MELINDA SMALE*

Economic Incentives for Conserving Crop Genetic Diversity on Farms:
Issues and Evidence

INTRODUCTION: THE DECISION TO MAKE

Scientific methods of genetic improvement, building on millennia of farmers' selection in their own fields, are the basis for changes in the supply of food on which societies depend. Whether farmer selection practices, conventional breeding methods or techniques of genetic transformation are the principal means of seed technological change, genetic improvement of crop plants depends on the exploitation of allelic diversity and genetic recombination.

Since the 1970s, when conservationists first raised public concern for the loss of plant populations believed to contain rare alleles, large numbers of landraces and wild relatives of cultivated crops have been sampled and stored in ex situ gene banks. An alternative form of conservation in situ has also received some scientific attention (Maxted *et al.*, 1997) though it raises intricate social and economic issues. For cultivated crops, conservation of genetic resources in situ refers to the continued cultivation and management by farmers of crop populations in the agroecosystems where the crop has evolved (Bellon *et al.*, 1997). Since the genetic diversity of populations evolves differently in situ and ex situ, the units conserved by these two strategies are not perfectly substitutable.

The basic economic problem for in situ conservation of cultivated plants is that crop genetic diversity on farms is an impure public good. Each choice of variety and management practices jointly produces a crop output with has private value to the farmer as well as a contribution to a public good, the genetic diversity of crop populations. Since farmers are not likely to be willing or able to consider the contributions of all other farmers to genetic diversity in their community or elsewhere, the theory of impure public goods implies that the farmers as a group will generate less genetic diversity than is socially optimal. While it is clear that public interventions are necessary to close the divergence between private and social optima, the magnitude of the divergence between them, and therefore the extent of public intervention as well as the appropriate form of the intervention, depends on the agroecology and economic system in which the farmer chooses varieties.[1]

*International Wheat and Maize Improvement Centre, Mexico, D.F. and International Plant Genetic Resources Institute, Rome, Italy.

This paper organizes evidence on the problem of in situ conservation for rice, wheat and maize around the decision-making criterion of the minimum viable reserve (Krutilla, 1967). Put simply, Krutilla argued that, while technological change can compensate for the depletion of some stocks, amenities that members of advanced economies (and developing societies) consume may be lost. Acknowledging that too little was known about the instrumental variables in this dynamic problem, he recommended the identification, based on scientific assessments, of a minimum reserve. He argued that these reservations should meet not only scientific purposes but also the demand for 'esoteric' or recreational consumer tastes, such as the enjoyment of the existence of a grand scenic wonder. Similarly, though modern biological techniques can in some instances modify the size of the crop genetic resource stock, proponents of in situ conservation of cultivated crops would argue that certain alleles may be lost as the spatial pattern of crop varieties grown by the world's farmers changes with economic development. Furthermore, some food-related amenities around which culture is now defined in local communities, as well as 'esoteric' (luxury) food attributes for which consumers in richer societies could eventually be willing to pay, may also disappear.

To implement this criterion even in simple terms, we need to be able to answer several questions. First is that of location. On the basis of past experience in breeding for crop improvement, theories of population genetics, ecosystems and geography, scientists have prior beliefs about the relative probabilities of finding rare alleles of a given crop species in different geographical areas. Though genetic analyses from samples drawn in the field are necessary to test and refine these hypotheses, these may be taken as the best available estimate of the relative ranking of expected, future, direct use benefits from on-farm conservation. Indirect future use benefits and existence values of crop infraspecific diversity are not likely to be great. Option values other than those subsumed in scientists' assessments of information value are not likely to be estimable (Brown, 1990).

Second is the question of size. Determining the minimum effective size of on farm crop genetic reserves involves some complex considerations since (a) isolating crop populations may destroy the very genetic structure that makes them potentially valuable (Louette, 1994; Henry *et al.*, 1991) and (b) identifying this underlying genetic structure and its evolutionary potential from the varieties named by farmers is a non-trivial scientific problem (Jarvis and Hodgkin, 1998; Brown, 1990; Brown, 2000). Most experts view farm conservation as a dynamic farmer-led process that cannot be constrained by artificially imposed boundaries.

A third issue concerns the nature of costs. Why should farmers choose to grow those varieties believed to be of great potential value to future crop improvement? While the costs of species preservation in protected reserves consists primarily of the opportunity costs of land use and enforcement, the cost of conserving crop genetic resources on farms is the opportunity cost to farmers who grow them – which varies according to their economic opportunities and shifts over time as economies change.

Briefly, least-cost conservation will occur in sites that are most highly ranked in terms of expected future benefits to producers and consumers and where, because farmers' private incentives for conservation are greatest, public interventions to encourage them to do so will be least. In these sites, private and social costs will be least.

The next section summarizes the evidence on the location and size of on-farm crop genetic reserves for the world's three major cereals, rice, wheat and maize. This section concludes that diversity in both systems of modern varieties and systems of mixed and/or landrace populations is relevant for the conservation of crop genetic diversity on farms and its utilization by society. Subsequent material presents hypotheses and evidence regarding the costs associated with maintaining diversity in these two systems.

EVIDENCE ON THE LOCATION AND SIZE OF RESERVES

Historical location of reserves

Our first candidates for reserves might be the areas where the crops were domesticated, based on popular notions of centres of origin and diversity (Kloppenburg and Kleinman, 1988). However, the idea that the world's most potentially valuable crop genetic resources are concentrated in delineable centres of crop origin and diversity is misleading. The latter are subjects of continuing scientific research rather than established facts. Vavilov's famous hypothesis (1926, 1951) was that the centres of origin of crop species are the areas that exhibit the greatest observed genetic variation. Harlan (1971, 1992) proposed instead that, although some crops exhibit centres of diversity, a number of ecological, natural or social factors may cause genetic variation to accumulate in secondary centres.

African rice (*Oryza glaberrima*) is one of the few examples of 'semi-endemic' variation, meaning that the crop originated in a definable centre (the upper Niger river, with two secondary centres to the southwest near the Guinean coast) with limited dispersal by humans (Harlan, 1992). Opinions remain divided (Oka, 1988; Vaughan and Chang, 1992) concerning the original point of domestication of Asian rice (*Oryza sativa*). Similarly, the origins of maize are 'diffuse' since the crop is believed to have been domesticated thousands of years ago in a limited geographical area of southern Mexico but to have changed radically as it dispersed across the continents of North and South America and throughout the Caribbean (Goodman, 1995). Wheat is an extreme example of 'diffuse' (Harlan, 1992) or 'confused' (Zohary, 1970) origins, and its centre of origin is disputed (Zohary, 1970; Zhukovsky, 1975; Harlan and Zohary, 1966; Harlan, 1971).

We might then propose areas where modern varieties are not grown, based on the assumption that they are narrower genetically than earlier plant types. Yet the timing and cause of genetic narrowing in the major cereal crops is also a matter of historical and scientific perspective (for examples, see Evenson and Gollin, 1997; Vaughan and Chang, 1992; Porceddu *et al.*, 1988; Hawkes,

1983). Modern cereal cultivars have developed through three main phases of selection: (a) subconscious selection by the earlier food growers in the process of harvesting and planting, (b) deliberate selection among variable materials by farmers living in settlements and communities, (c) purposeful selection by professional breeders using scientific methods. The last two phases are concurrent today.

The main attainment of the first phase was to make the crop more suitable for planting and harvest, threshing or shelling, and consumption. Higher germination rates, more uniform growing periods, resistance to shattering, and palatability were some of the products of this efforts. In the second phase, many farmers exerted (and continue to exert) pressure in numerous directions, resulting in variable populations adapted to local growing conditions and consumption preferences. These are broadly known as 'landraces'. During the third phase, fields of cereals have become more uniform in plant types with less spontaneous gene exchange and more planned gene migration through the worldwide exchange of germ plasm. The products of this third phase are loosely referred to as 'modern varieties'.

Wood and Cox (1999) have argued that, historically, bread wheat has always suffered from a precarious genetic base because it evolved through a natural genetic bottleneck: a rare spontaneous hybrid of emmer wheat with goatgrass. In plant breeding, the same scientific breakthrough that widens the gene pool at one point in time can lead to the widespread cultivation of a single, outstanding, variety. When many farmers choose to grow the variety, the germ plasm base of the materials grown in fields may narrow temporarily – until the next popular variety comes along. Hawkes (1983) cites the introduction of Rht1 and Rht2 genes into Western wheat breeding lines, which led to the development by Norman Borlaug of semi-dwarf wheat varieties, as an example of how diversity has been broadened by scientific breeders. These, and the rice varieties of the 'Green Revolution', have been cited elsewhere by scientists as the cause of genetic erosion.

The term 'genetic erosion' was used by Harlan (1972) to describe what he viewed as a potentially disastrous narrowing of the germ plasm base required for the improvement of food crops. Harlan was one of the first scientists to refer to the crop germ plasm base as economists refer to a natural 'resource'. Since major crop species of wheat, rice and maize are not likely to disappear in the foreseeable future, the term probably signifies a dramatic shift in population structure within a crop species that can result from a range of natural or human-led processes.

'Genetic erosion' has become synonymous with the displacement of landraces by modern varieties. Harlan asserted that the 'destruction of genetic resources is caused primarily by the very success of modern plant breeding programs' (1972, p.212). Frankel, also, was calling for urgent collection to forestall 'the loss of ancient patterns of diversity in the Vavilovian centres', since modern varieties contain 'a minimum of genetic variation' and 'in many instances ... have a narrow genetic base' (1970, p.11). We examine these hypotheses below.

Effective location and size of reserves

Have the world's rice, wheat and maize landraces been displaced by modern varieties? Recent estimates of the extent of the area planted to modern varieties and landraces are shown in Table 1. Based on CIMMYT data, roughly 80 per cent of the wheat area in the developing world was sown to semi-dwarf varieties in 1997, with the remainder split almost equally between improved tall varieties and landraces, or varieties with unknown ancestry (Heisey *et al.*, 1999). The relative importance of tall wheat varieties remains greater in the industrialized than in the developing countries, probably for reasons related to wheat growing environment and management practices.

IRRI estimates that about three-quarters of the rice area in Asia, which produces most of the world's rice, is sown to semi-dwarf varieties. These varieties dominate the irrigated rice ecosystems and cover large areas in the rainfed lowlands (M. Jackson and G. Khush, IRRI, personal communication). In sub-Saharan Africa, landraces are still planted to a greater proportion of rice area than modern varieties (T. Dalton, WARDA, personal communication; IRRI, 1995), while in Latin America they occupy a very small niche (L.R. Sanint, CIAT, personal communication). Figure 1 provides a depiction of the principal geographical locations of areas sown to rice and wheat landraces.

Data from maize surveys conducted by CIMMYT in 1992 and 1997 indicate that a much lower proportion of the maize area in the developing world is planted to modern types (see Table 1 and Figure 2). For sub-Saharan Africa and Latin America as a whole, roughly half of the maize area is planted to landraces, but they dominate in Mexico and Central America. At least some of the area listed under landraces is planted to populations that result from the genetic integration of modern varieties with landraces when farmers save seed or plant seed of different types in adjacent fields. Similarly, a substantial proportion of the maize area in sub-Saharan Africa is planted to advanced generations of improved varieties whose seed farmers could not afford to replace on a regular basis, introgressed with landrace populations brought to the continent with the slave trade several centuries ago. Though the proportion of area in maize landraces seems high in West Asia and North Africa, maize area in that region is limited and many of these materials are of unknown origin. In the industrialized world, only a trace of maize area is planted to either improved open-pollinated varieties or landraces.[2]

The data in Table 1, represented geographically in Figures 1 and 2, confirm that the effective 'size' of reserves for wheat and rice landraces is relatively small compared with the estimated share of maize area in landraces, though for maize this share includes advanced generations of modern types that visually resemble landraces. Even in regions of crop domestication, wheat landraces often persist 'as patches and islands of farming systems' (Brush, 1995, p.246) or 'micro-centres of diversity', '100 to 500km across' (Harlan, 1992, p.147). Oka (1988) has called the Jeypore Tract in India a micro-centre of diversity in Asian rice, and M. Jackson (IRRI) refers to some of the upland rice areas of Asia as 'pockets' of diversity.

TABLE 1 *Percentage distribution of rice, wheat and maize area by type of germ plasm in the 1990s*

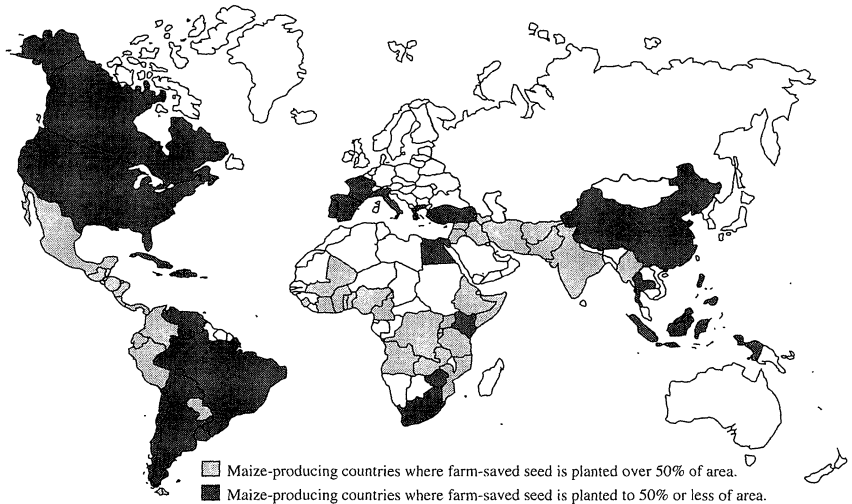| Region	Wheat			Maize			Rice		
	semi-dwarf improved	tall improved	landraces/ unknown	hybrid	improved open-pollinated	landraces/ unknown	semi-dwarf improved	other improved	landraces/ unknown
Sub-Saharan Africa*	66	14	20	38	8	54	25	15	60
West Asia/North Africa	66	10	24	22	7	71	11	—	—
Asia	86	7	6	70	7	23	73	13	14
Latin America	90	9	1	43	5	52	59	36	5
All developing countries	81	9	11	53	7	40	71		
Industrialized countries	55	45	(trace)	99	1	(trace)	78		

Note: *Figures for rice in sub-Saharan Africa are West Africa only.

Sources: IRRI World Rice Statistics (1995); CIMMYT Global Maize and Wheat Impacts Surveys (1992, 1997); Heisey *et al.* (1999), Morris and Heisey (1998); Morris and López-Pereira (1999); Luis Roberto Sanint, CIAT; Timothy Dalton, WARDA; Pardey *et al.* (1996); Cabanilla *et al.* (1999).

O Wheat
□ Rice

Source: Scientists at CIMMYT, IRRI, WARDA and CIAT.

FIGURE 1   *Pockets of wheat and rice landraces*

☐ Maize-producing countries where farm-saved seed is planted over 50% of area.
■ Maize-producing countries where farm-saved seed is planted to 50% or less of area.

Notes: Data not available for Eastern Europe and Former Soviet Union. Definitions: developing country maize producer = more than 0.1m. mt/yr; high-income maize producer = more that 1m. mt/yr. Farm-saved seed includes landraces, farmer-bred varieties and advanced generations of modern varieties.

Source: CIMMYT data files (M. Morris).

FIGURE 2   *Areas in farm-saved maize seed*

Systems of crop genetic variation

As predicted by Harlan and Frankel, modern varieties of the major cereal crops
have largely replaced 'the ancient patterns of diversity' in the fields of farmers.
Modern and traditional patterns of variation coexist, but on vastly different
scales.

    At least two aspects of these predictions are disputable. First, though it is
clear that the patterns of genetic variation in farmers' fields have changed over
time, the hypothesis that the spread of semi-dwarf varieties caused genetic
erosion cannot be tested because it 'goes beyond our knowledge of the facts of
genetic erosion' (Wood and Lenné, 1997; Smale, 1997). Second, evidence
from a number of studies does not support the pessimistic view that the genetic
base of modern varieties is restricted and tends to narrow (Witcombe, 1999).
For example, nearly 90 per cent of the modern varieties grown in 1997 (ex-
cluding those in China) are CIMMYT-related, meaning that they are CIMMYT
crosses or selections from CIMMYT crosses released as varieties, or they have
proximate or more distant CIMMYT ancestors in their pedigrees. CIMMYT-
relatedness does not imply uniformity, however, since these lines are a vast
array of germ plasm constituted by genetic recombination of different sources
of materials from throughout the wheat growing world. Genealogical analysis
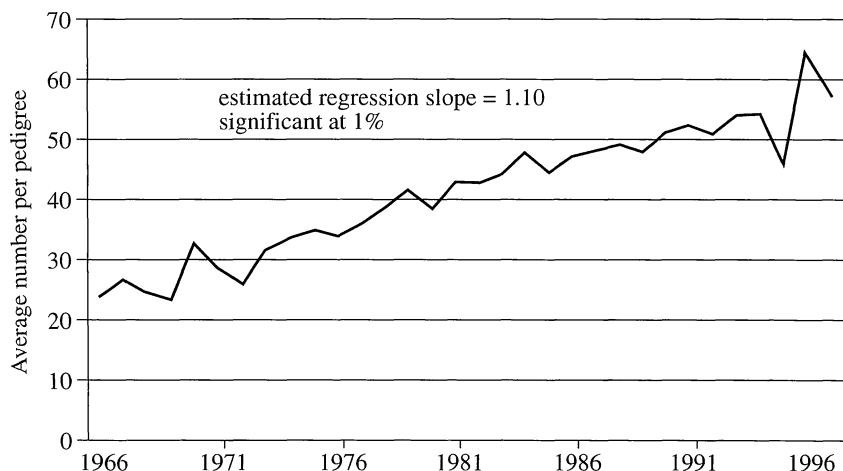
Notes: Calculations based on CIMMYT 1997 global wheat impacts survey data
            prepared by Heisey, Lantican and Dubin, and pedigree information in
            CIMMYT Wheat Pedigree Management System. Data were available for
            1162 (included here) of the 1749 spring bread wheats recorded (in the
            survey data) as released during these years. Coverage is less complete for
            China and for wheats released in the last few years.

FIGURE 3   *Landrace ancestors in spring bread wheats released by
developing countries, 1966–97*

shows (a) a significant positive trend in the number of distinct landrace ances-
tors in the pedigrees of over one thousand varieties of spring bread wheat
released by national agricultural research systems in the developing world
since 1966 (Figure 3) and (b) a significantly higher number of different landrace
ancestors among releases that are CIMMYT-related than those with no known
CIMMYT ancestry.

Numbers of landraces, in and of themselves, do not constitute diversity since
their genetic contribution is likely to be small. In modern breeding programmes,
landraces are typically distant ancestors. Rather, these numbers demonstrate
conclusively that germ plasm with different genetic backgrounds is continually
brought into the crossing blocks of CIMMYT and national programme col-
laborators through an international research system. Though the numbers are
smaller for rice than for wheat, Gollin and Evenson's findings (1998) demon-
strate a similar breadth of genetic backgrounds.

In addition, cumulated scientific evidence (summarized in Smale *et al.*,
2001) presents a strong case that, while the molecular genetic diversity and
genealogical diversity of CIMMYT wheats has been maintained or has in-
creased over the past 30 years, their performance with respect to yield stability,
nitrogen use efficiency, genetic resistance to disease and tolerance to heat and
drought has improved. The genetic diversity in CIMMYT lines represents a
lower bound on the diversity of the wheat germ plasm currently available in
national programmes since national breeders cross them with their own mate-
rial.

These statements in no way contradict the idea that society may be willing
to pay to conserve some of the remaining on-farm variability in landraces,
provided that these sources are assessed to be of value. Instead, I use them to
argue that both diversity in modern systems and diversity in landrace systems
matter for the future utilization of crop genetic resources by society. What are
the economic incentives for maintaining diversity in these two systems? The
next section presents hypotheses and references to case studies concerning the
private costs of diversity in (a) systems dominated by modern varieties today
(b) systems where both modern varieties and landraces, or landraces only, are
grown.

EVIDENCE ON THE COSTS OF CONSERVING CROP GENETIC DIVERSITY ON FARMS

Systems dominated by modern varieties

In systems of modern varieties the central economic questions involve the
direction of the relationships between genetic diversity and productivity, ge-
netic diversity and stability, and genetic diversity and economic efficiency. The
positive role that diversity in genetic mechanisms *within* a variety can play in
enhancing the longevity of its resistance to some biotic stresses is now fairly
well accepted (Vanderplank, 1963; Johnson, 1984). A relationship between
genetic uniformity in disease resistance *across* the varieties or crop populations

grown in a producing region and vulnerability to potentially costly yield losses has also been generally accepted. Genetic uniformity occurs in this sense when many varieties share the same source of resistance, meaning that resistance is conferred by the same gene or gene complexes.

Applied economists have also recently sought to estimate the impact of genetic diversity on productivity and economic efficiency in modern production systems. Gollin and Evenson (1998) have investigated the economic value of yield enhancement and of traits incorporated through the utilization of specific types of genetic resources in rice breeding, including specialized search materials and landraces from ex situ collections. Widawsky and Rozelle (1998), Smale *et al.* (1998) and Meng *et al.* (1998) related indices of diversity in modern wheat varieties to productivity and economic efficiency through estimating production functions, cost functions and total factor productivity. While the more recent research in China is promising, there is still a need to overcome methodological problems and expand research to other crops and areas of the world. Preliminary results from Pakistan, China and Australia (Smale *et al.*, 1998) confirm the dampening effects of older variety age on productivity, demonstrating beneficial effects of genealogical diversity on productivity and yield stability, and suggesting that marginal costs may be associated with greater evenness in the spatial distribution among modern wheat types.

Though an inverse relationship between genetic uniformity in crop populations and crop yield stability has been generally postulated, the assertion that the spread of modern varieties increases yield instability has not borne statistical scrutiny. In 1989, on the basis of a comprehensive review of the evidence, Hazell concluded that the overwhelming sources of rising production variability in cereals over the 1960–82 period were increases in yield variance and simultaneous loss of offsetting variations. Contemporaneous covariance in crop yields were more likely to have resulted from synchronization of water, fertilizer, and other purchased inputs over large areas, than from greater sensitivity of new seed types and genetic changes.

In Hazell's analysis, production variability did not increase for all crops – in particular, it declined for wheat during the years of the Green Revolution. Later analyses conducted by either agronomists or economists confirmed this result for subsequent decades and different geographical scales (Pfeiffer and Braun, 1989; Sayre *et al.*, 1997; Singh and Byerlee, 1990; Smale *et al.*, 1998). Nor did crop yield instability appear to increase with the diffusion of modern varieties in the cradle areas of crop domestication and genetic diversity for rice and wheat (Brush, 1992) or for rice in Bangladesh (Alauddin and Tisdell, 1988).

Mixed and landrace systems

In mixed and landrace systems the essential question involves the costs to farmers from development opportunities forgone. The assumption has been made that modern varieties will inevitably replace traditional varieties. Brush (1995) and others have argued that the persistent cultivation of landraces in centres of crop origin and diversity such as Turkey for wheat and Mexico for

maize, termed de facto conservation, attests to their continued private value to farmers or their competitive advantage relative to modern alternatives (Brush and Meng, 1998; Perales *et al.*, 1998).

To what extent do farmers forgo development opportunities when they grow landraces? The three factors hypothesized to determine the likelihood that farmers in a region will choose to cultivate landraces are population density, agroecology and commercialization. *The ratio of labour to land* explains much about where the transition from low-yield, land-extensive cultivation to land-intensive, double and triple crop systems has occurred (Boserup, 1965; Hayami and Ruttan, 1985; Pingali and Binswanger, 1987). The genetic changes embodied in seed constitute one type of intensification, which refers more broadly to the increase in output per unit of land used in production. Seed genetic change can lead to change in land productivity (yield) both directly and indirectly, in combination with other inputs. Predictably, the adoption of modern rice and wheat varieties in the developing world has been most complete in densely populated areas of their cultivation where traditional mechanisms for enhancing yields per unit area have been exhausted.

Intensification occurs in the less densely populated areas provided that soil conditions are suitable and markets are accessible, when (a) higher prices and elastic demand for output imply that the marginal utility of effort increases and/or (b) higher returns to labour encourage migration into well connected areas from neighbouring regions with higher transport costs (Pingali, 1997).[3]

Labour to land ratios interact with *agroecology* in predicting adoption of modern varieties. Since the initial adoption and rapid diffusion of the first semi-dwarf varieties in the high-potential, irrigated areas of the 1970s, more widely adapted descendants of these varieties have spread gradually into less favourable environments, including rainfed areas with relatively modest production potential. Today, the adoption of modern varieties of rice is virtually complete in irrigated areas and uneven in rainfed zones, while they are largely absent in the uplands and deepwater areas. Wheat landraces are cultivated extensively only in portions of the drier production zones of the West Asia–North Africa region and highlands of Ethiopia.

Maize is grown over a greater range of latitudes, altitudes, temperatures and moisture regimes than rice or wheat and, of the three crops, still has the greatest proportion of area planted to landraces. For many of these environments, suitable improved materials have not been developed by centralized breeding programmes (Byerlee, 1996; Perales *et al.*, 1998). The maize germ plasm that performs well in temperate climates of industrialized countries cannot be introduced directly into the non-temperate regions of developing countries without considerable additional breeding for adaptation (Morris, 1998). Nor are there economic incentives for a commercial seed industry since, even if adaptation problems could be overcome through breeding, farmer demand for improved seed may be small (ibid.). In maize, agroecology interacts with the development of commercial seed systems in determining where modern varieties will be grown.

Economic growth, urbanization and the withdrawal of labour from the agricultural sector lead to the *increasing commercialization of agricultural systems*

(Pingali, 1997). Agricultural commercialization implies that (a) production and consumption decisions of farm households are separated and mediated across markets, and (b) product choice and input use decisions are based on the principles of profit maximization. Farmers trade the output of specialized enterprises produced with purchased inputs for the attributes they demand on markets where transactions are impersonal. Agricultural production as a whole is reorganized from many units, each of which produces a similar set of crops and livestock products, into fewer, specialized units, each of which produces a single crop or livestock product. The opportunity costs of producing staple food, even in intensive systems, will rise with competing demands for farmers' time.

As the orientation of crop production shifts from subsistence towards commercial objectives, the locus of crop improvement and seed distribution moves from individual farmers towards an organized seed industry composed of specialized private and public organizations (Morris, 1998). Maize has moved substantially faster than rice and wheat in terms of increased reliance on commercially produced seed. In a stylized depiction of the maize seed industries in developing countries, subsistence production is characterized by open-pollinated varieties improved through farmer selection and on-farm seed production with local seed markets governed by custom. In a fully commercial system, the predominant seed type is a hybrid that is purchased annually. Seed is a globally traded product of specialized research that is both privately and publicly funded. The exchange of seed and the genetic resources used to improve it are enabled and protected by strict forms of intellectual property rights (Morris *et al.*, 1998).

In rice and wheat, which are self-pollinating crops, the incentives for privatization of research have not been as strong as for maize, although this depends on the institutional and economic context. In the industrialized countries, profound changes in science and in intellectual property protection over the past 20–30 years have been associated with a higher rate of investment in agriculture by the private sector than by the public sector and a shift in the composition of private investment from agricultural machinery and processing into chemical research and plant breeding (Alston *et al.*, 1998; Fuglie *et al.*, 1996). Privatization is greatest in the maize seed industry in developed countries and is increasing in the developing world, but has only occurred to a limited extent for wheat – in Europe. Almost all of the seed research for rice has been and continues to be conducted by the public sector, and most research has occurred in Asia (Pray, 1998).

Predictions

We can employ the three axes specified above to predict probabilities of landrace survival. Since rice and wheat are self-pollinated crops whose seed can be passed from farmer to farmer, the popularity of their modern varieties has depended more on agroecological factors and land to labour ratios than on commercialization. The high propensity of maize plants to cross-pollinate makes it difficult for farmers to maintain the genetic purity of maize seed

saved from their own harvest. Maize growers who seek to commercialize their production are therefore dependent on reliable external sources of affordable seed in a way that growers of self-pollinated rice and wheat are not (Morris, 1998). It also explains the historical importance of hybrids, which are a self-enforcing form of intellectual property that generates strong incentives for privatization. Commercialization and the structure of the private seed industry will remain important for predicting where maize landraces will be grown.

We can also predict that, in the high-potential environments where commercialization occurs, landraces will be grown only when unique end-use characteristics for which specialized markets exist cannot be transferred efficiently through advanced breeding techniques (biotechnology) to modern types. In the worst growing environments, crop production may be abandoned entirely, as has already occurred in parts of Asia (Pingali, 1997). When there are limited opportunities for migration in these environments, farmers may remain on small landholdings growing landraces for subsistence.

Between these two extremes, the prospects for landrace cultivation are more interesting. In some of the more difficult growing environments for maize, landraces and rusticated modern types may remain the choice of farmers for some time, since germ plasm that better meets their needs may not be available. Even when an agroecological zone is suitable for the production of modern varieties, the development of commercial seed systems is not sufficient to ensure that modern types will replace landraces because of market imperfections (de Janvry *et al.*, 1991). Case studies demonstrate that, in many of the regions of the developing world where landraces are still grown, either markets for commercially produced seed or markets for the attributes demanded by farmers are incomplete (Brush and Meng, 1998; Brush *et al.*, 1992; Smale *et al.*, 2001). In some local communities, the traits demanded by farmers (grain quality, fodder, suitability for a certain soil type) cannot be obtained through the production of modern varieties or procured through impersonal market transactions, so that farmers must rely on their own or neighbours' production for their supply (Renkow and Traxler, 1994; Bellon and Taylor, 1993). The specialized uses of certain landrace varieties for medicinal purposes, rituals and festivals have been extensively documented by ethnobotanists and anthropologists.

Farmers often choose to grow both landraces and modern varieties. Small-scale farmers' choice to grow more than one variety simultaneously is likely to reflect their need to address numerous concerns that no single variety can satisfy (Bellon, 1996). Viewed in the conventional microeconomic literature as partial adoption, this observed pattern has been explained theoretically through attitudes towards risk and uncertainty, missing markets and differential soil quality or nutrient response combined with fixity or rationing (reviewed in Meng, 1997; Smale *et al.*, 1994).

Though treated as a transitional period to full adoption, the coexistence of modern varieties and landraces may represent an equilibrium if one or several of these aspects persist despite economic change. Zimmerer (1999) found that the capacity of farmers to grow diverse food plants (including maize) in Peru and Bolivia depends on whether they can cultivate them in combination with commercially developed, high-yielding varieties. Meng *et al.* (1998) concluded

that multiple factors, including missing markets, yield risk, grain quality and agroclimatic constraints influence the probability that a Turkish household will grow a wheat landrace; a change in any single economic factor is unlikely to cause farmers to cease growing it.

Even when the pressures for commercialization are strong, the coexistence of modern varieties and landraces may persist with certain types of market-based incentives. The post-industrial agricultural economy is characterized by growth in demand for an array of increasingly specialized goods and services (Antle, 1999). Though the income elasticity of demand for staple grains may be low or even negative (Huang *et al.*, 1991), the income elasticity of demand for attributes of the grains is higher (Ben Senauer, personal communication; Pingali *et al.*, 1997). For example, high-income consumers spend more on rice by paying higher prices for varieties with preferred eating quality which they substitute for the lower-quality variety consumed when the income level was lower (Unnevehr *et al.*, 1992). In Asia, traditional varieties are generally of higher quality and fetch premium prices in the market (Pingali *et al.*, 1997). Thailand still grows low-yielding traditional rainfed varieties extensively for the export market. In South Korea, the modern 'tongil' variety was replaced by relatively low-yielding, traditional *japonica* rice as consumers expressed preference for *japonicas* by offering higher prices as incomes rose. Higher prices more than compensated for lower yields. As rice scientists have had limited success in developing high-yielding cultivars with better eating quality, the price difference between the standard and high-quality varieties has been growing in Asian markets.[4]

CONCLUSIONS

Crop genetic diversity is an impure public good, and as long as it is 'good', theory predicts that farmers will maintain a level of diversity in their fields that is lower than is socially optimal. There are intergenerational and political dilemmas associated with making decisions about whether or not to conserve it, and by how much. Estimating the quantitative value of the difference between the optima requires positing a social welfare function and private objective functions, imposing a rule of aggregation and assigning dollar values to abstract notions of benefits other than direct, current use value. Here, the discussion of this decision has been organized around a more intuitive criterion of least cost, minimum viable reserve.

Identifying the viable reserve relies to a large extent on the state of scientific knowledge concerning the location of on-farm genetic resources with the greatest expected use value to future producers and consumers, and the required size to allow for crop evolution. Depending on popular notions of centres of origin and diversity to locate reserves may be misguided. Nor is the belief that modern varieties categorically have a narrower genetic base than their predecessors entirely accurate or useful. Decisions over location and size in the three major cereal crops are limited by the fact that modern varieties now dominate global area. I have argued that conserving crop genetic diversity

on farms involves both systems of modern varieties and systems dominated by landraces.

In modern systems, the major economic issue is the effect of genetic diversity on productivity, stability and economic efficiency. The evidence about productivity and efficiency in modern systems is as yet inconclusive; the hypothesis that the genetic structure of modern wheat and rice varieties has increased variability in crop output has been rejected.

In mixed and landrace systems, the economic question is the cost of growing landraces in terms of development opportunities forgone. Heuristically, three axes determine the probability that landraces will continue to be grown: population densities, the production potential of an area and commercialization. Predicted probabilities of landrace survival differ for rice, wheat and maize because of their biological properties. The propensity for maize to cross-pollinate and its capacity to withstand greater ranges in growing environment are of key importance.

The lower the predicted probability of landrace survival, the higher farmers' opportunity costs. As long as farmers find it in their own best interests to grow and manage these genetic resources, because of either market imperfections or market-based incentives, the public expense of mounting programmes to encourage them to do so is minimal since what is best for farmers and best for society at large, or the economic optima from both private and social standpoints, converges. Combining scientifically based assessments of location and size with economic analyses of costs can provide candidates for least-cost, minimum viable reserves of on-farm crop genetic diversity.

NOTES

[1]This divergence has both intergenerational and political aspects. The intergenerational aspect is that farmers today (and ironically some of the world's poorest) are asked to consider the needs of future generations in their decisions. The political aspect is that those who are encouraging them to do so for conservation purposes reside largely in other jurisdictions.

[2]These are speciality maizes or 'heirloom' varieties grown for fresh consumption, popcorns, or ornamental corns such as those marketed on holidays in the USA (M. Morris, personal communication).

[3]Examples of regions with low population density but intensive, market-oriented production are the central plains of Thailand and parts of Latin America's Southern Cone.

[4]The importance of Basmati rice in the irrigated production zones of India and Pakistan is another example of the way in which market demand for quality can influence the survival of traditional varieties and landraces even in the most favoured growing environments with dense populations.

BIBLIOGRAPHY

Alauddin, M. and Tisdell, C. (1988), 'Impact of new agricultural technology on the instability of foodgrain production and yield: data analysis for Bangladesh and its districts', *Journal of Development Economics*, **29**, 199–277.

Alston, J.M., Pardey, P.G. and Smith, V.H. (1998), 'Financing agricultural R&D in rich countries', *The Australian Journal of Agricultural and Resource Economics*, **42**, 51–82.

Antle, J.M. (1999), 'The new economics of agriculture' (Presidential Address), *American Journal of Agricultural Economics*, **81**, 993–1010.

Bellon, M.R. (1996), 'The dynamics of crop infra-specific diversity: A conceptual framework at the farmer level', *Economic Botany*, **50**, 26–39.

Bellon, M.R. and Taylor, J.E. (1993). '"Folk" soil taxonomy and the partial adoption of new seed varieties', *Economic Development and Cultural Change*, **41**, 763–86.

Bellon, M.R., Pham, J.-L. and Jackson, M.T. (1997), 'Genetic conservation: a role for rice farmers', in N. Maxted, B.V. Ford-Lloyd and J.G. Hawkes (eds), *Plant Genetic Conservation: The* In-Situ *Approach*, London: Chapman & Hall.

Boserup, E. (1965), *Conditions of Agricultural Growth*, Chicago: Aldine Publishing Company.

Brown, A.H.D. (2000), 'The genetic structure of crop "landraces" an*'* the challenge to conserve them in situ on farms', in S.B. Brush (ed.), *Genes in the Field: On Farm Conservation of Crop Diversity*, Ottawa: IPGRI, IDRC, Lewis Publishers.

Brown, G.M. (1990), 'Valuation of genetic resources', in G.H. Orians, G.M. Brown, Jr, W.E. Kunin and J.E. Swierbinski (eds), *The Preservation and Valuation of Biological Resources*, Seattle: University of Washington Press.

Brush, S.B. (1992), 'Reconsidering the green revolution: Diversity and stability in cradle areas of crop domestication', *Human Ecology*, **20**, 145–67.

Brush, S.B. (1995), '*In situ* conservation of landraces in centers of crop diversity', *Crop Science*, **35**, 346–54.

Brush, S.B. and Meng, E. (1998), 'Farmers' valuation and conservation of crop genetic resources', *Genetic Resources and Crop Evolution*, **45**, 139–50.

Brush, S.B., Taylor, J.E. and Bellon M.R. (1992), 'Biological diversity and technology adoption in Andean potato agriculture', *Journal of Development Economics*, **38**, 365–87.

Byerlee, D. (1996), 'Modern varieties, productivity, and sustainability: recent experience and emerging challenges', *World Development*, **24**, 697–718.

Cabanilla, V.L., Hossain, M. and Khush, G.S. (1999), 'Diffusion of breeding materials and genetic composition of improved rice in South and Southeast Asia 1965–98', paper presented at the IAEG Germplasm Research Impact Study Workshop in Nashville, Tennessee, 7–8 August.

Cox, T.S., Murphy, J.P. and Goodman, M.M. (1988), 'The contribution of exotic germplasm to American agriculture', in J.R. Kloppenburg, Jr (ed.), *Seeds and Sovereignty*, Durham, NC and London: Duke University Press.

de Janvry, A., Fafchamps, M. and Sadoulet, E. (1991), 'Peasant Household Behaviour with Missing Markets: Some Paradoxes Explained', *Economic Journal*, **101**, 1400–1417.

Evenson, R.E. and Gollin, D. (1997), 'Genetic resources, international organizations, and improvement in rice varieties', *Economic Development and Cultural Change*, **45**, 471–500.

Evenson, R.E., Gollin, D. and Santaniello, V. (eds) (1998), *Agricultural Values of Plant Genetic Resources*, Wallingford: CABI, FAO and Centre for International Studies on Economic Growth, Tor Vergata University, Rome.

Frankel, O.H. (1970) 'Genetic dangers of the Green Revolution', *World Agriculture*, **19**, 9–14.

Fuglie, K., Ballenger, N., Day, K., Klotz, C., Ollinger, M., Reilly, J., Vasavada, U. and Yee, J. (1996), *Agricultural Research and Development: Public and Private Investments Under Alternative Markets and Institutions*, Washington, DC:U.S. Department of Agriculture, Economic Research Service, AER no. 735.

Gollin, D. and Evenson, R.E. (1998), 'Breeding values of rice genetic resources', in R.E. Evenson, D. Gollin and V. Santaniello (eds), *Agricultural Values of Plant Genetic Resources*, Wallingford: CABI, FAO and Centre for International Studies on Economic Growth, Tor Vergata University, Rome.

Goodman, M.M. (1995), 'Maize', in J. Smartt and N.W. Simmonds (eds), *The Evolution of Crop Plants*, New York: Wiley.

Harlan, J.R. (1971), 'Agricultural origins: centers and noncenters', *Science*, **174**, 468–73.

Harlan, J.R. (1972), 'Genetics of disaster', *Journal of Environmental Quality*, **1**, 212–15.

Harlan, J.R. (1992), *Crops and Man*, Madison, WI: American Society of Agronomy, Inc. and Crop Science Society of America, Inc.

Harlan, J.R. and Zohary, D. (1966), 'Distribution of wild wheat and barley', *Science*, **153**, 1074–80.

Hawkes, J.G. (1983), *The Diversity of Crop Plants*, Cambridge, MA: Harvard University Press.

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

Hazell, P.B.R. (1989), 'Changing patterns of variability in world cereal production', in J.R. Anderson and P.B.R. Hazell (eds), *Variability in Grain Yields*, Washington, DC: Johns Hopkins University and the International Food Policy Research Institute.

Heisey, P.W., Lantican, M.A. and Dubin, H.J. (1999), 'An overview of the global wheat impacts study', in CIMMYT (ed.), *1998–9 World Wheat Facts and Trends*, Mexico, DF: CIMMYT.

Henry, J.P., Pontis, C., David, J. and Gouyon, P.H. (1991), 'An experiment on dynamic conservation of genetic resources with metapopulations', in A. Seitz and V. Loeschcke (eds), *Species Conservation: A Population-Biological Approach*, Basle: Birkhauser Verlag.

Huang, J., David, C.C. and Duff, B. (1991), 'Rice in Asia: Is it becoming an inferior good? Comment', *American Journal of Agricultural Economics*, **73**, 515–21.

Jarvis, D.I. and Hodgkin, T. (eds) (1998), *Strengthening the scientific basis of in situ conservation of agricultural biodiversity on-farm. Options for data collecting and analysis*, Rome: International Plant Genetic Resources Institute.

Johnson, R. (1984), 'A critical analysis of durable resistance', *Annual Review of Phytopathology*, **22**, 309–30.

Kloppenburg, J. and Kleinman, D.L. (1988), 'Seeds of controversy: National property versus common heritage', in J.R. Kloppenburg (ed.), *Seeds and Sovereignty: The Use and Control of Plant Genetic Resources*, Durham, NC: Duke University Press.

Krutilla, J.V. (1967), 'Conservation reconsidered', *American Economic Review*, **57**, 777–86.

Louette, D. (1994), 'Gestion traditionnelle de variétés de maïs dans la réserve de la Biosphère Sierra de Manantlán (RBSM, états de Jalisco et Colima, Mexique) et conservation in situ des ressources génétiques de plantes cultivées', PhD thesis, Ecole Nationale Supérieure Agronomique de Montpellier, France.

Maxted, N., Ford-Lloyd, B.V. and Hawkes, J.G. (eds) (1997), *Plant Genetic Conservation: The In-Situ Approach*, London: Chapman & Hall.

Meng, E.C.H. (1997), 'Land allocation decisions and in situ conservation of crop genetic resources: The case of wheat landraces in Turkey', PhD thesis, University of California, Davis.

Meng, E.C.H, Taylor, J.E. and Brush, S.B. (1998), 'Implications for the conservation of wheat landraces in Turkey from a household model of varietal choice', in M. Smale (ed.), *Farmers, Gene Banks and Crop Breeding: Economic Analyses of Diversity in Wheat, Maize and Rice*, Boston: Kluwer Academic Press and CIMMYT.

Meng, E.C.H., Smale, M., Rozelle, S., Ruifa, H. and Huang, J. (1999), 'The cost of wheat diversity in China', paper presented at the 1999 Meetings of the American Agricultural Economics Association, Nashville, Tennessee.

Morris, M.L. (ed.) (1998), *Maize Seed Industries in Developing Countries*, Boulder: Lynne Rienner and CIMMYT.

Morris, M.L. and Heisey, P.W. (1998), 'Achieving desirable levels of crop diversity in farmers' fields: Factors affecting the production and use of commercial seed', in M. Smale (ed.), *Farmers, Gene Banks and Crop Breeding: Economic Analyses of Diversity in Wheat, Maize and Rice*, Boston: Kluwer Academic Press and CIMMYT.

Morris, M.L. and López-Pereira, M.P. (1999), *Impacts of maize breeding research in Latin America, 1966–67*, Mexico, DF: CIMMYT.

Morris, M.L., Rusike, J. and Smale, M. (1998), 'Maize seed industries: a conceptual framework', in M. Morris (ed.), *Maize Seed Industries in Developing Countries*, Boulder: Lynne Rienner and CIMMYT.

Oka, H.I. (1988), *Origin of Cultivated Rice*, Tokyo: Japan Scientific Societies Press and Elsevier.

Pardey, P.G., Alston, J.M., Christian, LE. and Fan, S. (1996), *Summary of Productive Partnership: The Benefits of U.S. Participation in CGIAR*, EPDT Discussion Paper no. 18, Washington, DC: International Food Policy Research Institute and University of California, Davis.

Perales R.H., Brush, S.B. and Qualset, C.O. (1998), 'Agronomic and economic competitiveness of maize landraces and *in situ* conservation in Mexico', in M. Smale (ed.), *Farmers, Gene Banks and Crop Breeding: Economic Analyses of Diversity in Wheat, Maize and Rice*, Boston: Kluwer Academic Press and CIMMYT.

Pfeiffer, W.H. and Braun, H.J. (1989), 'Yield stability in bread wheat', in J.R. Anderson and

P.B.R. Hazell (eds), *Variability in Grain Yields*, Washington, DC: Johns Hopkins University and the International Food Policy Research Institute.

Pingali, P. (1997), 'From subsistence to commercial production systems', *American Journal of Agricultural Economics*, **79**,628–34.

Pingali, P.L. and Binswanger, H.P. (1987), 'Population density and agricultural intensification: a study of the evolution of technologies in tropical agriculture', in D.G. Johnson and R.D. Lee (eds), *Population Growth and Economic Development – Issues and Evidence*, Oxford: Clarendon Press.

Pingali, P., Bigot, Y. and Binswanger, H.P. (1987), *Agricultural Mechanization and the Evolution of Farming Systems in sub-Saharan Agriculture*, Baltimore, MD: Johns Hopkins University Press.

Pingali, P., Hossain, M. and Gerpacio, R.V. (1997), 'Asian Rice Market: Demand and Supply Prospects', in P. Pingali, M. Hossain and R.V. Gerpacio, *Asian Rice Bowls: the Returning Crisis?*, Wallingford: CABI and IRRI.

Porceddu, E., Ceoloni, C., Lafiandra, D., Tanzarella, O.A. and Scarascia Mugnozza, G.T. (1988), 'Genetic resources and plant breeding : Problems and prospects', Institute of Plant Science Research, *The Plant Breeding International Cambridge Special Lecture*, Cambridge, UK: Institute of Plant Science Research.

Pray, C.E. (1998), 'Impact of biotechnology on the demand for rice biodiversity', in R.E. Evenson, D. Gollin, and V. Santaniello (eds), *Agricultural Values of Plant Genetic Resources*, Wallingford: CABI, FAO and Centre for International Studies on Economic Growth, Tor Vergata University, Rome.

Renkow, M. and Traxler, G. (1994), 'Incomplete Adoption of Modern Cereal Varieties: The Role of Grain-Fodder Tradeoffs', selected paper presented at the annual meeting of the American Agricultural Economics Association, San Diego, 7–10 August.

Rozelle, S., Jin, E., Meng, E.C.H., Hu, R. and Huang, J. (2000), *Genetic diversity and total factor productivity: The case of wheat in China*, Economics Working Paper, Mexico, DF: CIMMYT.

Sayre, K.D., Rajaram, S. and Fischer, R.A. (1997), 'Yield potential progress in short bread wheats in northwest Mexico', *Crop Science*, **37**, 36–42.

Singh, A.J. and Byerlee, D. (1990), 'Relative variability in wheat yields across countries and over time', *Journal of Agricultural Economics*, **41**, 21–32.

Smale, M. (1997), 'The green revolution and wheat genetic diversity: some unfounded assumptions', *World Development*, **25**, 1257–69.

Smale, M. (1998), 'Indicators of variety diversity in bread wheat grown in developing countries', in R.E. Evenson, D. Gollin and V. Santaniello (eds), *Agricultural Values of Plant Genetic Resources*, Wallingford: CABI, FAO and Centre for International Studies on Economic Growth, Tor Vergata University, Rome.

Smale, M., Bellon, M. and Aguirre, A. (2001), 'Maize Diversity, Variety Attributes and Farmers' Choices in Southeastern Guanajuato, Mexico', *Economic Development and Cultural Change*, forthcoming.

Smale, M., Just, R.E. and Leathers, H.D. (1994), 'Land Allocation in HYV Adoption Models: An Investigation of Alternative Explanations', *American Journal of Agricultural Economics*, **76**, 535–46.

Smale, M., Hartell, J., Heisey, P.W. and Senauer, B. (1998), 'The contribution of genetic resources and diversity to wheat production in the Punjab of Pakistan', *American Journal of Agricultural Economics*, **80**, 482–93.

Traxler, G. and Byerlee, D. (1993), 'A joint-product analysis of the evolution and adoption of modern cereal varieties in developing countries', *American Journal of Agricultural Economics*, **75**, 981–9.

Unnevehr, L., Duff, B. and Juliano, B.O. (1992), *Consumer Demand for Rice Grain Quality*, Terminal Report of IDRC Projects, National Grain Quality (Asia) and International Grain Quality Economics (Asia), Ottowa: IDRC and Los Banos, Laguna, Philippines: IRRI.

Vanderplank, J.E. (1963), *Plant Diseases: Epidemics and Control*, New York: Academic Press.

Vaughan, D. and Chang, T.T. (1992), '*In situ* conservation of rice genetic resources', *Economic Botany*, **46**,369–83.

Vavilov, N.I. (1926), 'Centers of origin of cultivated plants', *Works of Applied Botany and Plant Breeding*, **16**, (2) (Leningrad).

Vavilov, N.I. (1951), 'The origin, variation, immunity and breeding of cultivated plants', *Chronica Botanica*, **13**, 139–248.

Widawsky, D. and Rozelle, S. (1998), 'Varietal diversity and yield variability in Chinese rice production', in M. Smale (ed.), *Farmers, Gene Banks and Crop Breeding: Economic Analyses of Diversity in Wheat, Maize and Rice*, Boston: Kluwer Academic Press and CIMMYT.

Witcombe, J.R. (1999), 'Does plant breeding lead to a loss of genetic diversity?', in D. Wood and J. Lenné (eds), *Agrobiodiversity: Characterization, Utilization and Measurement*, Wallingford: CAB International.

Wood, D. and Cox, T.S. (1999), 'The nature and role of crop biodiversity', in D. Wood and J. Lenné (eds), *Agrobiodiversity: Characterization, Utilization and Measurement*, Wallingford: CAB International.

Wood, D. and J. Lenné (1997), 'The conservation of agrobiodiversity on-farm: questioning the emerging paradigm', *Biodiversity and Conservation*, **6**, 109–29.

Zhukovsky, P.M. (1975), *World Gene Pool of Plants for Breeding: Mega-gene-centres and micro-gene-centres*, Leningrad: USSR Academy of Sciences.

Zimmerer, K.S. (1999), 'Overlapping patchworks of mountain agriculture in Peru and Bolivia: Toward a Regional–Global Landscape Model', *Human Ecology*, **27**, 135–65.

Zimmerer, K.S. (1996), *Changing Fortunes: Biodiversity and Peasant Livelihood in the Peruvian Andes*, Berkeley: University of California Press.

Zohary, D. (1970), 'Centres of diversity and centres of origin', in O.H. Frankel and E. Bennett (eds), *Genetic Resources in Plants: Their Exploration and Conservation*, Oxford: Blackwell.