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Working Paper 97-01

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Contents

Tables

Page

Figures

Page

Abstract

This study makes use of data on wheat production in the Punjab of Pakistan from 1979 to 1985 to 1) examine patterns of varietal diversity in farmers' fields both at the regional and district levels and 2) identify how and in what ways genetic resources have contributed to wheat productivity and yield stability — important considerations to farmers and national authorities where wheat is a staple food crop. Five indicators are used to describe the system of wheat genetic resource use and diversity in farmers' fields. The contribution of farmers' previous selections is expressed as the number of different landraces appearing in the pedigree of a cultivar . The contribution of scientific breeding efforts is expressed as the number of parental combination appearing in a cultivar's pedigree. The diversity of wheat varieties in a geographical area, as related to productivity, is captured by measures of area concentration (diversity in space) and age of varieties (diversity in time). Finally, the relative dissimilarity of cultivars grown in a geographical area is measured using a distance indicator constructed from genealogical information. Disaggregated analysis at the district level demonstrates how diversity patterns are influenced by the production environment and by possible differences in the availability of suitable varieties.

The study finds no indication that modern plant breeding technologies have reduced diversity among the wheats grown in the districts of the Punjab of Pakistan during the study period, although brief. Analysis of the genealogical background of the varieties grown by farmers reveals patterns of greater use of genetic resources and dissimilarity of parentage. For some factors related to genetic resource use and diversity, there are large differences between production environments (specifically, irrigated and rainfed areas) and individual districts, which suggest that efforts to increase genetic diversity in farmers' fields will require policy instruments tailored to the individual circumstances of each production environment. Econometric results suggest that greater genealogical dissimilarity and higher rates of varietal replacement are likely to have positive payoffs relative to aggregate yield stability, while in areas where production constraints inhibit farmers' ability to exploit the yield potential of their varieties, better production management is likely to have greater yield enhancing effects than the varietal attributes related to diversity.

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The Contribution of Genetic Resources and Diversity to Wheat Productivity: A Case from the Punjab of Pakistan

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Introduction

The ability to meet the world's growing food demand improved dramatically with the release of modern semidwarf or "Green Revolution" wheat varieties in the early 1960s.[1] However, despite the improved yield potential, yield stability, maintenance of disease resistance, and other characteristics possessed by those varieties and subsequent releases, the Green Revolution has provoked criticism and debate. A major issue in this debate is how scientific plant breeding technology has affected the biodiversity of food grains, which is thought to have important implications for global and national food security and producer welfare.

The concern for biodiversity in food crops is an extension of the general recognition that much of the earth's natural diversity in flora and fauna is eroding at an alarming rate (Zohrabian 1995). Diversity, broadly considered in the biological sense, refers to the number of different species or the collective dissimilarity of species. Within a single crop species, diversity refers to the genetic variation that results in differing expressions of traits among individuals. This variation, in turn, is the basis of plant breeding and selection programs (National Research Council 1993).

Lack of diversity can potentially limit the ability of natural systems, or scientists who work with systems or species, to respond to unknown or evolving pests, pathogens, or environmental conditions. In the case of wheat rusts, for example, widespread cultivation of varieties with a similar genetic basis of resistance increases the risk of pathogen mutation and the spread of disease once the mutation occurs. It is suggested that agricultural production systems may be similarly vulnerable based on the assumption that modern breeding programs utilize a narrow range of genetic material, that different varieties are in fact closely related, and that genetic uniformity in breeding and production is increasing (see, for example, Frankel 1970 and chapters in Cooper, Vellvé, and Hobbelink 1992; see also National Research Council 1993).

[1] By "Green Revolution" in wheat we refer specifically to the development and diffusion of semidwarf wheat varieties in the developing world, which began in South Asia during the 1960s. These semidwarf varieties contain the *Rht*1 and *Rht*2 genes, individually or in combination. *Rht*1 and *Rht*2 (two of the numerous dwarfing genes that have been found in wheat) confer a positive interaction between a wheat genotype and its environment, by which yield increases prove greater given a favorable combination of soil moisture, soil fertility, and weed control. The genes were initially introduced into Japanese breeders' materials through Daruma, believed to be a Korean landrace (Dalrymple 1986). A cross descended from Daruma, Norin 10, was introduced into a US breeding program at Washington State University in 1949, and the dwarf characteristic from Norin 10 was successfully incorporated into the first Green Revolution wheats by N. Borlaug in Mexico. The semidwarf wheats currently developed by CIMMYT and many national breeding programs in developing countries are descendants of the first Green Revolution wheats, but their pedigrees also contain many distinctive ancestors and landraces from other sources.

A frustration in the diversity debate is that measures of genetic diversity within a species frequently differ within and among disciplines. First, measurement difficulties arise from the simple fact that not everything is known about the relationship between DNA sequences, genotypes, environment, and plant expression. Whether a given indicator is appropriate also depends upon the perspective or focus of the research. Furthermore, confusion arises from the use of similar terms to describe very different ideas. In the following sections, we attempt to clearly mark the boundaries of examination and to develop a set of diversity indicators that are both measurable and meaningful for this study of wheat productivity across the Punjab of Pakistan between 1979 and 1985.

In an attempt to enlighten the debate and provide guidance to those who formulate policy and allocate research funds, we pursue two tracks of inquiry. The first is an examination of the patterns of varietal diversity in wheat as they occur in farmers' fields. Assessment at the farm level, rather than in materials in gene banks or breeders' stocks, allows us to examine several dimensions of diversity simultaneously, including the contribution of breeding programs. This is also the appropriate point of observation given our interest in how farmers' production choices and constraints affect diversity.

The second point of inquiry deals with how much and in what ways genetic diversity and genetic resource use enhance the economic value of the wheat crop. The lack of an understanding of the relationships between diversity and resource use and their effect on production outcomes, in the absence of market valuation, raises the possibility of underinvestment from the perspective of producers and society and leaves little to guide policy (Schuh and Tollini 1979). However, other means of valuation are available. One method is to analyze how genetic diversity and the use of genetic resources, among other conventional inputs, contribute to increased agricultural output of a commodity. A second aspect of crop production that has economic importance is aggregate yield stability.[2] Again, it is possible to analyze the contribution of inputs — including genetic resources and their attributes — to yield variability.

In both cases, our perspective derives from our interest in how genetic resources and diversity affect farmers' production outcomes. Such a valuation assessment has important implications for funding germplasm resource collection and other investments designed to enhance diversity at the farm level.

We selected the Punjab of Pakistan as the region of study because it represents one of the first areas in the developing world where farmers adopted semidwarf wheats. Pakistan is also one of the four largest wheat producers among developing countries, and its per capita wheat consumption ranks among the highest in the developing world (CIMMYT 1995). In the Punjab, one of the two major wheat-producing provinces of Pakistan, wheat, produced during the cool, dry *rabi* season, is one of two staple food grains. Ninety percent of the province's farmers cultivate about 7 ha or less of wheat on farms of less than 10 ha.

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2 Aggregate yield stability refers to the variability of all wheat output over time. This is different from yield stability as used by plant breeders, which refers to variation in yield for a single genotype across environments and over time.

Related Research

Genetic Resources and Productivity

Few studies have directly addressed the valuation of particular attributes of germplasm through productivity analysis of varietal improvement. Evenson and Gollin (1990) studied the contribution of genetic resources to Indian rice productivity over 1956-83. The study sought to separate the effects of varietal improvements from other productivity-enhancing inputs and to measure the relative contribution of genetic resources to varietal improvement and indirectly to productivity change. The analysis involved estimation of two production functions, both regressed over a yield index for the period examined. The first regression used area planted to high-yielding varieties (HYVs) as a variable to measure the contribution of varietal change. Regression results were used in a growth accounting over the period 1972-84, which estimated that varietal change in rice contributed more than one-third of realized productivity gains, while public research and extension explained much of the remaining growth. The second regression analysis replaced the HYV variable with sets of genetic resource variables weighted by the proportion of HYV area for each variety actually planted by farmers over 1975-84. The genetic resource variables were defined by conducting a pedigree analysis of the 306 rice varieties released in India.

Widawsky (1996) used a Just and Pope (1979) specification of a production function to estimate effects of varietal diversity on rice yield variability among townships in eastern China. He measured varietal diversity using coefficients of parentage constructed from pedigree analysis (explained below) and an area-weighted version of a distance index developed by Solow and Polasky (1994). He concluded that varietal diversity was effective in reducing rice yield variability and only slightly reduced mean yields for the time period under study.

In a sense, any study investigating the impact of plant breeding on yield is analyzing the effects of genetic resources on productivity, broadly defined. Recent studies of agricultural research impact, for example, have differentiated among varieties based on their ancestry or the source of the germplasm. Bagnara, Bagnara, and Santaniello (1996) estimate effects of local germplasm and international germplasm on the adaptability, yield, grain quality, and yield stability of Italian durum wheats. Other examples include Byerlee and Traxler (1995), Pardey et al. (forthcoming), Brennan and Fox (1995), Brennan, Singh, and Lewin (1996), and Thomas (1996). The two studies noted above, however, as well as this study, attempt to measure the effects on productivity of particular attributes of genetic resources, such as their diversity.

Varietal Diversity in the Punjab of Pakistan

Several previous studies have examined patterns of diversity among wheat varieties grown in the Punjab of Pakistan. Byerlee and Heisey (1990) documented farmers' use of wheat varieties across districts and years from 1978 to 1986, with points of comparison to the Yaqui Valley of Mexico and the Indian Punjab. The rate of varietal replacement is an important indicator of the impact of plant breeding programs through genetic gains in yield or other desirable characteristics, and it serves as a measure of potential exposure to disease epidemics, because newer releases generally carry different genetic bases of resistance.

For these data, Khan (1987) reported that the average longevity of rust resistance among wheat varieties in the Punjab of Pakistan was 6.3 years.[3] Simple cost-benefit analysis based on this estimate suggests that wheat varieties in the Punjab should turn over every five to six years.

Brennan and Byerlee (1991) compared the average age of wheat varieties in the Punjab of Pakistan, weighted by their planted area, to that of wheat varieties in several other regions in developed and developing countries. Weighting the ages of varieties by the percentage of planted area they occupy captures, in part, the effects of concentration in the distribution of varieties over space. A higher concentration of wheat area in fewer varieties increases the likelihood that mutations in rust pathogens will survive and break down a given genetic basis of resistance. The weighted average age of wheat varieties in the Punjab of Pakistan was 11.1 years, which was longer than the average of 7.2 years for the all regions investigated and nearly twice the estimated longevity of genetic resistance based on single genes. The authors attributed the relatively slow rate of varietal turnover in the Punjab of Pakistan to a poorly developed seed industry and extension service. Arguing that the socially optimal period for replacing wheat varieties is a function of a number of biological and economic factors, Heisey and Brennan (1991) developed a more complete economic model for analyzing farmers' demand for replacement seed using data from the Punjab of Pakistan.

Souza et al. (1994) combined indicators of varietal replacement over time, spatial distribution of varieties by planted area, and genealogical analysis in their study comparing trends in wheat genetic diversity between the Punjab of Pakistan and the Yaqui Valley of Mexico. They used coefficient of parentage analysis based on pedigree data (described below) as an indicator of "latent diversity" (defined as "the underlying genomic variation that is not obvious until challenged by the appropriate biotic or abiotic stress") (p. 774). These researchers found a small trend towards greater latent diversity among the cultivars grown in the Punjab of Pakistan over 1978 to 1990, compared to large oscillations and generally lower levels of latent diversity in the Yaqui Valley. On the other hand, the rate of varietal replacement in the Yaqui Valley was considerably higher than in the Punjab of Pakistan, higher even than recommended by research services. Souza et al. concluded that wheat improvement programs did not erode genetic diversity in these two areas where Green Revolution wheats had been widely adopted. Further, they argued that farmers' patterns of varietal use have a greater effect than the composition of varieties recommended by research services on the level of genetic diversity observed in farmers' fields.

Heisey et al. (forthcoming) used an approach from the theory of impure public goods to explain why farmers in the Punjab of Pakistan may not choose to grow wheat varieties with

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[3] Historically, the rusts (stripe, stem, leaf) have been the major diseases of wheat. They are endemic to the Asian subcontinent, where they have caused major yield losses that have been recorded in government documents since the late 18th century. An average of five to six years has been estimated as the effective period of genetic resistance in an individual cultivar when resistance is based on single genes with major effect. Increasingly, however, wheat breeders and pathologists work to diversify the genetic basis of resistance to rust pathogens through accumulating several different genes, each with a minor effect and/or different mechanisms for controlling resistance to disease, in individual cultivars. Such polygenic forms of genetic resistance are expected to be more "durable."

the level of resistance to rust that is socially desirable. They argued that (1) farmers choose to grow wheat cultivars whose yields are high even though they are known to be susceptible to virulent strains of rust and (2) farmers choose to grow high-yielding cultivars whether or not they have the same basis of genetic resistance as those grown by other farmers. When many farmers grow cultivars possessing similar resistance genes, there is a lower level of genetic diversity in farmers' fields than would most effectively protect against the emergence and spread of rust. The authors investigate some of the costs (in terms of yield foregone) associated with pursuing various policies to increase genetic diversity.

Wheat Production in the Punjab of Pakistan

The Punjab accounts for 68% of the cropped area in Pakistan, most of which is situated on the Indus Plains. Irrigation systems composed of tubewells and canals serve approximately 83% of this area (CIMMYT 1989). There are two production seasons. The summer monsoon (*kharif*) season runs from approximately June to October, and the winter low-rainfall (*rabi*) season runs from October to May. Throughout the Punjab, wheat is by far the most important *rabi* season crop.

Important differences emerge, however, when total production area is disaggregated into irrigated and nonirrigated (*barani*) areas. When delineated by district, the *barani* areas correspond primarily to those of Rawalpindi Division, which is situated in the higher plains of Northern Punjab and represents nearly 10% of the total Punjab wheat area. Outside Rawalpindi Division, most districts have near complete irrigation coverage, with the exception of Gujrat, Sialkot, Khushab, and Mianwali, in which less than 70% of the cropped area is irrigated.

Limited evidence of the contrast between irrigated and *barani* areas is sufficient to suggest that there are structural differences in the two production environments. Consequently, treating the entire Punjab as a homogenous production environment would lead to erroneous coefficient estimation. Differences between irrigated and *barani* areas emerge in farming system interactions and the use of improved high-yielding wheat varieties. In the irrigated areas cropping intensity is high, with double cropping of cash and food crops. Rice, cotton, sugarcane, or maize are typically grown during the summer, followed by wheat during the cooler *rabi* season. The double cropping system may cause management difficulties because of the short turnaround time between crops. Often the wheat crop is planted later than the optimal time due to later maturing of the rotation crop or other harvesting constraints, particularly labor shortages during peak demand. Also, in an effort to sow the wheat crop in a timely manner, land preparation commonly suffers. Generally, however, farmers in the irrigated areas are self-sufficient in food production and earn their cash income primarily from the summer crop (Renkow 1991).

The dominant farming system in the *barani* areas is a crop-livestock mix. Wheat or maize is the primary food crop and both crops are also important sources of livestock fodder. In fact, the value of crop by-products and intercrops in relation to grain is around 40% in *barani* areas, compared to 10-20% in irrigated areas (Byerlee and Husain 1992). In contrast to the irrigated areas, the *barani* areas are generally not self-sufficient in food production, and people earn most of their income from off-farm work and, to a lesser extent, livestock production (Renkow 1991).

Beginning around 1967, HYVs were adopted in the irrigated areas and rapidly replaced the local (*desi*) varieties, including both scientifically bred tall varieties and local landrace types such as Rodi. In most irrigated districts adoption exceeded 90% by the period covered in this study. Adoption of HYVs in the *barani* areas began about ten years after HYVs were first adopted in irrigated districts. By 1985/86, the final year considered in this study, adoption of HYVs generally did not exceed 50% of the wheat area in the drier *barani* environments. The persistence of improved tall varieties (predominantly C-591, released in 1934) and landrace varieties may be attributed partly to farmers' need for livestock fodder, which the newer short-statured varieties provided in lower quantities. Nor did the new short varieties give the dramatic yield increase experienced in the irrigated areas. In many cases, the milling and baking qualities of the older varieties were preferred to those of the HYVs. Serious pathogen infestations in the older varieties and the release of HYVs that performed better in rainfed environments have accelerated adoption in *barani* areas during and after the period analyzed here. By 1989/90, 70-80% of the *barani* wheat area was planted to HYVs (Government of Pakistan 1991; Hobbs, Saeed, and Farooq 1992; Byerlee and Moya 1993).

Genetic Resource Use and Diversity in the Districts of Punjab, Pakistan, 1979-85

As mentioned in the introduction, the study of genetic resource use and diversity has many dimensions, and the specific question at hand, as well as the available data, guide the choice of indicators employed to describe diversity or resource use. Here we are interested in the diversity embodied in the wheat varieties farmers actually grow in the Punjab of Pakistan. We have already reviewed some of the previous findings on varietal diversity in the Punjab of Pakistan; now we will discuss the conceptual basis for the genetic resource and diversity variables used in the regression analysis described in this paper. Some descriptive statistics for these variables are provided and interpreted.

Measures of Genetic Resource Use

"Genetic resources" are the germplasm or genetic material of all organisms containing useful characteristics of actual or potential value (Skovmand, Varughese, and Hettel 1992). For wheat, the genetic resources most often used in conventional breeding programs can be conveniently divided into two categories — landraces and varieties — which are distinguished by their crossing history. A third grouping includes 27 wild and weedy relatives of wheat, which are not grown commercially and are used very infrequently in plant breeding (Skovmand et al. 1992). Two measures of the use of these genetic resources are described below.

Number of different landraces in the pedigree of a variety. A landrace is a cultivated variety developed in traditional agriculture over many years of farmer selection. Individual wheat populations are usually genetically heterogeneous and location specific in their adaptation (National Research Council 1993). Although genetically heterogeneous, a wheat landrace consists of homozygous lines. Landraces are commonly thought of as sources of novel genetic diversity and resistance to pests and pathogens because they have undergone a centuries-long selection process, usually within specific production environments.

Only rarely do modern plant breeders cross landraces directly with advanced breeding lines, primarily because of the effort needed to breed out concurrent undesirable characteristics and also because sources of resistance to evolving pathogenic threats are often already present in existing highly selected, adapted breeding lines (Duvick 1984). As expressed by Harlan, plant breeders "want the genes and not the linkages" (Harlan 1992:155).

An inspection of the pedigrees of modern wheats reveals that it is less common for new landrace ancestors to be introduced as direct parents of new wheat varieties than to be incorporated into the genetic background of new wheat varieties when breeders cross advanced lines with distinct genealogies. However, wheat breeders do not generally know the genealogies of new materials they borrow or obtain from other nations beyond the first or second generation. Typically, the new materials brought into a wheat breeder's program are advanced lines with long pedigrees that contain numerous landraces. Many of these advanced lines have pedigrees similar to the breeders' older materials. Some have fairly distinct pedigrees. Only a few new materials are landraces that have never before been used in the genetic background of any of the breeders' materials.[4]

A recent survey of wheat breeders in developed and developing countries found that landraces and wild relatives comprised only 7.2% of the parent material used in crossing, while advanced materials were used in 78% of all crosses (parental combinations) (Rejesus, van Ginkel, and Smale 1996). Despite this fact, analysis of the pedigrees of 800 wheat releases in developing countries over the past 30 years shows an increasing number of different landraces in the genetic background of materials.

In this study, we use the number of landraces in the genetic background of semidwarf wheats to represent anonymous farmers' contribution of germplasm resources. We measure the number of *different* landraces by recording each landrace ancestor only the first time it appears in its pedigree. To develop a variable that can be used with district-level data, it is also possible to compute the average number of different landraces among the pedigrees of the varieties grown in each district, in each year. Similarly, we can weight this average by the proportion of planted area for each variety in that district and year.

Number of different parental combinations in the pedigree of a variety. Wheat breeders systematically assemble and reassemble gene combinations with the objective of producing economically novel and environmentally viable varieties with characteristics demanded by

[4] The more access the wheat breeding program has to international sources of germplasm, the more likely it is that new materials will contain ancestors in their genetic background that have not been used previously in that particular breeding program.

producers and consumers. Because plant breeding is a continuous process, and because the potential remains to exploit different genetic combinations in the future, this resource continues to evolve and expand. Crossing produces genetically unique offspring carrying different combinations of characteristics from each parent. Successive generations of the offspring are then grown, selected for particular desired traits, and then either released to the public, discarded, and/or retained in breeders' lines.

In this study, we use the number of different parental combinations (crosses) in the pedigree of the wheat variety to represent anonymous scientists' contribution to the germplasm resource base. The number of different parental combinations is calculated by counting the parent combination only the first time it appears in the pedigree of a wheat variety. The number of different parental combinations appearing in a variety's pedigree can again be expressed as the simple or weighted average for varieties grown in a production environment.

Measures of Diversity

According to the International Plant Genetic Resources Institute (IPGRI), the "diversity" in the genetic base of a population of crop plants is related to the number of possible responses to selection pressures and is likely to be related to its potential value in production (IPGRI 1991). In applied genetics, genetic diversity is a complex statistical concept referring to the variance at individual gene loci, among several loci, between individuals within populations and between populations (Brown et al. 1990). The relationship between precise quantitative measures and what can be casually observed in farmers' fields, and between these measures and what could be potentially observed, is indeed complex.

An important limitation of most measures of genetic diversity is the inability of any single measure to capture either the complex interaction among genes or the interaction between the genes and the environmental factors affecting plant performance. We can construct diversity indices using molecular, morphological, and genealogical data (Dudley 1994), but the empirical relationship among them or between any such diversity index and the expression of particular traits of interest is often weak.

Because of our focus in this study on the characteristics that farmers observe and their choice among cultivars, our use of the term genetic diversity refers more to broad indicators of varietal diversity in farmers' fields than to diversity as measured at the molecular level or in the theoretical literature of population genetics. Our particular concern here is the relationship of types of genetic resources and their attributes to productivity and yield stability.

Spatial diversity. Spatial diversity refers to the relative distribution or concentration of unique varieties, plant characteristics, or even particular gene combinations over space. Growing a number of different varieties rather than a single variety is a strategy that individual farmers and nations can use to limit their exposure to crop diseases and some environmental risks (Heisey 1990). A greater number of varieties planted over smaller areas will presumably reduce potential losses and ease recovery, with the caveat that the varieties possess different sources of resistance to pathogens and environmental stresses (Duvick 1984).

Spatial diversity of wheat varieties has been assessed using several concentration measures (Duvick 1984; Byerlee and Heisey 1990; Smale 1996), although only two are employed in this paper. The first is the proportion of area devoted to the single most popular variety. The second, the Herfindahl index, is borrowed from the economic literature on industrial organization. Here, the Herfindahl index is the sum of squared shares of area planted to each unique variety, which is essentially the weighted average of the proportionate area of each variety, with the weights being the shares themselves[5] (Pardey et al., forthcoming). A Herfindahl value of 1 indicates that all area is planted to a single variety, whereas a value of 0 indicates that a large number of varieties are each planted on a very small area. The index weights those varieties covering greater area more highly than those under fewer hectares.

Temporal diversity. Temporal diversity refers to the rate of change or turnover of varieties. Duvick (1984) has described it as "genetic diversity in time" (1984). The replacement of varieties reduces the potential exposure to disease epidemics resulting from the breakdown of disease resistance in older varieties. Varietal turnover is important for modern agriculture and in some ways substitutes for spatial diversity (Apple 1977; Plucknett and Smith 1986). The economically optimal rate of varietal turnover in a given area is jointly determined by a number of factors, including the rate of mutation of disease organisms, the structure of disease resistance of a variety, and the production environment (Heisey and Brennan 1991).

Brennan and Byerlee (1991) have developed and applied several indicators of varietal turnover in farmers' fields. In addition to observing changes in the spatial diversity indicators discussed above, we use the simple and weighted average age of varieties appearing in farmers' fields as indicators of varietal turnover.

Genealogical diversity and distance. Analysis of ancestry of a set of wheat varieties has been used to estimate total genomic (excluding cytoplasmic genes) diversity (Cox, Murphy, and Rodgers 1986). The coefficient of parentage (COP) is a common measure that employs detailed pedigree information to describe the pairwise degree of genetic similarity among a group of varieties. This indicator measures the probability that two varieties are identical by descent for a character (observable or unobservable) that varies genetically, based on Mendelian rules of inheritance. Souza et al. (1994) have described the COP as expressing "latent" genetic diversity — the genetic variation that is not manifested until the plant is subjected to stress from biotic or abiotic agents.

The COP is a theoretical estimate of the genetic relationship between two varieties based on an analysis of their pedigrees. It estimates the probability that a random allele taken from a random locus in a variety X is identical, by descent, to a random allele taken from the same locus in variety Y. Values range from 0 to 1, with higher values indicating greater relatedness. The concept of COP was originally developed by Wright (1922) and Malecot (1948) and applied to maize. St. Martin (1982) adapted the COP analysis to inbred crops. He calculated coefficients of parentage using the algebraic method of Kempthorne (1969) and included the following assumptions: each cultivar is completely inbred (homozygous), varieties without

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5 Herfindahl index: $h = \sum_i \left(\frac{\alpha_i}{\sum_i \alpha_i} \right)^2$, where α_i = the share of area planted to variety *i*.

common parentage are unrelated, parents contribute equally to the offspring despite inbreeding and selection, and the relationship between a cultivar and itself is 1. To account for the effects of recurrent selection from a parental combination, Cox, Murphy, and Rodgers (1986) proposed that (1) the COP between a parental combination and a reselection from it be 0.75 and (2) the COP between two selections from the same parental combination be 0.56.

The coefficient of diversity (COD), calculated as 1- COP, measures the dissimilarity of parentage among varieties. For a set of wheat varieties, such as the set grown in district *x* in year *t*, the matrix of pairwise coefficients of diversity can be summarized in a simple average coefficient of diversity. By pre- and post-multiplying the matrix by a vector of areas planted to each cultivar, a weighted coefficient of diversity that reflects the spatial distribution of cultivars can be calculated. In a sense, the unweighted average COD reflects the degree of diversity of varieties at the time of their release by research services. The difference between the average and weighted coefficients of diversity can be understood as the effect of factors related to farmer choice and seed systems on the diffusion of the varieties that have been made available.

In our analysis, we have summarized pairwise coefficients as an index of genealogical distance, following the proposal of Weitzman (1992, 1993). Weitzman has shown that, given that pairwise distances are ultrametric, the genetic distance among all members of a set can be calculated as the total branch length of a dendrogram constructed from the pairwise distances. The pairwise distances can be measured by molecular, morphological, genealogical, or other methods. After verifying that the matrix of pairwise coefficients of diversity satisfies ultrametric properties, Ward's fusion strategy was used as the clustering method to generate a dendrogram from all pairwise coefficients or genealogical "distances" (see del Toro 1996). The sum of branch lengths was then calculated from the dendrogram. The analysis was conducted for each variety grown in each district of Punjab in each year.

Patterns of Genetic Resource Use and Diversity

Genetic resource use. During the study period (1979-85), 18 varieties of semidwarf bread wheat were cultivated among the districts of Punjab. This number excludes *desi* varieties (farmers' traditional varieties, improved only through farmer selection) and farmers' tall-statured varieties that are older releases of wheat breeding programs. Figure 1 shows that for the province of Punjab as a whole, the area planted to *desi* and other tall varieties declined from slightly above 20% in 1979/80 to about half that amount in 1985/86. The area planted to tall varieties remained relatively high in the dry *barani* areas, but it declined fairly sharply in both the wet and dry *barani* areas over the brief period of study.

The genetic resources embodied in the pedigrees of semidwarf wheats grown in the Punjab also increased over the period of study, both in terms of the average number of different landraces per pedigree and the average number of different parental combinations per pedigree (Table 1). The number of different landraces is positively correlated with the number of different parental combinations in the pedigree, demonstrating that wheat breeders are using materials with new ancestors in their pedigrees.

The average number of landraces and parental combinations in the pedigrees of wheat varieties grown in farmers' fields increased in most districts of the Punjab and for the province as a whole from 1979 to 1985 (Tables 2 and 3). The magnitude of the increase varies

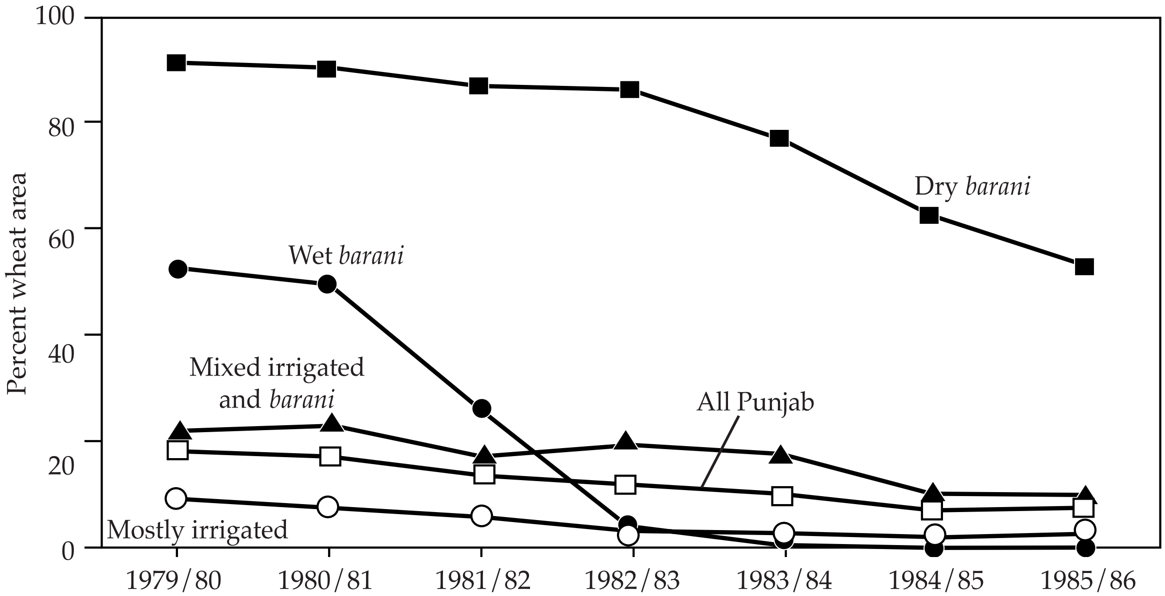

Figure 1. Proportion of wheat area planted to tall varieties, Punjab, Pakistan, 1979/80 to 1985/86.

Table 1. Semidwarf bread wheat varieties grown in the Punjab of Pakistan, 1979-85

Variety	Year released	Number of different landraces in pedigree	Number of different parental combinations in pedigree	Peak area during study period (%)
Mexipak	1966	37	58	7.4
Chenab 70	1970	36	62	7.5
Blue Silver	1970	39	90	3.8
Yecora	1970	42	94	55.6
Nuri	1970	42	94	1.4
SA-42	1971	38	88	0.5
Sandal	1971	42	94	5.0
Lyallpur 73	1973	44	111	11.3
Pari 73	1973	42	94	1.1
SA-75	1975	41	71	2.6
Lu-26	1976	44	112	1.6
Pavon	1976	47	127	4.7
HD-2009	1976	37	71	0.2
Sonalika	1977	39	90	10.1
WL-711	1978	45	109	18.4
Bahawalpur 79	1979	38	88	2.0
Punjab 81	1981	41	89	14.0
Pak 81	1981	49	131	9.4

Source: Calculated from data in the CIMMYT Wheat Pedigree Management System and Bureau of Statistics (1986).

by district, however, and is probably related to the combination of the number of varieties grown and their age. When weighted by area sown, the district averages also show the effect of the popularity of certain varieties. At one extreme, in the *barani* districts of the Rawalpindi Division, the average and weighted average values are similar or identical, which reflects the fact that the area sown to a single improved variety (Lyallpur 73) remained large even after the adoption of subsequent varieties (Appendix Tables 1 and 2).

Spatial diversity. Figure 2 shows the percentage distribution of area for all of the province of Punjab by variety and groups of varieties. Quite clearly the concentration of the most popular variety (Yecora) declined for all Punjab. From 1979 to 1984 the percentage of wheat area it occupied dropped from 56 to 12. At the end of the period, WL-711 became dominant. That the dominant variety in the final period accounted for only 18% of the area indicates the presence of an increasing number of varieties, each covering a relatively small area, and suggests that the spatial diversity of varieties increased during the study period. Since the adoption and disadoption of varieties follow cyclical patterns, however, this finding depends on the time period.

Table 2. Average number of different landraces in the pedigrees of varieties grown in the Punjab of Pakistan, by district, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	41.54	41.54	41.21	41.23	41.27	42.14	42.08
Bahawalpur	41.21	41.21	41.54	41.58	41.85	41.53	42.15
Rahim Yar Khan	41.58	41.54	41.15	40.93	41.50	41.50	41.73
D.G. Khan	41.44	41.22	41.33	41.00	40.79	41.17	41.58
Layyah/Liaha	41.00	41.54	41.54	41.07	41.00	41.50	41.75
Muzaffargarh	41.00	41.54	41.54	41.15	41.47	41.73	42.07
Rajanpur	41.44	41.22	41.33	41.00	41.23	40.92	41.15
Faisalabad	41.25	41.27	41.21	41.27	41.53	41.75	42.00
Jhang	41.00	41.25	41.54	41.29	42.20	41.75	41.50
T.T. Singh	41.25	41.25	41.21	42.20	41.75	42.40	42.55
Gujranwala	41.00	41.38	40.92	41.57	41.92	41.81	42.14
Gujrat	41.00	41.22	41.33	41.00	41.36	41.75	41.53
Sialkot	40.90	41.40	42.20	42.09	41.57	41.53	42.62
Kasur	41.00	41.40	41.58	42.30	41.90	42.91	42.09
Lahore	41.63	40.78	42.30	41.86	42.78	41.70	42.50
Okara	40.92	41.21	41.21	41.27	42.00	42.78	42.38
Sheikhupura	41.25	41.54	41.54	41.62	41.80	41.75	41.80
Khanewal	41.00	41.21	41.21	41.06	41.53	41.86	42.00
Multan	41.00	41.21	41.21	41.06	41.53	41.86	41.80
Sahiwal	40.92	41.15	41.21	41.00	42.00	41.25	42.78
Vehari	41.00	41.15	41.21	41.46	41.55	41.73	42.00
Attock	40.00	44.00	44.00	44.00	44.00	41.00	42.00
Chakwal	40.33	40.20	39.75	44.00	40.75	41.14	44.67
Jhelum	40.33	40.20	39.75	44.00	40.75	40.00	41.83
Rawalpindi	40.20	44.00	41.50	42.50	42.50	42.50	40.67
Bhakkar	41.00	41.25	41.25	41.18	41.67	41.89	42.00
Khushab	41.75	41.25	41.25	41.00	40.78	41.60	40.78
Mianwali	41.00	41.25	41.25	41.00	41.09	41.89	42.00
Sargodha	41.75	41.20	41.25	41.00	41.60	42.00	41.86
All Punjab	41.21	41.21	41.21	41.06	41.53	41.53	41.53

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (1986).

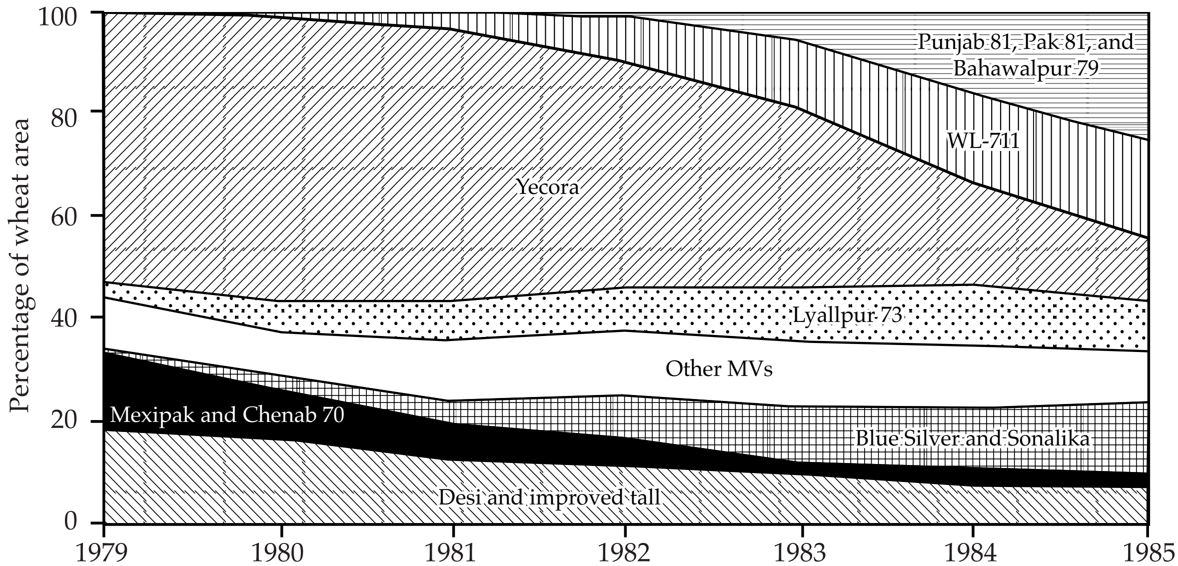

Figure 2. Percentage distribution of wheat varieties by area, Punjab of Pakistan, 1979-85.
Note: Other MVs (modern varieties) include HD-2009, Lu-26, Nuri, Pari, Pavon, SA-42, SA-75, and Sandal.

Table 3. Average number of different parental combinations in the pedigrees of varieties grown in the Punjab of Pakistan, by district, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	92.77	92.77	91.21	92.31	92.20	98.93	97.54
Bahawalpur	91.21	91.21	92.77	95.17	98.85	95.80	99.31
Rahim Yar Khan	91.42	92.77	91.00	91.64	94.75	94.75	94.67
D.G. Khan	89.44	91.56	91.17	92.45	90.36	93.67	95.25
Layyah/Liaha	89.55	92.77	92.77	92.13	91.80	94.25	94.63
Muzaffargarh	89.55	92.77	92.77	91.92	94.27	94.67	97.29
Rajanpur	89.44	91.56	91.17	92.45	93.92	93.23	93.38
Faisalabad	91.42	93.27	91.21	92.20	94.24	94.63	95.07
Jhang	89.55	91.42	92.77	92.43	98.20	94.63	94.25
T.T. Singh	91.42	91.42	91.21	98.20	94.63	98.60	98.64
Gujranwala	89.55	95.25	89.85	94.64	97.17	96.50	98.93
Gujrat	89.55	91.56	91.17	91.15	92.36	94.63	93.67
Sialkot	89.10	92.70	97.70	96.91	94.64	93.67	101.77
Kasur	90.25	92.70	94.58	99.30	97.30	102.09	98.64
Lahore	92.88	88.89	97.40	97.57	102.22	94.70	99.60
Okara	89.25	91.21	91.21	92.64	96.33	102.22	98.88
Sheikhupura	91.42	92.77	92.77	96.46	96.20	94.63	96.20
Khanewal	89.62	91.21	91.21	91.94	94.24	98.50	99.20
Multan	89.62	91.21	91.21	91.94	94.24	98.50	96.67
Sahiwal	89.25	91.00	91.21	90.62	95.07	95.08	102.22
Vehari	89.62	91.00	91.21	92.38	96.91	97.27	96.80
Attock	86.50	111.00	111.00	111.00	111.00	90.17	97.60
Chakwal	81.67	83.80	81.25	55.50	89.00	90.71	110.33
Jhelum	81.67	83.80	81.25	111.00	89.00	82.80	96.17
Rawalpindi	83.80	111.00	100.50	100.00	100.00	100.00	86.00
Bhakkar	85.71	91.42	91.42	91.18	92.58	97.22	94.45
Khushab	93.00	91.42	91.42	90.86	90.56	94.60	90.56
Mianwali	85.71	91.42	91.42	91.15	90.73	97.22	94.45
Sargodha	93.00	89.50	91.42	89.50	93.47	95.07	93.86
All Punjab	89.20	92.56	92.32	93.33	95.04	95.47	96.76

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (1986).

The spatial distribution of semidwarf wheats is shown in Table 4 as the percent area planted to the single most popular variety. When spatial distribution of varieties is measured at the level of the district rather than for the province as a whole, there is also a more volatile pattern in the percent of wheat area occupied by the dominant variety. The rainfed areas of Rawalpindi Division show an increasingly large concentration of area planted to Lyallpur 73 as it displaced landrace and other tall varieties. This adoption pattern seems to suggest a relative lack of varietal development geared to the drier rainfed production environments. Other districts, such as Bahawalnager and those of Multan Division, are characterized by a rapid decline in the dominant variety, Yecora, and its replacement by WL-711 at even higher concentrations by the period's end. The cycle of varietal replacement demonstrated here may also be related to greater disease pressure in favorable production environments where varieties that become susceptible are replaced by resistant varieties.[6]

Table 4. Percentage of area planted to most popular semidwarf wheat varieties in the Punjab of Pakistan, by district, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	38.83	32.87	33.72	25.78	30.67	37.52	42.02
Bahawalpur	32.59	43.57	28.28	17.69	26.80	25.28	30.13
Rahim Yar Khan	54.40	62.16	54.14	35.85	21.99	25.00	31.02
D.G. Khan	24.87	26.97	19.32	30.34	38.66	38.68	32.80
Layyah/Liaha	28.11	35.29	32.30	21.05	18.68	27.49	32.91
Muzaffargarh	28.11	35.29	32.30	32.17	20.61	21.76	26.28
Rajanpur	24.87	26.97	19.32	20.20	29.44	21.00	20.10
Faisalabad	73.71	77.92	78.95	72.79	60.33	31.23	25.31
Jhang	67.68	60.97	71.63	68.57	61.22	29.66	27.60
T.T. Singh	70.61	69.18	75.14	83.02	64.75	34.16	43.64
Gujranwala	79.03	87.42	91.46	89.70	83.28	48.38	22.60
Gujrat	53.21	51.85	54.19	48.85	43.67	36.23	28.85
Sialkot	63.33	76.48	52.13	51.97	41.10	34.24	35.60
Kasur	65.63	81.77	91.49	87.11	85.02	71.64	54.42
Lahore	61.21	81.73	81.45	91.97	65.15	55.20	41.13
Okara	76.02	64.11	87.41	81.89	78.71	47.63	31.98
Sheikhupura	73.79	83.84	82.80	80.10	67.86	43.58	28.74
Khanewal	73.65	53.30	62.73	35.41	49.57	61.87	67.11
Multan	73.65	53.30	62.73	35.41	49.57	61.87	60.53
Sahiwal	82.61	53.17	84.89	54.49	39.33	61.06	64.84
Vehari	61.74	56.78	56.50	32.71	59.02	56.13	57.81
Attock	7.20	9.62	9.45	9.40	9.43	26.20	39.44
Chakwal	6.36	8.48	11.25	13.93	19.29	30.96	29.24
Jhelum	3.90	5.16	16.54	26.98	48.15	44.89	25.53
Rawalpindi	24.72	50.45	73.66	95.05	97.59	97.93	82.53
Bhakkar	13.66	12.37	13.02	26.03	34.59	35.21	43.17
Khushab	33.53	28.76	37.12	18.34	21.86	22.27	20.45
Mianwali	13.66	12.37	13.02	13.38	8.71	35.21	43.17
Sargodha	45.06	47.29	54.19	70.77	66.22	52.99	34.57
All Punjab	52.0	55.6	53.3	43.9	34.6	19.8	18.4

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (1986).

6 The Herfindahl index of varietal concentration for Punjab districts, found in Appendix Table 3, also suggests a general increase in spatial diversity, although there is a decreasing trend in the *barani* areas and a cyclical pattern found in Multan Division.

Temporal diversity. As explained above, the average age of the varieties grown by farmers is an expression of the rate of varietal replacement. A high average age among the varieties grown by farmers indicates that they retain the same varieties for many years. While the simple average reflects the turnover of varieties released by the research system, the weighted average age adjusts for the effects of the distribution of varieties by area. For example, when the area-weighted average age among varieties grown in the province of Punjab exceeds the unweighted average age, we can conclude that the distribution of area favored the older varieties (see Table 5, Appendix Table 4).

Among districts temporal diversity exhibits a pattern similar to that observed for spatial diversity. In districts that produce more wheat, the weighted average age is much lower than the average, which may reflect the need to replace varieties with obsolete sources of genetic resistance to rust diseases. Where disease pressure is less severe the rate of turnover appears to be slower. As is the case with the other indicators of diversity in farmers' fields, while the average age of varieties for the province as a whole suggests that farmers have responded slowly to disease pressure on the wheat crop, district-level figures indicate that turnover can be near to and occasionally greater than recommended rates.

Table 5. Average age of varieties grown in the Punjab of Pakistan, by district, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	6.31	7.31	8.07	8.62	9.33	9.36	9.85
Bahawalpur	6.07	7.07	8.31	8.25	8.15	10.07	10.23
Rahim Yar Khan	6.17	7.31	8.08	8.21	8.33	9.33	10.80
D.G. Khan	7.44	9.00	8.58	10.00	9.64	10.75	11.33
Layyah/Liaha	7.09	7.31	8.31	9.00	9.27	9.81	10.88
Muzaffargarh	7.09	7.31	8.31	8.62	8.73	9.60	10.00
Rajanpur	7.44	9.00	8.58	9.73	9.92	10.31	10.92
Faisalabad	6.75	8.00	8.07	9.27	9.06	10.38	11.20
Jhang	7.09	7.75	8.31	9.43	8.50	10.38	10.81
T.T. Singh	6.75	7.75	8.07	7.50	9.38	9.00	10.00
Gujranwala	7.09	7.88	8.46	8.36	9.25	9.56	10.93
Gujrat	7.09	8.22	8.58	9.85	9.86	10.38	11.67
Sialkot	7.20	7.50	7.90	8.18	9.36	10.67	10.62
Kasur	8.00	7.50	8.50	7.80	8.80	9.45	10.64
Lahore	6.25	7.89	7.70	9.57	8.33	9.90	10.60
Okara	6.08	7.07	8.07	8.55	8.33	8.78	9.88
Sheikhupura	6.75	7.31	8.31	8.46	9.47	10.38	11.47
Khanewal	6.31	7.07	8.07	8.50	9.06	9.50	9.20
Multan	6.31	7.07	8.07	8.50	9.06	9.50	10.47
Sahiwal	6.08	6.85	8.07	8.00	9.20	9.25	9.78
Vehari	6.31	7.08	8.07	8.69	8.36	8.91	9.20
Attock	7.50	7.00	8.00	9.00	10.00	9.33	10.80
Chakwal	8.33	10.20	11.25	4.50	9.50	10.00	6.67
Jhelum	8.33	10.20	11.25	9.00	9.50	12.00	9.67
Rawalpindi	9.20	7.00	6.00	5.00	6.00	7.00	11.67
Bhakkar	7.43	7.75	8.75	9.55	9.17	10.78	10.82
Khushab	6.08	7.75	8.75	9.86	10.11	10.30	12.11
Mianwali	7.43	7.75	8.75	9.85	9.64	10.78	10.82
Sargodha	6.08	7.90	8.75	9.33	9.00	10.20	11.36
All Punjab	6.07	7.07	8.07	8.06	9.06	10.06	11.06

Source: Calculated from Souza et al. (1994) and Bureau of Statistics (1986).

Genealogical distance. Changes in average and weighted average "latent diversity," as calculated from the matrix of pairwise coefficients of diversity among the varieties cultivated in each year in the Punjab of Pakistan, are depicted graphically in Figure 3. Average diversity for the province appears to have increased slightly during the study period and remained fairly stable around the value of 0.76.[7] The average values are sensitive to the number of varieties. Since an additional variety can only increase diversity, the long-term persistence of some varieties, even as new varieties are added, contributes to high average diversity (Souza et al. 1994). The patterns of varietal concentration shown previously clearly have an impact on the level of latent diversity in farmers' fields, as demonstrated by the weighted coefficient. Weighted diversity was nearly one-half of its potential in 1980/81 when the variety Yecora accounted for 56% of the area planted to wheat. Subsequent greater spatial diversity, as shown by the falling Herfindahl index values, has resulted in overall greater system diversity.

The difference between the area-weighted and unweighted average coefficients of diversity varies considerably among districts, reflecting differences in farmer's objectives and in the availability and suitability of varieties to production environments. Among the *barani* districts of Rawalpindi Division, where relatively few varieties are grown, the area-weighted coefficient of diversity is typically 50% lower than in the irrigated districts of the province. The interaction of spatial and temporal influences on latent diversity in other production environments is more complicated. Estimates of genealogical distance for each district and the province also show that values are heavily influenced by the numbers and types of varieties grown in a particular region, with high variability among districts (Appendix Table 5).

Summary

The evidence gathered here demonstrates a clear trend towards greater genetic resource use embodied in the wheat varieties grown in the Punjab of Pakistan during 1979-85. Similarly, the indicators of spatial and genealogical diversity also show movement towards greater diversity. The rate of varietal turnover, or temporal diversity, however, seems to be declining, partly because of the long-term persistence of varieties grown by farmers. The persistence of some popular varieties even as newer varieties are adopted has the effect of increasing the average coefficient of diversity ("latent diversity") as well as genealogical distance. A decreasing concentration of area among popular varieties also has a positive effect on the diversity found in farmers' fields — as expressed through the weighted average coefficient of diversity.

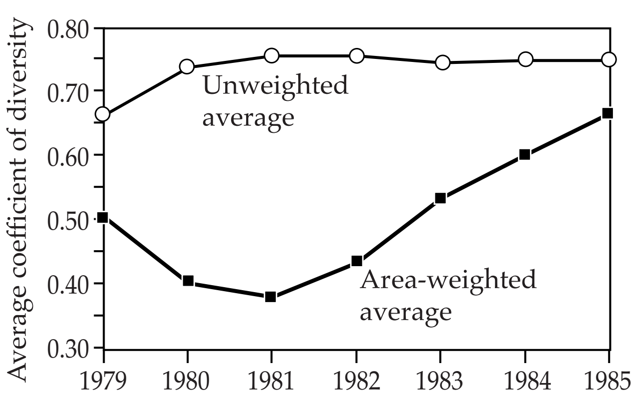

Figure 3. Genealogical diversity of wheat varieties grown in the Punjab of Pakistan, 1979-85.

Note: Average pairwise coefficients of diversity for varieties grown in each year. Coefficient of diversity = 1-coefficient of parentage.

[7] As a benchmark, recall from above that 0.56 is the COP value assumed by Cox, Murphy, and Rodgers (1986) and in this analysis for two selections from the same cross. The COP associated with a COD of 0.76 is only 0.24.

The particular portfolio of varieties grown in an area is influenced by the intensity of plant breeding effort for that location, seed multiplication and distribution systems, farmers' perceptions of the benefit of diversifying their holdings or replacing varieties, the system of wheat production, and public agricultural policy. Yet widely different patterns of diversity, which are likely to be highly related to the production environment, are evident from our examination of district-level data. An inspection of these data reveals considerable variability and interactions among diversity indicators, which are not so apparent when the analysis is conducted at the level of the province as a whole. This finding suggests that efforts to increase diversity at the farm level may require sets of policy instruments specially tailored to each environment, which may be relatively costly.

The Effects of Genetic Resource Use and Diversity on Yield and Yield Stability

Methodology

Estimating yield effects. Improvements in the quality of inputs may result in greater crop production. When the crop output has a market value and a supply response to changes in the quantities of inputs used is observable, it is possible to estimate, using statistical methods, the value of the contribution of both inputs that are traded on markets and those that are not — as well as certain attributes of inputs or input quality. Known as the productivity method, this technique has been widely used to assess the returns to scientific research and technology in agriculture (see Evenson, Waggoner, and Ruttan, 1979, for a partial list organized by commodity). This approach is also appropriate for valuing the use of germplasm resources in varieties released by plant breeding programs (Evenson and Gollin 1991).

Measurement of the contribution of an improved input is complicated by the simultaneous use of other inputs, and estimation of a production function through regression analysis is a commonly used method for assigning contributions of different sources to output changes while holding the effects of other inputs constant (Schuh and Tollini 1979). Using a production function affords an examination of returns from marginal, or incremental, changes rather than average returns. The Cobb-Douglas functional form is a widely used functional form in partial productivity studies (e.g., Nagy 1984; Peterson 1995), in part because the physical relationship it depicts can be readily interpreted with conventional theory. This function assumes a constant substitution elasticity among inputs equal to one. The general equation of the Cobb-Douglas production function is:

$$Y = a\, X_1^{b_1} X_2^{b_2} \ldots X_k^{b_k} \qquad (1)$$

Estimating coefficients is simplified by converting the equation to a linear form and taking its natural logarithm. In logarithmic form, the coefficient of each independent variable X_k (b_k) is interpreted as that variable's production elasticity — which measures the change in output due to an incremental change in that k-th input. The estimated coefficients may be used to calculate the marginal products of inputs, given a level of input use — such as the mean.

The contribution of genetic diversity and germplasm resource use as distinct from other inputs to wheat yield has been estimated using the following production equation in logarithmic form:

(2) $$YLD_{ht} = A\prod_{i=1}^{m} X_{hit}^{\beta i} \prod_{j=1}^{n} Z_{hjt}^{\beta i}$$

where YLD_{ht} = output (yield/ha) of the h-th observation in period t, X_{hit} = the i-th conventional input, including education and weather effects, of the h-th observation in period t, and Z_{hjt} = the j-th genetic resource or diversity input of the h-th observation in period t.

A possible criticism of including the set of genetic resource and diversity variables directly in any production function analysis is that they are not generally thought of as production inputs over which the farmer makes explicit decisions. When a farmer chooses to plant a wheat variety or a combination of wheat varieties based on observable characteristics, he or she also chooses to use an unobservable set of genetic resources and their attributes. Further, the Cobb-Douglas functional form implies a certain physical relationship among inputs that is not likely to capture well the physical relationship of genetic resource variables to crop output. In general, care must be taken in drawing conclusions from the performance of any single variable in the set and we should bear in mind that farmers' choices may be restricted or limited by factors other than production factors.

Estimating effects on yield stability. A yield stability model has also been estimated to focus more specifically on the effects of genetic resource use and diversity on yield variation. A common choice of dependent variable for yield variability studies using time-series data is either the coefficient of variation or the Cuddy-Della Valle index (see Singh and Byerlee 1990). Since the number of years covered in the data are few compared to the number of districts, an alternate method has been used to isolate the effects of inputs on yield variation while preserving all observations for use in the regression analysis.

The dependent variable in the yield stability model was obtained by detrending mean yield over the seven-year period. The detrending procedure used a linear time-trend regression to identify the yearly yield increase. This amount was then subtracted from mean yield for years following the midpoint, here 1982. Similarly, the yearly yield increase was added to mean yield for years preceding the midpoint. With the effect of yield increases removed from the mean, the new dependent variable is calculated by subtracting the detrended mean yield over the time period from each district's observed yield.

Economic theory provides little guidance in the use of a particular functional form or variables to include in a yield stability regression. The regression model was specified as:

(3) $$Y{-}D\overline{Y}_{ht} = \beta_0 + \sum_{I=1}^{m} \beta_i X_{iht} + \sum_{j=1}^{n} \beta_j Z_{jht} + e$$

where $(Y\text{-}DY)_{ht}$ = absolute value of yield first difference of the h-th observation in period t, X_{iht} = the i-th conventional explanatory input, such as weather and fertilizer effects, of the h-th observation in period t, and Z_{jht} = the j-th genetic resource or diversity input of the h-th observation in period t.

Data and variables.

Data source. Cross-sectional time-series wheat production data were obtained for the six years 1979/80 to 1985/86 for each of the 29 districts of the Punjab of Pakistan. Production data were obtained from various issues of *Punjab Development Statistics*, Government of Pakistan, Punjab, Lahore. Genealogical data were obtained from the Wheat Pedigree Management System, maintained at CIMMYT (see Fox and Skovmand 1996). As the objective was to measure the contribution of specific inputs to wheat yield over geographic areas, the unit of observation is input and output per land unit (hectare) for each district. Output is measured in physical units, i.e., yield in tons per hectare. However, some variables, such as measures of education, are expressed as a proportion of the total population in the area.

Sources of error. Specification bias emerging from this data set includes errors in the variables in addition to problems from possible omitted or irrelevant variables. Operational errors in variable measurement occur when quality differences are not included. Where appropriate and when possible, data are adjusted for quality as suggested by Peterson (1987). The anticipated direction of biased estimates, if known, is noted below in the section on regression results when quality adjustment is not possible. Two other possible sources of measurement error noted by Heisey (1990) are varietal identification problems and the use of inappropriate sampling methods in the annual estimates of Punjab wheat varietal distribution conducted by the Crop Reporting Service (CRS) in Lahore.

Conventional input variables. Dependent variables and conventional inputs thought to be important determinants of wheat output are:

Yield	Wheat yield in metric tons per hectare for each district and year.
Yield-DY	Wheat yield variability expressed as tons per hectare from the detrended mean for each district and year.
Irrigation	Calculated as the proportion of wheat cropped area under irrigation for each district.
Fertilizer	Calculated as the total nitrogen, phosphorus, and potassium fertilizer used in the production of wheat in units of kilograms of nutrients per hectare.
Rain	Weather variable calculated as the total cumulative annual rainfall for each district in millimeters.
Literacy	Education variable given as the proportion of the district's population that is literate.
Tractors	A measure of the availability of mechanized traction in each district, expressed as the number of tractors per hectare.
Bullocks	A measure of the availability of non-mechanized traction in each district, expressed as the number of bullocks per hectare.
Labor	A measure of human labor used in the production of wheat for each district. Expressed as total man hours per hectare, where one man-day is the amount of labor performed by a healthy male working seven hours.

As suggested by the section on production environments, irrigated and rainfed areas differ significantly in mean levels of input use and wheat yields (Table 6).

Genetic resource and diversity variables. Genetic resource use and diversity variables were developed from the concepts described above:

Landraces	Average different landraces per pedigree of varieties grown.
Parental combinations	Average number of different parental combinations per pedigree of varieties grown.
GDistance	Genealogical distance of varieties grown, measured as the total branch length of a dendrogram constructed from cluster analysis of pairwise coefficients of diversity. Coefficient of diversity = 1-coefficient of parentage (discussed earlier).
Concentration	Spatial distribution or concentration of wheat area in varieties grown. Measured using the Herfindahl index (defined earlier).
Age	Average age of cultivars grown in each district, used as a measure of varietal turnover.

Table 7 shows that the variables representing genealogical distance and the concentration of area among varieties differ significantly at the mean between rainfed and irrigated production environments.

Table 6. Comparison of mean values for conventional input variables used in regression analysis, Punjab of Pakistan, 1979-85

Variable	All districts	Irrigated		*Barani*
Yield (d)	1.598	1.696	*	0.989
Irrigation	0.788	0.901	*	0.083
Fertilizer	86.487	97.64	*	16.778
Tractors	0.019	0.02	*	0.012
Bullocks	0.684	0.736	*	0.36
Literacy	30.672	27.9	*	47.975
Labor	577.225	614.46	*	344.474
Rain	537.164	444.808	*	1114.392

Note: * indicates a rejection of the null hypothesis that the means are from the same population. Based on a two-independent sample T test. Variables are defined in text.

Table 7. Comparison of mean value for genetic resource and diversity variables used in regression analysis, Punjab of Pakistan, 1979-85

Variable	All districts	Irrigated		*Barani*
GDistance	9.007	10.209	*	1.495
Concentration	0.416	0.3611	*	0.759
Age	8.73	8.733		8.71
Landraces	41.56	41.52		41.806
Parental combinations	93.527	93.534		93.482

Note: * indicates a rejection of the null hypothesis that the means are from the same population. Based on a two-independent sample T test. Variables are defined in text.

Results

Effects on yield: pooling, collinearity, and specification issues. Given significant differences in mean levels of input use between irrigated and rainfed areas, a Chow test was used to determine whether regressions should be estimated separately for each type of production environment. The Chow test compares the residual sums of squares between the restricted model (R = single regression model, all districts) and unrestricted model (UR = separate regression models, by production environment), with the number of parameters in the model denoted by *k*, and number of cases (*n* + *m*):

(4) $$F_{(k,n+m-2k)} = \frac{(RSS_R - RSS_{UR})/k}{RSS_{UR}/(n+m-2k)}$$

An observed F-value of 8.036 confirmed that the models should be estimated separately for irrigated and rainfed production environments.

Two methods of pooling the cross-sectional time-series data were considered. The first combines the data set into one cross-section, implying that individual cross-section parameters remain constant over time, which may not be unreasonable given the relatively short seven-year series. The second method of pooling recognizes that omitted variables, other errors, or changing structural circumstances may lead to changing cross-section and time-series intercepts, which can be captured by including an indicator variable for time, thus allowing for intercept shifts (Pindyck and Rubinfeld 1981).

A test of heterogeneity was also performed to determine the appropriate pooling method. The null hypothesis states that all intercept terms are the same across cross-sections. Two models are regressed. One is restricted (R) to a single intercept whereas the second allows unrestricted (UR) intercepts by the inclusion of indicator variables for different years. The appropriate F-test is as follows:

(5) $$F_{(dfR-dfUR,dfUR)} = \frac{(RSS_R - RSS_{UR})/(df_R - df_{UR})}{RSS_{UR}/df_{UR}}$$

Tests for each of the three possible groupings (all districts and irrigated and *barani* areas) had observed F-statistics greater than their critical value, leading us to reject the null hypothesis suggesting shifting regression intercepts and the inclusion of indicator variables for time when pooling the data.

Examination of the simple correlation matrix of the entire data set reveals a possible mild correlation between predictors with an *r* value of 0.7 between irrigation and parental combinations, genealogical distance, literacy, labor, and fertilizer. Correlation is also evident between age of varieties and the indicator variable for year and between bullock use and labor (*r* = 0.75 for both). However, standard errors of regression coefficients were all generally small and little change occurred when variables were dropped, suggesting that the regression effects of correlation among the explanatory variables are mild.

Among irrigated districts, variance inflation factors (VIFs) for the independent variables ranged between 29.5 and 14.9 for age of variety and indicator variables for year.[8]

[8] The VIF represents the increase in variance due to correlation between predictors, which is suggestive of collinearity.

Some degree of correlation might be expected, since age of varieties will advance one unit for each year. Removing the variable for age of varieties resulted in a reduction of all VIFs as well as a drop in the *condition number k* from 20.3 to 8.7, but changed the signs on the coefficients for the cross and genealogical distance variables (although their t-values remained non-significant).[9] The signs on other coefficients did not change, nor did their level of significance. Based on these results, the age of varieties variable was retained because its coefficient is significant at the 5% level among the irrigated districts.

Collinearity appears to be a moderate problem in these data, but this problem is not easily solved in the absence of new data and because economic theory suggests that each of these variables should be included in the yield decomposition regression. In the *barani* data set, VIFs are generally higher but with changes in coefficients, t-values, and standard errors that are similar to the irrigated areas when variables are omitted.

Finally, diagnostic plots of Studentized residuals versus fitted values for both irrigated and *barani* areas were used to check for correct model specification. Each plot shows little in the way of systematic patterns. Systematic patterns would indicate nonlinearity in the model and the need for respecification. A check for the presence of heteroscedasticity, using non-constant variance score plots, has little evidence in the regression model for irrigated regions but is strongly evident in the model for the rainfed districts. This implies that for the rainfed districts the parameter estimators are inefficient, although they are unbiased and consistent (Pindyck and Rubinfeld 1981).

Interpretation of parameter estimates. Regression results for the effects on yield of conventional inputs and genetic resource and diversity indicators are shown in Table 8. Coefficients of conventional inputs for irrigated areas are of the anticipated positive signs, except for labor. This result is surprising, along with its high significance, because of labor shortages in this production environment. In this instance, the construction of the labor variable may have actually over-stated the true level of labor use. Also of interest, but without explanation, is the lack of significance of the coefficient for tractor use, given the increased role of tractors in wheat production in irrigated areas.[10]

In *barani* areas, negative coefficients were found for rain, bullock use, literacy, and tractor use; all except literacy are significant at a minimum 10% level. Why increased use in these inputs would result in yield reduction is not readily apparent. Wheat in the *barani* areas relies primarily on residual moisture from the summer season, and therefore yearly cumulative annual rainfall at one location is likely to be a poor predictor of soil moisture availability in different districts during the *rabi* cropping cycle. For the rainfall variable, a negative sign might imply that rainfall occurs at the wrong times, such as during harvest, but we cannot draw this conclusion with certainty because the variable is constructed as a yearly cumulative measure. A negative tractor use coefficient could result from adverse soil compaction associated with tractor movement on relatively thinner *barani* soils.

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[9] The *condition number k* is a summary of collinearity based on eigenvalues given as the square root of the ratio of the largest eigenvalue to the smallest eigenvalue. Large values suggest collinearity.

[10] The number of tractors does not reflect changes in tractor quality (e.g., horsepower). Further, the labor and mechanization variables may be inversely related and consequently may be capturing the same effect.

Table 8. Effects on yield of conventional production inputs and genetic resource and diversity indicators

Explanatory variable	Irrigated	*Barani*
Constant	4.493	-8.154
	(1.20)	(-2.41)**
Log[Rain]	0.027	-0.167
	(1.910)**	(-1.84) **
Log[Bullocks]	0.097	-0.707
	(1.88)**	(-2.61) **
Log[Fertilizer]	0.232	0.076
	(6.029)***	(2.03) **
Log[Irrigation]	0.558	0.073
	(8.55)***	(3.266) ***
Log[Labor]	-0.287	0.391
	(-2.84)***	(4.748) ***
Log[Literacy]	0.263	-0.044
	(3.419)***	(-0.905)
Log[Tractors]	0.019	-0.052
	(0.51)	(-1.650)*
{F}Year[80]	0.167	0.078
	(3.73)***	(2.260)**
{F}Year[81]	0.173	0.011
	(2.87)***	(0.242)
{F}Year[82]	0.204	0.169
	(2.72)***	(2.264)**
{F}Year[83]	0.048	-0.084
	(0.56)	(-1.084)
{F}Year[84]	0.193	-0.214
	(1.74)**	(-2.1)**
{F}Year[85]	0.363	0.013
	(2.92)***	(0.116)
Log[GDistance+1]	-0.012	0.168
	(-0.37)	(2.476) **
Log[Age]	-0.399	0.056
	(-2.03)**	(1.041)
Log[Concentration]	0.052	0.028
	(2.12)**	(0.376)
Log[Landraces]	-0.559	1.765
	(-0.44)	(2.131)**
Log[Parental combinations]	-0.258	-0.118
	(-0.42)	(-1.366)
R^2	0.82	0.98
n	175	28
d.f. 156	9	

Note: t-value given in parenthesis; * denotes significance at the 10% level; ** denotes denotes significance at the 5% level; *** denotes denotes denotes significance at the 1% level.

Or perhaps tractor use is positively correlated with the lighter, lower yielding soils.

In the irrigated areas, the estimated effects of the genetic resource and diversity variables are negative except for the coefficient for concentration of area among fewer varieties. Only coefficients for age of varieties and area concentration of varieties are significant. A positive sign for area concentration is anticipated because increased planting of the highest yielding variety will also increase total yields. A negative sign on age of varieties is also anticipated because low varietal turnover suggests the continued use of varieties whose disease resistance is weakened. Slow varietal turnover also denies producers the use of new varieties possibly having greater yield potential as well as other sources of disease resistance.

In *barani* areas, all signs of coefficients of genetic resource and diversity variables are positive with the exception of that for crosses, and only coefficients for genealogical distance and landraces are significant. A positive and significant coefficient on genealogical distance suggests that an increasing dissimilarity of genetic background enhances yield. Here, genealogical diversity may be associated with a widening (or targeting) of the adaptability of varieties to this particular production environment, which would enhance yields. The value of adaptability may also explain the yield enhancing effect of having incorporated additional landrace material, which is often used by breeders for sources of resistance to abiotic stress. However, confidence in the *barani* area regression results is eroded by the small sample size of 28 observations and only 9 degrees of freedom, which may also explain the unusual signs on many of the conventional production inputs.

The yield equations show how different components of the genetic resource use and diversity set become relatively more or less important determinants of yield as one changes production environments. However, because the resource and diversity variables are meant to jointly describe the patterns of diversity found in farmers' fields, it is appropriate to test the significance of their inclusion as a group. F-tests identical to those for testing the hypothesis of unchanging intercepts were employed to test the null hypothesis that all coefficients for the genetic resource and diversity variables are equal to zero. For both irrigated and *barani* areas the observed F-statistics were smaller than their critical values, suggesting that the group of variables provided no explanation for variation in yield. This result is not entirely surprising, considering the strong effects of traditional inputs versus diversity effects, which may be quite subtle determinants of yield growth and yet very important in the maintenance of yield and other qualities. This result may also express shortcomings in our specification.

Effects on yield stability. *Pooling, collinearity, and specification issues* — Because the dependent variable in the yield stability model was detrended, it is not necessary to include indicator variables for each year in order to pool the cross-sectional time-series data set. Independent variables included in the model are the group of genetic resource and diversity variables defined previously in addition to the rainfall and fertilizer use variables. No transformations were made on the dependent or independent variables.

Again, three regressions — for all districts and irrigated and *barani* areas — were performed, followed by a Chow test to determine if it is appropriate to pool or disaggregate the data set. The null hypothesis asks if the coefficients for irrigated and *barani* areas are the same. An observed F-value of 1.515 failed to reject the null hypothesis at the 5% level, allowing use of the regression with all districts.

A plot of Studentized residuals versus fitted values shows that the model is correctly specified but may indicate a degree of heteroscedasticity opening to the right. However, a non-constant variance score plot indicates that heteroscedasticity is not a problem.

Interpretation of parameter estimates — Table 9 presents the regression results for the yield stability model. A positive (negative) sign on regression coefficients implies a decreasing (increasing) effect on yield stability among the districts. Results suggest that those

Table 9. Effects on yield variability of conventional production inputs and genetic resource and diversity indicators

Explanatory variables	All districts
Constant	-3.368 (-4.37)***
Rain	-4.95e-05 (-1.03)
Fertilizer	0.001 (3.17 ***
GDistance	-0.01 (-2.52)**
Age	0.06 (6.60)***
Concentration	-0.05 (-0.64)
Landraces	0.078 (3.56) ***
Parental combinations	-0.004 (-1.37)
R^2	0.29
n	203
d.f.	195

Note: t-value given in parenthesis; * denotes significance at the 10% level; ** denotes significance at the 5% level; *** denotes significance at the 1% level.

variables that contribute to decreasing yield stability are fertilizer use, age of varieties, and landrace content. All three are significant at the 1% level. The only variable that appears to have a significantly positive effect on yield stability is genealogical distance.

This result supports the hypothesis that a wider genealogical distance among cultivated varieties, implying greater "latent diversity," may be associated with greater aggregate yield stability among the districts of Punjab. The effect of fertilizer use is not surprising, since fertilizer use can be either variance-increasing or variance-decreasing, depending on the production circumstances (Just and Pope 1979). Increased age of varieties is likely to tend to increase aggregate yield fluctuations, again because of varietal obsolescence resulting in yield losses (this also depends, of course, on local disease pressure and weather conditions).

Conclusions

Questions concerning the diversity of genetic resources in today's agricultural production and plant technology systems have prompted economists to study the relationships between genetic resources, genetic diversity, and production outcomes. An understanding of these relationships will eventually provide guidance in formulating policies that influence patterns of varietal diversity in farmers' fields and in the allocation of genetic resources to their profitable use.

This study has sought to augment the understanding of genetic resource diversity and value by pursuing two tracks of inquiry that take wheat production in the Punjab of Pakistan from 1979 to 1985 as an example. The first was an examination of patterns of varietal diversity occurring in farmers' fields both at the regional and district levels. The second sought to identify how and in what ways genetic resources have contributed to wheat productivity and yield stability — two important considerations both to individual farmers and national authorities where wheat is the staple food crop.

A prerequisite for any diversity study, however, is the development of indicators appropriate to the task. Here we have expressed genetic resource use and diversity in terms of five distinct concepts. The use of genetic resources is expressed as the number of different landraces and parental combinations appearing in the pedigree of a cultivar. This measure captures the contribution of farmers' previous selections and scientific breeding efforts. The diversity of wheat varieties in a geographical area, as related to productivity, is captured by measures of area concentration (diversity in space) and age of varieties (diversity in time). Finally, the relative dissimilarity of cultivars grown in a geographical area is measured using a distance indicator constructed from genealogical information. Together, these indicators are used to describe the system of wheat genetic resource use and diversity in farmers' fields.

Disaggregated analysis at the district level demonstrates how diversity patterns are influenced by the production environment and by possible differences in the availability of suitable varietal technologies. Generally, the most productive irrigated areas show a cyclical pattern of varietal adoption characterized by more rapid turnover (seven to nine years) but higher concentration of area among fewer varieties.

The marginal, rainfed production environments are characterized by a later and more gradual replacement of landrace types and other tall varieties with semidwarf wheats. However, it appears that fewer varieties are released in these areas or are suitable for their growing conditions, resulting in a high concentration of area in a single variety and low varietal turnover. Other characteristics, such as fodder value, may also have an impact on what varieties farmers choose to grow.

The contribution of the various components of resource use and diversity to wheat production and stability vary by production environment. In the irrigated areas, only concentration of area among fewer varieties and age of varieties has a significant impact on yield. The positive sign on the coefficient of concentration implies that as more area is planted to a single variety, presumably the highest yielding variety, yields rise. The negative coefficient on age of varieties demonstrates that slow varietal replacement has a depressing effect on yield. When more area is concentrated among fewer varieties, however, diversity over space decreases and the risk of yield losses caused by disease increases. Increasing the rate of varietal replacement in farmers' fields counters the likelihood of an epidemic occurring but requires a highly organized and efficient seed multiplication and distribution system. In the *barani* areas, genealogical distance and number of landraces in the genetic background of varieties are positively associated with mean yield.

Test results suggest, however, that the yield effect of genetic resource and diversity variables, as measured by our indicators, is statistically insignificant when those variables are tested as a group. A partial explanation for this result may be that plant breeders are faced with a variety of breeding objectives, of which yield is not of the highest priority. Another explanation is that the genetic resource variables used here do not capture differences in yield potential or genotypic variation in yield, especially when constructed over districts. Even when the yield potential of newly released varieties is higher, current production practices may not fully exploit the benefits. A more likely explanation is that we have not adequately captured biological relationships in the Cobb-Douglas functional form.

The yield stability equation suggests that greater genealogical diversity and increased varietal turnover are associated with reduced yield variability among the districts of Punjab over the study period. The positive effect of genealogical distance, which we have used to measure the dissimilarity of varieties grown, may reflect the value of wide adaptability (or targeted adaptability) of varieties across locations. Higher rates of varietal turnover decrease yield variability by maintaining the disease resistance of varieties in farmers' fields, which reduces the yield destabilizing effects of uneven disease pressure across locations and time.

To synthesize, among the wheats grown in the districts of the Punjab of Pakistan from 1979 to 1985, there are patterns of greater diversity in the varieties grown by farmers. In some factors, there are large differences between production environments and individual districts, which suggest that efforts to increase diversity in farmers' fields will require policy instruments tailored to the individual circumstances of each production environment. Greater genealogical dissimilarity and higher rates of varietal replacement are likely to have positive payoffs relative to aggregate yield stability. In areas where production constraints inhibit farmers' ability to exploit the yield potential of their varieties, better production management is likely to have greater yield enhancing effects than the varietal attributes related to diversity.

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Appendix Table 1. Average number of different landraces in the pedigrees of wheat varieties grown in the Punjab of Pakistan, by district, weighted by proportion of area planted to each variety, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	41.04	42.13	42.95	42.82	43.15	43.29	43.63
Bahawalpur	40.39	41.84	41.59	41.20	41.08	40.91	40.94
Rahim Yar Khan	41.41	41.25	41.17	40.99	40.99	40.71	40.87
D.G. Khan	38.39	39.69	36.01	41.82	43.09	43.31	42.81
Layyah/Liaha	39.41	40.47	40.74	41.27	42.09	41.43	41.67
Muzaffargarh	39.41	40.47	40.74	42.48	43.30	43.24	43.08
Rajanpur	38.39	39.69	36.01	41.94	41.95	41.39	41.97
Faisalabad	41.45	41.88	41.88	41.69	41.79	42.70	42.67
Jhang	41.18	41.16	41.53	41.50	41.47	42.79	43.29
T.T. Singh	41.31	41.51	41.70	41.81	41.89	43.32	43.60
Gujranwala	41.91	42.01	41.92	41.95	41.93	42.04	43.34
Gujrat	41.82	42.04	42.33	42.16	42.33	42.74	43.32
Sialkot	42.01	42.15	42.44	42.32	42.67	42.58	42.65
Kasur	41.98	41.95	41.95	41.94	41.94	42.22	42.69
Lahore	41.66	41.83	41.94	41.95	42.38	42.29	42.66
Okara	41.69	41.44	42.05	42.18	42.14	43.17	42.73
Sheikhupura	41.18	42.01	41.92	41.92	41.76	41.97	42.92
Khanewal	41.31	41.22	41.95	42.44	42.76	43.29	43.89
Multan	41.31	41.22	41.95	42.44	42.76	43.29	43.36
Sahiwal	41.53	41.10	42.10	42.71	42.79	43.84	43.86
Vehari	41.06	41.15	41.70	42.43	43.32	43.04	42.73
Attock	42.78	44.00	44.00	44.00	44.00	44.61	43.91
Chakwal	42.74	43.65	43.66	44.00	43.62	44.27	44.93
Jhelum	42.65	42.71	43.27	44.00	43.46	43.63	43.31
Rawalpindi	40.68	44.00	43.97	43.98	43.97	43.94	43.40
Bhakkar	39.95	39.83	40.45	40.33	40.64	41.33	40.28
Khushab	40.62	40.87	41.32	41.84	41.71	41.68	41.69
Mianwali	39.95	39.83	40.45	40.51	41.28	41.33	40.28
Sargodha	40.85	41.49	41.72	42.09	42.12	43.06	44.12
All Punjab	41.04	41.54	41.57	42.16	42.36	42.67	42.78

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (various years).

Appendix Table 2. Average number of different parental combinations in the pedigrees of wheat varieties grown in the Punjab of Pakistan, by district, weighted by percent of area planted to each variety, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	88.67	95.91	101.09	101.14	103.02	103.53	105.19
Bahawalpur	83.97	93.28	93.74	96.04	96.85	96.23	96.35
Rahim Yar Khan	88.45	89.83	89.42	91.40	94.30	93.70	94.48
D.G. Khan	72.30	81.62	77.35	95.02	102.80	104.77	101.10
Layyah/Liaha	77.25	84.25	86.49	92.87	98.16	92.90	93.02
Muzaffargarh	77.25	84.25	86.49	97.06	102.24	102.80	101.97
Rajanpur	72.30	81.62	77.35	96.31	95.77	94.09	97.40
Faisalabad	90.95	94.23	94.58	93.61	95.00	99.55	99.38
Jhang	89.41	90.85	92.01	92.64	93.48	100.44	102.49
T.T. Singh	90.16	92.49	93.25	94.57	94.83	102.25	103.12
Gujranwala	93.83	94.55	93.72	94.18	94.33	95.46	102.57
Gujrat	92.57	94.93	96.87	96.44	98.35	101.07	103.59
Sialkot	92.61	96.08	97.03	98.05	100.99	101.42	102.56
Kasur	94.03	94.30	94.03	94.08	94.22	95.84	98.28
Lahore	92.17	93.54	94.69	94.12	97.75	97.07	98.98
Okara	91.82	90.85	94.27	95.28	95.31	100.96	99.55
Sheikhupura	89.16	94.45	94.18	94.30	94.19	95.78	100.83
Khanewal	89.19	88.36	94.58	98.19	100.34	102.91	105.27
Multan	89.19	88.36	94.58	98.19	100.34	102.91	103.53
Sahiwal	90.59	88.56	94.43	98.02	99.48	104.64	105.21
Vehari	88.02	88.44	94.11	97.80	102.94	101.73	101.23
Attock	103.51	111.00	111.00	111.00	111.00	112.94	108.78
Chakwal	102.57	108.23	108.28	111.00	107.82	111.28	114.51
Jhelum	99.83	100.70	105.12	111.00	106.47	108.16	104.58
Rawalpindi	86.38	111.00	110.89	110.83	110.77	110.54	106.62
Bhakkar	80.97	84.06	86.65	90.40	93.62	97.28	91.87
Khushab	85.45	89.75	91.09	95.43	95.61	96.40	96.92
Mianwali	80.97	84.06	86.65	86.30	92.04	97.28	91.87
Sargodha	86.96	93.14	93.15	95.96	96.34	101.21	106.95
All Punjab	88.29	92.51	94.04	97.28	98.91	100.87	101.32

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (various years).

Appendix Table 3. Herfindahl index of varietal concentration for wheat in the Punjab of Pakistan, by district, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	0.28	0.22	0.21	0.15	0.17	0.19	0.23
Bahawalpur	0.20	0.25	0.16	0.13	0.16	0.16	0.17
Rahim Yar Khan	0.36	0.43	0.36	0.19	0.14	0.15	0.16
D.G. Khan	0.30	0.28	0.18	0.23	0.26	0.25	0.21
Layyah/Liaha	0.25	0.22	0.18	0.12	0.11	0.15	0.18
Muzaffargarh	0.25	0.22	0.18	0.21	0.15	0.13	0.16
Rajanpur	0.30	0.28	0.18	0.13	0.19	0.16	0.14
Faisalabad	0.56	0.63	0.64	0.55	0.39	0.17	0.16
Jhang	0.49	0.41	0.54	0.50	0.43	0.15	0.16
T.T. Singh	0.52	0.50	0.58	0.70	0.44	0.22	0.28
Gujranwala	0.65	0.79	0.85	0.81	0.70	0.29	0.16
Gujrat	0.42	0.59	0.50	0.41	0.31	0.25	0.20
Sialkot	0.52	0.63	0.35	0.34	0.29	0.19	0.19
Kasur	0.62	0.68	0.85	0.77	0.74	0.53	0.34
Lahore	0.43	0.69	0.68	0.85	0.45	0.35	0.23
Okara	0.67	0.46	0.77	0.69	0.64	0.31	0.22
Sheikhupura	0.58	0.74	0.71	0.68	0.51	0.24	0.18
Khanewal	0.60	0.33	0.43	0.26	0.31	0.42	0.47
Multan	0.60	0.33	0.43	0.26	0.31	0.42	0.41
Sahiwal	0.71	0.36	0.73	0.41	0.30	0.41	0.45
Vehari	0.44	0.36	0.36	0.22	0.41	0.36	0.41
Attock	0.74	1.00	1.00	1.00	1.00	0.66	0.54
Chakwal	0.58	0.76	0.75	1.00	0.70	0.69	0.65
Jhelum	0.36	0.39	0.56	1.00	0.61	0.77	0.40
Rawalpindi	0.45	1.00	0.99	0.99	0.98	0.96	0.71
Bhakkar	0.22	0.17	0.16	0.24	0.30	0.29	0.29
Khushab	0.31	0.24	0.30	0.26	0.22	0.20	0.18
Mianwali	0.22	0.17	0.16	0.14	0.13	0.29	0.29
Sargodha	0.37	0.42	0.45	0.53	0.47	0.32	0.21
All Punjab	0.38	0.35	0.36	0.25	0.18	0.12	0.11

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (various years).

Appendix Table 4. Average age of wheat varieties grown in the Punjab of Pakistan, by district, weighted by percent of area planted to each variety, 1979-85

District	1979	1980	1981	1982	1983	1984	1985
Bahawalnager	8.03	8.23	8.24	8.47	7.98	7.86	7.39
Bahawalpur	8.73	8.80	8.97	7.34	7.17	7.75	8.21
Rahim Yar Khan	8.22	9.63	10.55	9.99	8.63	8.49	9.07
D.G. Khan	9.70	9.65	8.76	9.93	9.76	9.40	10.23
Layyah/Liaha	8.82	9.99	10.00	8.97	8.22	9.37	9.55
Muzaffargarh	8.82	9.99	10.00	9.75	8.52	8.19	7.34
Rajanpur	9.70	9.65	8.76	10.10	10.53	9.02	9.22
Faisalabad	8.79	9.41	10.20	10.99	10.97	8.97	9.46
Jhang	8.85	9.04	10.37	11.07	9.98	9.14	7.97
T.T. Singh	8.82	9.22	10.29	10.92	11.40	5.85	5.73
Gujranwala	8.70	9.70	10.79	11.67	12.16	10.86	9.42
Gujrat	8.53	9.48	10.11	11.07	11.26	11.40	11.14
Sialkot	7.99	9.34	9.84	10.72	10.97	10.72	10.23
Kasur	8.72	9.39	10.74	11.53	12.28	12.05	11.31
Lahore	7.94	9.51	10.42	11.74	10.79	11.00	10.78
Okara	8.90	9.02	10.39	10.84	11.42	9.51	9.37
Sheikhupura	9.01	9.69	10.51	11.46	11.68	10.59	9.68
Khanewal	8.88	9.05	9.26	7.82	7.22	6.63	7.21
Multan	8.88	9.05	9.26	7.82	7.22	6.63	7.43
Sahiwal	9.00	8.77	10.17	8.82	8.36	6.48	7.33
Vehari	8.77	9.49	9.24	7.76	6.15	6.61	7.45
Attock	6.46	7.00	8.00	9.00	10.00	9.66	11.89
Chakwal	6.79	7.43	8.44	9.00	10.51	10.20	10.26
Jhelum	7.76	8.61	8.95	9.00	10.72	11.20	12.13
Rawalpindi	9.10	7.00	7.98	8.94	9.92	10.83	10.86
Bhakkar	8.92	8.49	9.69	8.90	8.83	9.64	9.79
Khushab	9.01	8.60	10.15	10.48	11.08	10.40	11.43
Mianwali	8.92	8.49	9.69	10.29	9.11	9.64	9.79
Sargodha	9.04	8.66	10.36	10.79	11.43	10.96	9.73
All Punjab	8.74	9.18	9.81	9.90	9.76	9.18	9.20

Source: Calculated from data in CIMMYT Wheat Pedigree Management System and Bureau of Statistics (various years).

Appendix Table 5. Number of wheat varieties grown (NV) in the Punjab of Pakistan and their genealogical distance (GD), by district, 1975-85

	1979		1980		1981		1982		1983		1984		1985	
District	**NV**	**GD**	**NV**	**GD**	**NV**	**GD**	**NV**	**GD**	**NV**	**GD**	**NV**	**GD**	**NV**	**GD**
Bahawalnager	13	11.238	13	11.238	14	12.483	13	10.785	15	13.098	14	11.619	13	10.196
Bahawalpur	14	12.483	14	12.483	13	11.238	12	9.729	13	10.307	15	12.625	13	10.271
Rahim Yar Khan	12	9.230	13	11.238	13	11.045	14	11.739	12	9.340	12	9.340	15	12.532
D.G. Khan	9	5.315	9	5.607	12	9.355	11	8.500	14	11.374	12	9.609	12	8.915
Layyah/Liaha	11	8.571	13	11.238	13	11.238	15	13.675	15	13.079	16	13.948	16	13.921
Muzaffargarh	11	8.571	13	11.238	13	11.238	13	10.879	15	12.616	15	12.532	14	11.437
Rajanpur	9	5.315	9	5.607	12	9.355	11	8.500	13	10.701	13	10.425	13	10.194
Faisalabad	12	10.483	11	9.168	14	12.483	15	13.682	17	15.457	16	14.533	15	12.974
Jhang	11	8.571	12	10.483	13	11.238	14	12.790	10	7.161	16	14.533	16	13.948
T.T. Singh	12	10.483	12	10.483	14	12.483	11	7.352	16	14.533	10	7.253	11	8.944
Gujranwala	11	8.571	8	5.487	13	11.724	14	12.563	12	9.917	16	14.301	14	12.258
Gujrat	11	8.571	9	5.607	12	9.355	13	12.002	14	11.780	16	14.533	15	13.716
Sialkot	10	7.489	10	7.656	10	8.529	11	9.390	14	12.563	15	13.716	13	11.351
Kasur	4	1.571	10	7.656	12	9.946	10	8.232	10	8.164	11	7.889	11	9.801
Lahore	8	5.174	9	6.973	10	7.472	7	4.822	9	6.074	10	7.587	10	7.251
Okara	12	9.362	14	12.483	14	12.483	12	8.781	9	6.752	9	6.644	8	5.575
Sheikhupura	12	10.483	13	11.238	13	11.238	13	11.385	15	13.209	16	14.533	15	13.209
Khanewal	13	10.637	14	12.483	14	12.483	16	14.593	17	15.457	14	11.629	10	7.248
Multan	13	10.637	14	12.483	14	12.483	16	14.593	17	15.457	14	11.629	15	12.787
Sahiwal	12	9.362	13	11.045	14	12.483	13	10.918	15	12.974	12	10.049	9	6.644
Vehari	13	10.637	13	11.045	14	12.483	13	10.812	11	8.181	11	8.293	10	7.792
Attock	2	0.576	1	0.000	1	0.000	1	0.000	1	0.000	6	3.588	5	2.757
Chakwal	6	3.354	5	2.339	4	1.852	1	0.000	4	1.572	7	4.170	3	1.077
Jhelum	6	3.354	5	2.339	4	1.852	1	0.000	4	1.572	5	2.455	6	3.345
Rawalpindi	5	2.339	1	0.000	2	0.778	2	0.424	2	0.424	2	0.424	3	1.280
Bhakkar	7	3.976	12	10.483	12	10.483	11	9.201	12	9.227	9	6.654	11	8.160
Khushab	12	9.506	12	10.483	12	10.483	8	5.379	9	6.104	10	6.841	9	6.104
Mianwali	7	3.976	12	10.483	12	10.483	13	12.002	11	8.875	9	6.654	11	8.160
Sargodha	12	9.506	10	6.889	12	10.483	12	9.445	15	11.953	15	12.974	14	11.001
All Punjab	14	12.48	14	12.48	14	12.48	16	14.59	17	15.46	16	14.53	16	13.95

Source: Calculated from data in CIMMYT Wheat Pedigree Management System.

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