regulation.
- The international community should assist developing countries in enhancing their institutional capacities for regulatory development and enforcement.
- Regulatory procedures should be regionally and/or internationally harmonized to facilitate international trade and scientific collaboration. When requested, FAO and other international agencies should continue to offer a meeting place for governments to discuss common governance measures.

Uptake of biotechnologies

- Biotechnology knowledge and expertise should be included in extension, educational and advisory services to facilitate uptake by farmers and the spread of reliable public knowledge about crop biotechnologies.
- Development agencies should assist developing countries in enhancing seed production systems to facilitate farmers' utilization of the fruits of crop biotechnologies.

Shared access to technologies

The international community should facilitate effective mechanisms for South-South collaboration including:

- the training of scientists and technicians;
- joint research projects (pooling complementary resources to work on projects of common interest);
- the sharing of technologies, techniques, protocols and materials;
- the sharing of information relevant for biotechnology development and adoption;
- assistance in the establishment of mechanisms for the dissemination to developing countries of biotechnologies developed in industrialized countries (North-South collaboration, PPPs).

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