

Crop genetic resource policy: the role of *ex situ* genebanks[†]

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The world-wide capacity of genebanks for *ex situ* conservation of crop genetic resources has increased greatly since the 1970s, improving the access of crop breeders to landraces and wild and weedy relatives. But utilization of genebank resources has not kept pace. The set of popular cultivars in major crops is typically rather small, and their ancestry encompasses only a fraction of the genetic diversity currently available in other cultivars. Discussions of farmers' rights that focus on compensation for current incorporation of farmers' varieties in new cultivars have diverted attention from the question of why so little of the newly accessible genetic diversity is currently being utilized by public and private breeders. To optimize the future provision of genebank services, research is needed on the costs of genebanks, the market for their services, the use of genetic resources by breeders, and the implications of recognition of farmers' rights, evolving intellectual property rights, continued funding problems and developments in biotechnology.

1. Introduction

Agricultural genetic resources have been vital in supporting a vastly increasing human population at a secularly increasing standard of living and they will be increasingly important in the near future. According to Wilkes, in the two decades of the next century as much food will be produced as the total production since the beginning of agriculture (Wilkes 1992, p. 3), and very little increase will be had from an expansion of cultivation.

[†]A lengthier progenitor of this paper, entitled 'Agricultural Genetic Resource Policy: Towards a Research Agenda' was presented at the Technical Consultation on Economic and Policy Research for Genetic Resource Conservation and Use, International Food Policy Research Institute, Washington, DC, 21–22 June 1995. I would like to thank, with the usual caveat, Phil Pardey, Don Duvick, Bob Evenson, Pablo Ezaguirre, Mike Freeling, Peter Hazell, Masa Iwanaga, Mike Jackson, Peter Oram and Henry Shands for their help, and K. Lena Miller, Zihua Shen and Paul Speck for research assistance. Work on this paper was supported in part by the International Food Policy Research Institute and the International Plant Genetic Resources Institute.

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Since at least the Mesopotamian civilization, rulers have sent out expeditions in search of new plants and animals. Nations have jealously guarded their monopolies on agricultural genetic resources. Thomas Jefferson risked a penalty of death in smuggling Piedmont rice seeds out of Italy (Witt 1985, p. 19). Valuable plants were strategic commodities. Indeed, the discovery of America was motivated by the search for access to Indian spices after the Turks cut off the land route to the East (Juma 1989, p. 40).

In the present century, advances in genetics based on rediscovery of Mendel's work have enabled crop breeders to move beyond identification and selection of the best landraces in different regions. Breeders began to search for specific genetic material for incorporation into new elite cultivars that often outperformed their predecessors over a wide range of environments. Since the 1960s, this enterprise has been fostered as an international effort, with multilateral collaboration between individual countries and the International Agricultural Research Centers in exchange of germplasm, the 'material that controls heredity' (Witt 1985, p. 8), and elite new releases.

As breeding of high-yield varieties has progressed, the need for diverse sources of pest resistance became apparent. Since the occurrence of the Southern corn leaf blight in the United States in 1970, facilities for storing crop germplasm, in the tradition pioneered by Vavilov in Russia much earlier, have expanded rapidly. More recently, countries of the North and the South have become concerned with the contentious issue of the rights to germplasm involved in international exchanges. (See, for example, United Nations Food and Agriculture Organization 1996.)

At present, the issues of how germplasm should be stored, and what should be stored, are intertwined with the question of the distribution of property rights and the appropriate means of enforcement and compensation. To complicate matters further, technological advances are changing the costs and capacities of crop storage and genebanking, as well as the values of different sources of genes for crop breeders.

This paper restricts the discussion to agricultural resources, mainly grain crops, and focuses on some researchable economic issues relevant to the management of national and international crop genetic resources *ex situ*.¹

¹At the outset, I must emphasize that *ex situ* conservation is a complement to, not a substitute, for *in situ* conservation. There is unanimity in the literature that the only way to maintain the complex evolving diversity of life that comprises a natural ecosystem is to do so *in situ*. Effective preservation *in situ*, as the ideal method of maintenance of general genetic diversity, has received extensive attention in recent years. It preserves the whole complex of life forms, known and unknown, and allows them to continue to evolve together. But effective *in situ* conservation presents special challenges, discussed in a longer draft available from the author.

I begin in Section 2 with a brief review of *ex situ* genebank facilities and some aspects of their management. I then consider the current situation with respect to diversity of cultivars of major crops in various areas in Section 3. This topic is expanded in Section 4 to consideration of diversity of the underlying germplasm of modern varieties of major crops, and how it has been surprisingly little affected by availability of international germplasm sources. After briefly reviewing recent trends in means and variances of yields in Section 5, a few very brief observations about some relevant issues in intellectual property rights are presented in Section 6.

The remainder of the paper is devoted to presentation of a menu of research issues and researchable questions. These include the value of yield stability in Section 7, and a long list of questions regarding *ex situ* conservation in Section 8. The conclusion follows in Section 9.

The topic involves a heady mix of genetics, plant biology, ecology, anthropology, political science, history, entomology, agronomy, and economics. In preparing this work, it has been necessary to try to make judgments (preferably by adopting the judgments of those more knowledgeable) about social, scientific and technical issues in which I claim no expertise.

2. Current *ex situ* facilities and their management

Historically, crop germplasm has been stored in centres of diversity, on farmers' farms and in gardens. Over the past three centuries, germplasm has in addition been stored *ex situ*, in researchers' own collections and in a wide array of public institutions, beginning with Botanic Gardens in Europe and then on public agricultural experiment stations, in academic institutions, and in special-purpose germplasm depositories of which the Vavilov Institute in Russia is the prototype. Private seed-breeding firms have also maintained collections; less public information is available about these.

In the 1970s, problems with high-yield varieties of two major crops encouraged great expansion of germplasm storage facilities. The danger of genetic vulnerability of major modern crops was graphically illustrated by the epidemic of the Southern corn leaf blight which caused a 15 per cent corn output drop in the United States in 1970. Susceptibility to this disease was inherent in the Texas male-sterile cytoplasm widely used in breeding hybrid corn. The vulnerability exposed by this epidemic had not been widely anticipated by crop breeders, and it led to an enhanced concern with the danger of reliance on a narrow genetic base for important agricultural crops. A study by the National Academy of Sciences (National Research Council (NRC) 1972) found that major US

Table 1 Germplasm facilities with sub-freezing storage

Facility	Number
National facilities in developed countries	25
National facility in a developed country	1
National facilities in less-developed countries	23
Regional facilities in less-developed countries	2
International Agricultural Research Centers (IARCs)	7
Total	58

Source: Chang (1992).

crops were 'impressively uniform and impressively vulnerable'. Around the same time, experience with the initially highly successful International Rice Research Institute (IRRI) cultivar IR-8 directed attention to germplasm as a source of genes in landraces² and weedy and wild relatives for resistance to pests and diseases that were emerging as serious challenges to the rice breeding programme.

The result was a widespread effort to invest in *ex situ* storage of germplasm. Storage facilities burgeoned from 25 long-term centres (12 of which were in industrial countries) and 28 medium-term centres (13 in industrial countries) in 1978 to a total of 133 centres in 1984 (Hanson, Williams and Freund 1984). As table 1 shows, by 1991 there were 58 facilities with sub-freezing storage, including 7 international agricultural research centres (IARCs), the remainder being split almost equally between developed and developing countries.

The germplasm holdings of the major national and international centres are listed in table 2. The largest are the USA, China, and Russia (the Vavilov Institute), the others, with the prominent exception of India, are all members of the Consultative Group on International Agricultural Research (CGIAR), a relatively informally structured international organization overseen by over 50 member countries and donor agencies. The large depositories of germplasm at its various centres include large numbers of accessions from public national collections in many countries.

Further information about world-wide accessions of major crops and their wild relatives, compiled by Chang (1992, table 1, p. 19), is shown in table 3. Note that most accessions are duplicates. Though somewhat dated, the table correctly indicates that for most of these crops, as for most others, wild accessions are a small minority.

²A landrace is a cultivated variety ('cultivar') that has evolved under traditional cultivation by generations of farmers.

Table 2 Estimates of germplasm holdings in major national PGR systems and international centres

Country/IARC	Categories concerned	Total
USA	All crops	557,000
China	All crops	400,000
	Rice (National Rice Research Institute)	61,000
	Wheat (National Gene Bank)	40,000
USSR	All crops	325,000
IRRI	Rice	86,000
ICRISAT	Sorghum, millet, chickpea, peanut, pigeon pea	86,000
ICARDA	Cereals, legumes, forages	77,000
India	All crops	76,800
CIMMYT	Wheat, maize	75,000
CIAT	Common bean, cassava, forages	66,000
IITA	Cowpea, rice, root crops	40,000
CIP	Potato, sweet potato	12,000

Sources: Chang (1992), table 2, p. 20, compiled from IBPGR (1990), Paroda (1988), Shands *et al.* (1989), Vitovskij and Kuznetsov (1990), Zhang and Dong (1989), Pray (1996, p. 3) for Chinese rice, Yang and Smale (1996, p. 17) for Chinese wheat.

As Hawkes noted in his 1985 assessment of the CGIAR centres (Hawkes 1985, p. 101), 'There is a tendency to underplay the importance of wild relatives', a point that will be raised again later in this paper. Cultivar collections are well on the way to becoming comprehensive in terms of cultivars (as distinct from the alleles present in their population) for most of the crops listed (column 4), with the prominent exceptions of yams and

Table 3 Conservation of major crops

Crop	Total accessions in genebanks	Distinct accessions	Wild accessions	Percentage cultivars uncollected	Major needs ^a
Wheat	410 000	125 000	10 000	10	E,M
Grain and oil legumes	260 000	132 000	10 000	30–50	C,E,M for peanut
Rice	250 000	120 000	5 000	10	C (wild), E,M
Sorghum	95 000	30 000		20	E,M
Maize	100 000	50 000	15 000	5	M,E
Soybean	100 000	30 000	7 500	30	C (wild), E
Common potato	42 000	30 000	15 000	10–20	C,E
Yams	8 200	3 000	60	High	C
Sweet potato	8 000	5 000	550	> 50	C,E

Note: ^aC = collection, E = evaluation, M = maintenance.

Source: Chang (1992, table 1, p. 19). Data were combined from Lyman (1984), Chang (1985), Plucknett *et al.* (1987), and Williams (1989).

sweet potatoes. More generally the coverage of germplasm facilities is summarized by Wilkes (1992, p. 29): 'Approximately 75 to 90 percent of the variation in the major crops and less than 50 percent for many minor crops is found in genebanks.' Recently the work of public genebanks has been complemented by impressive private efforts to collect and maintain stocks of heirloom fruit and vegetable varieties (Vellvé 1992, chapter 4), and a few large decentralized exchange networks have been formed.

Collection is one thing; proper documentation, evaluation and maintenance are something else again. Problems with these issues were widely discussed in the 1980s. Reid and Miller (1989, p. 62) reported that nearly half of all world-wide accessions were not accompanied by passport data, which describe the ecogeographic origin of a sample, or characterization data, which describe highly heritable aspects of appearance and structure. Various sources reflect widespread concern with the lack of evaluation information regarding stored materials. In the absence of responsible levels of long-term financial support, seeds may not be 'grown out' sufficiently frequently to maintain the appropriate size of stored population, given the storage technology, or grown out without the care necessary to maintain satisfactory genetic diversity in the sample. In Goodman's (1990) words, 'genebanks' are often more accurately characterized as 'seed morgues'. These problems are not restricted to minor institutions. The US facilities have in the past been the subject of concern (US Department of Agriculture 1981) as have some of the CGIAR facilities (Hawkes 1985); rice conservation at IRRI and the International Institute for Tropical Agriculture (IITA) was singled out as an exemplary exception.

In 1987 a report to the International Board for Plant Genetic Resources (IBPGR) Board of Trustees revealed that 7 of 17 designated base germplasm banks did not meet IBPGR registration standards (Rural Advancement Foundation International 1987). The problem obviously related to funding, but it was not clearly correlated with underdevelopment; of the top eight centres in the RAFI ranking, only three were in developed countries (United Kingdom and Italy). Indeed, Juma (1989, p. 99) suggests that lower personnel costs and proximity to centres of diversity can give Third World germplasm banks a comparative advantage.

In the intervening years, performance of genebanks has no doubt changed, but availability of adequate long-term funding is a chronic problem.

There is a wide range of motivations for maintaining the diversity of species in general. But here the focus is on current and future agricultural production, and consequently on genetic resources as sources of options for future agricultural production. Effective *ex situ* storage aims to complement *in situ* preservation in maintaining the existing gene pool. But for this

purpose, it is not enough to preserve the diversity of the germplasm of different cultivated varieties ('cultivars'). They must be economically available to the breeding enterprise on a timely basis. If breeders' needs change rapidly and unpredictably, as is often the case with respect to genes for disease resistance, the value of good communications and ready availability of seed stocks for distribution and evaluation becomes critical. For these purposes, plants or their seeds, preserved *in situ* or in small units in long-term storage, are not useful for current breeding purposes. Just as financial banks offer their customers liquidity, that is, low transaction costs for money, so germplasm banks afford breeders liquidity in the form of cheap and convenient transmission of genetic materials and information among plant breeders, and between breeders and storers.

The efficiency of different facilities as germplasm banks (in common parlance 'genebanks'), as opposed to long-term storage facilities, varies widely. Cohen *et al.* (1991) found the performance of IRRI and CIMMYT (International Maize and Wheat Improvement Center) to be exemplary, having 90 per cent of accessions sufficient for distribution, and the performance of the other IARC centres was apparently good relative to most other germplasm facilities.

It is obvious, then, that there has in the past several decades been an expansion of *ex situ* facilities for gene storage and genebanking, even if the balance between the two functions is not always appropriate. Are any effects visible in the diversity of major crops? The following sections address this question and conclude that, for the most part, the answer is 'negative'.

3. The diversity of currently prevalent crop cultivars

3.1 Location of production vs. centre of diversity

Crops grown in their geographic centres of diversity can benefit from ongoing genetic interactions with their wild and weedy relatives. In Mexico, for example, farmers believe that cross-fertilization of their maize with *teosinte*, a wild forbear that persists in some locations as a weed, strengthens the corn crop. In Arizona, Native American Pima farmers appreciate the taste benefits of cross-fertilization of chili peppers with piquant wild relatives (Nabhan 1989, chapter 2). Moreover, farmers in centres of diversity often exploit the yield-stabilizing effects of mixing several cultivars in a single field, as well as the ecological benefits of mixing complementary species in a single plot of land.

Despite the various benefits of farming in a diverse environment, the bulk of major crop production takes place as monoculture far away from

centres of diversity, in relatively gene-poor ecosystems. Although most centres of diversity are in the tropical or sub-tropical regions of the 'South', the distinction is not essentially 'North' vs. 'South'. Most of the countries of the 'South' lie outside the centres of diversity, as does most 'Southern' production of major crops.

The major exception that proves the rule that gene-poor areas are centres of production is the major rice species *Oryza sativa* L., which is still predominantly grown near its centres of origin in Asia. But within Asia, major areas of irrigated cultivation seem rather removed from the gene-rich natural habitats from which the species arose.

Wheat production is dominated by production regions in China, the ex-Soviet countries, India, France, the United States, Canada, Argentina and Australia, distant from Ethiopia, one of wheat's centres of diversity, and from its major centre of domestication in the Syrian–Mesopotamian plains (Harlan 1970, p. 21). Corn production in the United States, China, Europe and Africa is similarly remote from its Latin American origins. Commercial soybean production in the United States and Latin America dominates soy output in its Asian centre of origin. A similar story holds for potatoes, a predominantly European crop originating in the Andes, and sugar and sugar beets. The 'Radiata Pine' in New Zealand outclasses its 'Monterey Pine' counterpart in California. The bulk of sunflower production takes place outside the United States, the country of origin.

Even crops that are grown almost exclusively in the South tend to flourish away from their genetic origins. This is true of coffee in Latin America, India, Indonesia and sub-Saharan Africa, manioc in mainland Latin America and Africa, rubber and oil palms in South-East Asia, cocoa in Africa, and bananas in Africa, Latin America and the Caribbean. (Tea is a more mixed case; still important in its birthplace in India and China, but also flourishing in Sri Lanka, Africa and New Guinea, for example.) Thus we have the following generalization:

Observation 3.1: Agricultural crops are predominantly produced in gene-poor environments far from their centres of diversity.

Why is this so? This question is beyond the scope of this paper, but two points seem pertinent: Relatives are, as all well know, not always unambiguously helpful and congenial house guests. A plant's relatives are often among its most vigorous weedy competitors. Second, a plant's centre of origin tends to be rich in the plant's pests and diseases. Removal of the crop to a gene-poor environment often is an effective, economical, non-chemical means of pest control.

3.2 Temporal diversity vs. cross-sectional uniformity of high-yield cultivars

Within a country, a few popular cultivars often dominate planted acreage. The National Research Council (1972) shows that this was true for most of the major US crops in 1969. A similarly comprehensive summary is not available for later years, but Duvick (1984, table 2, p. 163) shows the situation for a smaller set of major US crops in 1970 and 1980. In 1970 six cultivars had an aggregate share of about two-thirds of cotton and maize acreage, over half of soybeans and 40 per cent of wheat. By 1980 the shares of the top six cultivars had all declined to about 40 per cent, and the identities of the principal cultivars had changed substantially (Duvick 1984, tables 3, 4, 5 and 6). This supports a view that modern breeders trade cross-sectional cultivar diversity with temporal diversity as new cultivars follow one another in a cycle of introduction and obsolescence (Reid and Miller 1989).

The average life span of a cultivar was reported for the crops in Duvick's survey to be around only 7–9 years, and falling (Duvick 1984, tables 7 and 8).

Information from Europe also reveals a rather narrow set of popular cultivars for many major crops (Vellvé 1992, chapter 2). In many cases, producers of major crops in less developed countries appear to rely even more heavily on a narrow base of cultivars than do their developed-country counterparts. In 1983, for example, one wheat variety, Sonalika, covered 30 per cent and 67 per cent of the wheat lands in India and Bangladesh respectively (National Research Council (NRC) 1993, p. 70). Indonesia planted 66 per cent of its rice land with just two varieties in 1984 (Duvick 1990, p. 46). The situation seems less serious in many other less-developed countries (LDCs), where local landraces have maintained a larger share in competition with modern hybrids (NRC 1993, pp. 74–5). In 1987, CIMMYT reported that 49 per cent of maize area in LDCs was planted to local landraces or open-pollinated purchased seed. Pioneer Hi-Bred International (1994, p. 5) reports that 40 per cent of the world's corn acreage is still open-pollinated. This situation probably reflects the greater complexity and higher cost of producing hybrid maize seed. Since maize is cross-fertilizing, producing hybrid corn seeds is relatively difficult and expensive, and it might be beyond the capacity of many seed research and production organizations in LDCs.

The IRRI rice breeding effort initially emphasized sequential widespread dissemination of the high-yield varieties beginning with the famous IR-8. This must have decreased varietal diversity. But now IRRI policy has shifted to encourage national agricultural research institutes to cross their releases with local varieties. Hence this time it is not clear whether *national* cultivar diversity is increasing or decreasing in rice.

The tendency of modern agriculture to concentrate on a narrow set of high-yield cultivars is reinforced by the needs of processors and marketers for uniformity of product. Wheats have long been intensively selected for seed quality traits related to specific end uses. Increasingly, processors value uniformity of other agricultural crops to simplify processing and to facilitate automation of processing. Marketers know the advantages of offering consumers a steady supply of a familiar product that can be widely advertised.

These commercial tendencies towards uniformity are sometimes augmented by the force of law. In the United States, for example, marketing orders for fruit stipulate size limitations, and meat grading imposes a public judgment on what fat content constitutes 'choice'. In California, there has been a 'one-variety' cotton law (see Constantine, Alston and Smith 1994), and there may well be other analogous examples. In the European Union, the logic of market integration generated a need for harmonization of names of vegetable varieties in member states in a Common Catalogue and elimination of duplication across countries. Only registered varieties can now be legally marketed. According to Mooney (1983, p. 114) seed companies responded enthusiastically to a 1980 request for a list of duplicates as an opportunity for eliminating not just duplication and confusion but also unwanted competition including non-proprietary traditional cultivars. Lawrence Hills' Henry Doubleday Research Association examined the 1547 'synonyms' and concluded that only 38 per cent were true duplicates (Vellvé 1992, pp. 59–60).

4. Introduction of new germplasm in high-yield cultivars

Has expansion of genebanks over the last two decades led to an increase in the incorporation of new genes into cultivars? In answering this question, one must consider that the share of major cultivars in production, and their rapid sequential replacement, do not directly indicate the diversity of the genetic material that they offer to farmers. New releases often share much of the ancestry of the cultivars they supersede.

I shall consider the situation in the major crops in turn.

4.1 Rice

The evidence of significant use of farmers' varieties and wild varieties is strongest for rice in developing countries, where the dissemination of new germplasm is by no means proportional to the number of IRRI releases. Evenson and Gollin (1996 forthcoming) report that 885 landraces and some wild varieties have been incorporated in 1709 releases since the 'green revolution'. IRRI breeders have effectively incorporated successive

single genes, mainly for pest and disease resistance, from exotic germplasm; the complexity of this enterprise is illustrated in the account of Plucknett *et al.* (1987, chapter 9) of the development of IR-36.

The most-quoted achievement has been introduction by IRRI of a gene for resistance to the brown plant hopper, which carries the grassy stunt virus. This gene was identified via mass screening in a few plants in a sample of a wild species, *Oryza nivara*, and transferred to modern cultivars using embryo rescue. (This example also shows the importance of preservation of in-sample diversity in regeneration of conserved accessions.) The popularity of this example may, however, imply a paucity of similarly widespread successes. As Evenson and Gollin (1994, p. 13) note, 'Curiously, however, relatively few additional materials have entered the ancestor pool through IRRI's efforts since the mid-1970's.'

As shown in Evenson and Gollin (1994), the amount of new germplasm introduced in IRRI releases seems to have declined in recent years as these releases share much of the germplasm of previous releases. Importantly, as noted above, all incorporate the same semi-dwarfism locus *sd-1*, and the Cina cytoplasm is still pervasive (NRC 1993, p. 76). But the genetic narrowness of the germplasm of IRRI cultivar has, as noted above, been counterbalanced via the widespread crossing with landraces by the National Agricultural Research Systems (NARS), in the International Network for the Genetic Evaluation of Rice (INGER) nurseries (Evenson and Gollin 1994). These crosses are no doubt greatly facilitated by the liquidity provided by IRRI as a germplasm 'bank'. This bank has been screened several times for traits for pest and/or disease resistance. It is not clear how much the expansion of the IRRI genebank since 1970 has contributed to the success of these screenings. Note that Evenson and Gollin have found that expansion of the stock of IRRI accessions is empirically related to expansion of the INGER rice nurseries in developing countries; they interpret this as evidence for the marginal value of germplasm conservation.

The US rice industry, as noted above, has a rather narrow base, but it has widely adopted the semi-dwarf germplasm from IRRI, from Taiwan, and more recently from China (Rutger and Bollich 1991, p. 9). Rice production has, it appears, gained substantially from acquisition of the same international germplasm for semi-dwarfism that has proven so effective in raising yields elsewhere, but it is not clear that it has achieved a very great diversification of germplasm via access to sources from the 'South'. Pray (1996) reports that 'In the past twenty years only one US breeder has used IRRI's wild material' (p. 5), once for disease resistance and once to search for apomixis. The Australian rice industry has had an even narrower base.

Beyond the introduction of dwarf genes, two avenues of yield-increasing innovation are currently important. China's hybrid rice programme, covering nine million hectares in 1991 (Rutger and Bollich 1991, p. 9), relies on a single cytoplasmic source for male sterility (NRC 1993, p. 76) derived originally from a wild species found in 1970 on Hainan Island. Is this a potential source of disaster in the world food supply system? It is possible that the narrow base of germplasm in popular rice crops increases the threat that a widespread disease or pest outbreak will cause a short-run food crisis. Although different hybrids of rice are available, many of them are very similar genetically, and tapping the greater diversity of germplasm available in IRRI and other genebanks takes time. The issue of vulnerability of hybrids is gaining importance as their adoption spreads to other important producing countries such as India.

Another path to yield increases is being pursued at IRRI, where declines in yields of currently popular cultivars are causing some concern. This is the project to produce a super-rice with a new plant architecture believed to be capable of producing higher yields. The nature and extent of use of germplasm in this project would be an interesting topic for further investigation.

4.2 Maize (corn)

The major United States corn cultivars all trace back to six pure line ancestors. Though 77 per cent of a sample of US corn breeders maintained that their base of germplasm was broader in 1981 than in 1970 (Duvick 1984, table 16, p. 169), Smith (1988) concluded that there was no change in genetic diversity of Corn Belt maize from 1981 to 1986, and Cox, Murphy and Goodman (1988) found that less than 1 per cent of US hybrid corn had non-North American exotic germplasm. Moreover, NRC (1993, p. 73) notes that 'Most surveys have shown that there is little immediate prospect for a large-scale increase in diversity of hybrid maize' in the United States.

Apparently, within the narrow germplasm base of US hybrid corn (relative to the total world germplasm), the pool of diversity remains sufficient to provide disease resistance as needed in the high-input US environment, and to provide an as-yet-undiminished, remarkable rate of yield increase. This finding is relevant to the politics of genetic exchange. The genetic resources from the 'South' made available to CIMMYT and other germplasm facilities have not been of very significant benefit to the US corn producers, nor to other growers of modern hybrids.

Recognizing the failure of corn breeders North and South to utilize available genetic resources, Pioneer Hi-Bred in 1987 contributed \$1.5

million to the US Department of Agriculture to help fund the public-private Latin American Maize Project (LAMP) which screened over 14,000 accessions from twelve countries for their potential to produce high-yield crosses in diverse environments. Though it is too early to evaluate the effect of the project on world-wide corn production, the initiative is a dramatic exception to the generalization that landrace germplasm has predominantly been exploited, in recent times, via screening for single-gene pest and disease resistance. (For more on the LAMP project, see, for example, Salhuana, Jones and Sevilla 1991.)

4.3 Wheat

For US wheat, of 224 cultivars released before 1975 only 31 per cent had any germplasm introduced apart from their foundation germplasm, none of which was introduced later than 1920 (Cox 1991, table 3-1, p. 26, and p. 28). Of cultivars released subsequently, Cox found 75 per cent had some more recently introduced parentage, but usually it constituted only a small part of the cultivar's germplasm, typically introduced for disease resistance via crosses and back-crosses. He notes that, 'The limited use of landraces is most striking' (Cox 1991, p. 29).

Cox's remarks do not mean that there has been no genetic improvement in developed-country wheat. A major feature of developed-country wheat breeding in the last few decades has been the release of semi-dwarf varieties based on CIMMYT materials. In Australia, for example, over 90 per cent of wheat area is now semi-dwarf (Brennan 1994). But this apparently has not involved significant use of landrace germplasm. In Italy, modern durum wheat varieties have been produced using crosses of varieties based on CIMMYT dwarfs and semi-dwarfs with Japanese bread wheats. Contributions from international durum collections and nurseries of CIMMYT and ICARDA are continuing (Bagnara, Bagnara and Santaniello 1996, pp. 1-2).

For European wheat as a whole, the picture reported by Vellvé (1992, pp. 35-6) is less encouraging. While emphasizing that data on the diversity of European wheat varieties are sparse, he states that:

90 per cent of the French wheat bread varieties registered and sold to farmers over the past 30 years share a common parent in their pedigree, [and] only 9 per cent are original types. Nearly half of the German wheat varieties registered for sale in 1986 derived from the same parent, Caribo, [a derivative of] Cappelle, one of the top three wheat progenitors used in France. . . . [And] the top four varieties represent 71 per cent of Britain's winter wheat acreage.

Similar figures have been presented by other authors for Eastern Europe and the former Soviet Union.

4.4 Soybeans

Sprecht and Williams found that of 136 successful soybean cultivars released by the US breeders from 1939 to 1981, 121 had cytoplasm of just five introductions (Sprecht and Williams 1984, p. 65) and the same six ancestral strains accounted for nearly 60 per cent of the germplasm in these 136 releases. These same six ancestors accounted for a similar percentage of germplasm of cultivars released from 1971 to 1981 (Sprecht and Williams 1984, table 3–7, p. 68), even though there was large turnover in the set of leading cultivars between 1970 and 1980 (Duvick 1984, table 4, p. 164). In an attempt to more fully utilize the potential of soybean germplasm, a joint university–industry programme has been testing exotic cultivars for desirable traits (Duvick and Brown, 1989).

4.5 Edible beans

The continued narrow genetic base of US soybeans has been noted above. For common beans (*Phaseolus vulgaris* L.), NRC (1972, p. 225) reported that ‘for a considerable part of the edible dry bean acreage in the United States, annual production rests upon a dangerously small germ plasm base’. Adams (1977) refined this report by stating that pinto beans faced the highest risk due to their extreme homogeneity. Within five years this warning was vindicated by a rust epidemic that caused losses of 25 to 50 per cent in Colorado and Wyoming at a cost of \$15–20 million in 1982 (NRC 1993, p. 68).

Though this experience has prompted development of rust-resisting cultivars using the CIAT gene pool, the susceptible variety is still widely grown (NRC 1993, p. 68). Silbernagel and Hannan (1992, p. 2) comment that ‘the need for genetic diversity and enactment of PVPA have not stimulated the utilization of the *Phaseolus* collection of more than 11000 accessions’ [at Pullman, WA].

The decline in public breeding resources, and absence of private response, have taken their toll:

The gap between identification of useful characters in exotic germplasm and the transfer of these potentially useful characters to cultivars had widened. It is economically prohibitive for private companies to commit the time and expense on cultivar development incorporating exotic germplasm in such a minor crop as common beans, and there is no

longer much career incentive for public scientists to perform this work. Therefore, the gap ever widens. (Silbernagel and Hannan 1992, pp. 2–3)

The fact that potential prevention of a multi-million dollar disaster offers insufficient incentive for private breeders to utilize available genebank accessions gives us some clues to the extent to which private plant breeders can hope to capture the social value of their work. It also gives us a reality check about the scope of concerns about ‘profiteering’ by seed companies using germplasm from the ‘South’. It also suggests that public support will be needed if producers of all but the largest crops are to benefit from the diversity available in genebanks. (Of course the markets for some crops might be too small, and with too little prospect of expansion, to justify much investment of any kind.)

4.6 Industrial crops

Thus far I have discussed some of the popular crops that have been cultivated for long periods and have extremely large, established, world-wide markets. Perhaps it is natural that breeders of such crops tend to have settled on a rather narrow set of germplasm after centuries of intense selection in different countries. But what is the role of germplasm for crops at the other end of the spectrum, that is, crops under research and development for commercial production?

Thompson, Dierig and White (1992) reviewed the development of a set of potential industrial crops: guayule (for rubber), kenaf and roselle (for paper pulp), guar (for gum), jojoba (for oil for cosmetics, lubrication, and other uses), meadowfoam, industrial rapeseed, lesquerella (for oils), buffalo and coyote gourd (for high-protein, high-oil seeds, and starchy roots), cuphea (for palm oil substitute), and vernonia and Stokes aster (for coatings, plasticizers and stabilizers).

The development of each of these crops is a highly speculative project, and so it is not surprising that financing is a major constraint. What is surprising is first, that a total of 6481 accessions of these varieties was identified as available to researchers, and second, that only 2.1 per cent of these have been ‘used in developing new germplasm lines or cultivars’. (Thompson, Dierig and White 1992, p. 39). If this means that the remainder have never been used in any breeding experiments, it seems that, at least till now, collection of germplasm has moved ahead of utilization, as is the case for crops with well-established production basis and experimental programmes.

In conclusion, the above discussion of the germplasm base of major crops suggests the following general observation:

Observation 4.1 The very great increase in *ex situ* crop germplasm storage capacity and number of accessions has not been matched by a similarly great increase in diversity in the germplasm of popular cultivars.

Allard (1992, pp. 144–5) implies that the relative neglect of germplasm from genebanks is rational:

Breeding in barley and corn, as well as in other major crops, has increasingly focused on crosses among elite materials and rates of progress indicate not only that this strategy has been successful but also that there has been little, if any, slowing of progress due to reduction of exploitable genetic material ... It consequently seems unlikely that readily exploitable genetic variability will soon be exhausted.

Allard also claims that the rare alleles are rarely useful. In reviewing this paper, Day (1992, pp. 518–19) remarks: ‘This suggested to some of us that very large gene banks may be unnecessary.’ Of course, no common definition of ‘very large’ exists. Many breeders prefer around 5000 accessions, far fewer than the largest banks now hold, but who should define how many accessions are enough, and how? Establishing an optimal size for a genebank of a given purpose (e.g., pre-breeding, breeding, conservation) is important. Studies are needed in this area.

5. The evolution of yields: mean and variance

In discussions of crop genetic resources, the scope, complexity and contentiousness of the issues can tend to obscure the importance of yield as an ultimate objective, and the interests of consumers in price and availability. (For example, the words ‘price’ and ‘consumption’ do not appear in the index of influential works by Fowler and Mooney (1990) and Fowler (1994).)

Unfortunately, given the influence of random fluctuations in weather and in losses due to pest and disease, and changes in input mix and intensity, it is difficult to infer the genetic contribution to mean output over the 6–9-year useful lifetime of a typical popular cultivar. Detection of effects on higher moments is an even greater challenge. This is a major problem for the management of breeding programmes. The development of an improved crop cultivar apparently takes about 7–15 years. Thus it may be well over a decade before any useful evidence regarding performance in producers’ fields becomes known, and around another decade before this feedback can have any significant influence on new releases. Accordingly, breeders are forced to rely heavily on comparisons of

cultivars in experimental plots, and hope the results are relevant to the environments in farmers' fields. The evolution of pests and diseases in response to the spread of new cultivars adds great complexity to the conceptualization and measurement of crop performance.

To the extent that usable inferences can be drawn regarding the evolution of yields, what should we expect them to show? It is obvious that higher yield is a major breeding objective of virtually all breeding programmes, and also of farmers in general. Furthermore, mean yield is sufficiently measurable to enable effective selection both by seed breeders and by farmers. Therefore it is natural to expect that breeding efforts have measurably improved yields over time.

With respect to variability, *a priori* expectations are less clear. The very brief sketch-survey above indicates that modern varieties generally continue to have a rather narrow germplasm base relative to the diversity available in genebanks. The modern varieties also are often much more widely adopted at any given time than the cultivars grown before the 'green revolution', which in turn tended to be more geographically homogeneous than the local landraces of the last century, and this fact alone should make for higher aggregate variance, given yields of different landraces are not mutually perfectly correlated.

What does the yield evidence show? There is no doubt that, for major crops, mean yields have been increased greatly by replacement of landraces with modern cultivars over the past century. Furthermore, rice and wheat yields have increased greatly overall since the establishment of IRRI and CIMMYT, which are widely acknowledged to have had a crucial role in generating these impressive yield improvements. The record of private breeders is most impressive with respect to hybrid corn in the United States. The yield increase is associated with heavy increases in other inputs, in particular nitrogen fertilizer, and with increased plant density. About half of the overall increase is commonly attributed to the genetic input.

Extensive critiques of these breeding efforts usually dispute neither the extent of the overall yield increases nor the importance of the genetic contribution. Rather, critics claim that similar achievements might have been achieved by other means. Alvares (1986) implies that rice yields could have been raised via pursuit of other, more diverse and stable sources of yield improvement within the Indian national rice breeding programme. Kloppenburg (1988) views the development of hybrid corn (and hybridization in general) as a means of exploitation of farmers by private seed breeders; he implies that similar yield increases could have been achieved by development of open-pollinated varieties. (He does not discuss how his analysis applies to the original public development

and large-scale adoption of hybrid rice in China under a communist regime.)

Whatever the merits of 'roads not taken', the following fundamental generalization is clearly established over the long term:

Observation 5.1 Modern cultivars have greatly increased the yields of major crops over the long term.

Whether this rate of increase is as high now as it was a decade or two ago is a question that is much more difficult to answer. There seems to be a widespread perception that the aggregate yields of all rice cultivars (not individual varieties) incorporating IRRI germplasm are not increasing as fast as they once were; much of the aggregate yield increase is due to the continued geographic dispersion of this high-yield technology (Evenson and Gollin 1994). Various factors may be contributing to the slower yield growth, including the possibility that high yielding variety (HYV) response may be lower in areas with poorer soils and little or no irrigation, that is, precisely in those areas where recent HYV introductions have been concentrated. The response may be weaker for less advanced farmers, who have taken more than their share of recent HYV introductions. Finally, the HYV response may be suffering increasingly from pollution, soil degradation, and other human-induced environmental change.

It might be natural to suspect that this claimed slowdown in rice yield improvement is attributable to the failure of the IRRI programme to make effective use of IRRI's extensive genetic resources to expand the germplasm in the more recent cultivars that it has made available to national agricultural research systems. However, it is reported that no yield ceiling is apparent in comparative trials of new versus older releases (Don Duvick, personal communication). Hybrid corn yields in the United States continue their 60-year record of improvement at a rate that is probably above the historical average (Duvick 1996). The almost total failure to incorporate new germplasm from a huge international stock has apparently in no way reduced progress in mean yield. Similarly, failure to incorporate much new germplasm in soybeans has not been associated with any significant decline in observable yield improvements.

Though wheat breeders have made more use of germplasm of wild varieties and related species for single genes for disease resistance, they are perceived to have failed to incorporate sufficient landrace germplasm, as noted above. But, as in soybeans and corn, failure to exploit all available germplasm has not prevented progress with respect to mean yield.

Limitations in the scope of this paper preclude discussion of numerous other significant crops in which a narrow germplasm has not apparently

prevented continued progress in mean yield. Though exceptions no doubt exist, and I have no overall information on important crops such as potatoes and manioc, I offer the following generalization:

Observation 5.2 Continued general failure to widen the genetic base of major crops, with the major exception of introduction of single genes for pest resistance in wheat and rice, has not generally resulted in obvious decline in the rates of increase of mean yields of major crops.

Recent trends in variability of major crops are unclear. In a situation of increasing yields, the appropriate index of variability is the coefficient of variation (standard deviation divided by mean), not the variance. Anderson, Hazell and Evans (1987) and Hazell (1989) report increased correlations between yields of a given crop in different countries or regions, and between different crops, between the 1960s and the period 1971–72 and 1982–83. These increased correlations account for most of the change they observed in the coefficient of variation of cereal yields around trend (excluding China) from 2.8 per cent to 3.4 per cent. It is possible that these results are dominated by the two widespread crop failures in the early 1970s. For the longer period 1951–1986, Singh and Byerlee (1990) showed declining variability in wheat, and no effect of high-yield germplasm on variability.

Statistical detection of a change in variability is difficult over a time series of only a few decades. Separating genetic sources of changes in yield variability from possible secular changes in environmental variability (perhaps related to global warming) is an additional challenge. Finally, if agriculture has become more market-oriented over time, supply responsiveness may have increased. For a storable commodity such as a grain, a given weather-induced shortfall in one year reduces stocks, raises future price if market participants have rational expectations, and induces an increase in planned supply for the following harvest. This response augments measured yield variation via changes in intensity of variable inputs. To the extent that this effect is not offset by expansion into lower-yield farmland, more responsive supply will increase measured yield instability, even though it actually stabilizes consumption. (See Williams and Wright (1991), chapter 5.)

Many discussions of crop germplasm emphasize the greater inherent vulnerability of modern cultivars relative to the landraces they replace. Even if there were no difference in inherent yield stability, greater specialization in the form of increased market shares of the most popular cultivars should, as noted above, cause greater overall variability. Measurement problems notwithstanding, it is surprising that these

expectations have not been more convincingly supported in the aggregate data.

Observation 5.3 There is no empirical confirmation of claims that yields of major crops in a given country (as measured by the coefficient of variation) are more variable when modern high-yield germplasm is used.

Observation 5.4 The hypothesis that greater world-wide uniformity of germplasm due to the increased dominance of high-yield varieties is not associated with greater relative yield fluctuations cannot be rejected at present.

The current state of the argument calls for further empirical investigation. Perhaps our prior expectations also need review. Are breeding programmes that are focused on high-yield germplasm actually less capable of adapting to environmental fluctuations and pest infestations than if they used more germplasm from the landraces in genebanks?³ Has breeding for shorter maturity and increased double-cropping avoided some environmental stresses (such as frost) and 'smoothed out' others? Or has it increased the incidence of pests and diseases? Has the 'high-input' regime placed more of the relevant climate under human control? Have better transport and communications increased the flexibility of response to environmental surprises?⁴

Of course an increased danger of cataclysmic collapse may be present in the food production system without being evident in recent data. Economists recognize this as the 'peso problem': a currency may have a good chance of collapse even if its recent behaviour has not been volatile. Similarly, the collapse of US corn output in 1970 due to the Southern leaf blight was not anticipated in previous yield data. To identify vulnerability

³Duvick, himself a plant breeder for Pioneer Hi-Bred International, admits that, 'It was my expectation that breeders only rarely would find useful pest resistance in elite-adapted lines. I thought that for pest resistance they nearly always would need to cross out to exotics such as landraces or related species. But I was surprised to find that for all five crops included in my survey [cotton, soybean, wheat, sorghum and maize], elite adapted lines were said to be one of the most important and widely used sources of useful pest resistance ... Their experience directly contradicts commonly-heard statements to the effect that gene pools of elite materials have been so narrowed by successive generations of selection for yield that they no longer contain the diversity needed to counter new disease and insect problems.' (Duvick 1984, p. 168).

⁴For example, when corn planting was delayed by rain in southern Ohio and Indiana in 1981, the hybrids normally grown there would have suffered frost damage before harvest. But seed companies provided short-season varieties designed for more northerly areas to avoid the problem (Duvick 1984, p. 175).

before it becomes obvious, it is necessary to go beyond the time series evidence. This is one good reason why scientists look for signals of vulnerability in the germplasm. Analysis of a previous occurrence of the corn leaf blight overseas failed to raise a warning flag about the problems with Texas male-sterile cytoplasm. But, prompted by this experience, the National Research Council (1972, p. 225) issued a warning regarding the narrow genetic base of US edible beans. In 1977, Adams used a genetic distance index for each cultivar and data on share of acreage to predict that pinto beans faced the highest risk of an epidemic within the dry bean class. In 1981 and 1982 an epidemic of rust did in fact occur; it caused losses of 25–50 per cent in Colorado and Wyoming (NRC 1993, p. 68).

In short, lack of recent severe crop losses related to genetic vulnerability does not mean that such losses will not occur in the near future. Some clues for identifying these dangers lie in the germplasm, which also can contribute an important part of the remedy.

6. Intellectual property rights: a few modest observations

Discussions of intellectual property issues relating to plant breeding have been vigorous and extensive over the last few decades. The legal protection of new plant material has expanded quite rapidly over this period, especially in the United States, and the World Trade Organization (WTO). Agreement on 'Trade-related Aspects of Intellectual Property Rights, Including Trade in Counterfeit Goods', known as 'TRIPS', calls for protection of plant varieties world-wide. (See Contracting Parties to the General Agreement on Tariffs and Trade, Uruguay Round (including GATT 1994) ('Contracting Parties') (1994).) Article 27, 3(b) includes the provision that 'Members shall provide for the protection of plant varieties either by patents or by an effective *sui generis* system or by any combination thereof.' There is a novelty requirement in Article 27, 1, and exclusions in Article 27, 2 include those necessary to protect 'human, animal or plant life or health or to avoid serious prejudice to the environment'.

Attitudes to germplasm rights had also been evolving in a different direction in less developed countries. They became concerned about the great imbalance between the free acquisition of landraces and wild and weedy varieties, mostly from the South, by plant breeders, mostly in the North or in the North-sponsored CG system. This concern materialized in the 22nd FAO conference in 1983 as the 'International Undertaking on Plant Genetic Resources'. As Article 1 states:

The objective of this Undertaking is to ensure that plant genetic resources of economic and/or social interest, particularly for agriculture,

will be explored, preserved, evaluated, and made available for plant breeding and scientific purposes. This Undertaking is based on the universally accepted principle that plant genetic resources are a heritage of mankind and consequently should be available without restriction.

Article 2 states that access should extend to 'newly developed varieties and special genetic stocks (including elite and current breeders' lines and mutants)'. (See Witt 1985, pp. 107–8.)

This Undertaking, intended as a moral rather than legal commitment, did not receive unqualified support even from some of its original advocates (Witt 1985, p. 112). More recently, the Convention on Biodiversity 1992 (CBD), Article 8(j), stated that each Contracting Party shall:

Subject to its national legislation, respect, preserve and maintain knowledge, innovations and practices of indigenous and local communities embodying traditional lifestyles relevant for the conservation and sustainable use of biological diversity and promote their wider application with the approval and involvement of the holders of such knowledge, innovations and practices and encourage the equitable sharing of benefits arising from the utilization of such knowledge, innovations and practices.

Thus both *in situ* conservation, and compensation for the providers of indigenous knowledge, innovations and practices are mandated by CBD. This is not achieved under TRIPS. The latter adopts standards of patentability, which include novelty. It provides only for compensation of individuals as distinct from communities, and does not cover disembodied knowledge.

Concern with the operation of the US patent system is eloquently expressed in RAFI (1994) in which several cases are presented in which indigenous knowledge of the South appears to have been used to obtain patents in the North. Other cases in which sweeping claims to plant biotechnology technology have been accepted are also discussed. Problems with broad biotechnology patents in the United States, and in Europe, are further explored in van Wijk (1995).

Part of the problem is that US patent law relies heavily on court challenge to define the validity and scope of patent rights. Observers become understandably nervous when sweeping claims to application of biotechnology to a crop are initially accepted, as in the case of the Agracetus 1992 patent on genetically engineered cotton and its 1994 European patent on genetically transformed soybeans (RAFI 1994, p. 8), even if the claims are rejected in a subsequent challenge. Second, this

modus operandi is very expensive, and places economically disadvantaged challengers in a weak position.

But I do not wish to discuss these issues, or related topics such as the very interesting innovative INBIO-Merck agreement for pharmaceutical prospecting, or the FAO International Code of Conduct in this paper. Rather, I wish to concentrate on applications relevant to plant breeding. Two observations are helpful in informing the debate.

Observation 6.1 Crop germplasm flows have been mainly from relatively small centres of diversity, mostly in the South, to major crop-producing, gene-poor regions in the North and South.

Most of the world's genetic resources reside in the South, and so do most of the crop genetic resources. But most of the South is, like the North, poor in native crop genes. The Vavilov centres of diversity (which were originally defined in relation to crop resources) are a small portion of the South. As Kloppenburg and Kleinman (1987) show, if the world is divided into 10 production regions, all the regions that are predominantly 'North' are heavily dependent for food crops on germplasm originating in other regions. But of the other 'South' regions, only three, West Central Asia, Indo-China, and Hindustan, get a majority of their germplasm from their own region. Most of the world's germplasm originates in Latin America and West Central Asia.

With respect to non-food crops, only Indo-China is less than 70 per cent dependent on other regions. Latin America (South) and the Mediterranean (which includes countries of both the North and the South) are the largest sources for the world as a whole. Dependence at the country (rather than regional) level would be substantially greater for most of the South. Note that Africa, currently the region with the most severe agricultural challenges, is about 80 per cent dependent on other regions for its germplasm, although this figure may be partly an artifact of the neglect of useful indigenous cereals.

Observation 6.2 The current demand of northern breeders for germplasm from centres of diversity is very modest, especially in the private sector.

The tables just discussed show historical aggregate dependence. Breeders of major crops are not greatly dependent on continued access to southern germplasm. This is especially true of corn, in which the bulk of private breeding profits are generated. If no corn germplasm had been allowed to flow into the United States in the last half-century, there would apparently be little difference in the set of hybrid corn cultivars sold by breeders today. In other words, there would currently be virtually no market for maize germplasm from farmers in the South if it were offered at any price

to US private corn breeders. A retrospective calculation of 'just compensation' would be another matter entirely, but that is not the centrepiece of current discussions.

7. The value of yield stability in elite cultivars: a research question

The Irish potato famine of 1845–49 remains the seminal event that has established in the minds of plant breeders and policy-makers the magnitude of human suffering that can result from heavy reliance of a population on a genetically uniform, introduced food plant. The power of this one example often forecloses a more extensive exposition of motivation in discussions of the genetic vulnerability in agriculture. Discussion tends to proceed along the following lines: 'Why be concerned with genetic vulnerability? Consider the Irish potato famine, caused by genetic vulnerability to *Phytophthora infestations*. What do we do about it? Read on.'

Writers are usually careful to emphasize that the Irish 'great hunger' cannot be understood in isolation from the condition of colonial subjugation experienced by Ireland at the time, including the continued forced export of abundant grain to pay the rent of English landlords. Genetic homogeneity was nevertheless a necessary (as distinct from sufficient) cause of the disaster.

But the lesson of the Irish famine may be excessively persuasive in establishing the case for concern with the genetic effect on the stability, as distinct from the mean level, of crop yields. This issue is ripe for a more critical analysis. The potato famine was so devastating because it translated directly into a life-threatening drop in food consumption. Some of the relevant proximate causes for this, given the negative socio-political context, include:

- (a) Potatoes were the staple subsistence food of the population; the consumption share was extremely high.
- (b) There was no sufficient marketable surplus of the staple that could be cut, to sustain the consumption of the producers, or sold at high price to fund consumption of other commodities.
- (c) Year-to-year potato storage to cushion such a consumption shock was technically infeasible.
- (d) Other resistant sources of germplasm were not available to farmers after the infestation became readily apparent.

The extremely high consumption share is critical. It was not just the homogeneity of the crop, but the homogeneity of the subsistence consumption set, that rendered the Irish population so exposed to the potato blight.

As a rough rule of thumb, the total cost to consumers of a given variance in food consumption is proportional to the consumption share (Wright and Williams 1988). Moreover, if producers have a large marketed surplus on average, a substantial yield collapse need not cause a proportional fall in their consumption. The price rise might more than offset a yield drop, especially for a staple in an economy isolated by transport cost or other barriers from world food trade.

In short, genetic vulnerability of a crop can have a cost to producers of the magnitude indicated by the Irish potato famine only in a subsistence culture in which a vulnerable staple has a very large share of food consumption, and short-run adjustment to a crisis via trade, loans, aid or adjustment of genetic resources is not feasible. How many crops, in how many countries, fit this bill? This question merits further serious study. Of one thing we can be sure: the process of development inevitably expands the consumption set beyond heavy reliance on a single food, and subsequently reduces the share of food in general.

Observation 7.1 The cost of yield instability due to genetic vulnerability can be extremely high for a staple commodity in a severely underdeveloped country isolated from the rest of the world. But most less-developed countries do not fall into this category, and in less-underdeveloped countries that are extremely isolated from the rest of the world, such as Iraq and North Korea in the mid-1990s, governments wishing to avoid the dangers of yield instability should consider attacking directly those policies which inhibit economic integration, rather than breeding for yield stability.

Observation 7.2 For crops that are not staples in developing countries, the case for breeding for stability, as against level, of yield is a case that has yet to be made.

A new look at the cost of genetic uniformity might well help explain some puzzles in the literature. In India and Bangladesh, farmers continued to plant large areas with the wheat variety Sonalika long after they were warned by plant breeders of its genetic vulnerability. In France, as the country has developed, wheat breeders have chosen releases with higher weights for yield and lower overall weights for disease resistance (Vellvé 1992, table 2.5, p. 47). In the United States, pinto bean breeders continued to grow large areas to the susceptible variety, despite several heavy infestations in the 1980s (NRC 1993, p. 68). Perhaps farmers do not value stability as highly as some observers have assumed; other characteristics, such as cooking qualities or taste, may dominate. To justify a policy of

intervention here, it would be necessary to show that farmers' choices are not in accord with society's interests.

8. *Ex situ* conservation: research questions

Much of the germplasm of major crops and their wild and weedy relatives already resides in genebanks. The effect of the vast increase in accessions since the 1970s on germplasm utilized for crop production has thus far been modest. What, now, are the issues relevant for *ex situ* genebank activities in the immediate future?

8.1 What is the current 'market' for genebank services?

More than a decade ago, a US survey found around three-quarters of soy and wheat breeders, around three-fifths of cotton and sorghum breeders, but only 45 per cent of corn breeders used genebanks more than 'rarely'. It is interesting that corn breeders, with a large private-sector contingent, used genebanks the least.

Who is using genebanks now? IPGRI has published listings by country. It would be interesting to have the breakdown by volume of use, and by type of use — experimental, crossing, direct adoption, accession for a local genebank, private breeding programmes, and so on.

Can we get an overall picture of the means used by plant breeders to acquire new germplasm? How much comes from CGIAR facilities, how much from other genebanks, from direct exchange with other breeders, or from the *in situ* source? What is the pattern of gross and net barter in gene resources?

How are the CG facilities using their own germplasm for breeding? Does use of landraces decline over time for a given breeder?

What is being used? Landrace accessions (very important for users in Evenson and Gollin (1994) for rice), elite CG releases, CG enhanced germplasm, weedy or wild relatives? In other words, is the most-used CG product currently the breeding service or the gene banking service?

What motivates use of CG germplasm? Search for genes for insect or disease resistance? For physical attributes like resistance to lodging? For taste or texture? For environmental adaptation (photoperiod sensitivity)? For resistance to stress (salt tolerance, drought tolerance, cold tolerance, bad soils)? For yield enhancement? For fertilizer response or herbicide resistance?

The answers to the above questions would say much about the current 'market' for the gene banking (as distinct from gene storing) function. The future stochastic demands for gene banking constitute the principal

motivation for current gene conservation via storage. (Existence values may also have some weight.) Current investments in these facilities should be guided by expectations of the evolution of these demands over time, and of costs of gene storage and gene banking. All of these depend heavily on questions about technical change.

8.2 How is the cost of efficient storage likely to change over the next few decades?

Effective storage conserves, not just the species, but a large percentage of the population germplasm. Stocks must be assessed for viability, and in doing so, by current methods of germination testing, some part of the stock is lost. When viability declines beyond some threshold, a sample is ideally replanted to generate new seed. The sample must be large enough, given germination rates, to maintain the breadth of germplasm stored. For out-crossing varieties, crossing of different plants must also be carefully controlled to prevent loss of germplasm diversity during regeneration.

A most obvious, crucial factor is the rate of decline in viability, which determines the frequency of the need for viability checks and regeneration. New technology maintains long-term stocks in sub-freezing conditions with controlled humidity. If these can assure viability of a variety's seeds for, say, a century instead of a decade, the payoff would seem to be very great.

If non-destructive means were developed to assess viability, this would also alleviate the problem. If, to pursue a perhaps far-fetched notion, germplasm of out-crossing plants could be cloned for regeneration, the existing challenges to maintaining diversity of their germplasm could be solved. In addition, perhaps new means will be found to assess the preservation of germplasm in a stored accession, and to indicate corrective action should problems arise.

8.3 The prospects for future crop germplasm demand

The evolution of crop germplasm demand depends on how several different elements of relevant technical change develop, including the following 3 options.

Use of wide crosses

Advances in conventional breeding have made wider crosses available between species. For example, wheat breeders have actively acquired genes for pest resistance from other species, sometimes by successive crosses involving an intermediate species, with subsequent back crossing to wheat. This trend should increase the value of related species as gene sources, and

perhaps reduce the value of other wheat cultivars as candidates for gene searches. Will these wide crosses become more prevalent in other crops? Until they do, conventional breeding will have no use for the existing accessions of wild and weedy relatives.

Use of genes from other species via genetic engineering

Advances in genetic engineering have made it possible to move a single gene from one species to another and have it expressed in the latter. For example, it is reported that the firefly gene for luminescence has been expressed in tobacco leaves. The gene for pest resistance from *Bacillus thuringiensis* has been incorporated into cotton, potato, corn and other plants and can be expressed in various parts of the plant. This means that breeders might be going far beyond the germplasm in current genebanks to find solutions to pest and disease problems.

This new capacity to move genes between species, beyond the scope of traditional cross-breeding, is currently restricted to single-gene characteristics. But it seems that the major use of germplasm at present is for single genes for pest resistance. The net effect on the demand for crop germplasm is a subject for consideration. On the one hand, the genes in the vast array of other living species are now potential substitutes for the resistance genes that might exist in crop germplasm in genebanks. This substitution effect might make crop genebanks less valuable. On the other hand, this genetic engineering capacity might also make the incorporation of single genes from other accessions in genebanks much less expensive, by eliminating the need for back crossing, and by reducing the time between gene identification and its incorporation in a new release. The process will also be more flexible and respond more quickly to new disease challenges.

In general, it is thought that productivity including mean yield and stress tolerance are determined by multiple genes. Genetic engineering techniques for transferring multiple genes between species are not yet available. For yield increases and stress tolerance, conventional breeding techniques will continue to be dominant in the near future. But in general breeders appear to make little use of genebanks in pursuing these objectives. In the survey by Duvick (1984, table 21, p. 172), only 8 per cent overall (mainly wheat and sorghum breeders) used landrace germplasm for stress tolerance, and only 1 per cent (all of the wheat breeders) used related species for this purpose.

Synthesis of new genetic material

Thus far, the discussion has focused on moving one gene or a set of genes existing elsewhere into elite cultivars, by traditional or modern means. The feasibility of this approach depends on the preservation of the genes, and

on their accessibility. But the breeder might instead be able to pursue one of several alternative routes to changing a cultivar's genetic characteristics. Several techniques have recently been used successfully (Orton 1988), including:

- (a) irradiation, which has been used to produce new barley cultivars, for example;
- (b) chemicals (including potent carcinogens) have been used to induce mutations;
- (c) somaclonal variation induced via *in vitro* propagation has been observed to result in genetic variation. A cultivar of corn resistant to glyphosate herbicide was produced in this way;
- (d) transposable elements, which apparently have the ability to move genes and sets of genes, and also to alter their expression, are being investigated as a source of variation in a cultivar's germplasm.

Where all these new technologies will lead is difficult to assess. Here are a few questions:

- (a) Will the value of accessions in existing genebanks rise at the expense of breeders' own collections of elite lines and enhanced germplasm if new technology increases the competitive position of landraces and wild relatives *vis-à-vis* elite lines in the search for new genetic material?
- (b) Could the value of crop genebanks fall if genes from other species emerge as competitive substitutes for the contents of genebanks?
- (c) Will more use be made of genes from species not in crop genebanks? Will the interests of crop breeders in the preservation of species as options for future use in crops tend to extend further beyond crops and their relatives to the whole array of living species?

Whatever the answers to these questions, there is no doubt that the genetic resources available for plant breeders are changing rapidly, and that the consequences will be of great importance for genebank operations. In the words of R.B. Flavell (Flavell 1992, pp. 409–26):

The days when plant breeders can consider their species as the only source of genes for crop improvement are gone forever, and the repercussions of this are legion in industry, in the public sector, in government research planning, and in the public understanding of crop germplasm.

9. Conclusion

The number, capacity and quality of facilities to store plant genetic resources *ex situ* have increased greatly since the 1970s. But this expansion

has not yet induced a similar increase in the diversity of new material incorporated in crop cultivars used by farmers. Thus far, the continued narrowness of the genetic base of major crops has in general resulted in neither a slowdown of yield improvements, nor any clear evidence of decreased stability of yield.

Rice breeders have for many years actively screened conserved landraces for pest and disease resistance to maintain the high yields already achieved and increase the geographic diffusion of high-yield cultivars. At least some genetic resources are also being utilized to increase yield potential by developing cultivars with a new plant architecture, on the one hand, and hybrid cultivars, on the other. How soon breeders of other crops will (or should) move much beyond occasional searches for single-gene resistance in utilization of genebanks is an open question. To what extent is modest utilization due to sub-optimal provision of liquid genebanking services? Will biotechnology help solve this problem?

These questions are difficult, because so many gaps remain in our knowledge of current germplasm conservation services. There is an obvious need for a comprehensive review of the extent of use of major genebanks, how they are used, what materials are used, what they are used for, and the nature of the users.

Valuation of services provided at the margin is a challenging task. A judicious prior step would be accurate assessment of the cost structure of germplasm conservation at major facilities such as those found in the CGIAR system. It might be much easier to judge whether the marginal benefits are likely to exceed measurable marginal costs of conservation than to accurately calculate those benefits. Estimation of costs will also facilitate efficient choice of conservation technology, size of facility, location, and extent of duplication. Costing of documentation and characterization of accessions might help inform the discussion of claims of general sub-optimal performance in these areas.

The appropriate use of means of conservation also merits attention. Though often supported as a superior conservation alternative, *in situ* conservation of crop germplasm has received scant critical economic scrutiny. The typically essential role of indigenous farmers in such conservation raises severe agency problems, especially if those farmers are free to experience the effects of economic development on the value of their time. There is little doubt that *in situ* and *ex situ* approaches are complements rather than substitutes in germplasm conservation, but they are too frequently discussed as competing alternatives.

Further research is not needed to support the conclusion that the 'farmers' rights' debate has raised false hopes regarding the potential of North-South transfers in compensation for southern germplasm. The

major beneficiaries of food crop breeding are consumers, and the benefits go mostly to the vast consumer populations of the South. Most of the world's population, North and South, is heavily dependent on germplasm historically derived from centres of genetic diversity in foreign countries. For the most 'Northern' and 'privatized' of the major crops, hybrid corn, the problem is not that breeders continue to use new southern landrace germplasm for free, but that they use hardly any of it at all. There is a real danger that the perfectly understandable desire of countries with centres of diversity to extract rents from landrace germplasm will lead to policies that hinder the expanded use of genebanking services, just when they may be crucial in enabling world food supply to keep pace with burgeoning population in the South. Designing reasonable compensation mechanisms that minimize this danger is a research task that is already overdue.

For the future, advances in biotechnology will reduce the cost of high-quality conservation, and lower the costs and time involved in breeding new cultivars using genetic material from landraces and wild and weedy cultivars. New alternatives to the germplasm of crop species, including genes of other life forms, will also be increasingly available to breeders. But there is no doubt that efforts to maintain and improve the world-wide 'liquidity' of genebanking services will be crucial in ensuring that conserved germplasm is efficiently used in increasing world agricultural output and, in particular, world food supply. If germplasm resources are not effectively used, long-term commitments to their effective conservation are likely to be increasingly difficult to secure.

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