Private Research and Public Goods: Implications of Biotechnology for Biodiversity

Terri Raney and Prabhu Pingali

ESA Working Paper No. 04-07

April 2004

Agricultural and Development Economics Division

The Food and Agriculture Organization
of the United Nations

www.fao.org/es/esa

ESA Working Paper No. 04-07

www.fao.org/es/esa

Private Research and Public Goods: Implications of Biotechnology for Biodiversity

April 2004

Terri Raney and Prabhu Pingali
Agricultural and Development Economics Division
Economic and Social Department
Food and Agriculture Organization
Italy
e-mail: terri.raney@fao.org

Abstract

The pattern of crop genetic diversity has changed over the past two centuries with the modernization of agriculture, accelerating with the advent of the green revolution. Since the green revolution, the locus of agricultural research has shifted from the public to the private sector. The growing importance of the private sector in agricultural R&D is changing the types of crop technologies that are developed and the ways they are delivered to farmers. The spread of transgenic crops will influence crop genetic diversity, but their implications for the availability of plant genetic resources and the resilience of agricultural ecosystems are not entirely clear. Transgenic crops may increase or decrease crop genetic diversity, depending on how they are regulated and deployed. This paper explores a range of policy options to increase the likelihood that private sector R&D, particularly in the form of transgenic crops, enhances rather than erodes crop genetic diversity.

Key Words: Biodiversity, Biotechnology, Agricultural Research, Transgenic Crops, Green Revolution.

JEL: O13, O33, Q16

This paper is forthcoming in Biodiversity, Biotechnology and Development, J. Cooper, D. Zilberman and L. Lipper (ed..), forthcoming 2004, Natural Resource Management and Policy Series, Kluwer Publishers.

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

TABLE OF CONTENTS

I. Introduction

The pattern of crop genetic diversity in the fields of the developing world has changed fundamentally over the past 200 years with the intensification and commercialization of agriculture. This process accelerated with the advent of the green revolution in the 1960s when public sector researchers and donors explicitly promoted the international transfer of improved seed varieties to farmers in developing countries. Since the green revolution, the locus of agricultural research and development (R&D) has shifted from the public sector to the private multinational sector, driven by the commercialization of agriculture, the scientific discoveries underpinning the "gene" revolution, stronger intellectual property rights protections and more open international markets. The growing importance of the private sector in agricultural R&D is changing the types of crop technologies that are developed and the ways they are delivered to farmers. Transgenic crops – which have been developed and disseminated almost exclusively by the private sector – provide perhaps the clearest illustration of the changes arising from the growth of private sector agricultural R&D. These crops will influence crop genetic diversity, but their implications for the availability of plant genetic resources and the resilience of agricultural ecosystems are not entirely clear.

The germplasm that dominates the area planted to the major cereals has shifted over time from the locally adapted populations that farmers historically selected from the seed they saved – often called "landraces" – to the more widely adapted seed types produced by scientific plant breeding programmes and purchased by farmers – often called "modern varieties". The genetic content and the geographical distribution of landrace populations are influenced by natural selection pressures and the seed and crop management practices of traditional farming communities. In contrast, the spatial and temporal diversity among modern varieties in farmers' fields is determined more by the economic factors affecting their profitability and by the performance of agricultural research institutions and seed industries (Pingali and Smale, 2001). The spread of transgenic crop varieties will also be influenced by farm level profitability and the performance of agricultural research institutions and seed sectors, but institutional and regulatory issues (private sector dominance, intellectual property rights and regulatory concerns and procedures) will have a greater influence over the spread of transgenic varieties than for conventional modern varieties. Finally, transgenic technology itself may influence biodiversity by enabling the more targeted exchange of genetic material in breeding programmes and through the inadvertent spread of transgenes to related modern varieties and landraces.

Private firms are responsible for most transgenic crop R&D and almost all of the commercialization of transgenic crop varieties being undertaken today. This is in sharp contrast with the development and diffusion of modern green revolution varieties for which the public sector – national and international – played a strong role. Four inter-related forces are transforming the system for providing improved agricultural technologies to the world's farmers. The first is the ongoing process of agricultural modernization, i.e. the intensification and commercialization of agriculture. The second is the strengthening environment for protecting intellectual property in plant innovations. The third is the rapid pace of discovery and the growing importance of molecular biology and genetic engineering. Finally, agricultural input and output trade is becoming more open in nearly all countries, enlarging the potential market for new technologies and older related technologies. These developments have created powerful new incentives for private research, and are altering the structure of the public/private agricultural research endeavour, particularly with respect to crop improvement (Pingali and Traxler, 2002).

This chapter explores the linkages among the modernization of agriculture, the changing locus of agricultural research and technology transfer and the resulting patterns of crop genetic diversity in the developing world. Section II describes the modernization of agriculture and the evolution of plant improvement research from prehistory through the era of conventional scientific plant breeding to the current gene revolution. Section III discusses the changing locus of agricultural research from the public to the private sector and the implications for crop variety development and technology transfer. Section IV explores the implications of these changes – particularly the spread of transgenic crops – for varietal use patterns and crop biodiversity. Section V concludes with some recommendations for the promotion of crop genetic diversity within the existing environment for agricultural research and technology transfer.

II. The transformation of agriculture and the evolution of plant improvement research

Modern cereal cultivars have developed through four main phases of selection: (i) subconscious selection by earlier food growers in the process of harvesting and planting, (ii) deliberate selection among variable material by farmers living in settlements and communities, (iii) purposeful selection by professional breeders using scientific principles of inheritance and observable physical traits, and (iv) selection based on genomic characteristics and the application of molecular markers and transgenic techniques to crop improvement. The latter two phases have emerged as a result of the intensification and commercialization of agriculture.

The transformation of agriculture

The transformation of agriculture over the past 200 years has involved the interrelated processes of intensification and commercialization. The intensification of agriculture refers to the increase in output per unit of land used in production, or land productivity. Population densities explain much about where and under which conditions this process has occurred (Boserup, 1981). The transition from low-yield land-extensive cultivation systems to land-intensive, double- and triple-crop systems is only profitable in societies in which the supply of uncultivated land has been exhausted. It is no accident that the modern seed-fertilizer revolution has been most successful in densely populated areas of the world whether traditional mechanisms for enhancing yields have been exhausted (Hayami and Ruttan, 1985).

Intensification could also occur in the less densely populated areas for two reasons: (i) in areas that are well-connected to markets, higher prices and elastic demand for output imply that the marginal utility of effort increases, hence farmers in the region will begin cultivating larger areas, and (ii) higher returns to labour encourage migration into well-connected areas from neighbouring regions with higher transport costs. Intensification of land use and the adoption of yield-enhancing technologies have occurred in both traditional and modern agricultural systems.

Economic growth, urbanization and the withdrawal of labour from the agricultural sector lead to the increasing commercialization of agricultural systems. Commercialization, in turn, leads to greater market orientation of farm production, progressive substitution of non-traded inputs in favour of purchased inputs, and the gradual decline of integrated farming systems and their replacement by specialized enterprises for crop, livestock, poultry and aquaculture products (Pingali, 1997). Agricultural output and input use decisions are increasingly guided by the market and are based on the principles of profit maximization. This in turn influences patterns of crop genetic diversity through changes in land use patterns and through crop choice changes.

The evolution of plant improvement

Domestication of wild species

Humans have manipulated the genetic make-up of plants since agriculture began more than 10 000 years ago (Table 1). Primitive societies of hunters and gatherers recognized wild species of cereals and harvested them for food. Societies of shifting cultivators gradually domesticated these wild species, creating the basis for sedentary or permanent agricultural systems. These early farmers unconsciously managed the process of domestication over several millennia, selecting and planting the best seeds through many growing cycles. The main attainment of this first phase of crop improvement was to develop domesticated crops more suitable for human cultivation – planting, harvesting, threshing or shelling – and consumption. Higher germination rates, more uniform growing periods, resistance to shattering, and improved palatability were some of the achievements of this effort. The human selection pressures that accompanied domestication narrowed the genetic base for these crops as farmers selected among the full range of plant types for those that produced more desirable traits (Smale, 1997).

Development of landraces

In the second phase of crop improvement, farmers deliberately selected plant materials suited to local preferences and growing conditions. Many farmers in many locations exerted pressures continuously in numerous directions, resulting in variable crop populations that were adapted to local growing conditions and consumption preferences. These populations, broadly known as landraces, often differ radically from their early ancestors. Although more genetically uniform than these early relatives, landraces are nonetheless characterized by a high degree of genetic diversity within a particular field.

[INSERT TABLE 1 ABOUT HERE]

Conventional breeding of modern varieties

The third phase of crop improvement through scientific plant breeding programmes relied on the application of classical Mendelian genetic principles based on the phenotype or physical characteristics of the organism concerned. Conventional breeding, which began about 100 years ago, has been very successful in introducing desirable traits into crop cultivars from domesticated or wild relatives or mutants. The first high-yielding hybrid maize varieties were produced about 50 years ago and the high-yielding, semidwarf varieties of wheat and rice that gave rise to the green revolution were developed less than 50 years ago. The products of this third phase – often called modern varieties – have been widely adopted in intensive agricultural production systems.

As a result of the spread of modern varieties, fields of cereals have become more uniform in plant types with less spontaneous gene exchange. Planned gene migration increased, however, with the worldwide exchange of germplasm among research institutions that was an integral part of the green revolution research paradigm (Pingali and Smale, 2001). Although the nature of crop genetic diversity has changed as a result of the spread of modern varieties, it is neither straightforward nor particularly meaningful to discuss whether genetic diversity has increased or decreased, because a simple count of the varieties in a particular area or measures of genetic distance among varieties may not tell us much about the resilience of crop ecosystems or the availability of crop genetic resources for breeding programmes (see Section IV).

Genomic selection in plant breeding

The latest phase of crop improvement research is based on the identity, location and function of genes affecting economically important traits and the direct transfer of these genes through transgenesis. Transgenesis permits the introduction of genetic material from sexually incompatible organisms, greatly expanding the range of genetic variation that can be used in breeding programmes. Unlike conventional breeding, transgenesis allows the targeted transfer of the genes responsible for a particular trait, without otherwise changing the genetic makeup of the host plant. This means that a single transgenic innovation can be incorporated into many varieties of a crop, including perhaps even landraces (see Qaim, Yarkin and Zilberman in this volume). Compared with conventional breeding in which an innovation comes "bundled" within a new variety that typically displaces older varieties, transgenesis allows an innovation to be disseminated through many varieties, preserving desirable qualities from existing varieties and maintaining or, potentially, increasing crop genetic diversity.

On the other hand, the widespread incorporation of a single innovation, such as the Bt genes that confer insect resistance, into many crops/varieties may constitute a type of genetic narrowing for that particular trait. Furthermore, transgenic crops that confer a distinct advantage over landraces may accelerate the pace at which these traditional crops are abandoned or augmented with the transgenic trait. Regulatory regimes are concerned with the potentially harmful consequences of gene flow from transgenic crops to conventional varieties or landraces. In this context, it is important to recognize that gene flow from conventional varieties to landraces frequently occurs (especially for open-pollinated crops such as maize) and is often consciously exploited by farmers. In the same way, it is likely that farmers would consciously select for transgenic traits that confer an advantage (de Groote, *et.al*, 2004) unless biological or legal methods are used to prevent them from doing so. How these offsetting forces will ultimately affect crop genetic diversity depends on the incentives and constraints facing researchers, plant breeders and farmers. The changing locus of agricultural research from the public to the private sector is a key element in this regard.

III. The changing locus of agricultural research

The green revolution research paradigm

Most of the conventional breeding research that launched the green revolution was conducted by the public sector with the explicit goal of creating technologies that could be transferred internationally. International and national public sector researchers bred dwarfing genes into elite wheat and rice cultivars, causing them to produce more grain and shorter stems and enabling them to respond to higher levels of fertilizer and water. These semi-dwarf cultivars were made freely available to plant breeders from developing countries who further adapted them to meet local production conditions. Private firms were involved in the development and commercialization of locally adapted varieties in some countries, but the improved germplasm was provided by the public sector and disseminated freely as a public good.

The initial focus of the green revolution research was on raising yield potential for the major cereal crops. During the early decades of the green revolution, the crops grown by poor farmers in less favourable agro-ecological zones (such as sorghum, millet, barley, cassava and pulses) were neglected, but since the 1980s modern varieties have been developed for these crops and their yield potential has risen (Evenson and Gollin, 2003). In addition to their work on shifting the yield frontier of cereal crops, public sector plant breeders continue to have successes in other important areas of applied research. These include development of plants with durable resistance to a wide spectrum of insects and diseases, plants that are better able to tolerate a variety of physical stresses, crops that require significantly lower number of days of cultivation, and cereal grain with enhanced taste and nutritional qualities.

The public sector and international technology transfer

Prior to 1960, there was no formal system in place that provided plant breeders access to germplasm available beyond their borders. Since then, the international public sector (the

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

The international flow of germplasm has had a large impact on the speed and the cost of crop development programmes of national agricultural research systems (NARS), thereby generating enormous efficiency gains (Evenson and Gollin, 2003). Evenson and Gollin (2003) report that even in the 1990s, the CGIAR content of modern varieties was high for most food crops; 35 percent of all varietal releases were based on CGIAR crosses, and an additional 22 percent had a CGIAR-crossed parent or other ancestor. Thus, while the green revolution promoted the spread of genetically uniform modern varieties in the developing world, the genetic pedigrees of these modern varieties were more complex than the landraces they replaced.

The emergence of private sector agricultural research

In the decades of the 1960s through the 1980s, private sector investment in plant improvement research was limited, particularly in the developing world, due to the lack of effective mechanisms for proprietary protection on the improved products. This situation changed in the 1990s with the emergence of hybrids for cross-pollinated crops such as maize. The ability of developers to capture economic rents from hybrids led to a budding seed industry in the developing world, started by multinational companies from the developed world and followed by the development of national companies (Morris, 1998). Despite the rapid growth of the seed industry in some developing countries, its activity has been limited to date, leaving many markets under served.

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

The relative importance of the private sector in agricultural research, particularly in transgenic crop biotechnology, is shown in Table 2. While these estimates are imperfect, they reveal a sharp dichotomy between public and private research expenditures and between industrialized and developing countries. Industrialized countries spend ten times as much on crop biotechnology research as developing countries, and this constitutes a higher percentage of their total agricultural research budget. While total research expenditures in the industrialized countries are almost evenly split between the public and private sectors, the latter concentrates a higher share of it total expenditures on transgenic crop biotechnology. In the developing countries, in contrast, the public sector spends a smaller total amount on agricultural research and devotes a smaller share of its total research budget to transgenic crop biotechnology. The CGIAR centres (where much of the green revolution research was conducted) have a combined annual budget for crop biotechnology research of less than $50 million, less than 5 percent of the private multinational budget. Comprehensive data on private sector crop biotechnology research in developing countries are not available, although most of this research appears to be carried out by multinationals conducting trials of their transgenic varieties (Byerlee and Fischer, 2002).

[Table 2 about here]

The large multinational agro-chemical companies invested early in the development of transgenic crops, although much of the basic scientific research that paved the way was conducted by the public sector and made available to private companies through exclusive licenses. The agro-chemical companies entered the plant improvement business by purchasing existing seed companies, first in industrialized countries and then in the developing world (Pray and Naseem, 2003). These arrangements among the public sector, large multinational corporations and national seed companies are economically rational because the three specialize in different aspects of the seed variety development and delivery process (Pingali and Traxler, 2002). This process is a continuum that starts upstream with basic scientific research (largely in the public sector), moves on to generating knowledge about economically valuable genes and engineering transgenic plants (public sector and large multinationals) and moves downstream to the more adaptive process of backcrossing the transgenes into commercial lines and delivering the seed to farmers (mostly private sector at the national or sub-national level).

The products from upstream activities have worldwide applicability across several crops and agro-ecological environments. On the other hand, genetically modified crops and varieties are typically applicable to specific agro-ecological niches. In other words, spillover benefits and scale economies decline in the move to the more adaptive end of the continuum. Similarly, research costs and research sophistication decline in the progression towards downstream activities. Thus, a clear division of responsibilities in the development and delivery of biotechnology products has emerged, with the multinational firm providing the upstream biotechnology research and the local firm providing crop varieties with commercially desirable agronomic backgrounds (Pingali and Traxler, 2002).

As discussed above, private sector research focuses on the more applied end of the research spectrum. Indeed, the private sector has developed all of the genetically transformed crops that have been commercialized in the world so far with the exception of insect resistant cotton in China and virus resistant papaya in Hawaii, USA. The dominance of the private sector suggests that most transgenic crop development will focus on crops and traits that are aimed at commercially viable markets, to the neglect of small-holders in marginal production environments. Evidence on field trials and commercialization of transgenic crops supports this thesis. More than 11,000 field trials have been performed for 81 different transgenic crops in at least 58 countries since 1987; however most R&D efforts focus on a few crops and traits of interest to temperate-zone commercial farmers (Pray, *et al*., 2002a). Data on commercialization are even more concentrated: six countries, four crops and two traits accounted for 99 percent of all transgenic crops planted commercially in 2003 (James, 2003). In contrast, the crops and agronomic traits of particular importance to developing countries and marginal production areas are the subject of very few field trials and no commercialization thus far. This neglect is due to the limited commercial potential of these so-called ‘orphan’ crops and to the technical difficulty of finding transgenic solutions for complex traits such as potential yields and abiotic stress tolerance (e.g. drought and salinity).

The private sector and international technology transfer

One of the lessons of the green revolution was that agricultural technology could be transferred internationally. This was especially true for countries that had sufficient national agricultural research capacity to adapt the high-yielding cultivars developed by the international public sector to suit local production environments. Unlike the high-yielding varieties disseminated in the green revolution, the products of the gene revolution are encountering significant regulatory and market barriers. Companies are unwilling to develop and commercialize transgenic crops for countries that lack transparent, science-based regulatory procedures. Furthermore, many of the technical innovations of the gene revolution are held under patents or exclusive licenses. The improved germplasm and varieties that were responsible for the green revolution, in contrast, were disseminated freely as international public goods. While stronger intellectual property protections have greatly stimulated private sector research in developed countries, they can restrict access to new technologies where countries lack appropriate regulatory structures or where farmers lack the financial means to pay for proprietary technologies. Public sector breeders in developing countries may not have access to proprietary genes and enabling technologies and their farmers may be unable to afford the technology fees charged by private technology developers.

Unlike the green revolution technologies, transgenic technologies are transferred internationally primarily through market mechanisms. The commercial relationship between the multinational bio-science firms and national seed companies was described above. This system of technology transfer works well for commercially viable innovations in well-developed markets, but perhaps not for the types of innovations needed in developing countries: crops and traits aimed at poor farmers in marginal production environments. These “orphan” technologies have traditionally been the province of public sector research. Given the dominance of private sector research in transgenic crop research and meagre resources being devoted to public sector research in most developing countries, it is unlikely that public sector research can play this role for transgenic crops.

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

Pingali and Traxler (2002) suggest three possible avenues for public sector institutions in developing countries to gain access to transgenic technologies: (i) directly import private- or public-sector transgenic varieties developed elsewhere, (ii) develop an independent capacity to develop and/or adapt transgenic varieties, and (iii) collaborate on a regional basis to develop and/or adapt transgenic varieties. The second option is the most costly and requires the highest degree of national research capacity, while the first option depends on the availability of suitable varieties developed elsewhere. The third option would require a higher degree of cooperation across national boundaries than has typically characterized public sector research. Pingali and Traxler (2002) ask whether incentives exist or can be created for public/private partnerships that allow the public sector to use and adapt technologies developed by the private sector. The implications of these options for crop genetic diversity are discussed below.

IV. Agricultural modernization, varietal adoption and crop biodiversity

Crop genetic diversity has changed over time along with the modernization of agriculture and the evolution of plant improvement and the changing locus of agricultural research. Teasing out the effects of private sector research from those caused by the structural transformation of agriculture is not a simple task. This section examines the forces that have influenced the spatial and temporal spread of modern cereal varieties, including transgenic varieties, and their implications for crop genetic diversity.

Modern cereal varietal adoption patterns

Modern cereal varieties, developed by scientific breeding programmes, began to spread through many of the countries now considered “industrialized” in the late 19th century. The green revolution accelerated this process and extended it into much of the developing world. The adoption of modern cereal varieties has been most widespread in land-scarce environments and/or in areas well connected to domestic and international markets, where the intensification of agriculture first began. Even in these areas, the profitability of modern variety adoption has been conditioned by the potential productivity of the land under cultivation. For instance, while modern rice and wheat varieties spread rapidly through the irrigated environments, their adoption has been slower in the less favourable environments – the drought-prone and high-temperature environments for wheat and the drought- and flood-prone environments for rice. Maize has an even spottier record in terms of farmer adoption of modern varieties and hybrids. For all three cereals, traditional landraces continue to be cultivated in the less favourable production environments throughout the developing world (Pingali and Heisey, 2001).

Evenson and Gollin (2003) provide information on the extent of adoption and impact of modern variety use for all the major food crops. The adoption of modern varieties (for 11 major food crops averaged across all crops) increased rapidly during the two decades of the green revolution, and even more rapidly in the following decades, from 9 percent in 1970 to 29 percent in 1980, 46 percent in 1990 and 63 percent by 1998. Moreover, in many areas and in many crops, first generation modern varieties have been replaced by second and third generation modern varieties (Evenson and Gollin, 2003).

According to Smale (1997), the adoption of modern cereal varieties has been characterized first by a concentration on a few varieties followed by diversification as more varieties became available. In the 1920s, for example, a single variety accounted for more that 60 percent of the wheat crop in the Northern and central parts of Italy. Single cultivars became similarly dominant in many countries in Europe and North America, as mechanization created a need for uniform plant types and uniform grain quality. As the process of modernization proceeded and the offerings of scientific breeding programmes expanded, the pattern of concentration declined in many European and North American countries (Lupton, 1992 and Dalrymple, 1988, cited in Smale, 1997). Similarly, in the early years of the green revolution, the dominant cultivar occupied over 80 percent of the wheat area in the Indian Punjab, but this share fell below 50 percent by 1985. By 1990, the top five bread wheat cultivars covered approximately 36 percent of the global wheat area planted to modern varieties (Smale, 1997).

Implications of modern varietal distribution for crop genetic diversity

Whether the changes in crop varietal adoption described above have resulted in a narrowing of genetic diversity remains largely unresolved due to conceptual and practical difficulties[1]

[1] Crop genetic diversity broadly defined refers to the genetic variation embodied in seed and expressed when challenged by natural and human selection pressure. In applied genetics, diversity refers to the variance among

(Pingali and Smale, 2001). Scientists disagree about what constitutes genetic narrowing or when such narrowing may have occurred. Several dimensions of diversity must be considered in this regard, including both the spatial and temporal variation between landraces and modern elite cultivars and the variation within modern cultivars. Hawkes (1983, cited in Smale, 1997) argued that the genetic diversity of landraces and modern varieties is incomparable by definition because landraces, which are mixtures of genotypes, "could not even be called varieties" and he called the range of genetically different varieties available to breeders the "other kind of diversity" (pp. 100-101). Smale (1997) argued that the range of genetic material available to breeders is not directly correlated with the number of varieties in use because a single modern variety may contain a more diverse range of genetic material than numerous landraces.

Scientists also disagree about what constitutes genetic narrowing within modern varieties. For example, Hawkes (1983) cites the introduction of the *Rht1* and *Rht2* dwarfing genes into wheat breeding lines as an example of how diversity has been broadened by scientific plant breeders, while Porceddu *et al*. (1988) argue that the spread of semidwarf wheat varieties during the green revolution led to a narrowing of the genetic base for that crop (Pingali and Smale, 2001).

These points imply that comparing counts of landraces and modern varieties or changes in the number of modern varieties over time may not provide a meaningful index of genetic narrowing. They also imply that even if reliable samples of the landraces originally cultivated

---

alternative forms of a gene (alleles) at individual gene positions on a chromosome (loci), among several loci, among individual plants in a population, or among populations (Brown *et al*., 1990). Diversity can be measured by accessions of seed held in gene banks, lines or populations utilized in crop-breeding programmes, or varieties cultivated by farmers (cultivars). But crop genetic diversity cannot be literally or entirely observed at any point in time; it can only be indicated with reference to a specific crop population and analytical perspective (Smale, 1997).

in an area could be obtained, analyses comparing their genetic diversity might provide only part of the answer regarding genetic narrowing. Although the landrace in the farmers' field is a heterogeneous population of plants, it is derived from generations of selection by local farmers and is therefore likely to be local in adaptation. In contrast, the plants of a modern variety are uniform but the diverse germplasm in their genetic background may enable them to adapt more widely. The diversity in a modern variety may not be expressed until challenged by the environment. On the other hand, the landrace may carry and allele that occurs rarely among modern varieties and is a potentially valuable source of genetic material not only for the farmer who grows it today but also for future generations of producers and consumers. (Pingali and Smale, 2001).

Transgenic crop adoption

Like modern varieties, the adoption of transgenic crops depends in the first instance on economic factors. In addition to their purely agronomic characteristics, a number of institutional factors will affect the farm-level profitability of transgenic crops, particularly in developing countries. Economic research is beginning to show that transgenic crops can generate farm-level benefits where they address serious production problems and where farmers have access to the new technologies. So far, however, these conditions are only being met in a handful of developing countries. These countries have been able to make use of the private sector innovations developed for temperate crops in the North. Furthermore, they all have relatively well developed national agricultural research systems, intellectual property rights regimes, regulatory systems and local input markets.

Qaim, Yarkin and Zilberman (in this volume) summarize the available evidence on the varietal adoption of transgenic crops. The most widely adopted transgenic crops are available in a large number of varieties in the major markets (e.g. there are more than 1,100 varieties of

RR soybean and more than 700 varieties of Bt maize in the United States). Traxler (2004) reports that more than 35 different Bt and Bt/HT cotton varieties are on the market in the United States.

The Chinese Academy of Agricultural Sciences (CAAS) has developed the only source of transgenic insect resistance independent of the Bt genes patented by Monsanto. Pray *et al.* (2002b) reports that CAAS has developed more than 22 locally adapted transgenic cotton varieties for distribution in each of the Chinese provinces. The Monsanto *Cry1Ac* gene is also available in China through at least five varieties developed by D&PL (Pray *et al*., 2002b). In contrast, in Argentina, Mexico, South Africa and elsewhere, only a few Bt cotton varieties are available, all containing the Monsanto *Cry1Ac* gene, and often imported directly from the United States without local adaptive breeding (FAO, 2004).

Implications of transgenic crops for genetic diversity

The impact of transgenic crops on crop genetic diversity, like that of conventional crops, is a complex concept. Multiple dimensions of diversity must be considered, including the diversity of plant types in farmers' fields and the genetic pedigrees of those plant types. Whether the introduction of transgenes, *per se*, will increase or decrease crop genetic diversity is a matter of debate. Transgenesis, by definition, broadens the genomic content of plants by introducing genetic material from organisms that would not naturally breed with the host plant. Furthermore, since transgenic techniques are more targeted than classical breeding approaches, it is technically feasible for many individual varieties or landraces to be transformed with selected transgenes, retaining a wider range of genetic diversity in the background material. However, widespread gene flow from transgenic crops to other modern varieties or landraces could eliminate non-transgenic options, arguably reducing crop genetic diversity.[2]

How transgenic crops will influence the diversity of plant types in farmers' fields depends largely on the forces shaping agricultural research, variety development and adoption. If only a few transgenic traits or crop varieties are available and they are widely adopted, the spatial genetic diversity within agricultural fields could be reduced. The proprietary nature of private sector transgenic crop research means that germplasm is less readily shared between plant breeding programmes than it was during the green revolution. The reliance on a narrower range of germplasm may lead to genetic narrowing beyond any effect associated with the transgenic trait, *per se*. On the other hand, if many genetically diverse locally-adapted varieties become available at affordable prices, spatial diversity could increase. Temporal diversity could increase if the introduction of transgenic crops results in higher seed replacement rates among farmers, but unless a continual supply of new transgenic varieties is available, temporal diversity could subsequently decline.

Little evidence is available so far on the impacts of transgenic varieties on crop genetic diversity (Ammann, 2004). Sneller (2003) used coefficient of parentage analysis to determine whether the introduction of transgenic herbicide resistance in soybeans and the associated proprietary restrictions on germplasm exchange between breeding programmes have resulted in a narrowing of genetic diversity within elite North American soybean cultivars. He concluded that the advent of transgenic herbicide tolerant cultivars has had little impact on the diversity of soybean cultivars because of the wide use of this technology by many programmes and its incorporation in many lines. In contrast, he found that restricted

[2] Scientists agree that gene flow is possible, although they differ on whether it matters in and of itself. Technical methods and crop management strategies can reduce the risk of gene flow (International Council for Science, 2003).

germplasm exchange among breeders has reduced the diversity among the elite lines available from some companies and cautioned that the elite soybean population was becoming subdivided by the source of germplasm.

Bowman et al. (2003, cited in Ammann, 2004) examined genetic uniformity among cotton varieties in the United States. They found that genetic uniformity has not changed significantly with the introduction of transgenic cotton cultivars. On the contrary, the dominance of both the single most popular cotton cultivar and the five most popular cultivars has declined compared with the years immediately prior to the introduction of transgenic varieties, suggesting that spatial diversity may have increased. These examples suggest that the impacts of transgenic varieties on crop genetic diversity may depend more on the economic and institutional setting in which they are deployed than on the technology itself.

Scenarios for transgenic crop deployment and implications for crop biodiversity

Three scenarios for making transgenic technologies available in developing countries were mentioned above: (i) direct import, (ii) local development/adaptation and (iii) regional cooperation. Each has different implications for transgenic crop adoption and crop genetic diversity.

In the first scenario, transgenic crop varieties developed elsewhere are imported directly on a commercial basis. In this scenario, farmers pay for the technology through the seed price and technology fees. Although some countries are currently planting imported transgenic varieties, it is unlikely that imported varieties provide optimal performance outside their original agro-ecological zone. Furthermore, commercial transgenic innovations are unlikely to be available for crops grown by small farmers in marginal areas, who are unlikely to have the financial means to afford them. Qaim and Traxler (2004) argue that the transgenic Bt cotton varieties available in Argentina were originally developed for the US market and have lower agronomic potential yields than locally adapted conventional varieties. They identified this as one reason for the relatively slow adoption of Bt cotton in Argentina. The second (and main) factor cited by Qaim and Traxler (2004) were the high seed costs and technology fees for Bt cotton in Argentina, for which strict IPR protections are enforced. Due to the lack of local adaptation and their potentially high cost, imported transgenic varieties probably would not be widely adopted and the range of available varieties for a particular trait would be narrower. In these circumstances, the impact of transgenic technology on spatial genetic diversity would be small. In the areas where imported varieties are adopted, the narrow range of available varieties could contribute to genetic narrowing.

In the second scenario, each country would develop its own transgenic innovations or adapt imported technologies for local use. This scenario would depend crucially on the national research and regulatory capacity and the availability of transgenic constructs, either from the public sector or the private sector. Thus far only China has brought independently developed transgenic constructs to the market. A few other countries may have the capacity to do so, but they are exceptional, thus most countries will have to rely on imported constructs. In these countries, adaptive research could be conducted by the public sector, perhaps in cooperation with local seed companies that in turn are linked with a multinational firm through a joint venture or a licensing arrangement. Under these arrangements, licensing fees would be paid to the multinational company, but farmers would receive locally adapted varieties that potentially would be more profitable than imported varieties. The availability of a wider array of transgenic crops in locally adapted varieties would be expected to increase adoption rates, but the impact on crop genetic diversity is complex. The availability of many locally adapted transgenic varieties would promote both spatial and temporal diversity within the transgenic area. While the area planted to landraces and conventional varieties would probably be reduced, it is unlikely that they would disappear completely, as landraces have survived through the green revolution period. It is possible that transgenes could flow to landraces or conventional crops– inadvertently or by design – especially for open-pollinated crops, but the effect of this gene flow on biodiversity is a matter of debate. Gene flow could create legal and economic problems relating to the coexistence of transgenic varieties and other types of agriculture – landraces, conventional varieties or organic – but the biodiversity implications are not clear.

The third option identified above would involve regional cooperation among public sector institutions in developing countries to develop and/or adapt transgenic innovations for local conditions. In this scenario, several small institutions could work together, or institutions in small countries could work with their counterparts in the International Agricultural Research Centres (IARCs) or in large neighbouring countries. China, for example, could develop transgenic crops for its own tropical regions and share these with smaller neighbouring countries where similar agro-ecological conditions apply. Regional cooperation would permit greater economies of scale in research, and could place small national research institutes in a stronger position to negotiate licensing fees with the multinational companies.

Regional cooperation would assist countries that have weaker research capacity, and could make a wider range of transgenic crops and varieties available than would occur in either of the previous scenarios. This would tend to promote adoption of a larger number of transgenic crops and a wider array of varieties. Area planted to landraces could be reduced but, as with the green revolution modern varieties, this would not necessarily constitute genetic narrowing. The availability of a wider range of varieties could contribute to genetic diversity.

While regional cooperation could be beneficial to the smaller countries, it is unclear whether larger countries would have the necessary incentives to participate. Public sector research institutes have generally conformed to national boundaries, often with the explicit goal of promoting the economic competitiveness of the national agricultural sector. Incentives that promote cooperation would need to be put in place for such a scenario to materialize. The IARCs could play a stronger role in promoting regional cooperation, as they did during the green revolution, but given their declining resources, it is unclear whether they will be able to do so.

V. Conclusions

The changing locus of agricultural research from the public to the private sector is influencing the kinds of crop technologies that are being developed and the ways they are being disseminated. This in turn will influence both spatial and temporal patterns of crop genetic resources. Transgenic crops, *per se*, may increase or decrease crop genetic diversity, depending on how they are regulated and deployed. For example, regulatory regimes that focus on the transgenic innovation rather on than the individual variety would tend to promote the development of a larger number of transgenic varieties.

The green revolution modern varieties were developed and disseminated largely by the public sector. The IARCs developed the improved germplasm and made it freely available to researchers in national institutions. The countries that most widely benefited from the green revolution were those that had or quickly developed strong national capacity in agricultural research. Researchers in these countries were able to make the necessary local adaptations to ensure that the improved varieties suited the needs of their farmers and consumers. However since transgenics are often proprietary, they are more expensive and less accessible than green revolution technologies were. This means that national researchers may not have access, on affordable terms, to appropriate transgenic technologies and a diverse range of germplasm for breeding purposes. Thus there is a much stronger imperative for regionalized R&D to capture economies of scale and enhance the bargaining power of public research institutions relative to the technology suppliers.

The capacity to develop locally adapted transgenics is likely to lead to a wider range of relevant transgenic products (so more diversity of transgenics) and thus higher adoption and higher benefits to farmers. It is also more likely to lead to losses of areas planted to landraces and conventional varieties. Whether this would lead to genetic narrowing, however, is not entirely clear because varietal adoption cannot be directly associated with genetic diversity. It is unlikely that transgenics would entirely replace the landraces that have survived through the last 200 years of agricultural intensification and commercialization. Furthermore, transgenic varieties could be more genetically diverse than the landraces and conventional varieties they replace. The experience with varietal adoption in the early phases of agricultural modernization suggests that the rapid spread of a few transgenic varieties could be followed by a diversification as more varieties become available.

The international community, specifically the IARCs, could facilitate access to biotechnology for developing countries through sharing and coordinating research. Given their declining resources, however, the IARCs may not be able to play as strong a role in this area as they did during the green revolution. The IARCs and other international institutions can facilitate developing countries' access to biotechnology through other means, such as capacity-building and networks for research, regulation and IPR management. These institutional contributions may be as important as the scientific research in making a wider range of transgenic crops and varieties available in developing countries and ensuring that transgenic technology promotes rather than detracts from crop genetic diversity.

References

Ammann, K., 2004, Biodiversity and agricultural biotechnology: A review of the impact of agricultural biotechnology on biodiversity, Botanischer Garten Bern. (March 2004); http://www.botanischergarten.ch/EFB/Report-Biodiv-Biotech6.pdf.

Boserup, E., 1981, *Population and Technological Change: A Study of Long term Change,* University of Chicago Press, Chicago.

Bowman, D., May, O. and Creech, J., 2003, Genetic uniformity of the US upland cotton crop since the introduction of transgenic cottons, *Crop Science*, **43**: pp. 515-518.

Byerlee, D., and Fischer, K., 2002, Accessing modern science: Policy and institutional options for agricultural biotechnology in developing countries, *World Dev*., **30**(6): pp. 931-948.

deGroote, H., Mugo, S., Bergvinson, D., and Owuor, G., 2004, Debunking the myths of GM crops for Africa: The case of Bt maize in Kenya, Paper presented to FAO, 4 February 2004.

Evenson, R.E. and Gollin, D., 2003, Assessing the impact of the green revolution: 1960-1980, *Science*, **300**: pp. 758-762.

FAO, 2004, Agricultural biotechnology: Meeting the needs of the poor?, *The State of Food and Agriculture: 2003-04*, FAO, Rome.

Hawkes, J.G., 1983, *The Diversity of Crop Plants*, Harvard Univ. Press, Cambridge.

Hayami, Y. and Ruttan, V.W., 1985, *Agricultural Development: An International Perspective.* Johns Hopkins University Press, Baltimore, MD.

International Council for Science (ICSU), 2003, *New Genetics, Food and Agriculture: Scientific Discoveries – Societal Dilemmas*, (March 2004); http://www.icsu.org.

James, C., 2003, *Preview: Global Status of Commercialized Transgenic Crops: 2003*, ISAAA Briefs No. 30, ISAAA: Ithaca, NY, (March 2004); www.isaaa.org/kc/CBTNews/press_release/brief30/es_b30/pdf.

Morris, M., 1998, *Maize Seed Industries in Developing Countries*. Lynne Rienner Publishers: Boulder, CO.

Pingali, P., 1997, From subsistence to commercial production systems: The transformation of Asian agriculture," *Am. J. Agric. Econ*. **79**: pp. 628-634.

Pingali, P. and Smale, M., 2001, Agriculture, Industrialized. *Encyclopedia of Biodiversity, Vol. 1*. Academic Press, pp. 85-97.

Pingali, P.L., and Heisey, P.W., 2001, Cereal-crop productivity in developing countries: Past trends and future prospects, *Agricultural Science Policy*, J.M. Alston, P.G. Pardey, and M. Taylor, eds., IFPRI & Johns Hopkins University Press: Washington.

Pingali, P., Rozelle, S., and Gerpacio, R.V., 2001, The farmer's voice in priority setting: A cross-country experiment in eliciting technological preferences, *Econ. Dev. and Cultural Change,* **49**(3):591-609.

Pingali, P., and Traxler, G., 2002, Changing locus of agricultural research: Will the poor benefit from biotechnology and privatization trends?" *Food Policy,* **27**: 223-238.

Porceddu, E., Ceoloni, C., Lafiandra, D., Tanzarella, O.A., and Scarascia Mugnozza, G.T., 1988, Genetic resources and plant breeding: Problems and prospects, *The Plant Breeding International, Cambridge Special Lecture*, pp. 7-21. Institute of Plant Science Research: Cambridge, UK.

Pray, C.E., 2001, Public/private sector linkages in research and development: Biotechnology and the seed industry in Brazil, China and India, *Am. J. Agr. Econ.,* **83**(3): 742-747.

Pray, C. E., Courtmanche, A., and Govindasamy, R. 2002a. The importance of intellectual property rights in the international spread of private sector Agricultural Biotechnology. 6th International Conference convened by ICABR on Agricultural Biotechnologies: New Avenues for Production, Consumption and Technology Transfer. Ravello, Italy, 11-14 July 2002 (March 2004); http://www.economia.uniroma2.it/conferenze/icabr/download papers/2002download.htm.

Pray, C.E., Huang, J., Hu, R. and Rozelle, S., 2002, Five years of Bt cotton in China - the benefits continue, *The Plant Journal,* **31**(4): pp. 423-430.

Pray, C. E., and Naseem, A., 2003, The economics of agricultural biotechnology research, ESA Working Paper No. 03-07, FAO: Rome, Italy (March 2004); http://www.fao.org/es/esa.

Qaim, M. and de Janvry, A., 2003, Genetically modified crops, corporate pricing strategies, and farmers' adoption: the case of Bt cotton in Argentina. *Amer. J. Agr. Econ*., **85**(4): pp. 814-828.

Qaim, M., Yarkin, and Zilberman, D, 2004, this volume.

Sneller, C., 2003, Impact of transgenic genotypes and subdivision on diversity within elite North American soybean germplasm, *Crop Science*, **43**:409–414 (March 2004); http://crop.scijournals.org/cgi/reprint/43/1/409.pdf.

Table 1: An agricultural technology timeline

Technology	Era	Genetic Interventions
TRADITIONAL	About 10 000 BC	Civilizations harvested from natural biological diversity, domesticated crops and animals, began to select plant materials for propagation and animals for breeding
	About 3 000 BC	Beer brewing, cheese making and wine fermentation
CONVENTIONAL	Late 19th Century	Identification of principles of inheritance by Gregor Mendel in 1865, laying the foundation for classical breeding methods.
	1930s	Development of commercial hybrid crops
	1940s to 1960s	Use of mutagenesis, tissue culture, plant regeneration. Discovery of transformation and transduction, discovery by Watson and Crick of the structure of DNA in 1953, identification of genes that detach and move (transposons).
MODERN	1970s	Advent of gene transfer through recombinant DNA techniques. Use of embryo rescue and protoplast fusion in plant breeding and artificial insemination in animal reproduction.
	1980s	Insulin as first commercial product from gene transfer. Tissue culture for mass propagation in plants and embryo transfer in animal production.
	1990s	Extensive genetic fingerprinting of a wide range of organisms, first field trials of genetically engineered plant varieties in 1990 followed by the first commercial release in 1992. Genetically engineered vaccines and hormones and cloning of animals.
	2000s	Bioinformatics, genomics, proteomics, metabolomics

Source: FAO. 2004. *The State of Food and Agriculture.*

Table 2: Crop biotechnology research expenditures

	Biotech R&D (million US$/year)	Biotech as share of sector R&D
Industrialized countries	**1900-2500**	
Private sector*	1000-1500	40
Public sector	900-1000	16
Developing countries	**165-250**	
Public (own resources)	100-150	5-10
Public (foreign aid)	40-50	n.a.
CGIAR centres	25-50	8
Private sector	n.a.	n.a.
World total	**2065-2730**	

* Includes an unknown amount of R&D for developing countries
Source: Byerlee and Fischer (2002)

ESA Working Papers

WORKING PAPERS

The ESA Working Papers are produced by the Agricultural and Development Economics Division (ESA) of the Economic and Social Department of the United Nations Food and Agriculture Organization (FAO). The series presents ESA's ongoing research. Working papers are circulated to stimulate discussion and comments. They are made available to the public through the Division's website. The analysis and conclusions are those of the authors and do not indicate concurrence by FAO.

ESA

The Agricultural and Development Economics Division (ESA) is FAO's focal point for economic research and policy analysis on issues relating to world food security and sustainable development. ESA contributes to the generation of knowledge and evolution of scientific thought on hunger and poverty alleviation through its economic studies publications which include this working paper series as well as periodic and occasional publications.

Agricultural and Development Economics Division (ESA)
The Food and Agriculture Organization
Viale delle Terme di Caracalla
00100 Rome
Italy

Contact:
Office of the Director
Telephone: +39 06 57054358
Facsimile: + 39 06 57055522
Website: www.fao.org/es/esa
e-mail: ESA@fao.org