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Crop Genetic Resources

An Economic Appraisal

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Abstract: Crop genetic resources are the basis of agricultural production, and significant economic benefits have resulted from their conservation and use. However, crop genetic resources are largely public goods, so private incentives for genetic resource conservation may fall short of achieving public objectives. Within the U.S. germplasm system, certain crop collections lack sufficient diversity to reduce vulnerability to pests and diseases. Many such genetic resources lie outside the United States. This report examines the role of genetic resources, genetic diversity, and efforts to value genetic resources. The report also evaluates economic and institutional factors influencing the flow of genetic resources, including international agreements, and their significance for agricultural research and development in the United States.

Keywords: Genetic resources, genetic diversity, germplasm, R&D, international transfer of genetic resources, *in situ* conservation, *ex situ* conservation, gene banks, intellectual property.

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Summary

Half the yield gains in major U.S. cereal crops since the 1930s are attributed to genetic improvements. Demand for crops continues to grow, and environmental conditions change, so continued productivity growth—and the genetic diversity that helps sustain it—remains important. Genetic diversity can be conserved in farmers' fields, in ecosystems that contain wild relatives of cultivated varieties, and in national or international germplasm collections. It is difficult to determine the best mix of conservation strategies. Regardless, the use of genetic resources by one farmer or plant breeder does not preclude their use by another, so private incentives to sustain diverse genetic resources are low. This motivates public measures (and underlying research) to conserve genetic resources.

What Is the Issue?

Crop genetic resources are the basis from which all crop production stems. But habitat loss, the dominance of scientifically bred over farmer-developed varieties, and genetic uniformity are all threats to continued diversity. Plant breeders need diverse germplasm to sustain productivity growth. The U.S. system for genetic resource conservation may lack sufficient diversity to reduce some crops' vulnerability to pests and diseases. The genetic uniformity of many modern crop varieties has also raised concerns that crop yields and production will become more vulnerable to evolving pests and diseases. At the same time, genetic resource conservation is expensive, and both private incentives and public funding are limited.

Many sources of diverse genetic resources lie outside the United States. To slow or prevent loss of crop genetic diversity worldwide, international agreements have been designed to encourage preservation of genetic diversity and promote the exchange of germplasm. For example, the new International Treaty on Plant Genetic Resources for Food and Agriculture will govern the exchange of germplasm for crops like wheat, maize, and cotton. But implementation has been hampered by a lack of consensus among the treaty's parties on the value of particular genetic resources. Thus, many of the treaty's provisions, such as procedures for transferring germplasm, are still vague. U.S. policymakers and genetic resource managers will face new exchange terms and rules governing the sharing of benefits from commercialized products among the treaty's parties, so the time is right to examine of the costs and benefits of conserving genetic resources.

What Did the Study Find?

Since crop genetic resources are largely public goods, private returns to the holders of crop genetic resources are lower than their values to the world. Thus, private incentives for conservation are likely not sufficient to achieve a level of crop genetic diversity that is socially optimal. Significant economic benefits derive from conserving and using genetic resources. For example, a one-time, permanent yield increase from genetic improvements for five major U.S. crops has generated an estimated $8.1-billion gain in economic welfare worldwide. The estimated stream of benefits from genetic enhancement activities exceeds the cost of investments in genetic resource preservation and use. Consumers in both the developed and developing world have benefited from

higher yields and lower world prices for food. Without continued genetic enhancement using diverse germplasm from both wild and modified sources, the gains in crop yields obtained over the past seven decades are not sustainable, and yields might eventually grow more slowly (or even decline). Agricultural production increasingly relies on "temporal diversity," changing varieties more frequently to maintain resistance to pests and diseases.

Three factors contribute to loss of genetic diversity—habitat loss, conversion from landraces (farmer-developed varieties) to scientifically bred varieties, and genetic uniformity in scientifically bred varieties. The loss of wild relatives occurs mainly through habitat conversion for agricultural use. Habitat loss is particularly problematic in developing countries, which often face greater pressures for wild land conversion than do developed countries. Crop genetic diversity also has diminished as landraces are displaced by scientifically developed varieties. Studies show that far less area is planted to landraces worldwide than a century ago. Finally, crop genetic diversity may decline with reductions in total numbers of varieties, concentration of area planted in a few favored varieties, or reductions in the "genetic distance" between these varieties. Thus far, yields for many major crops have been relatively stable as a result, at least in part, of frequent changes in modern varieties and breeders' continued access to diverse genetic resources.

This economic assessment suggests that crop genetic resources are essential to maintaining and improving agricultural productivity. However, a General Accounting Office (1997) study found that current conservation efforts may fall short of what scientists believe are necessary levels for future crop breeding needs, suggesting a role for public policy. Policy initiatives include broad-based programs of multilateral and bilateral financial assistance, stronger intellectual property rights, and international agreements for germplasm exchange. But institutional constraints may prevent these initiatives from achieving their stated goals.

How Was the Study Conducted?

This report examines the role of genetic resources and genetic diversity in agricultural production, and efforts to value genetic resources. From a review of published literature, the report addresses the value of genetic improvements over time and among regions of the world. Given the role of genetic diversity in minimizing pest and disease epidemics, the report explores how incentives for land conservation, the breeding process, and access to modern varieties can affect diversity in the field.

The report also evaluates economic and institutional factors influencing the flow of genetic resources—including international agreements such as the Convention on Biological Diversity and the International Treaty on Plant Genetic Resources for Food and Agriculture—and their significance for agricultural research and development in the United States. This report synthesizes existing literature to review three proposed policy tools to conserve plant genetic resources: (1) public investments in genetic resource preservation in their natural settings (*in situ* conservation) and of genetic resources saved in gene banks (*ex situ* conservation); (2) stronger intellectual property rights over genetic inventions, particularly in developing countries; and (3) agreements for transferring genetic materials among countries.

Introduction

Genetic resources provide the fundamental mechanics that enable plants to convert soil, water and sunlight into something of critical value to humans—food. Diverse genetic resources allow humans to select and breed plants and animals with desired characteristics, thus increasing agricultural productivity. U.S. agricultural productivity more than doubled over the last century (Ahearn et al., 1998), and much of this productivity increase came from rapidly rising crop yields. Half the yield gains in major U.S. cereal crops since the 1930s are attributed to genetic improvements (OTA, 1987). But demand for agricultural commodities continues to grow, and environmental conditions change, so continued productivity growth—and the genetic diversity that helps sustain it—remains important.

Genetic diversity can be conserved in the form of diverse cultivated varieties in farmers' fields, ecosystems that contain wild relatives of cultivated varieties, and/or germplasm collections that contain samples of wild and cultivated species. Each method is characterized by different costs and benefits, making it difficult to determine the optimal mix of conservation strategies. But each also shares a common feature. The use of genetic resources by one farmer or plant breeder does not generally preclude their use by another, so private incentives to hold and protect genetic resources are generally lower than their value to users as a group or society as a whole. This means that in the absence of appropriate public measures (and underlying research), private efforts to conserve genetic resources are likely to fall short of the conservation levels that are optimal for society.

Previous researchers have contributed to our knowledge about the use and conservation of genetic resources. The National Research Council published a detailed review of the National Plant Germplasm System that included extensive recommendations to improve the system (NRC, 1991). A second, related book presented a broader look at the management of genetic resources (NRC, 1993) and included chapters on economic value and ownership. However, economic methodology has evolved rapidly since this report was released, as have the policy instruments that are used to protect and exchange genetic resources.

The Food and Agriculture Organization of the United Nations developed a report based on studies submitted by member countries. *The State of the World's Plant Genetic Resources for Food and Agriculture* (1996b and 1998) was a useful snapshot of genetic resource conservation and technological methods, but provided minimal economic information such as incentive structures or policy tools. In 1997, the U.S. General Accounting Office presented a systematic analysis of the management of the U.S. national genebank system. Recently, the International Food Policy Research Institute published a set of research briefs focused on gene bank valuation. These last two reports focused only on gene banks, and not on all three genetic conservation options.

All these previous reports have been useful, but recent developments in the international exchange of genetic resources call for a concise and current summary of genetic resource conservation in an economic framework. This report focuses on our current understanding of the value of genetic resources, trends in genetic diversity (and the economic incentives that affect them), and recent strategies for protecting genetic resources (including the International Treaty on Plant Genetic Resources for Food and Agriculture, which entered into force in June 2004).

Origins of Crop Genetic Diversity

Human selection of plant varieties for desired traits (such as taste, pest resistance, or seed size) dates from the very beginnings of agriculture. For thousands of years, farmers have selected, saved, and replanted varieties of the crops that humans consume today. "Centers of diversity" developed where intraspecies diversity of crop varieties was particularly high. Most centers of diversity are found where crops were first domesticated, primarily in today's developing countries.

The pace of genetic improvement accelerated with the development of modern breeding techniques that facilitated selection of specific desirable traits. Breeders have crossed different parental material and selected traits to achieve high yields and improved quality for all types of crops. Breeders have also sought resistance to pests, diseases, drought, and other stress. In fact, resistance has become the primary goal of breeding for many crops.

Current Challenges

Changes in population, income, and other factors (such as urbanization) drive continuing increases in demand for agricultural commodities. Environmental conditions also change and pests and diseases evolve over time, so breeders continually need new and diverse germplasm from outside the utilized breeding stock, sometimes using wild relatives and landraces, to find specific traits to maintain or improve yields (Duvick, 1986). Maintaining resistance is a continual process, because new varieties are resistant to pests and diseases for an average of 5 years, while it generally takes 8 to 11 years to breed new varieties (USDA, 1990).

But private incentives to acquire and preserve genetic resources outside regular breeding stocks are limited, because genetic resources have strong "public goods" characteristics (Brown, 1987; Brown and Swierzbinski, 1985; Frisvold and Condon, 1994; Sedjo, 1992; Simpson and Sedjo, 1992; Reid, 1992; Swanson, 1996). For example, genetic resources are easily transported and replicated, and intellectual property protection has historically been relatively weak for biological innovations, making it difficult for an individual country, firm, or farmer to exclude others from their use. Furthermore, the usefulness of particular genetic resources is highly uncertain, and time horizons for improving genetic resources are long.

Despite the limits on private returns to their conservation and improvement, diverse crop genetic resources remain critical to agricultural production. Therefore, the public sector has played a pivotal role in their conservation. This raises three questions.

First, **what are genetic resources worth?** Most genetic resources are not market goods; that is, they are not sold as inputs into the breeding process

Definitions

Biological diversity refers to the number, variety, and variability among plant, animal, and microorganism species and the ecological systems in which they live. Biological diversity can be defined at three levels. *Genetic diversity* refers to the different genes and variations generally found within a species. The variation among genes across different wheat varieties is an example. *Species diversity* refers to the variety and abundance of different species in a region. Finally, *ecosystem diversity* is exemplified by the variety of habitats, such as grasslands or wetlands, occurring within a region. The term biological diversity can refer to any or all of the three levels of diversity, but in this report we will focus particularly on genetic diversity in agricultural crops.

Crop genetic diversity can be conserved in its natural setting (i.e., *in situ*), or it can be collected and conserved outside its natural environment (i.e., *ex situ*). Within the context of crop genetic diversity, there are five basic kinds of genetic resources:

1. **Wild or weedy relatives** are plants that share a common ancestry with a crop species but that have not been domesticated. These can also be a source of resistance traits, but these traits may be difficult to incorporate in final varieties.

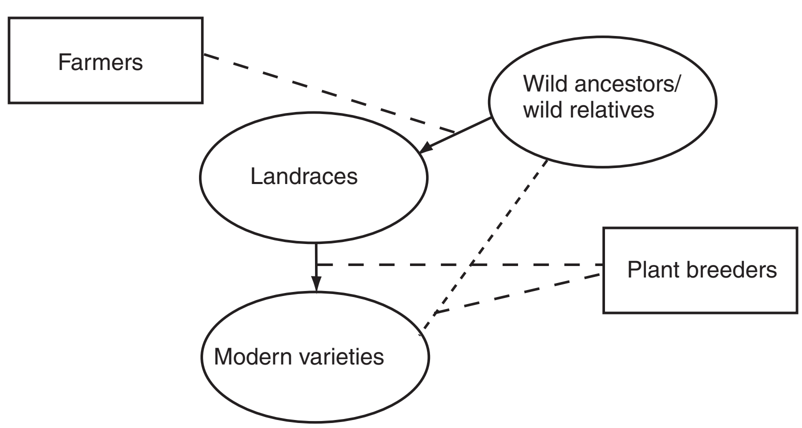
2. **Landraces** are varieties of crops improved by farmers over many generations without the use of modern breeding techniques. These varieties are generally very diverse within species, because each is adapted to a specific environment. Within a modern breeding program, they are sometimes used for resistance traits, and extensive efforts are generally required before their genes are usable in a final variety.

3. **Improved germplasm** is any plant material containing one or more traits of interest that has been incorporated by scientific selection or planned crossing.

4. **Advanced (or elite) germplasm** includes "cultivars," or cultivated varieties, suitable for planting by farmers, and advanced breeding material that breeders combine to produce new cultivars.

5. **Genetic stocks** are mutants or other germplasm with chromosomal abnormalities that may be used by plant breeders, often for sophisticated breeding and basic research.

Figure 1
Farmers, plant breeders, and genetic resources



and so lack simple indicators of their value. As such, policymakers find it difficult to compare investment in conservation with other uses for public funds. The international exchange of germplasm is also complicated, as countries may seek to maximize the returns from the set of resources that they hold.

Second, **how diverse are genetic resources,** not only in gene bank collections but also in the field? Diversity among genetic resources in the field can reduce the prospects for pest and disease epidemics. Farmers generally grow the most productive varieties (in terms of yield or quality), which may or may not be diverse. Society as a whole may prefer a higher level of diversity than farmers do. Incentives for land conservation, the breeding process, and access to modern varieties all can affect diversity in the field. Even the way in which diversity is defined can alter the assessment of benefits associated with different production and conservation decisions.

And finally, **what can be done to ensure we have the crop genetic resources that we will need?** The reliance of agriculture on these resources suggests the importance of continued preservation efforts. Policy instruments such as funding for *in situ* and *ex situ* conservation, intellectual property rights, and negotiated terms of transfer can be used to promote genetic resource conservation. While these policies can be implemented at the national level, genetic resources are found throughout the world. No nation has all the resources it wants or may need in the future. Thus, international coordination of genetic resource conservation is critical to meeting the long-term requirements of agricultural production.

Economic Values of Crop Genetic Resources

Attaching a value to genetic resources is a complex task. Describing the kinds of benefits associated with these resources is easier. The simplest benefit arises from the direct use of genetic resources: to produce food and fiber or to help create new varieties of crops and livestock. These direct uses are the focus of this report, although option value may also be an important motivation for their conservation.[1]

The ultimate direct-use benefits of crop genetic resources are measured in the increased output, higher quality, better resistance to pests, diseases, and other stress, and other characteristics found in improved crop varieties. These benefits derive not only from the genetic resources contained in precursor wild relatives, but also from the efforts of farmers who domesticated the crop and developed landraces through many years of selection; the work of collectors and gene banks that assembled and preserved genetic material in the form of landraces and wild relatives; and the work of plant breeders who have continued to develop and improve crop varieties.

Estimating the Benefits of Genetic Enhancement

Separating the contributions of breeders from the contributions of the germplasm with which they work is difficult. Thus, many studies have focused on the value of "genetic enhancement," or the value arising from both genetic material and its use by breeders. Most efforts to measure genetic enhancement have focused on specific crop breeding programs, using one of two related methods. The first measures benefits derived from a breeding program directly, and calculates rates of return to plant breeding efforts by comparing breeding program expenditures with their benefits. Many rate-of-return studies depend on the second method, some form of growth accounting. Growth accounting attempts to account for all factors affecting yields and then estimates the portion of the yield increase due to genetic enhancements.[2]

Rate-of-return studies sometimes base their estimates of the benefits from genetic enhancement on experimental estimates of yield gains. Plant breeders and other crop scientists may measure genetic gains in crop yield by conducting experiments that attempt to control for the effects of other inputs.[3] Although these studies focus specifically on genetic gains in yield, they do not always correctly value the economic benefits derived from the use of genetic resources for two reasons. First, yield trials that estimate genetic gains in yield are often conducted with input levels that farmers would not use or under environmental conditions that farmers would not face, in part because such experiments rely on control of other inputs for statistical validity. But plausible farmer responses in the face of changing technologies and market-environmental conditions suggest that yield gains in the field are likely to differ from experimental yield gains (Alston et al., 1995). Second, the resulting supply shifts for individual farmers would need to be aggregated to an industry supply shift in order to analyze economic costs and benefits to all producers and consumers.

[1]Genetic resources may also have economic value even if they are not currently being used. By preserving resources, we retain the option to use them in the future, when they may become important for agricultural, pharmaceutical, ecological, or industrial applications—even if we do not currently know precisely what those resources or applications are (Kaplan, 1998). Even if they are never used, diverse genetic resources may be valued by some people simply for their existence, or as a bequest left intact to future generations (Barbier et al., 1995).

[2]Growth accounting is often indicative rather than exact. Various factors (such as improved germplasm and improved crop management practices) frequently interact with one another, making it difficult to isolate the contributions of a single source. Interaction also means that the productivity gain from simultaneous adoption often exceeds the sum of the productivity gains when new varieties or crop management practices are adopted separately (Morris and Heisey, 2003).

[3] See Duvick (1977, 1984, 1992) on maize (corn) in the U.S., and Feyerherm and Paulsen (1981); Feyerherm, Paulsen, and Sebaugh (1984); Schmidt (1984); Cox et al. (1988); and others listed by Heisey, Lantican, and Dubin (2002) on wheat in both industrialized and developing countries.

Studies valuing the plant breeding component of genetic enhancement (see box, "Economic Studies of the Value of Genetic Enhancement") consistently demonstrate its high utility in creating new varieties with higher yields and better resistance to disease. In most cases, too, the economic benefits of genetic enhancement far surpass the costs. These studies do differ in methodology, so the magnitude of estimated economic benefits is often not consistent across studies. Although Evenson and Gollin (1997) made some efforts to estimate the values of genetic resources directly, for the most part, valuation methodologies have not separated out the contribution made by plant breeding from the

Economic Studies of the Value of Genetic Enhancement

Thirtle (1985) estimated the contributions of biological advances—which include both genetic enhancements and other land-saving technological change—in U.S. crop production using growth accounting (controlling for changes in other inputs such as fertilizers, machinery, and pesticides). Thirtle estimated that biological advances increased corn yields an average of 1.7 percent per year between 1939 and 1978; wheat 1.5 percent; soybeans 1.1 percent; and cotton 0.5 percent. Thirtle further concluded that biological improvements contributed to 50 percent of the yield growth of corn, 85 percent for soybeans, 75 percent for wheat, and 24 percent for cotton. In Thirtle's definition, however, biological improvements included both the use of improved varieties and other land-saving changes in agronomic practices.[1]

Byerlee and Traxler (1995) estimated a rate of return of 52 percent for joint international/national wheat breeding programs in developing countries. Pardey et al. (1996) also used rates of return, focusing on the spillover economic benefits of breeding research—i.e., benefits that accrue in regions or countries other than those originally targeted. They analyzed benefits in the United States (either to U.S. research programs or directly to U.S. farmers) from plant breeding research conducted in 2 of the 15 International Agricultural Research Centers (IARCs) that make up the Consultative Group on International Agricultural Research (CGIAR) system. Pardey et al. estimated returns on U.S. financial support to these two programs and found benefit-cost ratios for the United States of up to 48 to 1 for rice and 190 to 1 for wheat. Brennan et al. (1997) estimated that 64 percent of the genetic improvements to Australian rice came from international germplasm, and that the total Australian benefits of varietal yield improvement from 1962 to 1994 were $848 million (1994).

Evenson and Gollin (1997) estimated that without the International Network for the Genetic Evaluation of Rice, 20 improved varieties of rice would not have been released. The present value of that lost production over a 20-year period (the average length of time a rice variety is economically viable) was estimated to be $1.9 billion. Using a discount rate of 10 percent, the authors estimated that the present value of an added landrace (in a variety introduced by the program) was $50 million.

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[1]Technically, Thirtle estimated the rate of land-saving biological-chemical technical change as an exponential time trend within a nested Cobb-Douglas/CES production function. In the same function, a different exponential time trend was used to estimate labor-saving mechanical technological change.

contributions of conserving genetic resources in farmers' fields or in gene banks. Nor do most studies provide a detailed welfare analysis of costs and benefits across producers (including non-adopters) and consumers.

Frisvold et al. (2003) attempted to overcome some of the limitations of earlier studies by adding two features: a global welfare analysis, and a multi-market partial equilibrium model that could calculate the joint effects of genetic improvements in five major crops in the United States between 1975 and 1992.[4] They first estimated the size and distribution of the gross annual benefits of a single-year increase (fig. 2, first panel) in the U.S. yields of corn, soybeans, wheat, cotton, and sorghum. About half of the increase in yields can be attributed to improved seed varieties (Fuglie et al, 1996).[5] Accordingly, to simulate the effects of genetic improvement only, the authors increased the supply of crops by half of the average annual yield growth, implicitly assuming no changes in other inputs and no interactions between genetic improvements and other inputs.

Frisvold et al. estimated that the overall economic welfare of U.S. crop producers across the five commodities increased by more than $160 million and that consumer welfare increased by more than $220 million (1989 constant dollars) due to U.S. genetic improvements. Total U.S. economic welfare increased over $350 million. Producers in the rest of the world suffered losses, while consumers in the rest of the world gained from lower world food prices. Net global welfare increased by $590 million, with the United States capturing 60 percent of the total gain, other developed countries 25 percent, and developing and transitional economies 16 percent.

In fact, yield increases from genetic improvements are not limited to a single year, so Frisvold et al. also calculated the present value of a permanent increase in yields from genetic improvements (fig. 2, second panel).[6] The U.S. benefits of permanent U.S. yield increases range from just under $5 billion (1997 dollars) to over $9 billion. Global benefits range from $8 billion to $15 billion and benefits to developing and transitional economies range from $1 billion to $2.5 billion. (Consumer benefits in developing and transitional economies range from $6 billion to over $11 billion.)

These estimates are conservative for two reasons. First, growth in income and population over time would make the total benefits of yield increases even larger as demand grows. And second, "plant breeding and genetic improvements have not merely generated one-time permanent increases in yields, but rather an annual stream of permanent yield improvements. Every year there is a new incremental permanent increase in yields. The problem is equivalent to receiving a new annuity of varying value every year" (Frisvold et al., 2003) (fig. 2, third panel).[7]

These results suggest that investment in genetic enhancement has generated large returns. The United States was the major beneficiary of genetic enhancement in U.S. crops, although the genetic resources used in these improvements might have multiple sources. (Note that Frisvold et al.'s analysis did not include the U.S. research costs necessary to achieve these yield gains.) Nonetheless, developing and transitional economies also benefited from U.S. yield gains, and it is likely that poor consumers in these countries (including many small farmers) are among the major beneficiaries.

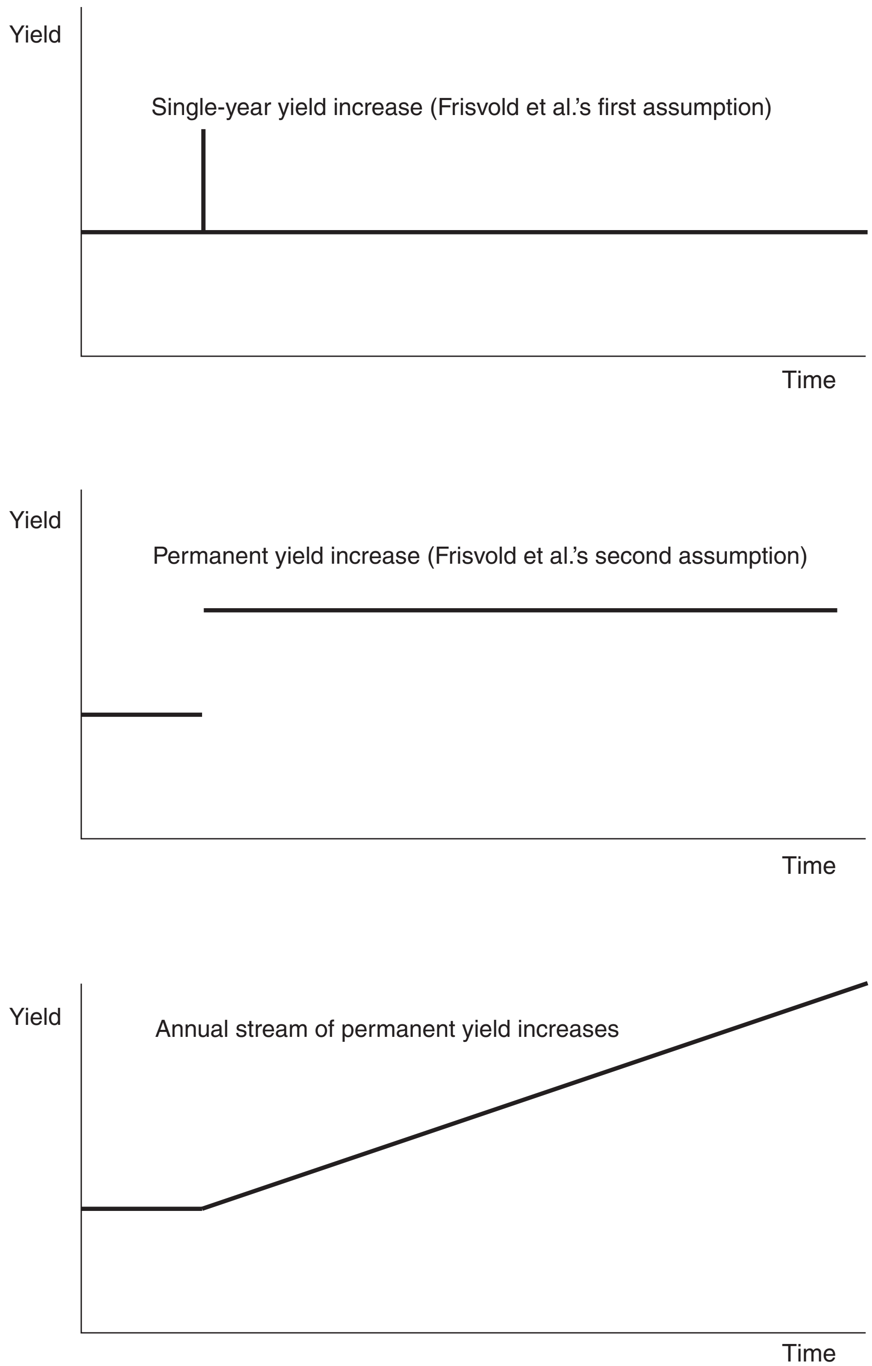
[4] Most studies have focused only on genetic improvements for a single crop.

[5] The average annual growth in U.S. crop yields during 1975–92 was 1.33 percent for corn, 1.54 percent for sorghum, 1.13 percent for wheat, 1.23 percent for soybeans, and 2.23 percent for cotton. The half of the yield growth not attributed to improved seed varieties came from other inputs and management factors, including more fertilizers and pesticides, better agronomic practices, and investments in irrigation and drainage. These other sources of productivity growth also may have been affected by agricultural research.

[6] In other words, annual yield gains attained in a given year are maintained in the years following.

[7] Of course in the long term, research gains may be counteracted by losses of resistance to pests and diseases, but in a successful research program the net gains are positive. The point here is that it is more realistic to look at research gains as a permanent stream over time rather than as an economic benefit occurring only once. If investments are ongoing, new additions to the permanent stream are received every year. Furthermore, avoidance of losses is in fact an economic benefit as well.

Figure 2
Alternative assumptions about benefits from genetic enhancement



Searching for Valuable Genetic Resources

Genetic enhancement depends on the availability of diverse genetic resources for use by plant breeders. In addition to evaluating genetic enhancement, economists have also attempted to evaluate the search for agricultural genetic resources *in situ* (in their natural habitat), the storage and characterization of these resources *ex situ* (e.g. in germplasm collections), and the search for particular traits within *ex situ* collections. Compared with estimates of returns to genetic enhancement, estimates of search costs and returns often are more complex conceptually and more demanding of scarce data (see box, "Economic Models of Searching for Genetic Resources").

Most models of the economics of searching for genetic resources held *in situ* or *ex situ* have been difficult to apply empirically due to data limitations. Several different types of empirical studies have, however, provided useful information about the economics of conservation. First, Evenson and Gollin (1997) directly estimated likely benefits of additional accessions to the rice collection maintained by the International Network for the Genetic Evaluation of Rice. They estimated that the present value of 1,000 additional accessions (discounted at 10 percent over a 20-year period) was $325 million.

Second, Pardey et al. (2001; 2004) estimated the marginal costs of adding accessions to the *ex situ* gene bank for wheat and maize (corn) at CIMMYT, the International Maize and Wheat Improvement Center, and estimated the cost of holding an additional accession in perpetuity. Though Pardey et al. did not estimate the expected values of benefits for additional accessions (and suggested it might not even be feasible), they argued that the cost of additional wheat accessions was so low that expected benefits would probably always outweigh this cost. They argued that some accessions to the maize gene bank—e.g., landraces and wild relatives—might be more likely to have an expected positive return than others, like recently created breeding lines. This is because useful genetic material contained in breeding lines might well be conserved elsewhere—for example, by maize breeding programs—but useful genetic material in landraces and wild relatives would probably be conserved only in the gene bank.[8]

Third, surveys of plant breeders and other users of gene banks have consistently showed that they find gene bank materials useful. For example, the U.S. National Plant Germplasm System (NPGS) is one of the largest national gene banks in the world; it distributes, for free, more germplasm samples internationally than any other supplier, including the international research centers of the CGIAR. Smale and Day-Rubenstein (2002) found that international users of the NPGS requested materials for a variety of uses, including basic research and breeding, and a majority expected that their use of NPGS materials would stay the same or increase in the future. Of NPGS samples distributed from 1995 through 1999, 11 percent had been used in breeding programs, 18 percent were found useful in other ways, and 43 percent were still being evaluated. Twenty-eight percent of the samples were not considered useful. Rejesus et al. (1996) found that wheat breeders around the world used released cultivars, advanced materials, and germplasm from international nurseries much more frequently than wild relatives and landraces. Wild relatives and landraces were used particularly in search of specific traits, such as disease resistance, drought resistance, and quality.

[8] Koo et al. present additional cost figures for CGIAR gene banks. For many cost compoinents of gene bank operation, cost estimates fall between the estimates for wheat and maize.

Economic Models of Searching for Genetic Resources

Simpson, Sedjo, and Reid (1996) applied a theoretical model, originally used in labor economics, to biodiversity conservation in the context of a search for species of interest to pharmaceutical research. Modifying this model, Simpson and Sedjo (1998) argued that the value to society of biodiversity prospecting (searching for genetic resources currently held *in situ*) for use in crop improvement programs was likely to be low.

Cooper (1998) approached the question as one of investment in "converting" *in situ* genetic resources into *ex situ* resources under (1) uncertainty concerning the measurement and value of *in situ* genetic resources, and (2) irreversibility since *in situ* resources, once lost, cannot be replaced. Cooper's simulations demonstrated that estimates of mean benefits might not be particularly useful, as the range of potential benefits could be quite large.

Evenson and Lemarié (1998) applied a search model to a two-stage process—first, collecting genetic resources *in situ* and placing them *ex situ*, and second, searching the *ex situ* collection for traits of interest. They showed that the optimal size of a collection depends on the number of traits being sought, and on the distribution of genetic resources across geographic regions.

Gollin, Smale, and Skovmand (2000) developed a theoretical model that characterizes the search for resistance to pests and diseases in *ex situ* collections of wheat genetic resources, and then analyzed data on frequency distributions, disease losses, and search costs. They concluded that "the optimal size of search for traits is highly sensitive to the economic magnitude of the problem, the research time lag, and the probability distribution of the trait." Furthermore, even though subcollections of landraces or wild relatives might be used only on rare occasions, high benefits might result on those occasions. The fact that "gene banks and some categories of accessions"—i.e., certain types of genetic materials held by a gene bank—"are infrequently demanded by crop breeders does not in itself imply that marginal accessions have low value."

Drawing on these earlier studies, Rausser and Small (2000) argued that scientific models that "channel research effort towards leads for which the expected productivity of discoveries is highest" significantly reduce search costs from earlier "brute force" models that assume no prior information can be brought to the search. In contrast to the results of Simpson et al., Rausser and Small's simulations suggest that market-based conservation of genetic resources might be possible in some cases because prior information reduces private search costs so they are lower than expected private benefits from searching.

One final consideration refers not to the economics of plant genetic resource conservation *per se*, but to a related scientific development bearing on economic decisionmaking. This is the potential of modern molecular biology, including genomics, to reduce the search costs for useful traits in conserved material. (Genomics refers to investigations into the structure and function of very large numbers of genes undertaken simultaneously.) At this point, however, it is relatively easy to generate mountains of raw genetic sequence data but difficult to transform these data into useful information (Attwood, 2000). Thus, conserved genetic resources may increase in value as genomics and other molecular techniques lower search costs and the costs of capitalizing on search results, but it is difficult to predict the pace at which this will take place.

The literature on searching for valuable genetic resources is less conclusive than the literature on evaluating the benefits of genetic enhancement. The majority of studies agree that economic benefits from searching for genetic resources either *in situ* or *ex situ* are positive compared with costs. This can be true even if successful searches are a small fraction of the total searches conducted. However, studies also conclude that it is quite difficult to value searches for genetic resources, and that the range of potential values may be large. The key variable is information. Application of prior information about the probability distribution of a desired trait or set of traits and where searches are likely to have the highest payoffs can significantly increase the economic value of a search for genetic resources. This prior information might be embodied in knowledgeable individuals, scientific publications, characterization of gene bank holdings, or the findings of molecular biology.

Taken together, economic analysis of genetic enhancement and the search for genetic resources indicate that returns to the discovery and use of crop genetic resources exceed the costs. Many scientists, however, have raised concerns about the continued availability of sufficient genetic resources for future plant breeding efforts. Furthermore, both the scientific and economic literatures agree that the measurement of genetic diversity is complex.

Factors Influencing Trends in Crop Genetic Diversity

Diverse genetic resources have been a source of large gains in agricultural productivity and, as a result, producer and consumer well-being. Such gains might provide incentives for conservation and efficient use of valuable resources, but these incentives are often muted in the case of genetic resources because returns to their identification and use are not always easily captured by individual farmers, firms, or countries. In fact, the loss of genetic diversity in a species, also called genetic erosion, has been reported in many commercially important crops (National Research Council, 1972; National Research Council 1993; Porceddu et al., 1988).

Genetic diversity is a particular concern because greater genetic uniformity in crops can increase vulnerability to pests and diseases (National Research Council, 1993). Genetic uniformity does not, in and of itself, mean that a particular variety is more vulnerable to pests and diseases or abiotic stresses. In fact, modern varieties often are bred for superior resistance, hence their popularity. Nonetheless, as pests and diseases evolve to overcome host plant resistance, genetic uniformity increases the likelihood that such a mutation eventually will prove harmful to a crop. The evolved pest or disease has a greater crop base that it can successfully attack, which could increase its severity. Instead of a particular disease harming only a small percentage of varieties on limited land, the disease now could affect a greater proportion of a crop's production. For example, genetic uniformity contributed to the spread of the Southern Corn Leaf Blight, which led to a 15-percent reduction in the U.S. corn crop in 1970.

Here, we identify three factors that might contribute to loss of genetic diversity—habitat loss, conversion from landraces to scientifically bred varieties, and genetic uniformity in scientifically bred varieties—and assess how much each factor is operative today. Considerable debate surrounds both the historic and current loss of genetic diversity, due in part to difficulties in defining an appropriate concept of genetic diversity and obtaining accurate measurements. (Formal measures of genetic diversity, as applied both by scientists and by economists, are discussed in the Appendix.) Formal measures of genetic diversity tend to be both wide ranging and data-intensive, and, in most cases, they are not available for long periods (see box, "Measures of Crop Diversity"). As a result, the discussion of trends in genetic diversity is indicative, not precise.

Most of the formal definitions of genetic diversity are applied either at the cross-species level or within a particular species. Within a crop species, these definitions may be related to the number of varieties, the distribution of varieties within a given area, and/or the genetic difference between varieties within a given area or period of time. In the context of crop genetic resources, for example, habitat loss is likely to affect diversity primarily at the cross-species level, where the relevant species are those closely related to the crop of interest. Conversion from landraces to scientifically bred varieties and genetic uniformity in scientifically bred varieties, on the other hand, may affect one or more of these types of indicators *within* a particular crop species.

Habitat Loss

One factor contributing to a decline in crop genetic diversity has been the loss of wild relatives of cultivated crops (National Research Council, 1993). The loss of wild relatives occurs mainly through habitat conversion for agricultural use. When forest and other wild lands are cleared, plant, animal, and microorganism populations generally fall, reducing the level of genetic diversity. Habitat loss is particularly problematic in developing countries, which often face greater pressures for wild land conversion than do developed countries (Houghton, 1994). Population growth and extensive farming techniques are often cited as factors fostering high rates of land conversion to agriculture. Other influences on land conversion are thought to include poverty, international trade, land degradation, and government policies, particularly where land tenure policies are not clearly defined or enforced (Day-Rubenstein et al., 2000).

Because the full economic values of wild relatives can rarely be captured by landowners, the use of land to preserve habitats for wild relatives remains

Measures of Genetic Diversity

Measures of genetic diversity are very numerous, although there are strong similarities and relationships among many of these measures. At a general level, most involve measures of the *number* of species, the *distribution* of species, and/or the *difference between* species within a given area or period of time. More narrowly, similar concepts might be applied within a crop species, with varieties rather than species becoming the relevant unit of observation.

One reason for the wide variety of measures of genetic diversity is that different people have different reasons for studying or using it. Evolutionary biologists might want to study the process of speciation or the formation of new species, or measure the evolutionary distance between species. Ecologists may be interested in the number and distribution of species within a given habitat. Plant breeders usually focus more closely on diversity within a crop species of interest, although they may also wish to tap diversity within the secondary and tertiary gene pools for that species. (The *secondary gene pool* consists of all biological species that can be crossed with the cultivated species, although these crosses are usually sterile. The *tertiary gene pool* consists of those species that can be crossed with the cultivated species only with difficulty, such as with genetic engineering).

Farmers, particularly those cultivating landraces in noncommercialized agriculture, may be interested in morphological diversity—i.e., diversity in certain physical traits. Because traits are influenced by environmental factors, and because, in many cases, many interacting genes contribute to trait expression, morphological diversity may not be considered to be a “true” measure of genetic diversity. Nonetheless, farmers may make their planting decisions based on such morphological diversity, so it is a potential influence on underlying genetic diversity. Policymakers may focus on preserving genetic diversity as a means to continue crop improvement and guard against the risks of pest or disease epidemics. Economists may wish to study the ways in which the variables important to farmers or policymakers interact with the variables important to plant breeders or ecologists. But no single measure fulfills all desired criteria (Meng et al., 1998).

undervalued compared with alternative uses such as clearing for agricultural or urban use. Thus, habitat conversion occurs in part because the private returns to genetic and other biological diversity are lower than the social returns (Hanemann, 1988). Private returns are important because resources are generally held (whether formally or informally) at the individual or local level. Therefore, many decisions that affect conservation of biodiversity, such as land clearing, are made at these levels. By contrast, many of the benefits of biodiversity conservation accrue at the national or global level. These differing returns contribute to biological resource depletion because conservation of habitat competes with alternative uses of land. Since keeping land in its natural state reduces or eliminates the land's earning capacity for its holders, returns to agricultural production form one opportunity cost of wild land preservation. Also, temporal issues come into play: individuals may place a greater value on current consumption, when weighing the tradeoff between present and future use of resources, than does society as a whole. Together, these factors generate private or individual decisions that differ from those that are socially or globally optimal.

Also, because certain genetic materials are easy to transport and replicate once collected, it is difficult for countries to capture more than a fraction of the value that flows from their genetic resources. Moreover, markets do not exist for most of the other environmental services provided by biological resources, such as carbon sequestration. Consequently, keeping land in less intensive uses favorable to the *in situ* preservation of genetic resources is often less profitable than more intensive agricultural production to individual countries as well as to individual landowners.

Although many habitat reserves have been established worldwide, wild relatives of agricultural species tend to be included only by accident (FAO, 1996b). Habitat preserves often focus on areas rich in species diversity—usually wildlife species or all plant species—and not on crop species alone. These areas are not necessarily those with the greatest crop genetic diversity.

Much empirical work has focused on the loss of tropical forests, but continued agricultural expansion onto other land is also expected (Day-Rubenstein et al., 2000), although at rates lower than previously projected (Bruinsma, 2003). Compared with the developing world, the developed world has lower rates of agricultural land expansion. For example, the amount of U.S. land used for agricultural production has remained stable since 1945 (ERS, 2002). This does not mean that the same land has been in production. Urban land expansion has displaced some agricultural lands, which have displaced some wild lands. Still, expansion of the agricultural production area has not been a significant factor in U.S. biodiversity loss in recent years.

Displacement of Landraces by Scientifically Bred Varieties

Crop genetic diversity also declines as landraces are displaced by scientifically developed modern varieties (National Research Council, 1972; Proceddu et al., 1988; Chang, 1994; Kloppenburg, 1988). The ongoing selection process is thought to have narrowed the genetic base of varieties used in agricultural production (Brush, 1992; FAO, 1996b; GAO, 1997;

Goodman and Castillo-Gonzalez, 1991). In particular, the spread of high-yielding “Green Revolution” varieties and associated changes in crop management practices beginning in the 1960s is thought to exemplify this transition from landraces to modern varieties (Frankel, 1970; Tilman, 1998). Far less area is planted to landraces worldwide than a century ago. But in many cases, the transition to modern varieties predates the Green Revolution. Improved crop varieties, such as hybrid corn or semi-dwarf wheat or rice, often replaced other varieties that were already the products of scientific crop improvement (see Smale, 1997, for an example). In the broadest sense, alteration and narrowing of crop genetic diversity began with the first domestication of wild plants. For example, the corn plant has been completely dependent on humans for reproduction for thousands of years, because farmer selection has resulted in kernels that can no longer disperse without human intervention.

Farmer choice is a key driving factor behind the replacement of landraces with scientifically bred varieties. When choosing varieties, farmers consider yield potential as well as other production and consumption attributes. Sometimes landraces offer superior yields or resistance to biotic and abiotic stresses, but often they do not. Landraces often provide consumption characteristics traditionally preferred to those of modern varieties (such as maize better suited for tortillas), but even this advantage is not absolute. While maintenance of a diverse set of landrace varieties may prove valuable to current or future plant breeding, individual farmers do not directly capture these benefits, so they have little incentive to account for them when selecting seed for planting. Landraces become extinct through disuse if farmers stop planting and maintaining them, unless stored *ex situ*. Even if many landraces are stored in gene banks, genetic diversity might be lower than if these landraces were planted by farmers, because in the gene bank they are not subject to ongoing evolutionary pressure.

The rate of landrace replacement by scientifically bred varieties differs by crop, world region, and environment. In most industrialized nations, commercialized crops—i.e., crops grown solely for the market, not home consumption—consist almost completely of scientifically bred varieties, although isolated use of landraces may occur.[9] In developing countries, genetic resource specialists often have information about the location of crop landraces and the rate at which they are being replaced by scientifically bred varieties, but published information that is accurate and aggregated is difficult to find.

[9] For example, certain isolated areas in Mediterranean Europe grow wheat landraces. Faro, or Triticum dicoccum, is grown in Italy.

Some information is available, however, for use of landraces of the three major world cereals, rice, wheat, and corn (maize). In the 1990s, approximately 15 percent of the global area devoted to rice was planted to landraces. Rice landraces are concentrated in southeast Asia, with some also found in the Indian subcontinent (Cabanilla et al., 1999). Use of rice landraces varies by environment and is much lower in the irrigated lowlands than in the more difficult rain-fed lowland and flood-prone and upland environments.

About 10 percent of the developing world’s wheat area was planted to landraces in the 1990s. Wheat landraces were concentrated in West Asia and North Africa, with some also found in Ethiopia, China, the Indian subcontinent, and small areas in Latin America. The proportion of wheat area planted to landraces also varied by wheat type and environment. For example, 23 percent of the area planted to durum wheat and 12 percent of the area planted to winter bread wheat was sown to landraces, while only 3 percent of the spring bread wheat area in developing countries was still planted to landraces (Heisey et al., 2002).

Unlike wheat and rice, which self-pollinate, corn cross-pollinates, which means that one plant is often fertilized by another. Because of this feature, corn populations are inherently less stable genetically. Therefore, corn landraces may be very diverse genetically. Furthermore, if farmers continue to replant seed (even from hybrids or other scientifically improved corn varieties) rather than buying new seed, the resulting progeny may also be quite genetically diverse. As a result, it is more difficult to define and measure what constitutes a landrace and what is "improved germplasm" for corn than it is for rice or wheat (Morris et al., 1999). That said, it is clear that a far higher percentage of the developing world's corn area (just under 40 percent) is planted to landraces than is the case for either wheat or rice. If developing countries that produce primarily temperate corn or countries that market "commercialized" corn[10] are excluded, nearly 60 percent of the developing world's corn area is planted to landraces (Morris, 2002). As with the other cereals, corn's wild relatives tend to concentrate in their zone of origin (in the case of corn, in Mexico and Central America), and landraces are most diverse in this zone. Nonetheless, corn landraces are found in many parts of the developing world.

[10] This refers to countries for which a large proportion of the corn produced enters the formal market.

Genetic Uniformity in Scientifically Bred Varieties

In situations where most or all landraces have been replaced by scientifically bred varieties, crop genetic diversity may also decline with (1) reductions in total numbers of varieties, (2) concentration of area planted in a few favored varieties, or (3) reductions in the genetic distance between these varieties. The National Research Council (1993) concluded that the genetic vulnerability of U.S. wheat and corn has become less of a problem since 1970, in part because of efforts to breed in greater diversity. However, the Council also determined that genetic uniformity of rice, beans, and many minor crops is still a concern.

Information for other countries is not readily available. Relatively little attention has been paid to genetic uniformity of scientifically bred varieties in developing countries, perhaps because there more focus has been placed on habitat conversion and displacement of landraces. One major study, however, analyzed trends in modern spring bread wheats planted in the developing world, both in the genetic diversity of varieties released and varieties planted in farmers' fields (Smale et al., 2001). This study was representative of over 50 million hectares of wheat planted in the developing world. Both pedigree analysis and molecular analysis suggested that the genetic diversity of these modern wheat varieties had increased, not decreased, over the past 30 years. Trends in genetic diversity for other crops in developing countries, however, as well as for crops in industrialized nations outside the United States, would likely vary by crop and region.

Whatever the trends in genetic diversity, the genetic uniformity of many crops has raised concerns that crop yields and production will become more variable from season to season (Swanson, 1996). As with other drivers of genetic erosion, individual farmers have limited incentives to consider the wider potential consequences of genetic uniformity, and, when choosing which varieties to plant, may perceive the benefits of uniform varieties to be greater. Farmers may be willing to accept the risk of greater variability if they expect to receive higher average yields.

Thus far, despite concerns about genetic uniformity, yields for many major crops have been relatively stable. An important reason may be that temporal diversity has replaced spatial diversity (Duvick, 1984). Although there may be greater spatial uniformity of crops planted at any given time today (compared with 100 years ago), modern plant breeding provides a steady release of new varieties with new traits for pest or disease resistance over time.

The ability of plant breeders to keep ahead of evolving pests and diseases through temporal diversity depends directly on the quality and accessibility of germplasm collections in public gene banks and in private breeders' collections. Because many of the benefits of raw germplasm cannot be appropriated, private breeders rely on the public sector to collect, characterize and perform pre-breeding enhancement of genetic materials to make them accessible for private use (Duvick, 1991).

Conservation of Plant Genetic Resources

In this section we examine two basic strategies for conserving genetic resources, three principal tools policymakers can use to support these strategies, and several multilateral agreements by which countries currently seek to coordinate international use of these tools. Decisions about these alternatives may affect U.S. access to genetic resources that are currently held outside the United States (and vice versa).

Basic Conservation Strategies

At the most basic level, genetic resources can be conserved either *in situ* (in their natural setting) or *ex situ* (outside their natural setting). *In situ* is the dominant method of conserving natural ecosystems. Crop genetic resources are commonly held *ex situ*, but they can also be held *in situ*—as wild relatives of cultivated varieties on wild land and as cultivated varieties in farmers' fields. Among the decisions policymakers face is the appropriate balance between *in situ* and *ex situ* conservation efforts. Each has its own benefits and drawbacks; the two are perhaps better viewed as complementary rather than as substitutes (table 1).

Table 1—Advantages and disadvantages of *ex situ* versus *in situ* conservation

***Ex situ* conservation**		***In situ* conservation**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Costs generally centralized	Certain types of germplasm not readily conserved	Genetic resources used to produce valuable product	Costs borne by farmers (for landraces)
Can preserve large amounts of diverse germplasm	Regeneration can be costly, time-consuming	Evolutionary processes continue	May reduce on-farm productivity
Germplasm can be readily accessed by more breeders	Potential for genetic "drift" can reduce integrity of collection	May better meet the needs of certain farmers	Requires land
High-security storage impervious to most natural disasters.	In practice, many collections lack the resources needed to organize, document, and maintain their samples.	More efficient for some germplasm, e.g., animals, or crops that reproduce vegetatively.	Farmer selections may not preserve targeted diversity
		Existing wild relatives can be preserved without collection	Loss of wild relatives when land use changes

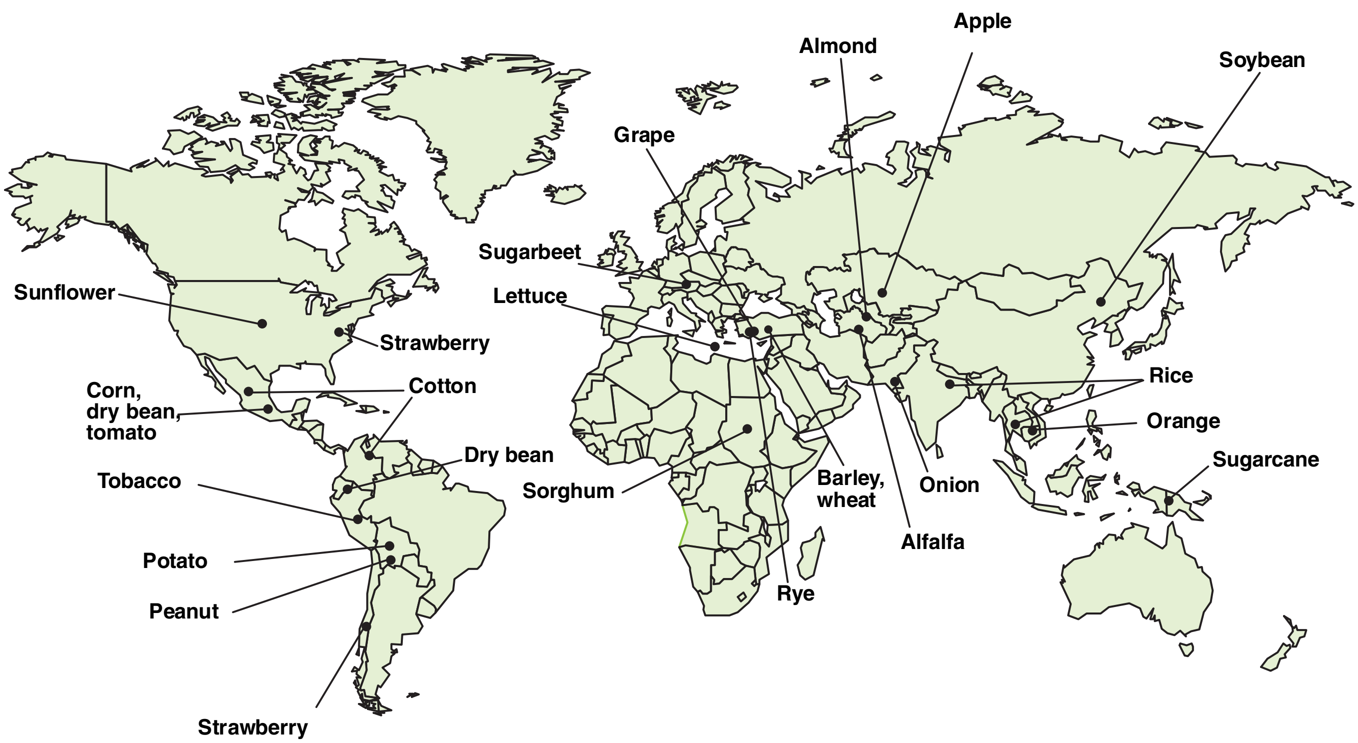
In situ conservation

Species preserved *in situ* remain in their natural habitat. Most of the world's genetic diversity is found *in situ*. For agriculturally important species, the greatest diversity in landraces and in wild relatives is typically found near where they were first domesticated. Early in the twentieth century, Russian botanist N. I. Vavilov defined "centers of origin" for most crops. These included Mexico and Central America (for corn, or maize as it is known in the rest of the world, and upland cotton); China (for soybeans); and West Asia (for wheat and alfalfa).

Since Vavilov's time, ideas about centers of origin have been refined. Some crops, such as sorghum, sugarcane, and peanuts, were probably domesticated over very broad areas rather than in a well defined center (Harlan, 1971, 1992). Furthermore, useful landraces of some crops have been found in parts of the world other than those in which they were originally domesticated. For example, wheat landraces found in the pedigrees of many modern wheat varieties have come from every continent except Antarctica (Smale and McBride, 1996).[11] Still, *in situ* preservation efforts, as well as germplasm collection activities for *ex situ* conservation, are often focused most closely in and around centers of origin (fig. 3).

[11]In another example, modern corn hybrids adapted to the Midwestern United States were derived from dent varieties from the Southeastern United States and flint varieties from the Northeast, which were themselves adapted by settler farmers from many locally distinct varieties selected and reselected by Native American farmers over many previous generations (Duvick, 1998)

Figure 3
Centers of origin of selected crops



Note: The pointer locations indicate general regions where crops are believed to have first been domesticated. In some cases, the center of origin is uncertain. Other geographic regions also harbor important genetic diversity for these crops.

Source: This map was developed by the General Accounting Office using data provided by the National Plant Germplasm System's Plant Exchange Office.

Because *in situ* conservation of agricultural genetic resources is carried out within the ecosystems of farmers' fields or wild lands, species continue to evolve with changing environmental conditions. *In situ* conservation thus can provide valuable knowledge about a species' development and evolutionary processes, as well as how species interact. By allowing genetic resources to act as part of larger ecosystems, *in situ* conservation may also provide indirect ecological benefits, such as hosting diverse pollinators. However, since restrictions on land use may be necessary, *in situ* conservation can be costly. To conserve agricultural genetic diversity *in situ*, for example, a farmer may have to forgo the opportunity to grow a higher yielding (and more profitable) variety. Or, in the case of wild *in situ* resources, the land may need to be set aside from agricultural production or other production-related uses completely. This suggests one important constraint on *in situ* conservation that has been addressed in our discussion of habitat loss—the divergence between the social and private returns to conserving genetic diversity.

Ex situ conservation

The *ex situ* method removes genetic material from its environment for long-term conservation (table 1). Botanical gardens and gene banks are examples of *ex situ* conservation strategies. Certain methods of *ex situ* conservation can be used to store large amounts of genetic material at relatively low cost, certainly in terms of land needed, compared with *in situ* strategies. The world's gene banks presently hold more than four million accessions, or specific samples of crop varieties. It is estimated that samples of many of the world's cereal landraces are now held in gene banks (Plucknett et al., 1987). Although very few important crop species originated in what is now the United States, the U.S. national gene bank system (the National Plant Germplasm System, or NPGS) is today one of the largest *ex situ* collections in the world. *Ex situ* conservation also is appealing because it allows plant breeders easier access to genetic resources than is provided by *in situ* conservation.

However, crop genetic resources first must be collected, and samples of only a small fraction of the world's plant genetic resources have been collected thus far. Stored plant materials must be kept under controlled conditions, and periodically regenerated (planted and grown) in order to maintain seed viability. Not all kinds of plant genetic resources are easily conserved *ex situ*. Some lose their varietal identity when stored as seed. These plants may need to be kept as living plants, a more costly process that requires additional land and labor. And gene banks in politically unstable areas may be in danger of losing valuable genetic material. Even in stable locations, the resources necessary to maintain or improve plant gene banks are not always forthcoming because of competing demands for public resources (GAO, 1997).

Policy Tools To Promote Genetic Resource Conservation

Three major types of policy tools are available to support conservation of genetic resources: (1) public investment in *in situ* and *ex situ* conservation; (2) stronger intellectual property rights over genetic inventions, particularly in developing countries; and (3) material transfer agreements.

Public funding of ex situ and in situ conservation

Funding conservation is the most direct method of preserving crop genetic resources. Past efforts have convinced plant breeders that the current germplasm stock, if properly maintained, is adequate to maintain steady yield growth over the next 20 to 50 years (Shands, 1994; Sperling, 1994; Siebeck, 1994). There is growing concern, however, that this may not be sustainable in the long term at current funding levels (Keystone Center, 1991; NRC, 1993; OTA, 1987; FAO, 1996b). Studies of gene banks worldwide (FAO, 1996a), the U.S. National Plant Germplasm System (GAO, 1997), and the Vavilov Institute collection in the former Soviet Union (Zohrabian, 1995) conclude that most gene banks lack sufficient funds, facilities, and staff to maintain their germplasm collections.[12] Funding problems arise, in part, because individual nations do not capture the full benefits of investments in genetic resource conservation. While multilateral funding of international crop research facilities has been used to alleviate this problem, free rider problems suggest that funding for international facilities will remain less than optimal.

[12] After the breakup of the Soviet Union, the Vavilov Institute, one of the largest collections in the world, has faced critical financial and structural problems. Funding for gene banks in Russia and in these republics has been greatly reduced and many accessions are at risk (Zohrabian, 1995; Webster, 2003).

The UN Food and Agriculture Organization (FAO) reported on the most pervasive problems facing gene banks worldwide (FAO, 1996a). First, since 1970, more emphasis has been placed on collecting materials, than maintaining accessions, and most gene banks lack adequate long term storage facilities. Even accessions in suitable long term storage cannot be maintained indefinitely; collected material must be grown out or "regenerated" periodically. Many gene banks lack the funds, facilities, or staff to carry out needed regenerations. Second, while gene bank coverage of elite and landrace varieties of major cereal crops is believed to be fairly complete, coverage of many "minor" crops (such as root crops, fruits, and vegetables) and wild relatives remains spotty. Third, only a small fraction of accessions has been characterized. This lack of information about what actually resides in these collections constrains breeders from using new genetic materials (NRC, 1993) and makes it difficult to identify gaps in collections. Fourth, many countries have reported that funding has been unstable and uncertain year to year, hampering investment and planning decisions. The FAO (1996c) concluded that "without prompt and significant intervention, much of the stored genetic diversity of food and agricultural crops in the world-as well as the large public investment made in assembling the collections-will be lost forever."[13]

[13] A GAO study of the U.S. Plant Germplasm System echoed the concerns of the FAO report (GAO, 1997).

The same public goods problem that inhibits optimal international investment in *ex situ* conservation of genetic resources-the inability of conserving nations to capture all the benefits from that conservation-also hinders optimal investment in *in situ* conservation. Moreover, *in situ* conservation is subject to several additional constraints. First, uncertainty surrounding the likely magnitudes of the benefits of in situ conservation is probably larger than it is for *ex situ* conservation. Second, the number of economic agents and levels involved in any *in situ* conservation effort (including landowners and/or individuals with rights to use the land) is likely to be considerably larger than for *ex situ* programs, making coordination of *in situ* programs more difficult.

In situ conservation of wild relatives and landraces require different strategies. Establishing habitat reserves could protect wild relatives. Turkey, for example, has received multilateral funding for an *in situ* pilot project to conserve wild relatives of wheat and barley (FAO, 1996b). For landraces, if farmers have private incentives to maintain local varieties, policy interventions for *in situ* conservation may be unnecessary. In areas where displacement of local varieties is more likely, access to modern varieties need not be completely prohibited. A less costly alternative might be to establish some type of conservation easement, paying local farmers the difference between returns to modern and local varieties if they grow a diverse set of varieties on part of their plots (Christensen, 1987). Yet another approach could be to purchase limited amounts of landrace seed from producers in regions with diversity

Most experts agree that *in situ* and *ex situ* conservation strategies are complementary, however the best allocation of resources is subject to debate. Plant breeders are concerned that increased investment in *in situ* conservation will compromise gene bank maintenance. Lack of data on the relative costs and benefits of *in situ* and *ex situ* conservation increases the difficulty of allocating funds across activities. Moreover, donor institutions, particularly at the national level, face competing needs, some of which offer more direct and immediate benefits.

Intellectual property rights

Adoption of stronger intellectual property rights (IPR) regimes has been one of the most commonly proposed methods to enhance genetic resource conservation internationally. Proponents argue that stronger IPR will allow the holders of genetic resources to reap the rewards from commercializing these resources and thus align private incentives more closely with public incentives for genetic resource conservation.

Historically, the set of IPR used for genetic resources internationally focused on the products of formal plant breeding programs rather than wild relatives and landraces. Even while varieties developed by breeders were protected by formal "plant breeders' rights", wild relatives and landraces continued to be considered a public good. For decades, many plant breeders have freely exchanged "raw" germplasm (Kronstad, 1996; Heisey et al., 2001).[14] National plant breeding programs and international agricultural research centers freely provide such unshielded genetic materials not only to other public breeding institutions but also to private breeders (many of them in developed countries) who may then use those materials to develop new commercial crop varieties for sale (Day, 1997).[15]

This asymmetry has proven controversial. Many developing countries and nongovernmental organizations (NGOs) make the case for "farmers' rights," arguing that farmers in developing countries have selected and saved landraces for thousands of years, making an essential contribution to plant breeding and crop variety development (Mooney, 1979, 1983; Brush, 1992). It is unfair, they argue, that private breeders have free use of wild relatives and landraces but require payment for elite varieties based, in part, on germplasm that originated in developing countries. Others counter that the exchange of genetic material for plant breeding has been beneficial to devel-

[14]Goodman and Castillo-Gonzalez (1991) also note that "improved breeding lines have been less freely exchanged, even among public agencies."

[15]Unshielded genetic materials also contain improved varieties; in fact, improved breeding materials are the type of germplasm most frequently distributed by the U.S. National Plant Germplasm System. While public research institutions are the primary source of germplasm placed in the NPGS, private breeding concerns donate materials as well, particularly obsolete breeding materials.

oped and developing countries alike, although they disagree about whether foregone earnings from sales of raw genetic material by lower-income countries are compensated for by other benefits, such as unrestricted access to public germplasm and lower food prices for consumers (Shands and Stoner, 1997; Fowler, 1991).

Proponents of stronger IPR regimes argue that, generally speaking, they encourage commercialization of genetic resources, thus enhancing the incentives for conservation, both *in situ* and *ex situ*. They also maintain that greater IPR stimulate private sector research, relieve public budgetary constraints, and increase national incentives for germplasm conservation (Barton and Siebeck, 1991). Critics counter that stronger IPR would do little to increase innovation or maintain crop genetic diversity, arguing that private incentives favor specialization and product uniformity rather than diversity in the production of new seed varieties (Mooney, 1979, 1983; Acharya, 1991; Reid, 1992; Brush, 1994).

These arguments raise two empirical questions. First, what impact would stronger IPR protection have on germplasm use and exchange? A survey of 84 private plant breeding firms by Pray et al. (1993) assessed the impacts of a 1985 decision by the U.S. Supreme Court that strengthened genetic resource IPR (for modern varieties) by allowing plant breeders to acquire utility patents for new varieties.[16] More than a third of the firms felt that utility patents limited germplasm exchange both between private firms and between the public sector and private firms. Six of 84 firms reported that they had increased their research expenditures because of the availability of utility patent protection. Most reported that utility patents increased profitability. Rejesus et al. (1996) surveyed wheat breeders internationally, and reported that respondents believed that stronger international IPR for plant varieties would reduce germplasm exchange between developed and developing countries, reduce exchange between developing countries and reduce the use of foreign landraces. Pray (1990) noted that stronger IPR in developing countries would entail significant enforcement costs and other transaction costs. The effect of IPR targeted toward land races and wild relatives remains unknown.

[16]Utility patents are the broadest class of patents and, unlike plant patents, they can be used for sexually reproducing plants.

Second, what are the implications of stronger IPR and increased private R&D for the diversity of new varieties developed? Some evidence suggests that the diversity of major crops has not declined in the United States as increasingly strong IPR protections have been enacted over the last 30 years, and diversity may have actually increased for some crops (Duvick, 1984; NRC, 1993; Smale and McBride, 1996; Falck Zepeda and Traxler, 1997; Pray and Knudson, 1994; Knudson, 1998). But the role of IPR is confounded by other efforts to increase crop genetic diversity (see NRC, 1993, pp. 67-81, for discussion on the impacts of its 1972 report “Genetic Vulnerability of Major Crops”).

Material Transfer Agreements

Material transfer agreements (MTAs) are legal instruments initially used as a means for transferring biological materials between entities, including public institutions, private companies, and countries. Initially, used for research only, MTAs may be bilateral agreements or may follow a standard template (such agreements are often used by public entities). The provider retains commercial rights to the material. MTAs have become a common instrument to outline the terms for sharing genetic resources and, sometimes, the gains from new product development. MTAs may include provisions for intellectual property rights, such as what, if any, IPR may be sought for the transferred material or inventions based on that material. However, not all MTAs address IPR and even if they do, IPR usually are just one element of the agreement.

Interest in using MTAs as an incentive to preserve germplasm stems from the idea that benefit sharing can reward suppliers of genetic resources (Barton and Christensen, 1988; Blum, 1993; Christensen, 1987; Simpson and Sedjo, 1992; U.S. Department of State, 1994; WRI, 1993). The benefits to be shared may include funds, materials, training, technology, or intellectual property rights (through provisions concerning their allocation).

The potential for benefit sharing MTAs to affect crop genetic resource conservation is unclear. Plant breeders of major crops use germplasm mainly from their own working collections, or acquire it from other breeders, botanists, or geneticists. Typically, this germplasm has already been enhanced and adapted for plant breeding purposes. While exotic germplasm may provide especially useful traits for disease or pest resistance, such germplasm is only one source of the many genes used in an individual variety. Statistics suggest that, for many commercially important crops, only a small percentage of the genes in released varieties are from newly incorporated exotic germplasm (Cox et al., 1988; Goodman and Castillo-Gonzalez, 1991). The expected value of such exotic germplasm is generally small, though on occasion benefits may be larger (Wilkes, 1991). When breeders do require genetic traits unavailable from their conventional sources, gene banks such as the Future Harvest Centers or the NPGS traditionally have had a vast, free supply of germplasm. To date, this germplasm has been provided freely to users, and not subject to MTAs that require benefit sharing. The use of MTAs to market germplasm from some developing countries may also be hindered by a lack of technical expertise. Breeders often require documentation of valuable genetic traits and the ease by which they can be transferred to commercial seed stock. Even if a country has rare and useful germplasm, breeders may remain unaware of its value or existence (Shands, 1994).

To date, the use of MTAs for crop genetic resources has not generated large financial gains for developing countries. In this respect, raw genetic resources, though lacking a well-developed market, are similar to primary export commodities such as timber or coffee. Much of the value added to commercial seed varieties comes from the laborious and time-consuming process of incorporating raw genetic material into elite crop varieties.

Multilateral Agreements Affecting Plant Genetic Resources

Because of the widespread geographic origins and current use of crop genetic resources and the public goods nature of their conservation, the three principal policy tools for conserving genetic resources involve considerable international overlap. A series of multilateral agreements embody the international coordination needed to preserve genetic resources, as well as the lingering debate over property rights for genetic resources.

U.N. Convention on Biological Diversity

The 1993 U.N. Convention on Biological Diversity (CBD) was designed to promote the conservation and sustainable use of biological diversity and to encourage the equitable sharing of resulting benefits. Language in the Convention relating to property rights over genetic materials, biological inventions, technology transfer, and benefit sharing was drafted more with pharmaceutical and industrial development in mind than seed variety development, though subsequent meetings to implement the Convention focused on agricultural biodiversity. On December 29, 1993, the CBD came into force for ratifying and acceding parties (which numbered 188 as of February 15, 2005).[17] Provisions of the Convention have direct implications for the collection, preservation, and exchange of genetic resources. The CBD states that countries have sovereign rights to their indigenous genetic resources, which institutionalizes the change from the practice of freely collecting and sharing of resources. Most countries have interpreted the CBD to allow countries to require payments or transfer of technology in exchange for access to germplasm. The Convention also included a provision for a biosafety protocol to regulate the international movement of the products of biotechnology. Adopted in January 2000, the “Cartagena Protocol” addresses only living modified organisms (LMOs), and makes a distinction between genetically modified organisms as seed and genetically modified organisms intended for food or feed (the assumption being that the latter will not be released into the environment). According to the protocol, LMOs (which include genetically modified seed) are subject to “Advanced Informed Agreement” procedures. Thus, implementation of the protocol has more impact on LMOs that are transferred as seed, or as germplasm for use in genebank system, than on food or feed.

[17]The United States signed the Convention in June 1993, but the U.S. Senate has not yet ratified it

Other agreements play a role. The World Trade Organization (WTO) agreements, which are negotiated, signed, and ratified by the bulk of the world’s trading nations, are enforceable through the WTO’s ability to levy sanctions. Therefore, countries have strong incentives for the CBD to be consistent with the Trade Related International Property (TRIPS) provisions and the WTO. The International Union for the Protection of New Varieties of Plants (UPOV) is another element affecting the exchange of genetic resources. UPOV-consistent IPR are the leading form of formal varietal protection globally (UPOV protection allows exemptions for breeding and research purposes). After the CBD came into force, the U.S. Department of State (1994) noted that the Convention could not be used to overrule existing intellectual property law, including TRIPS and UPOV. Therefore, both are likely to continue influencing implementation of the CBD.

The International Treaty on Plant Genetic Resources for Food and Agriculture

To address issues left unresolved by the CBD, the International Treaty on Plant Genetic Resources for Food and Agriculture was developed with the intention of (1) mandating conservation of plant genetic resources, (2) ensuring equitable sharing of the benefits created by using these resources, and (3) establishing a multilateral system to facilitate access. The

International Treaty entered into force in June 2004 (the U.S. has signed, but not yet ratified the treaty). Sixty-six countries are parties to the treaty. The treaty is to govern international exchange of germplasm and will cover 35 crops, including major cereals like rice, wheat, and maize, but excluding soybean and peanut and other important crops.

IPR have been a major source of debate in interpreting the treaty, particularly the patenting of materials discovered in public gene banks. The treaty states that "Recipients shall not claim any intellectual property or other rights that limit the facilitated access to the plant genetic resources for food and agriculture, [or their genetic parts or components,] [in the form] received from the Multilateral System." Interpretations of this clause abound, particularly with respect to whether the patenting of isolated compounds, such as genes, will be permitted.

The treaty is vague on a number of points. Disagreements remain about the implementation of benefit sharing and the development of a standard Material Transfer Agreement (MTA). The standard MTA is intended to establish the terms of access to plant genetic resources, and all germplasm exchanges under the new multilateral system will be governed by this standard MTA (rather than the bilateral approach suggested by the CBD). The benefits arising from commercial use of germplasm accessed under the multilateral system are to be shared through four mechanisms: (1) exchange of information, (2) access to and transfer of technology, (3) capacity building, and (4) sharing of monetary and other benefits of commercialization. A yet-to-be established portion of monetary benefits from commercial products are to flow, through a trust account managed by the Governing Body of the Treaty, primarily to farmers who conserve genetic resources, especially those in developing and transitional economies.[18] Because benefits will be shared according to conservation practices and income, rather than contributions to the multilateral system, the incentives for conserving genetic resources are likely to be less direct than originally envisioned. More broadly, the means and particulars of financing conservation activities also have not been specified.

[18]Other aspects of the MTAs, such as recordkeeping and means of assigning parentage of a variety, have yet to be worked out in detail.

Financing International Conservation of Genetic Resources

Given the public good characteristics of crop genetic resources, financing their conservation remains a challenge. Resources available under current and immediately foreseeable policies may be insufficient to conserve the resources agriculture will need. Though MTAs and the expansion of IPR are intended to be self supporting conservation policies, proposals to intensify *in situ* and *ex situ* conservation and to transfer technology and expertise would require additional public funds. Various efforts have been made to estimate actual amounts needed to finance gene banks, *in situ* preservation, and technology transfer. The Keystone International Dialogue (Keystone Center, 1990, 1991) recommended a fund of $300 million annually to support global and national efforts to conserve plant genetic resources. The U.S. National Research Council (1993) recommended that $240 million would be needed annually for maintaining worldwide base collections in addition to evaluation and documentation programs. The FAO (1997) estimated low (A), medium (B), and high (C) funding options ranging from

$150 million to $248 million to $455 million annually, averaged over more than ten years. The FAO figures include only costs that would be borne by the international community and do not include domestic program funding. The report considered Option A "basic or rudimentary" while Option B was "consistent with known and documented needs and realistic absorption and implementation capacity of countries" (FAO, 1997).

Grounded in the FAO's Global Plan of Action for genetic resources is a relatively new organization focused more directly on *ex situ* genetic resource preservation. The Global Crop Diversity Trust is an international organization whose establishment has involved a partnership with the FAO and the 16 Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR). The Trust aims to match the long-term nature of conservation needs with permanent, sustainable funding by creating an endowment that will perennially fund crop diversity collections around the world. The endowment is intended to facilitate the perpetual conservation of eligible collections that meet agreed standards of management. The Trust will serve as an element of the funding strategy to be implemented under the International Treaty described above.

The Global Crop Diversity Trust hopes to raise a minimum of $260 million from corporations, trusts, foundations, and governments as a permanent endowment for genetic resources. That figure is based on a study carried out by the International Food Policy Research Institute and the University of California, Berkeley, which provided best estimates of the annual funds needed to support the core services provided by the Future Harvest genebanks and the level of endowment needed to provide for the collections in perpetuity (Koo et al., 2002). (The annual costs were estimated to be $5.7 million, and the needed endowment was estimated to be $150 million). The Trust has approximately $45 million in commitments and $70 million under discussion to date (Global Crop Diversity Trust, 2005).

Some researchers have looked at methods beyond multilateral donor systems to fund conservation of genetic resources. Proposals have included a tax on seed sales to provide funds for conservation (Barton and Christensen, 1988). Barton and Christensen suggested either a "straight" sales tax on seed revenues or a system of royalty calculation similar to that used by record companies, with proceeds to be distributed among international, national, and private conservation programs to fund *in situ* and *ex situ* preservation. There are concerns that a royalty based system of direct payments may limit the exchange of genetic resources. Also, if royalty payments in the strict sense are used (i.e., payment upon use in a released variety), returns probably will be limited (Charles, 2001). Proposals to fund germplasm through sales taxes and user fees have been opposed by private seed companies. Even if the proposals were to overcome this opposition, formal seed sales are much less prevalent in self-pollinated crops and in some crops grown in developing countries. Thus, certain crops would not benefit as significantly from this approach.

Another proposal has been to tax agricultural commodities generally (Swaminathan, 1996). This proposal raises questions about the distributional implications (between regions and social classes within regions) of taxing seeds or all agricultural commodities. Because poor families generally spend more on food as a portion of the household budgets, such taxes may be regressive (though to raise equal revenues, the tax rate for a general commodity tax on agricultural, forest, and fish products would need to be only a small fraction of the tax rate for seeds). Another option lies with agricultural producer groups in developed countries (such as Australia, New Zealand, and the United States), many of which fund commodity specific research and market promotion through voluntary checkoff systems that act as a commodity tax. However, while national producer groups may be persuaded to help support domestic gene banks and germplasm characterization, they may be less willing to allocate checkoff funds to an internationally administered fund. As with other aspects of genetic resource use and conservation, private interests do not necessarily coincide with broader public goods.

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APPENDIX: MEASURING CROP GENETIC DIVERSITY

Evolutionary or ecological measures of genetic diversity focus particularly on genetic similarity or difference between different species. These kinds of comparisons might also be useful in the study of crop genetic diversity, particularly if a given crop is analyzed in the context of its wild relatives.[1] However, most studies of crop genetic diversity are based on the similarity or difference between different crop populations within the same crop species. Most commonly, named varieties are the crop populations in question, although two distinct varieties may in fact be very similar genetically (Meng *et al*., 1998). For the rest of this discussion, we will usually assume diversity is being measured within a particular crop species.

[1] See Smale (1998), and particularly the chapter by Meng et al. (1998), for one of the first attempts to summarize the application of various diversity-related measures to crops and to give these measures an economic interpretation.

Spatial diversity measures

Spatial diversity—diversity within a given geographical area—may be "the most commonly recognized concept of diversity" (Meng et al., 1998). Two concepts are often used in spatial measures of genetic diversity. "Richness" refers to a simple count measure, for example of the number of varieties of a particular crop species planted in a given area. "Abundance" is a measure of the evenness of the spatial distribution of elements of the set being considered (Magurran, 1991). For example, suppose the same ten crop varieties are planted in two identical regions. In one region, each variety is planted on one-tenth the area, but in the other region one variety is planted on 91 percent of the area and the other nine varieties occupy one percent each. By a simple count measure (such as richness), the two regions are equally diverse, but introducing abundance would suggest the first region is more diverse than the second. This, along with the fact that named varieties may be very similar genetically, is why simply counting numbers of varieties is likely to be an inadequate measure of crop genetic diversity. Simple diversity indices that reflect varietal distribution (thus partially capturing the concepts of richness and abundance), include the proportion of area planted to the most popular variety or given number of varieties (equivalent to concentration measures used in the industrial organization literature.) A related index is the number of varieties covering a given percentage of total crop area (Widawsky, 1996). Another measure taken from the industrial organization literature is the Herfindahl index, which illustrates the degree of concentration among varieties (Pardey et al., 1996). The Simpson index (one minus the Herfindahl index) and the Shannon-Wiener index, taken from information theory, are often applied in ecological studies of diversity (Magurran, 1991).

Measures of relationships between varieties

Other indices of genetic diversity are built up from measures of "genetic distance," i.e., the degree to which varieties or species differ genetically (Nei, 1972; Cavalli-Sforza and Edwards, 1967; Reynolds, Weir, and Cockerham, 1983; Gregorius, 1978). To a certain extent such measures address the problem raised by simply counting named varieties that may be very similar genetically. Genetic distance indices can be calculated based on observations of different crop characteristics, including morphological indicators such as plant height, grain weight, and so on. As indicated, morphological indicators have the advantage that they may be closely linked to the traits on which farmers base their decisions, but the disadvantage that they are often influenced by environment and multiple genes, and therefore not reflective of genetic distance at the chemical (enzyme) or molecular (DNA) level. Genetic distance indices have perhaps most commonly been applied to this biochemical information. The use of biochemical and molecular markers requires systematic physical sampling as well as laboratory time and materials, and as a result can be quite costly (Meng et al., 1998).[2] An alternative approach to measuring genetic distance between varieties, at least for scientifically-bred crops with documented pedigrees, is based on comparison of the heritage of pairs of varieties.[3]

Building diversity indices

Genetic distance indices measure differences between different crop varieties or species, but they themselves do not measure overall genetic diversity. Weitzman (1992; 1993) describes a diversity index calculated as the total length of the branches of a taxonomic tree. Such a tree could be calculated using morphological, genealogical (i.e. pedigree), or genetic distance data. Solow, Polasky, and Broadus (1993) also incorporate the size of the set (e.g., number of crop varieties) as well as genetic distance into genetic diversity indices. Both these tree-based measures, and other measures based on matrices of similarity coefficients, permit weighting to reflect the distribution of crop varieties (Souza et al., 1994; Meng et al., 1998).

Measures of plant breeding activity using genetic resources

A number of other measures have been applied to the study of genetic resources, but they usually refer to aspects of a scientific plant breeding program, or the development of such a program from initial crosses involving landraces, rather than to direct measures of genetic diversity. These include numbers and origin of landraces in the ancestry of the varieties being studied, or the number of breeding generations since the initial cross (Gollin and Evenson, 1990); numbers of distinct parental combinations and numbers of unique landrace ancestors per pedigree (Smale and McBride, 1996; Hartell, 1996; Smale et al., 1998); or coefficient of parentage (COP) based measures (Pardey et al., 1996). Note that all of these pedigree-based measures are less useful in a crop, such as corn, that may not always follow a strict pedigree breeding system, or in crops for which pedigrees are partially or completely private for proprietary reasons.

Temporal diversity

Duvick (1984) observed that in a number of scientifically-bred crops, *temporal* diversity (or diversity through time) has replaced spatial diversity as one means of maintaining or even raising resistance or tolerance to pests and diseases. Temporal diversity depends on maintaining breeding effort by humans. Meng et al. (1998) closely identify temporal diversity with "the rate of change or turnover of [planted] varieties" as defined, for example, by Brennan (1984) and Brennan and Byerlee (1991). Other things being equal,

[2]Another characteristic, infrequently noted, of both morphological and genetic measures is that they obviously require informed choice of the characteristics or genes that will be analyzed. No index will be constructed, for example, based on all genes in a crop that are polymorphic, i.e., genes that have more than one variant. In the first place, such a list is unknown, and in the second, costs would become completely prohibitive.

[3]This approach uses the coefficient of diversity (COD), which equals 1 - the coefficient of parentage (COP). The COP is a pairwise comparison based on pedigree analysis (Wright, 1922; Malecot, 1948; Kempthorne, 1969; Cox et al., 1985). COD/COP analysis is less costly than analysis of proteins or molecular methods, but it also has some disadvantages: 1) it ignores the possibility that alleles could be identical even without common heritage; 2) it relies on the assumption that the ultimate ancestors that are recorded in a pedigree are unrelated, which may not be true; and 3) it assumes that "each parent contributes equally to offspring, despite the effects of recurrent selection and random genetic drift" (See Nightingale, 1996; Cox et al., 1985; Meng et al., 1998)

faster varietal turnover might be expected to be associated with increased temporal genetic diversity, but like pedigree-based measures, varietal turnover is more a measure of the output of a plant breeding program than of genetic diversity *per se*. Newly released varieties might be genetically somewhat dissimilar to older varieties, or they might be very closely related genetically. Time-series of *spatial* diversity measures could provide useful information about *temporal* change in diversity, but such a series would not strictly measure “temporal diversity.” More formal assessment of temporal genetic diversity could be made by statistically testing differences between genetic distance measures over temporal samples (See Souza et al., 1994 and Tessier and Bernatchez, 1999).