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Using Crop Genetic Resources To Help Agriculture Adapt to Climate Change: Economics and Policy

Paul W. Heisey and Kelly Day Rubenstein

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Paul W. Heisey and Kelly Day Rubenstein

Abstract

Climate change poses significant risks to future crop productivity as temperatures rise, rainfall patterns become more variable, and pest and disease pressures increase. The use of crop genetic resources to develop varieties more tolerant to rapidly changing environmental conditions will be an important part of agricultural adaptation to climate change. Finding new genetic traits that can facilitate adaptation—and incorporating them into commercially successful varieties—is time-consuming, expensive, and technically difficult. The public-goods characteristics of genetic resources can create obstacles to rewards for private research and development. Because of insufficient private incentives, public-sector investment in the use of genetic resources will help determine the agricultural sector's ability to maintain crop productivity, and for society as a whole, the potential benefits of public investment are large. The study authors find, however, that factors such as intellectual property rules for genetic resources and for research tools, or international agreements governing genetic resource exchange, have the potential both to promote and to hamper greater use of genetic resources for climate change adaptation.

Keywords: Crop genetic resources, crop germplasm, climate change, plant breeding, agricultural resources

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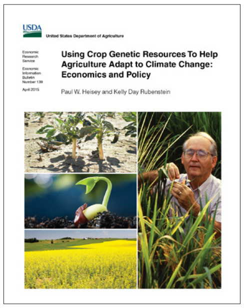
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What Is the Issue?

Climate change poses likely risks to future crop productivity as temperatures rise, rainfall patterns become more variable, and heat waves, drought, pests, and diseases increase. One strategy for helping farmers adapt to these changes is the development of crop varieties with better tolerance for increased stresses. Traits to boost crop adaptation, which may be found in genetic resources such as landraces (local varieties developed by farmers over many years) or in wild relatives of domestic crops, may be incorporated into varieties that gain wide commercial production. In light of their potential social and economic benefits, such resources have probably been underused. This report reviews the types of genetic resources, the ways they have been used, and how they might be used in the future. The report also discusses economic, scientific, and institutional factors that will determine the extent of genetic resource use and the benefits it might bring to climate change adaptation.

What Did the Study Find?

The authors first evaluated past and current use of crop genetic resources for stress adaptation and potential future demands on these resources. Their research led to the following conclusions:

- Empirical evidence from genetic resource use suggests that substantial economic benefits can follow from the collection, characterization, and use of genetic resources to improve crop resistance and adaptability.
- While the economic returns to genetic improvements in some U.S. crops have been substantial, contributions of the various stages of development—genetic resource discovery, conservation and use, biological research, and breeding of new commercial cultivars—are not always easy to differentiate and assess.
- Climate change is likely to increase demand for new crop varieties with better resilience to stresses such as heat, drought, pests, and diseases. In recent years, demand for crop genetic resources from the U.S. National Plant Germplasm System (NPGS) has increased rapidly, even as the NPGS budget has fallen in real dollars.

- The use of new genetic traits in crops has concentrated more on tolerance to pests and diseases than to stresses like heat and drought that are also expected to increase with climate change.
- Recent scientific literature suggests genetically controlled traits responding to heat and drought may need to be considered together to have the greatest impact.
- Direct or easily traceable use of new genetic traits from sources such as landraces and wild relatives has been relatively rare for some crops but more common for others (e.g., potatoes and tomatoes).

Next, the study focused on technical, economic, and institutional and political factors that help explain the current pattern of genetic resource use and that are likely to affect future use. A summary follows of the results.

- Two kinds of technical change could reduce the costs of using genetic resources and thus increase their use for climate-change adaptation:
    - Improvements in genetic resource collection, conservation, characterization, and evaluation methods (e.g., through geographic information systems for predicting adaptation based on spatial information and DNA genetic marker analysis), and
    - Increased efficiency in incorporating valuable genetic traits into commercial crop varieties (e.g., through genetic markers linked to genes and gene segments that govern desired traits).
- Private firms may find it difficult to market and profit from the largely social benefits of genetic resource collection, conservation, and prebreeding activities. With insufficient private-sector incentives, the public sector is left to play a major role in optimal development of genetic traits to aid climate-change adaptation.
- Institutional factors such as international agreements and intellectual property rules can promote or hinder increased use of crop genetic resources to adapt to climate change, meaning that access to genetic resources will be determined not only by supply and demand, but also by legal and political factors. This suggests the importance of considering unintended as well as intended consequences of such policies and agreements.

How Was the Study Conducted?

The authors reviewed the relevant scientific literature to determine how climate change may affect agricultural production, and thus the kinds of genetic traits that might be important for adaptation to climate change. They examined data from multiple sources to characterize past and current patterns of genetic resource use, including:

- Case studies of the use of particular genetic resources;
- Studies of the use of crop wild relatives for genetic improvement;
- Budget and distribution data for the National Plant Germplasm System (NPGS); and
- ERS analyses of data from USDA's Current Research Information System on U.S. public agricultural research, NPGS holdings from the Germplasm Resources Information Network, and information on traits used by the Germplasm Enhancement of Maize Project, a public-private collaborative effort.

The authors also reviewed the literature on the economics of genetic resource use and combined their observations into a supply/demand framework to analyze how genetic resource use for climate-change adaptation might increase over time. They also assessed existing intellectual property institutions and international agreements related to genetic resources.

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Introduction

Genetic improvement has contributed markedly to sustaining growth in crop yields since the mid-20th century. However, climate change poses a significant risk to future crop productivity. The impacts of climate change on crop yields will be complex and will operate through many pathways. Crop varieties that are optimal for current growing environments are unlikely to be the best varieties for these environments in the future, as temperatures rise, rainfall patterns shift, and pest and disease pressures increase. Although current crop varieties can sometimes be grown in new locations as conditions change, new crop varieties, with attributes such as better tolerance not only to pests and diseases but also to heat and drought, could help agricultural producers adapt to climate change.[1] The development of crop varieties better suited to a changing climate will require increased efforts to incorporate traits from different genetic resources into new varieties.

Greater use of genetic diversity in plant breeding may be a relatively high-return, low-cost way of helping farmers adapt to climate change, but institutional and technical constraints might impede optimal exploitation of this option. Economic theory indicates that private investments in genetic resource use—conservation, evaluation, and eventual incorporation into crop varieties suitable for farmers' fields—depends on the expected returns. An inventor or institution can only profit from certain products during the research process. Unless a discovery can be sold, it will not be in a firm's self-interest to incur the costs of collecting, preserving, and characterizing crop genetic resources. There is near-consensus among both public and private-sector institutions[2] that the public sector has an important role to play in crucial stages of crop genetic conservation and improvement if the best results for society as a whole are to be achieved.

An additional economic assessment of the quest for economically valuable traits in genetic resources is called the economics of search. This report considers how the costs and benefits of such searches may be affected both by increasing demand, such as for greater tolerance to environmental stresses resulting from climate change, and by changes in technology, such as advances in geographic information systems, genomics, and related technologies.

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[1] Climate change is also likely to lead to greater variability in weather. As a result, varieties that perform well under a wide range of conditions will be desirable.

[2] For example, the American Seed Trade Association, a trade organization of private seed companies, states "Federal investments to maintain . . . genetic resources are fundamental to the success of agriculture in the U.S." (See http://www.amseed.org/issues/state-federal/federal-key-issues/).

Genetic Resources: What Are They, and How Are They Accessed and Used?

Germplasm Types

Germplasm (i.e., "seeds, plants, or plant parts that are useful in crop breeding, research, or conservation because of their genetic attributes" (National Research Council, 1993)), fall into four major types (table 1):

- **Advanced ("elite") germplasm,** the advanced breeding materials developed in crop breeding programs.
- **Landraces, or farmer-developed varieties,** which often include more genetic diversity than advanced germplasm. Thus, they bring unique characteristics into the pool of available germplasm. However, it is more difficult to access and use landraces for crop improvement than to use advanced breeding materials.
- **Crop wild or weedy relatives,** which are generally even more difficult than landraces to use as a source of economically important traits in final varieties. This is mainly because they are genetically more distant from the crop of interest, and gene transfer by conventional crossing techniques ranges from problematic to impossible, making more radical techniques necessary.[3] This reduces their attractiveness as breeding material for some breeders, particularly those who

Table 1

Types of germplasm and other genetic materials used for crop improvement

Advanced germplasm	Recently developed varieties, obsolete varieties,* and other advanced breeding materials that are created with modern breeding techniques. These usually have higher frequencies of desirable genes than landraces or wild relatives.
Landraces	Varieties that were improved by farmers over many generations without modern breeding (generally requiring extensive efforts for use in a final variety).
Wild or weedy relatives	Undomesticated plants that share a common ancestry with a crop species (sometimes very difficult to incorporate in final varieties).
Genetic stocks	Germplasm that contains defined genetic variation (i.e., mutation), sometimes incorporated into an easy-to-use genetic base, which serves as a genetic research tool.
Cloned DNA sequences	"Transgenic" material from other organisms inserted into crops via molecular techniques. These differ from the other types of material because they cannot be used to regenerate an organism.

*Obsolete varieties are older varieties no longer widely used but still useful for breeding.

Source: USDA\Economic Research Service, based on Day Rubenstein et al. (2005) and National Research Council (1993).

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[3] Biotechnology can, and has, in some instances, reduced some of this difficulty by enlarging the range of "radical" techniques available to the plant breeder.

work in the private sector, which tends to operate with shorter time horizons. Nonetheless, the use of crop wild relatives as a source of genes for developing new cultivars has been increasing over time (Guarino et al., 2011).

- **Genetic stocks,** which consist of material that contains defined genetic variations and are used as genetic research tools rather than for developing new varieties.

There is a fifth type of genetic resource that differs from the other four types because it cannot be used to regenerate an organism and usually is not held in genebanks:

- **Cloned DNA sequences,** or genetic material from other organisms incorporated into crops by molecular techniques (for example, a gene from the bacteria *Bacillus thuringiensis* used for resistance to insects.)

Collecting and Conserving Genetic Resources

Genetic resources can be conserved either “in situ” (in their natural setting) or “ex situ” (outside their natural setting) (Bretting and Duvick, 1997). Much of the world’s plant genetic diversity occurs in situ. However, it usually needs to be collected before it can be used by breeders, who cannot readily access in situ material. The most important sources of in situ genetic resources can be found in regions where crops were originally domesticated. In situ resources can continue to evolve with climate conditions, expanding the range of available traits. However, climate change threatens the survival of some species in situ.

Ex situ conservation of some crops can store large amounts of genetic material as seeds at relatively low cost in terms of land required.[4] Breeders rely almost exclusively on ex situ materials. The world’s genebanks presently hold more than 4 million distinct samples, consisting of crop varieties as well as other advanced materials, landraces, wild relatives, and genetic stocks.[5] However, only a small fraction of the world’s plant genetic resources have been collected (Day Rubenstein et al., 2005).

The U.S. National Plant Germplasm System (NPGS) is the primary network that manages publicly held crop germplasm in the United States. This multi-institutional network is one of the largest national genebank systems in the world and is coordinated by USDA’s Agricultural Research Service. The world’s largest international system of genebanks is under the auspices of the Consultative Group on International Agricultural Research (CGIAR).[6]

The NPGS has extensive holdings, and it distributes germplasm to researchers, breeders, and educators free of charge and serves a large international scientific community. Table 2 shows NPGS holdings for the five U.S. crops with the largest gross value of commercial production, divided into the first four categories listed in table 1: (1) advanced materials, (2) landraces, (3) wild and weedy relatives, and (4) genetic stocks. The “improvement status” for NPGS accessions is sometimes unknown

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[4] Ex situ conservation in some cases (e.g., orchard plantings) can be expensive and require substantial land.

[5] “Other advanced materials” include breeding lines that have undergone significant genetic improvement but have not been released as a finished variety.

[6] Examples of member genebanks include the International Rice Genebank in the Philippines and the International Potato Center Genebank in Peru. Together, the CGIAR and the NPGS are the major distributors of plant germplasm internationally (Noriega et al., 2013).

Table 2

Distribution of National Plant Germplasm System accessions among major U.S. field crops by germplasm types

	Crop				
Germplasm type	Wheat	Corn	Soybeans	Cotton	Alfalfa
Advanced*	19,634	9,120	18,077	1,362	1,452
Landrace	28,206	4,621	84	31	725
Wild relatives	7,326	275	2,113	1,890	1,105
Genetic stocks	4,103	7,511	828	0	2
Uncertain or unspecified	4,612	56	332	3,504	450

With the exception of wild relatives, all accessions are listed by improvement status within the primary gene pool as defined by the Germplasm Resources Information Network (GRIN). Wild relatives may differ in their degree of relatedness to the crop of interest.

*Improvement status of advanced germplasm in GRIN includes an assessment of "breeding material," "cultivar," and "cultivated material."

Source: USDA\Economic Research Service analysis of Germplasm Resources Information Network data.

or simply unspecified. Wild relatives, for example, differ in the degree to which they are related to the crop of interest. The ease of trait transfer (and resulting improvement status) depends, in part, on this degree of relatedness.[7]

For many of the major crops listed in table 2, the largest number of holdings consists of advanced material. Genetic stocks, used more for genetic research than directly for crop breeding, appear to be important for corn, wheat, and to some extent, soybeans. Landrace accessions are relatively common, particularly for wheat and corn. For these two crops in particular, the numbers of wild relative accessions appear small compared with landrace accessions. The number of accessions alone does not indicate critical gaps in NPGS holdings, but accessions can supplement the insights of genetic resource specialists. National working groups of specialists familiar with a given crop, called Crop Germplasm Committees, identify gaps in the collections and develop proposals for filling those gaps.[8] At the international level, the Global Crop Diversity Trust, an independent international organization established in 2005, addresses many issues concerning genetic resources, including strategies for collection, conservation, and use of crop wild relatives (Khoury et al., 2010; Dempewolf et al., 2014).[9]

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[7] We follow the Germplasm Resources Information Network (GRIN) database of the NPGS in classifying species. For each crop, the scientific literature sometimes differs about how closely particular species are related to the crop of interest.

[8] For example, table 2 identifies a relatively large number of accessions of wheat wild relatives and landraces. Nonetheless, in 1996 the Wheat Crop Germplasm Committee identified as its first collection priority wheat wild relatives in regions in which they are native, ranging from Egypt across West Asia into the Turkic republics of Central Asia. The second priority was for landraces from countries such as Guatemala, where they had not previously been collected.

[9] The Global Crop Diversity Trust is funded by a diverse set of donors, including the United States through the U.S. Agency for International Development.

Improving Crop Performance Under Climate-Change Conditions

Crops need tolerance to various types of stress.

Crop genetic resources can be used to increase yield by increasing resistance or tolerance to different types of stresses. Although genetic resources can also contribute to increased yield by raising physiological yield potential, we focus on stress tolerance here because increased plant stress is likely to accompany climate change. The first type of stress is “biotic,” that is, due to the deleterious actions of pests or pathogens. The second type is “abiotic,” or stress from the environment, such as extremes of moisture or temperature. As table 3 indicates, the current amount of research and knowledge about how to adapt to both abiotic and biotic stresses is roughly inverse to the degree of certainty we have about their occurrence with climate change.

For example, rising temperatures are expected with climate change, yet genetic sources of heat tolerance in crop varieties are probably less developed than sources of tolerance to other kinds of stress. Changes in pest and disease pressure are also expected with climate change, and sources of such biotic stress tolerance are much better known. But it is much more difficult to predict the types and locations of climate-change-related alterations in pests and diseases.

Biotic Stress: Impacts of Pests and Plant Diseases

To date, research into genetic approaches to stress tolerance has been heavily focused on biotic stress; however, the relative impact of abiotic stresses due to climate change is likely to increase more than biotic stress.

Because germplasm providing resistance to pests and diseases has been easier to find and to incorporate, more crop varieties have been developed that resist insects or complement weed-management strategies. In the public sector, for example, over the past decade the number of projects focusing directly on genetic approaches to pest and disease tolerance for all crops was more than 20 times the

Table 3
Types of stress and genetic adaptation to climate change

Sources of stress	Will new crop traits be useful for adaptation to climate change-related stress?	Scientific knowledge of traits—identification, incorporation, and screening*
Temperature (overall and extremes)	Very likely—global climate models predict increasing temperatures under a variety of scenarios in many geographic regions	Less clear—fewest public-sector research projects, no stated products in private-sector research pipelines
Drought and excess moisture	Likely—greater unpredictability in precipitation is expected, but global climate models differ about geographic distribution of precipitation changes	Somewhat clear—some public research projects, recently released or private-sector products in the research pipeline.
Biotic stresses (pests and diseases)	Unclear—greater pressure likely, but extent and severity unknown	More established—many public research projects, considerable private-sector products

*These assessments might vary somewhat across crops.

Source: USDA\Economic Research Service.

number of projects focusing on heat tolerance and nearly 8 times the number of projects focusing on drought tolerance (Malcolm et al., 2012).[10] For major crops, privately produced seeds often offer pest and disease resistance. Private companies are beginning to promote some seeds for drought tolerance or to indicate that such varieties are in their research pipelines. But it is difficult to find evidence of private research for heat tolerance.

In 2000, end users of NPGS materials were asked about the traits they sought and the usefulness of the samples they received for improving resistance in 10 major crops over the period 1990-1999 (Day Rubenstein et al., 2006). Of the traits respondents sought to evaluate in the germplasm samples, biotic resistance or tolerance was by far the most frequently cited—37 percent of samples—regardless of the type of germplasm. Resistance to abiotic stresses was sought in only 14 percent of samples.

Documented use of genetic resources—particularly landraces—by a private-public collaborative Germplasm Enhancement of Maize (GEM) project in the United States has also demonstrated a focus on biotic stress tolerance in corn, as well as on quality or yield characteristics, with little emphasis on abiotic stress tolerance. Of GEM-developed varieties with traits specified, three-quarters were developed for biotic resistance and less than 2 percent for abiotic tolerance.

Similarly, to date, crop wild relatives have been used most frequently as sources of pest- and disease-resistant germplasm. Far more instances have been recorded of crop wild relative use for these purposes than for enhancing tolerance to abiotic stress or improving other traits (yield, quality, and fertility restoration, for example; see table 4). Nonetheless, genetic resource and genomics experts believe crop wild relatives will be particularly valuable sources of traits for adaptation to climate change (Dempewolf et al., 2014).

Table 4

Global use of germplasm from crop wild relatives has concentrated on pest and disease resistance[1]

	Number of wild relatives contributing			
	Pest & disease resistance	Abiotic stress	All other traits*	Total number of contributed traits
Wheat	16	1	5	19
Corn	1	0	0	2
Soybeans	0	1	2	4
Tomato	10	2	2	55
Potato	6	0	0	12
Rice	7	3	2	12
All other crops	22	5	6	40
TOTAL	62	12	17	144

*Yield, quality, male sterility, fertility restoration, etc.

[1] Data from released varieties and advanced breeding materials. Source: USDA\Economic Research Service calculations based on Hajjar and Hodgkin (2007) and Maxted and Kell (2009). Calculations take into account the likely overlap in reported use from the two sources. Cotton and alfalfa—two field crops with large economic value in the United States—were not surveyed.

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[10] A count of research projects was taken from USDA's Current Research Information System (CRIS) database.

Abiotic Stress: Environmental Impacts

The use of genetic resources for abiotic stress tolerance can have major impacts; however, identifying and developing these traits may be more challenging than for traits for resistance to biotic stresses.

Despite being the focus of less research, traits that confer tolerance to environmental stresses have had major impacts on increasing the production of some crops. For instance, beginning in the 1960s, a short-growth-habit characteristic (referring to size), derived from landraces in Asia, was combined with other desirable production characteristics to create the semidwarf rice and wheat varieties that were the basis of widespread "Green Revolutions" in those crops. Much of the yield gains from these semidwarf varieties came from greater innate yield potential. But some of the gains came from resistance to lodging (i.e., the collapse of the cereal stem when it can no longer support its own weight). Lodging is caused by a combination of plant characteristics and environmental stress from rain, wind, or hail. (Resistance to lodging also allowed plants to be fertilized at higher rates.)

More recently, complex genetic combinations providing tolerance to abiotic conditions—including delayed flowering to enable greater flexibility in adjusting to daylight at low latitudes, aluminum tolerance, and calcium-use efficiency—were major factors in the large-scale expansion of soybean production in Brazil. The varieties used included landraces from the Philippines and Peru, as well as advanced germplasm from Brazil and the United States. The aluminum and calcium characteristics also permitted deeper rooting and greater drought tolerance (Spehar, 1994).

In the near future, other genetic contributions to abiotic stress tolerance from a wide variety of sources may have large impacts. *Oryza rufipogon*, a wild relative of rice, has contributed traits that enable rice varieties to better survive prolonged submersion in deep-water or flooded rice-growing environments. Major seed companies operating in the United States have recently released several corn hybrids with greater tolerance to drought, using sources as divergent as nonplant organisms (e.g., bacteria) through genetic engineering, as well as elite corn germplasm using conventional approaches to breeding (i.e., rather than genetic engineering).

Notwithstanding these advances, abiotic stress tolerance in many cases is a complex trait characterized by the actions of multiple genes, so the assumption that a genebank accession is either "drought tolerant," for example, or "not drought tolerant" is an oversimplification. (Even in breeding for resistance against biotic stresses such as diseases and pests, the genetic controls for key traits sometimes become more complicated as breeders move away from resistance strategies based on single genes.) For example, a plant variety may be drought tolerant, but that drought tolerance may not hold under higher temperatures. Therefore, it may be more advantageous to study the genetic responses to individual stresses such as heat and drought simultaneously rather than separately (Mittler, 2006; Cairns et al., 2013).

The increasing likelihood of using multiple genes to achieve greater environmental resilience suggests that alternative sources of traits (e.g., crop wild relatives, nonplant organisms) are complementary rather than competitive. It is unclear what the changes in relative demand will be for traits from, say, crop wild relatives vis-à-vis traits from nonplant organisms. In part, the demand may depend on access to genetic resources. But it is likely that the demand for genetic resources of *all* types will increase.

Public and Private Incentives for Genetic Enhancement

Economic returns to genetic enhancement have been significant.

Crop genetic improvement (i.e., the combination of genetic resources, biological research, and plant breeding) can result in new varieties and better genetic material. Large economic returns to genetic improvements have been demonstrated. Approximately half the yield gains in major U.S. cereal crops since the 1930s are attributed to genetic improvements (see Day Rubenstein et al., 2005, and sources cited therein).

To adapt varieties to climate change, scientists and breeders will continue to look for genetic resources with helpful traits. The ability to develop new varieties depends on several factors. These include breeders' and scientists' access to genetic traits of interest; their technical ability to incorporate these traits, first into breeding materials and then into commercial varieties; and the economic incentives that motivate their work. Economic incentives generally differ for scientists/breeders in the public sector from those they face in the private sector. Genetic resources—in the sense of the genetic information contained in seeds or plant cells—have "public goods" characteristics. Public goods have two classic characteristics: nonrivalry (use of a resource does not reduce the amount available to others) and nonexcludability (others cannot be prevented from using a resource once it is first made available). When seeds or other plant-propagating materials are purchased, the genetic content of the materials is purchased at the same time. As a result, genetic resources are easily transported and replicated. Unless legal limits exist and are honored, it is difficult for an individual country, firm, or farmer to exclude others from using the genetic information in seeds or other materials for propagating crops, and other users have little incentive to pay an entrepreneur for developing that information. With no exclusion and a resulting lack of compensation, the seller lacks incentive to develop improved varieties or germplasm populations that can be sold.[11]

Furthermore, the usefulness of particular genetic resources is highly uncertain, and time horizons for improving genetic resources are long. A basic economic argument underlying public policy related to genetic resources is that the private sector tends to underinvest in research incorporating these resources. The private sector generates returns by selling marketable items, such as "finished varieties" (e.g., the seeds farmers plant in fields) or the research tools used to create final varieties. There are few private incentives for conducting "upstream" research; that is, for adding new samples of genetic resources (also called accessions) to genebanks, screening accessions for desired traits, and incorporating genes from unimproved genetic resources into the advanced breeding materials used to create marketable final varieties. These activities are long term and risky, and the potential for protecting intellectual property is less the earlier the stage of development. For example, advances in basic biology and the scientific understanding of plant functions generally are not products that inventors can prevent other people from using. Thus, for the private sector, only a part of the results of the long process of technical improvement can be protected for sale (or "appropriated"). Therefore, private-sector investments in genetic resource conservation and use are likely to be below those that are best for society as a whole.

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[11] Some of the technical and institutional means that have been used to overcome this obstacle for private seed provision, in part, are alluded to below. For more detail, see Fernandez-Cornejo (2004).

Germplasm Conservation Benefits

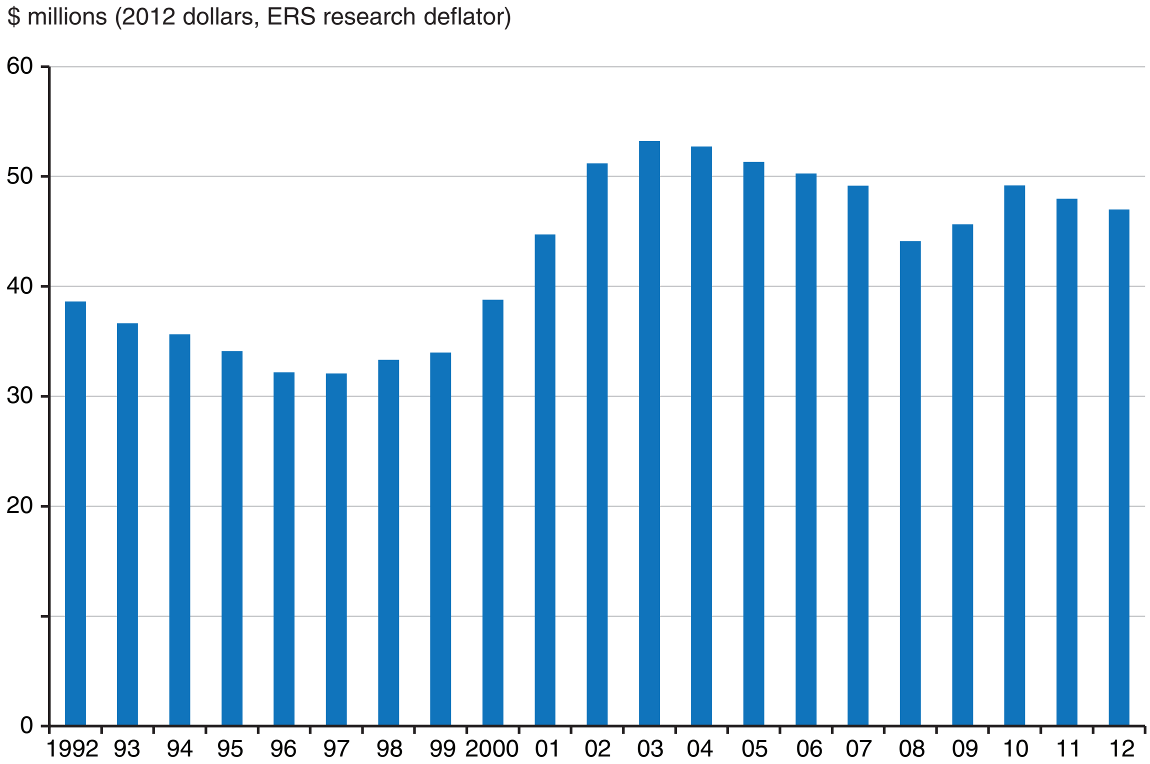
The costs of conserving germplasm are small compared with the gains from genetic enhancement.

In 2012, The NPGS budget was approximately $47 million. Funding for the NPGS has been relatively stagnant over time. In real terms, agency funding peaked in 2003, at approximately $53 million in 2012 dollars (fig. 1). While direct comparisons between costs of a genebank and its benefits are not possible, for context, we note that U.S. farmers paid $20.3 billion for seed in 2012 (USDA\National Agricultural Statistics Service, 2013). Thus, the costs of public ex situ plant conservation in the United States are a small fraction—under half of 1 percent—of the value of the eventual seed market. At the same time that budgets have decreased, demand for NPGS germplasm has reached historic highs (fig. 2).[12]

It is also not possible to make exact comparisons of the NPGS budget with other research expenditures on crop improvement, public or private, but estimates of related expenditures may help put these costs in perspective. In 2009, for example, total public-sector crop-related research investment

Figure 1

National Plant Germplasm System (NPGS) budget, 1992-2012



Note: The NPGS budget peaked in 2003 and then fell slightly in subsequent years, adjusting for inflation.
Source: Bretting (2013) and USDA\Economic Research Service.

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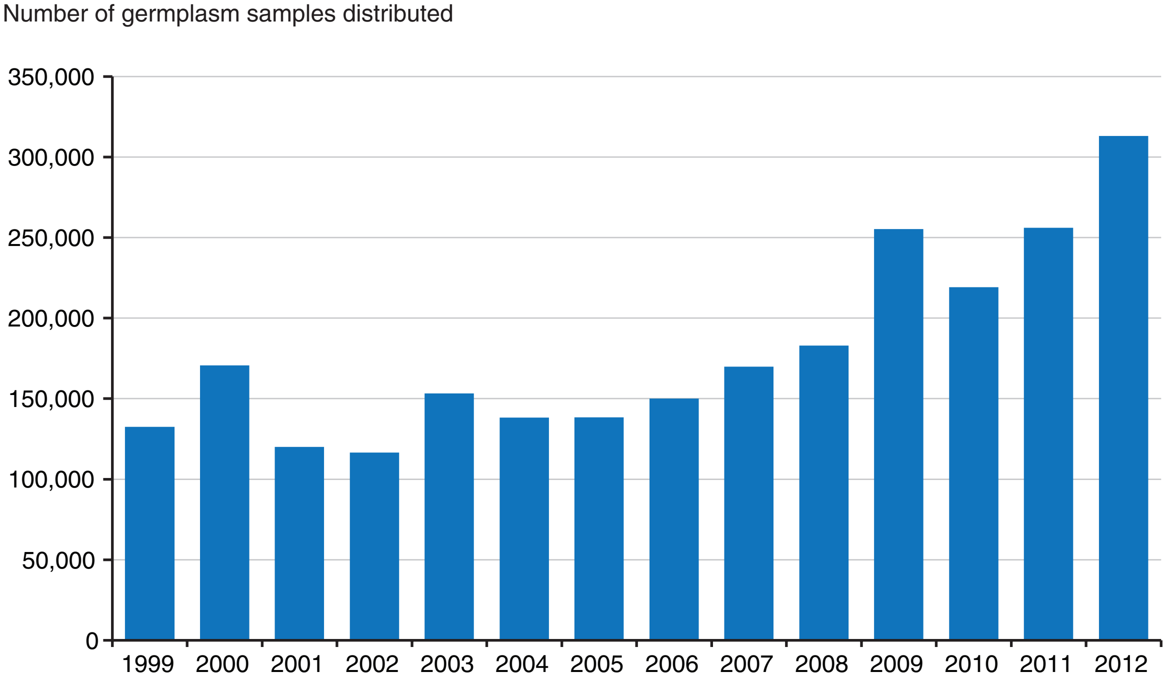
[12] During the period 1990-99, about three-quarters of accessions distributed by NPGS were distributed domestically, with the rest distributed to countries outside the United States. Of accessions distributed domestically, just under a quarter went to private companies. The rest went mainly to nonprofit institutions, primarily USDA\ARS and universities (Day Rubenstein et al., 2006).

Figure 2

National Plant Germplasm System (NPGS) germplasm distribution, 1992-2012



Note: In 2012, NPGS germplasm distribution was double its 2006 volume.
Source: Bretting (2013).

in the United States was just over $1.7 billion (2012 dollars). Of this, just over $400 million was in the areas of "plant genome, genetics, and genetic mechanisms" and "plant biological efficiency and abiotic stress" (calculated from the USDA Current Research Information Systems database). In 2009, the private sector invested over $2.6 billion (2012 dollars) in crop-related research. Over $2 billion of this was in crop seed and biotechnology (Fuglie et al., 2011).[13]

Climate Change and Genetic Resource Use

Climate change may increase the benefits of genetic resource use; scientific advances may reduce the expense of identifying and incorporating helpful traits.

Because plant breeders usually breed advanced germplasm from their own program's gene pools, both public and private breeders incorporate only a small percentage of the material in genebanks into their programs. This is illustrated in the appendix to this report. Taking wheat as an example, the appendix provides estimates of the use of wheat landraces and wild relatives in wheat breeding programs. The available data, summarized in the appendix, suggest that use of both types of genetic resources has increased over time in global wheat breeding programs. At the same time, however, the data show that many of the programs do not use these kinds of genetic resources directly. Economic incentives favor incorporating traits from landraces and crop wild relatives only to the degree

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[13] There are often significant lags between private agricultural research investments and economic benefits, and even longer lags between public investments and economic benefits. Therefore, recent research expenditures are presented not as an indicator of likely current benefits, but for comparative purposes only.

they are available through advanced materials, rather than incorporating them through direct use. Consequently, one economic question is whether the benefits from adding more accessions to genebanks and incorporating them into breeding programs can justify the costs of these activities.

Economists have analyzed genetic resource acquisition and use through the application of search models (i.e., probabilistic and economic models that analyze which germplasm to search for, when to search for it, and when to stop searching for it).[14] A simple model is:

The expected benefits from investments in genetic resources
=
the probability of uncovering useful traits
x
the expected value of those traits.

Even if the probability of finding a useful trait is low, the total benefit might be high if the expected value of the trait is high. The optimal use of genetic resources will depend on the research costs, the value of the anticipated technological improvement, and the "discount rate" (essentially, the weight given to consuming in the present as opposed to consuming in the future). The type of materials also may affect the costs of searching among samples, and more exotic kinds of germplasm (e.g., landraces and wild relatives) may take much longer to add value to the final varieties. This may increase search costs and redirect efforts toward more easily transferred materials.

To illustrate the effects of climate change and of scientific advances on genetic resource use, we use an economic approach to examine financial investments in the identification and use of genetic resources. For now, we will set aside one of the major constraints identified earlier: insufficient private incentives. The simple assumptions we make concern only whether demand for genetic resources becomes greater with factors such as climate change and whether costs of using genetic resources fall with advances in technology.[15]

This analytical framework examines (1) the role of information (or discovering traits in germplasm); (2) the role of improved applied techniques (or incorporating traits in varieties); and (3) the need for climate-related traits. In figure 3, evaluating more genetic resource traits and incorporating them into commercial varieties is represented by moving to the right on the horizontal axis. Before considering the effects of climate change, the area under the "marginal benefit" line MB_0—at any point, say point A— measures the expected value of the benefits given that level of effort. The height of the line measures the expected value of analyzing and incorporating one more genetic resource. (The downward slope of the line illustrates the economic principle of diminishing returns.)[16] A simple version of this framework shows that each additional search increases the probability of finding the

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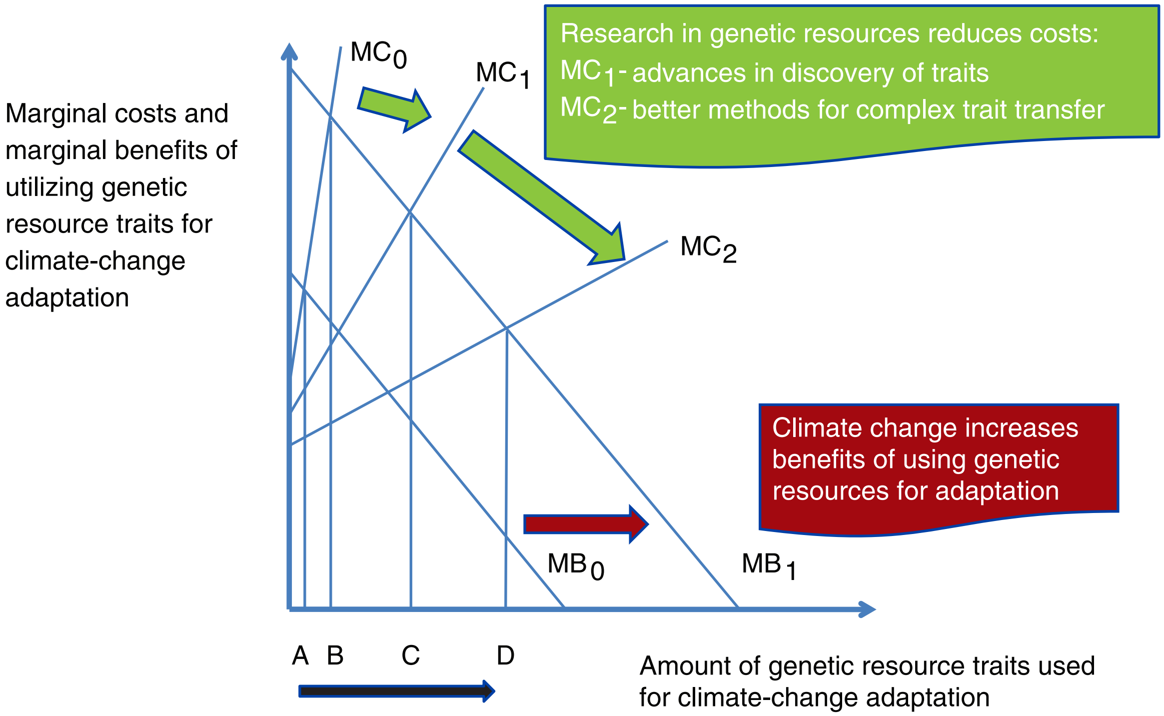
[14] The first economic applications to genetic resources analyzed the question of whether potential pharmaceutical benefits from plants growing in the wild were great enough to induce private efforts to conserve the native habitats of those plants (Simpson et al., 1996). Economists later explored how information can affect the value of searches (Rausser and Small, 2000). In contrast to the search for traits with pharmaceutical value, traits with agricultural value need to be incorporated into existing varieties in order not to lose traits from earlier selection and breeding.

[15] The search-model approach is not inconsistent with the fact that genetic resources have public goods characteristics. Using these assumptions, the same conclusions would hold even if a graphical representation of supply and demand of public goods (e.g., Kolstad, 2000, Chapter 5) is superimposed on figure 3. However this would complicate the discussion without altering the conclusions.

[16] This is similar to a simple graph illustrating returns to research in general; each additional dollar spent pushes the expected rate of return downwards.

Figure 3

Climate change and research advances in crop genetics could increase the use of genetic resources



Source: USDA\Economic Research Service.

trait, but by a lesser amount as more genetic resources are searched. Increasing the scope of search or the resources devoted to incorporating useful traits into commercial varieties increases the probability of finding and incorporating useful traits, but by lower increments each time.

The height of the “marginal cost” line, MC_0, shows the current cost of evaluating and incorporating an additional genetic resource. If new genetic resources need to be found, or if it becomes increasingly difficult to incorporate traits into successful commercial varieties, MC_0 would be upward-sloping, as depicted in figure 3.[17] In any scenario, as long as the expected marginal benefits of searching for and incorporating additional genetic traits are greater than the marginal costs, it makes sense to expend additional effort in search and incorporation activities, as this will increase expected total benefits, net of cost. If marginal costs are greater than marginal benefits, then research efforts should be reduced. The optimal level of effort is when the expected marginal benefits equal the marginal costs. In this first scenario, use of traits for climate change adaptation remains limited, at point A.

Climate change (observed or even anticipated) would increase the benefits from using genetic resources for better adapted varieties and would shift the marginal benefit line out to MB_1. This does

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[17] In many specific empirical situations, it might be difficult to characterize MC accurately. For example, it may not be linear—it could be a curve instead of a straight line. On the other hand, in the case of simply searching within an already-collected and defined set of genetic resources, MC could be flat rather than upward sloping. None of these modifications would change the conclusions about the effects of lowered costs for utilizing genetic resources.

not represent any change in the probabilities of finding useful traits from genetic resources or in the ease of incorporating these traits into useful varieties. Rather, the value of a trait like heat or drought tolerance, when found and incorporated into commercial varieties, would become greater as climate change leads to more problems in crop production. Genetic resource use would increase to point B.

If scientists could improve the process of trait discovery, the additional cost of finding a new trait would become lower as the probability of identifying a useful trait becomes higher.[18] In figure 3, as the marginal cost line becomes lower, MC_1, genetic resource use would move to point C. If, in addition to accelerated trait discovery, new and more efficient methods to transfer complex traits to finished varieties became available, costs would fall further to MC_2 and genetic resource use would move further, to point D.[19]

Costs of Genetic Resource Use: Current Evidence

The cost of searching for traits appears to be less than the value of the benefits of finding them, making it likely that genetic resource use for climate change adaptation will increase over time.

A few empirical studies have examined the economics of genebank acquisitions and use of genebank materials. An analysis of resistance to soybean cyst nematodes, a biotic stress, found that the expected marginal value of acquiring a new accession is anywhere from 36-61 times the marginal cost of such an acquisition, even though the probability of finding resistance in any particular acquisition is very low (Zohrabian et al., 2003). Another model of searching within an existing genetic resource collection applied empirical studies of resistance to Russian wheat aphid or *septoria* leaf blotch in wheat. Researchers concluded that just because some genebank accessions are not frequently incorporated into breeding programs does not mean that marginal accessions have low value (Gollin et al., 2000). When compared to the rather large benefits of genetic enhancement, the costs of genebank operation appear relatively small. Therefore, genetic resource conservation has probably been underfunded. Further, assuming genetic resource conservation is valuable, steady funding probably will be necessary as genetic resources must be conserved under controlled conditions and periodically regenerated to maintain their viability.

Scientific techniques related to genetic resource collection methods and to evaluation and incorporation of genetic resources into commercial varieties have benefited from technological improvements and are expected to benefit more over time. Increasingly sophisticated technologies that provide more information add usefulness to the germplasm acquired (i.e., shifting the marginal cost line downward in figure 3). For example, geographic information systems provide data on location (and by extension, climatic conditions) that may be particularly relevant for adaptation to changing temperature, precipitation, or day length.[20] Researchers have found that when genetic resources are accompanied by geospatial data, they are more useful (Day Rubenstein et al., 2006). New technologies (e.g., genetic markers, sequencing, and mapping, as well as genomic analysis) might lower both

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[18] This discussion does not mean to imply that technological change in trait discovery or trait transfer has not already occurred. For example, the use of molecular markers in plant breeding has become an important practical tool over the last two decades. The discussion in the text refers to further technological advances.

[19] The analysis depends only on costs shifting downward, not on the specific geometry of the shift.

[20] Some crops, such as soybeans, are sensitive to the length of the day. These crops could move to different latitudes in response to changing temperatures or precipitation. If relocated, these crops' day length requirements would need to be adapted to their new location. (Day length itself does not change with climate change.)

the costs of identifying useful traits and the costs of incorporating them into commercial varieties.[21] Such advances might reduce the costs and shorten the time lags associated with both trait searches and transfer of traits into advanced breeding materials, even when the source of the trait—such as a landrace or wild relative—has been traditionally more difficult for breeders to incorporate. The economic implications of using such techniques in the evaluation of genetic resources, along with an assessment of their costs, have not yet been addressed empirically.[22]

Returning to figure 3, the analysis suggests that, in addition to the possibility of insufficient private incentives, another reason for the relatively infrequent incorporation of genetic resources into breeding programs for heat or drought tolerance may be related to relatively high search costs and other costs to incorporate these traits compared with biotic resistance traits. The economic search models that are the basis of the analysis in this section may not capture the complexity of the search for genes that confer superior heat or drought tolerance. As noted earlier, all of the economic search models to date have focused on biotic stresses such as pest or disease resistance, and most of them have been based on expected probabilities of successful searches for single traits.[23]

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[21] Genomics refers to investigations into the structure and function of large numbers of genes simultaneously. See Henry (2014) for an analysis of the potential contribution of genomics to characterizing crop wild relatives and to the development of climate resilient crops.

[22] Koo and Wright (2000) address, theoretically, search decisions such as when to begin a search, and assuming a desired trait is found, whether to develop a variety incorporating the trait.

[23] A further limitation is that current models assume that whether accession x possesses the trait in question is independent of whether accession y possesses the trait.

Impact of Institutional Factors on Genetic Enhancement

In addition to natural and scientific factors, institutional factors can also affect the utilization of genetic resources for adaptation to climate change (Noriega et al., 2013). These factors can be of particular concern because of the public goods characteristics of genetic resources. Institutional factors can shape access to and research on crop genetic resources and their commercial use. Institutional arrangements, such as international agreements and intellectual property rights, are generally intended to promote the use of crop genetic resources, but it can be difficult to design smoothly functioning and compatible legal arrangements and policies. Moreover, public investment will likely be necessary to promote the conservation, characterization, and enhancement of crop genetic resources, and global public investment requires even greater coordination than public investment within a given country.

Of particular importance are institutions that affect access to genetic resources that cross national boundaries. Like all countries, the United States depends in part on genetic material that is not already held in its own genebanks or found within its borders.[24] Wide access to genetic resources from multiple countries is needed.

Twenty-five years ago, germplasm was exchanged in a relatively open system (Noriega et al., 2013). Now, access to genetic material might be governed by one of several international agreements. The Convention on Biological Diversity ("the Convention") entered into force in 1992.[25] The Convention was developed under the auspices of the United Nations (U.N.) with the goal of conserving biodiversity. It recognizes nations' sovereign rights to their genetic resources, both in situ and ex situ. Exchange takes place primarily on a bilateral basis; countries have the power to negotiate their own terms. To collect genetic resources, the collector must have prior informed consent from the country holding the resource. Important provisions of the Convention include those addressing access and benefit sharing (ABS), which are intended to provide returns to the holders of genetic resources. In advance of guidelines that outlined implementation of ABS, several influential agreements promoted cooperation between countries that held genetic resources and pharmaceutical companies (Blum, 1993; Laird, 1993). The values of genetic resources for pharmaceuticals were assessed, and high returns were estimated (Mendelsohn and Balick, 1995).

However, the benefits of genetic resources, as seen by their holders, have often been more than the commercial values seen by industry (Laird and Wynberg, 2006). The use of genetic resources for agricultural varieties differs significantly from that for pharmaceutical products. Unlike drugs that can be used globally, agricultural varieties often need to be adapted for individual regions. As a result, crop genetic resources are rarely likely to yield the single, highly profitable developments that sometimes occur in pharmaceutical applications. Profit margins associated with products from medical research and development are generally higher than those for crop genetic improvement. For crops, overall benefits are likely to come from large numbers of small benefits. Because the returns to any particular genetic trait are likely to be limited, the incentive to conserve resources—particularly those in situ—may be inadequate.

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[24] Relatively few crop genetic resources originated in the United States. Native crops include sunflowers, strawberries, blueberries, cranberries, and pecans.

[25] The Convention on Biological Diversity is an international, legally binding treaty for all countries party to it. As of December 2013, all U.N. member States except the United States, Andorra, and South Sudan are parties to the treaty.

On October 12, 2014, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization entered into force. The Nagoya Protocol formalizes the Convention on Biological Diversity provisions for the sharing of benefits, provided that they conform to a nation's particular legislation.

A second agreement, the International Treaty on Plant Genetic Resources for Food and Agriculture (the International Treaty), addresses a subset of genetic resources from member countries for 64 food and forage crop species. The International Treaty has roots in the International Undertaking on Plant Genetic Resources for Food and Agriculture of 1983 (the International Undertaking), which provided for the free flow of genetic resources. The International Treaty was intended to encourage the exchange of the genetic resources found in the International Undertaking, while harmonizing exchange with the provisions of the Convention on Biological Diversity (Moore and Williams, 2011).

The incentive structures of the two agreements differ substantially as to how they motivate conservation of genetic resources. The Convention places the responsibility for negotiating genetic resources agreements primarily on individual countries, who determine the means of exchange (possibly including financial returns to the supplying institution). The International Treaty creates a more formal mechanism to facilitate the benefits of exchanging germplasm through a multilateral system, in which all members agree to share ex situ materials with each other via a single legal instrument called the Standard Material Transfer Agreement. The members also agree to share the benefits from the use of this material. The country or institution supplying a resource does not receive the financial returns from its germplasm; however, all members to the Transfer Agreement will benefit from access to and improved conservation of the genetic resource. The crops covered by the agreement include most of the major food crops important for food security, such as wheat and corn, but do not cover some others, including soybeans, peanuts, and tomatoes.

The United States has signed but not yet ratified the Convention on Biological Diversity and the International Treaty. Access to genetic resources by U.S. researchers and breeders can require extensive negotiations with different countries. In the case of the International Treaty, if the recipients, including the United States, accept germplasm from the Multilateral System, they also must accept its access and benefit-sharing provisions, which are triggered when materials are used in commercial products. In other words, if an accession from the International Treaty's Multilateral System is incorporated into a product that is sold commercially, some of the proceeds should be shared within the system according to a predetermined formula. Users of materials from the Multilateral System should not claim intellectual property rights that would limit access by others to that material in the form in which the users received it. Restricting access to a product (as with intellectual property protection) changes the benefit-sharing provisions. When a product using material from the Multilateral System is commercialized, recipients are encouraged to share 0.77 percent of the gross sales; however, if access to the product is limited through intellectual property rights, such a payment is mandatory (Moore and Williams, 2011). International genebanks of the CGIAR Centers follow the International Treaty's provisions. However, national genebanks either use the Standard Material Transfer Agreement when exchanging plant genetic resources with the United States or develop specific terms in bilateral negotiations with U.S. institutions for noncovered crops.

In terms of the number of accessions, the United States has a net positive balance of international exchanges of ex situ materials from the NPGS system. The NPGS distributes approximately six accessions to other countries for every accession it receives from other nations (Bretting, 2007).

The NPGS and other gene banks may want access to in situ genetic resources to add to existing collections. Recently, USDA has faced greater obstacles to collecting germplasm in other countries. This can be especially problematic in acquiring germplasm limited to a specific region. Many countries have not allowed USDA access, or the terms required are not acceptable for material entering the NPGS. As a result, USDA/ARS no longer requests permission for collecting expeditions (Williams, 2014).[26] Limitations on access to in situ resources reduce opportunities to collect materials such as crop wild relatives that may have traits useful for adaptation to climate change (Noriega et al., 2013).

Intellectual property (IP) rights also can affect genetic improvement directly through incentives that both foster innovation and limit access to new discoveries. IP rights offer limited-duration monopolies over inventions, offering creators opportunities to reap returns from their inventions. Historically, the United States has offered strong protections for intellectual property.[27] In the case of plant breeding, in the United States, IP restrictions applied to genes, such as patenting specific crop genetic resources,[28] are intended to create incentives for companies to invest in further improvement or distribution of the material in question (Noriega et al., 2013). However, the World Trade Organization, of which the United States is a member, has moved toward greater international harmonization of IP rights systems through the 1994 Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS), which requires member countries to adopt minimum standards of IP protection. Nonetheless, different countries have maintained different levels of IP protection for crop genetic resources. One result may be that seed companies are less willing to invest in countries with lower levels of protection.

IP restrictions may also increase incentives to conduct related research. In addition to the patenting of improved genetic resources, some of the research tools needed for plant breeding can also be patented. Because many of the traits needed for climate change adaptation are expected to be complex and involve multiple genes, IP protections on the numerous research techniques used in plant breeding could have greater impacts than patents on individual genes.

Not all IP protection involves patents. The United States also uses Plant Variety Protection Certificates (PVPCs). Although PVPCs allow private crop breeders exclusive rights to multiply and market protected varieties, they offer weaker protections than patents because they include a research exemption that allows others to use the new variety for research purposes. Such protection is usually less contentious for international negotiations than stricter patent protections, and breeders make significant use of PVPCs (Fernandez-Cornejo, 2004). Unlike utility patents, PVPCs are not used for research tools because they pertain only to crop varieties.

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[26] There may be other instances of USDA scientists receiving material for uses other than those of the NPGS. Noriega et al. (2013) note that some GCIAR members also have had to reject materials because they are subject to too many restrictions.

[27] Article 1 of the U.S. Constitution: “The Congress shall have power ... To promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries.”

[28] In their natural state, genetic resources cannot be patented in the United States. (See *Association for Molecular Pathology v. Myriad Genetics*, 2013).

Conclusions

Climate change is expected to place large demands for agricultural adaptation. Use of genetic resources to develop new crop varieties—more tolerant of both abiotic and biotic stresses—is likely to be an important component of agricultural adaptation to climate change. The usefulness of genetic resources in climate adaptation could be improved if:

- They are available (i.e., identified and preserved, probably in a combination of in situ and ex situ locations) and are widely accessible to plant breeders and researchers on acceptable terms;
- Information about the important characteristics of individual genetic resources are generated, recorded, and made widely available;
- Information concerning the genetics of complex traits are expanded; and
- Desirable characteristics are transferable to commercially competitive genetic materials. Private firms may have insufficient incentives to make such transfers, because the length of time required may conflict with the immediate need to produce varieties salable to farmers.

Economic analysis has demonstrated that although the costs of supporting these activities usually are relatively modest, potential benefits may be very large. Technological advances—either in more effectively screening genetic resources for desirable characteristics or in more rapidly incorporating these characteristics into commercially competitive germplasm—would likely increase the value of genetic resources. Furthermore, international agreements and intellectual property rights could possibly both increase access to genetic resources and incentives to pursue research. But as noted, such institutional constraints could also have the opposite effect, limiting international access to crop genetic resources or to the research tools needed to develop them.

The expanding options for climate-change adaptation would benefit from public support. Although social gains from genetic resource use may be large, the long time lags between initial research and commercially viable products highlight the financial riskiness of many of these activities. Furthermore, private appropriation of the social benefits from genetic resource use is often difficult. These concerns indicate that, in many cases, genetic resource collection, conservation, and prebreeding activities are likely to be primarily financed by the public sector, even where access to genetic resources is unlimited by institutional constraints.

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Appendix: Contributions of Landraces and Crop Wild Relatives in Crop Breeding: Empirical Evidence for Wheat

Landraces and crop wild relatives have been found to make important contributions of traits used in crop improvements, and genetic resource managers have stated that diverse germplasm, particularly crop wild relatives, may become increasingly important sources of traits useful for crop adaptation to climate change (Dempewolf et al., 2014). At the same time, the use of landraces and wild relatives has been relatively uncommon in many crop breeding programs. These seemingly paradoxical statements are explained by the difficulty of incorporating traits from sources such as landraces or wild relatives and the time often required to transfer these traits into commercially successful germplasm. A few examples from wheat breeding illustrate this.

In 1981, Duvick (1984) surveyed leaders of breeding programs for five U.S. crops—cotton, soybean, wheat, sorghum, and corn—concerning the genetic diversity of those crops. Eighty-five percent of the wheat breeders said the breeding base in their program was broader than it was in 1970. *All* of the wheat breeders who said they had broadened their genetic base stated that one major source of new germplasm consisted of elite unadapted lines, in other words, advanced materials from other breeding programs in dissimilar growing environments. Twenty-five percent mentioned wheat landraces as a major source of broadening germplasm, and 15 percent noted “related species”—a category that would overlap with wild relatives of wheat—as an important source. Thus, some breeders had increased their use of landraces and wild relatives, but more were increasing genetic diversity only through access to advanced materials from other breeding programs whose genetic bases differed from those in their own programs.

Over time, the overall use of landraces and crop wild relatives in wheat breeding remained relatively small. In 1994, the International Maize and Wheat Improvement Center (CIMMYT) surveyed wheat breeders around the world, in both developing and high-income countries, concerning their use of different types of germplasm (Rejesus et al., 1996). Breeders were asked about their use of different types of materials in the breeding process (appendix table 1).

This study showed that globally, less than 8 percent of the entries in breeders’ crossing blocks were landraces. Landrace entries were relatively more common in developing countries, particularly in West Asia—the zone of origin for domesticated wheat—and nearby North Africa, both of which are separated out in the appendix table 1 summary.

Rejesus et al. also analyzed pedigrees of spring bread wheat releases in developing countries, and this analysis was updated by Smale et al. (2002). Between 1965 and 1997, fairly complete pedigree information was available for 1,162 releases of spring bread wheat cultivars by developing countries. Very few of these releases used a landrace, or a selection from a landrace, as a direct parent.[29] At the same time, the average number of *distinct* landraces in the pedigrees of spring bread wheat cultivars released by developing countries in the 1960s ranged between 20 and 30. The average number of *distinct* landraces in the pedigrees of releases in the mid-1990s ranged between 50 and 60. The annual rate of increase in unique landraces across all pedigrees was about one landrace per year. In other words, the diversity of unique landrace use was increasing over time not because most

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[29] One notably successful commercial variety that used a landrace selection as a parent was the Turkish cultivar “Gerek 79.”

Appendix table 1

Type of parent materials in wheat breeders' crossing blocks, 1994

	Average percent of entries				
Region	Wild relatives	Landraces (local origin)	Landraces (foreign origin)	Landraces (TOTAL)	All other*
North Africa	0.0	14.0	6.5	20.5	79.5
West Asia	1.3	14.5	0.5	15.0	83.7
All developing countries	0.8	6.3	1.8	8.1	91.1
Former Soviet Union/East Europe	0.1	1.8	4.1	5.9	94.0
High income	0.9	1.8	4.9	6.7	92.4
World	**0.8**	**4.5**	**3.0**	**7.5**	**91.7**

*Includes own advanced materials, advanced materials from other countries, released varieties, international nurseries, and other unspecified materials.

Source: Rejesus et al. (1996).

breeders were using landraces as direct parents, but because they had increasing access to advanced materials with more diverse genetic composition.

Regarding crop wild relatives, appendix table 1 shows that in 1994, wheat wild relatives were an even smaller part of wheat breeders' materials than were landraces. Indeed, the data are consistent with a scenario in which many, but not all, breeders were probably not using wild relatives. On the other hand, Khoury et al. (2010) state that over the past 20 years, the wild relatives of wheat have proved to be highly useful sources of resistance to both biotic and abiotic stresses in wheat. This implies that the use of wheat wild relatives in breeding programs continues to increase, albeit from a small base. The estimates for wheat reported in table 4 still represent only a tiny fraction of the total numbers of wheat advanced materials used or wheat cultivars released worldwide. This does not mean that these traits will not be economically important. Rather, it illustrates that in many breeding programs—given current technology—economic incentives favor incorporating traits from crop wild relatives only to the degree they are available through advanced materials, rather than incorporating them through direct use.