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Working Paper 99-12

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Contents

Abstract

Spatial diversity indicators may serve an important function for policymakers as they seek to manage crop genetic diversity and potential externalities associated with diffusion of some types of genetically improved crops. This paper adapts spatial diversity indices employed by ecologists in the study of species diversity to area distributions of modern wheat varieties in contrasting production systems of Australia and China. The variation in three interrelated concepts of diversity—richness, abundance, and evenness—is explained by factors related to the demand and supply of varieties, agroecology, and policies using the econometric method of Zellner's seemingly unrelated regression (SUR). Results suggest that in addition to expected yield and profitability, other variety characteristics are important in explaining variation in the spatial distribution of modern wheat varieties. Environmental factors and policy variables related to the supply of varieties, international research spillins, and market liberalization are also determinants of the diversity in these systems. Explanatory factors affect richness, abundance and evenness in the distribution of modern wheat varieties in different ways. Comparing results between a small, commercial wheat-producing shire in Australia and a large, heterogeneous area in seven provinces of China illustrates the importance of scale and the nature of the farming system. Further research might include: (1) refinement of methods used to construct spatial diversity indices by incorporating geographically-referenced information; (2) more explicit treatment of the relationship between scale of measurement and diversity indices; (3) refinements in the specification of policy variables, and (4) application of similar methods in zones where traditional varieties are grown.

Using Economics to Explain Spatial Diversity in a Wheat Crop: Examples from Australia and China

Melinda Smale, Erika Meng, John P. Brennan, and Ruifa Hu

Introduction

The management of crop genetic diversity in *ex situ* gene banks, and in areas favorable to the production of modern varieties as well as those still dominated by landraces, is part of the global initiative to conserve biodiversity. Many biodiversity issues involve the costs and benefits of avoiding the extinction of species that have aesthetic, intrinsic, or indirect use value to humans through supporting the ecosystem in which they live. By contrast, crop genetic diversity issues pivot on whether maintaining diversity or offsetting its decline in a production zone involves trading the welfare benefits of today's productivity gains for the uncertain benefit of future generations of producers and consumers. As in the species diversity of ecosystems, conservation of crop genetic diversity more accurately refers to the management of complex, evolving systems than to their static preservation. Communities of natural species are transient, although the species of which they are composed possess temporal continuity. Similarly, some groups of crop populations cease to be cultivated as the species to which they belong evolve under human and natural selection pressures.

As priorities are defined and policies are developed to monitor the management of crop genetic diversity, indicators of spatial diversity may serve an important function. "Spatial diversity," probably the most recognized concept of diversity, refers to the amount of diversity found in a given geographical area. Indicators of spatial diversity can be constructed by grouping crop populations cultivated in a specific geographical unit and period of time based on the names given to them by farmers or plant breeders, their genetic content, or their morphology.

Plant pathologists have long been concerned about the "deployment" or spatial distribution of resistance genes and pathogens across crop-producing regions. Scientific concern for genetic vulnerability and uniformity in major crops—at least in developed countries—was renewed during the 1970s following an epidemic of leaf blight in U.S. maize (NRC 1972). As some forms of genetically modified crops gain popularity, the need to ensure genetic "refuges" –or crop areas planted to varieties not carrying the transgene—has emerged (Rissler and Mellon 1996).

Attempting to influence the distribution of cultivars over space is one avenue for *preventive* control of genetic diversity in disease resistance. Priestley and Bayles (1980) describe efforts to enhance genetic diversity in the U.K. through encouraging farmers to grow a mosaic of cultivars with different resistance genes. Deploying artificial gene barriers by planting resistant cultivars along paths of pathogen outbreak is also a strategy for controlling epidemics, although there are few recorded examples of its successful implementation (Dempsey 1990). Variety mixtures (different varieties with similar agronomic requirements) and multilines (closely related varieties differing only in sources of resistance) have been used on a small scale. Taxing farmers for growing susceptible cultivars has also been considered (Brennan, Murray, and Ballantyne 1992).

This paper adapts commonly used ecological indices of spatial diversity to the analysis of diversity in a wheat crop, using data on the area shares of varieties or crop populations. The economic factors that determine the allocation of crop area among varieties, or the supply of and demand for wheat populations and their characteristics, affect variation in diversity indices. The relationship of three concepts of spatial diversity—richness, abundance, and evenness—to economic factors is explored econometrically using seemingly unrelated regressions (SUR). The same economic factors are hypothesized to affect variety richness, abundance, and evenness in different ways.

We would expect the economic factors influencing the spatial diversity of a crop to differ between commercial systems consisting of varieties released by plant breeding programs and semi-commercial or noncommercial systems with more heterogeneous landrace populations. Here we compare analyses of diversity between two modern wheat production systems—a single shire in New South Wales, Australia, over the 1950 to 1998 period, and seven wheat-producing provinces in China from 1982 to 1997.

In China bread wheats are produced for both commercial and subsistence purposes. Approximately 19.2 million hectares of bread wheat were grown in 1997 in the seven provinces included in this study (Anhui, Hebei, Shanxi, Jiangsu, Shandong, Henan, and Sichuan). Most of the wheat grown in these provinces is facultative and winter habit wheat, although spring habit wheat is cultivated in parts of Anhui, Jiangsu, Hebei, and Shanxi Provinces and particularly in Sichuan Province. Percentage distributions of wheat area by habit are difficult to estimate since both spring and winter habit varieties may be planted either in spring or fall. Spring habit varieties planted in the spring are found primarily in parts of Hebei and Shanxi Provinces, which are situated at the conjunction of the main winter and spring wheat producing zones in China. In Anhui and Jiangsu Provinces, the small area that is cultivated in spring wheat is planted in the fall. Sichuan Province in southwestern China is somewhat separated both physically and climatically from the other six provinces included in this study. Sichuan has warmer conditions, where farmers generally plant spring habit wheat in the fall.

On about 40,000 ha in Temora Shire, Australia, wheat farmers generally produce spring habit bread wheats exclusively for sale. In farmers' fields in Temora Shire many of the wheat varieties released since 1973 are related to wheats developed by CIMM YT, but in the seven Chinese provinces the overall influence of CIMMYT materials has been less pronounced. The difference can be attributed in part to CIMMYT's research emphasis on spring wheat, as opposed to winter and facultative wheat,[1] and on disease complexes distinct from those commonly found in China.

With the Temora Shire data, we can examine in detail the effects of variety characteristics, including yield and bread-making quality, on the spatial diversity of a wheat crop within a relatively small geographical area. With the data from China, we can then observe how changes in factors that vary across larger units of analysis, such as agroecology and farming

[1] CIMMYT impacts are more pronounced in spring wheat growing areas, such as Yunnan and Gansu Provinces.

system, condition spatial diversity. The next section of this paper discusses the use of diversity indicators in policy analysis, followed by an explanation of spatial diversity indices used in ecology and adapted in this paper for the study of wheat varieties. The indices are then described for Temora Shire in Australia and seven wheat-growing provinces in China, and regression results are presented.

Using Indicators in Policy Analysis

Indicators are necessary for policy-makers to set priorities and monitor the process of biodiversity conservation. In 1993, Reid et al. commented that the push for action to conserve biodiversity had outpaced the development of the analytical means for doing so. They developed a set of 22 biodiversity indicators for use by policy-makers, only 5 of which were geared to the assessment of diversity in crops and livestock. Of these, only two were related to the genetic uniformity or vulnerability of a crop grown in a production area: (1) varieties grown as a percent of those grown 30 years ago, and (2) the coefficient of kinship or parentage among varieties. While both of these are useful, each, like most indicators, has limitations in terms of definition (e.g., what is a variety?) and the amount of genetic information it reveals. Since we measure the variation in heterogeneous landrace populations and nonsegregating varieties released by plant breeding programs with different metrics, counts comparing them have little meaning. Coefficients of parentage can be calculated only for varieties released by plant breeding programs. They measure latent rather than apparent diversity, since the relationship between ancestry and genetic expression is not easily predicted.

The study of diversity is an old one for ecologists. Diversity indicators are used as a measure of ecosystem well-being in conservation projects and environmental monitoring. Reid et al. (1993) mention the use of ecological indices to gauge species diversity. Begossi (1996) has related ecological indices to questions asked by ethnobotanists, such as how well the diversity of plant species used by human populations represents the diversity available to them, whether most individuals use the same plant species, and whether their usage differs by socioeconomic status or age group.

Similarly, area shares allocated by farmers among varieties measure the extent of their use. Area shares are the revealed preferences of farmers regarding the varieties available to them, and one would hypothesize that the more "useful" a variety (in terms of either profitability or non-commercial uses), the more farmers would plant it. Monitoring farmer demand for varieties and/or their characteristics is one way of monitoring their diversity. In modern crop production, farmer demand is constrained by the supply of varieties released by public breeding programs or private companies. Spatial diversity indices constructed from area shares can be compared between regions, farm types, and crop production systems, while controlling for total hectares represented and other socioeconomic characteristics.

Adapting Ecological Indicators of Spatial Diversity to the Study of Crop Populations

In the ecology literature, Magurran (1988) classifies ecological indices of the spatial diversity of species in terms of three concepts: (1) richness, or the number of species encountered in a given sampling effort; (2) abundance, or the distribution of individuals associated with each of the species; and (3) proportional abundance. A count of species reported or collected in the area, although usually simplest to implement, assumes that all species at a site contribute equally to its biodiversity (Harper and Hawksworth 1995). Since often this is not the case, frequency counts of individuals within a species provide more information. Indices of abundance detect whether or not certain species dominate others.

The third concept, which combines the richness of species with a measure of their relative abundance, includes the widely used Shannon[2] and Simpson indices, as well as the Pielou index, which is also called the Shannon-evenness index. "Evenness," or "equitability," refers to the degree of equality in the abundance of the individuals or the relative uniformity of their distribution across species. When all species in a sample are equally abundant, evenness reaches a maximum (Ludwig and Reynolds 1993). The Shannon and Simpson indices have been termed "heterogeneity indices" and "nonparametric indices" because they account for both and make no assumptions about the shape of the underlying distributions of species. The Shannon index was originally used in information theory but has been commonly employed to evaluate species diversity in ecological communities. It has also been applied in the agronomic literature to compare sets of varieties by transforming qualitative traits into a scalar measure (Spagnoletti, Zeuli, and Qualset 1987; Jain et al. 1975).

Economists studying crop genetic diversity have also begun to use indicators of spatial diversity in empirical applications. In an economic analysis of diversity among landraces of Turkish wheat, Meng (1997) has applied a Shannon index constructed with morphological data measured on seed samples collected from farmers. Brennan et al. (1999) used the area share of the top four varieties as an indicator of dominance in a study of Australian wheats. Widawsky and Rozelle (1998) used the number of varieties accounting for a given percentage of cultivated area. The Herfindahl index, borrowed from the industrial economics literature on market shares and used by Pardey et al. (1996) and Smale et al. (1998), is defined as the sum of squared shares of total crop area planted to each unique variety, or one minus the Simpson index of area shares. Smale, Bellon, and Aguirre (1999) used Pielou and Margalef indices constructed from samples of maize landraces in a variety choice model.

No index is perfect. Any index compresses a lot of information into a scalar and is bound to be ambiguous. The Simpson and Shannon indices each have the disadvantage of confounding the effects of more than one variable by treating them as one (Ludwig and Reynolds 1988). Here, we have adapted and applied several of the ecological indices used to

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2 Shannon and Wiener independently derived the function, which is generally known as the Shannon index (Magurran 1998).

represent spatial diversity to data on wheat varieties grown in Australia and China. Table 1 lists each index used by its name, category, concept, and mathematical construction, with an accompanying explanation.

Spatial diversity indices for Temora Shire

Figure 1 shows the relationship in terms of scale and relative variation of the richness (Margalef), inverse dominance (Berger-Parker), and relative abundance or evenness (Shannon, Simpson, Pielou) for the wheat varieties grown by farmers in Temora Shire, New South Wales, from 1950 to 1997. Richness and inverse dominance show the greatest variation, with the three evenness indices expressing almost the same pattern over time, but with different scales by construction (see Table 1). Peaks in richness occur in the second half of the 1950s and roughly 30 years later, in the late 1980s, with the lowest levels occurring in the late 1970s

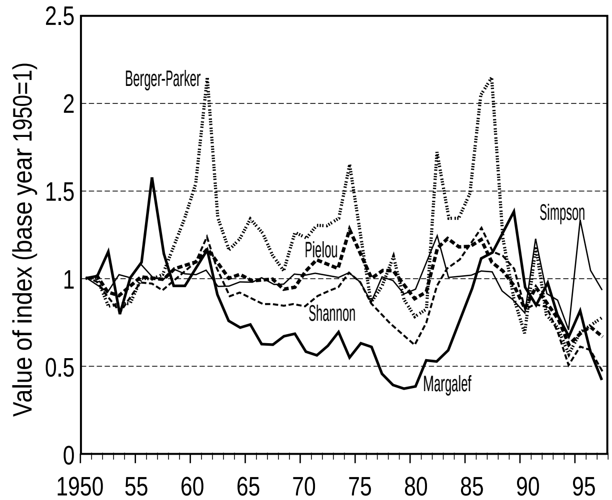

Figure 1. Spatial diversity indices for wheat varieties grown in Temora Shire, 1950-97.

Table 1. Definition of spatial diversity indices used in this paper

Index	Concept	Mathematical construction[a]	Explanation	Adaptation in this paper
Margalef	Richness	$D=(S-1)/\ln N$ $D\geq 0$	Number of species S recorded corrected for the total number of individuals N summed over species	S=number of wheat varieties grown in a season; N=total hectares of wheat in that season
Berger-Parker	Dominance	$D=1/(N_{max}/N)$ $D\geq 1$	The less dominant the most abundant species, the higher the index value	Inverse of maximum area share occupied by any single wheat variety
Shannon	Richness and evenness	$D=-\Sigma p_i \ln p_I$ $D\geq 0$	p_i is proportion, or relative abundance, of a species	p_i is area share occupied by ith variety
Pielou	Evenness	$D=-\Sigma p_i \ln p_I/\ln S$ $0\leq D\leq 1$	Shannon corrected by the logarithm of the number of species recorded	S=number of wheat varieties grown in a season
Simpson	Richness and evenness	$D=1-\Sigma p_i^2$ $0\leq D\leq 1$	Also represented in the form of $D_s=1/\Sigma p_i^2$	

Source: Table adapted from Aguirre, Bellon, and Smale (1998). Mathematical construction as defined by Magurran (1988).

[a] Magurran (1988) reports that in species diversity models the value of the Shannon index is usually found to fall between 1.5 and 3.5, rarely surpassing 4.5. The maximum of the Shannon index is ln S (when all species are equally abundant), so the Pielou (or Shannon-Evenness) index is the Shannon index relative to its maximum. The value of this index should therefore range from zero to 1.

and 1997. Richness and dominance are more independent of each other. Both large numbers of varieties (a peak in the Margalef index) and dominance of a single variety (a trough in the Berger-Parker index) can occur at the same time, as in 1974 and the late 1980s. All of the indices show peaks of different magnitudes in the early 1960s and early 1980s.

Observed ranges, mean, standard deviation, and correlation among the indices are shown in Table 2. As suggested by Figure 1, richness is not highly correlated with any of the other indices. All evenness indices are interrelated, and the inverse dominance index is correlated with each of them. As confirmed by the descriptive statistics, the coefficient of variation is lowest in the Pielou index and highest in the Margalef index.

Spatial diversity indices for seven wheat-producing provinces in China

Spatial diversity indices for wheat varieties grown in the seven major wheat-producing provinces of China are presented in Figures 2-7. Falling in roughly descending order of richness over the 1982-97 period are Hebei, Henan, Shandong, Anhui, Jiangsu, Shanxi, and Sichuan (Figure 2).

A peak in the Berger-Parker index expresses the inverse of dominance (Figure 3). When a number of varieties are available but no variety is clearly superior to others for the traits demanded by farmers, the Berger-Parker index is likely to be high, since the maximum area share represented by any single variety is low. Inadequate seed supplies relative to demand may also constrain the area planted to popular varieties. Like the variety diffusion paths on which it is based, the inverse dominance index for any province shows a cyclical pattern with the emergence and disappearance of popular varieties. A wheat variety may disappear because it is replaced

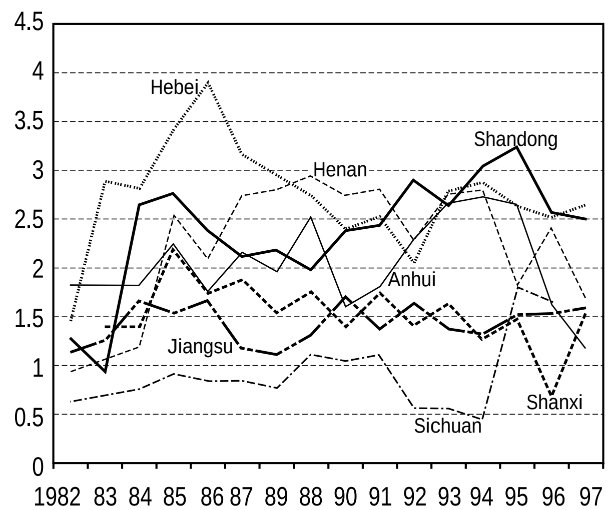

Figure 2. Margalef (richness) index for wheat varieties grown in seven provinces of China, 1982-97.

Table 2. Descriptive statistics for spatial diversity indices, Temora Shire, New South Wales, Australia, 1950-97

				Correlation				
Index	**Mean**	**Standard deviation**	**Range**	**Margalef**	**Berger-Parker**	**Simpson**	**Shannon**	**Pielou**
Margalef	2.59	0.885	1.21–-5.07	1.00	0.168	0.347	0.573	0.098
Berger-Parker	2.69	0.848	1.31–5.00	–	1.00	0.824	0.771	0.790
Simpson	0.744	0.106	.403–.909	–	–	1.00	0.905	0.896
Shannon	1.57	0.311	.819–2.26	–	–	–	1.00	0.834
Pielou	0.681	0.097	.424–.873	–	–	–	–	1.00

by new varieties or because its seed sources gradually diminish, or both. No province is clearly superior to another province, although the inverse dominance index reaches its lowest levels (associated with the greatest dominance by a single variety) in Sichuan and Jiangsu.

The contrast between Sichuan and the other provinces recurs in the evenness indices (Figure 4-6). Sichuan appears to be the least "rich" in wheat diversity. The dominance of a single variety in that province is pronounced. As illustrated in the evenness indices, the spatial distribution of wheat varieties in Sichuan is both relatively "poor" and relatively "inequitable." The reasons for this relative lack of diversity are not immediately clear. Common characteristics of wheat varieties bred in Sichuan are large, dense spikes and high

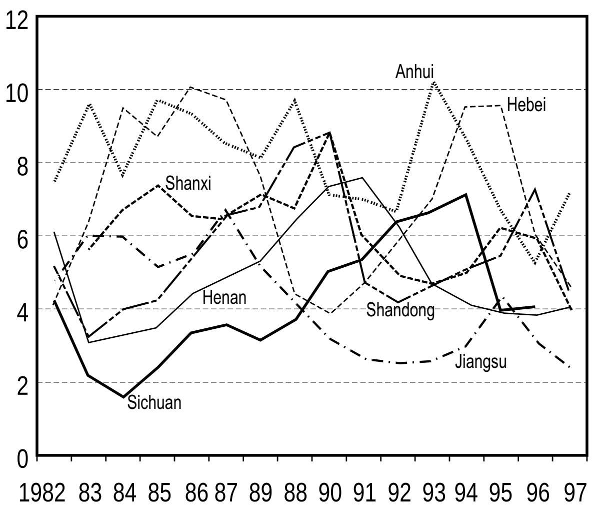

Figure 3. Berget-Parker (inverse dominance) index for wheat varieties grown in seven wheat-producing provinces of China, 1982-97.

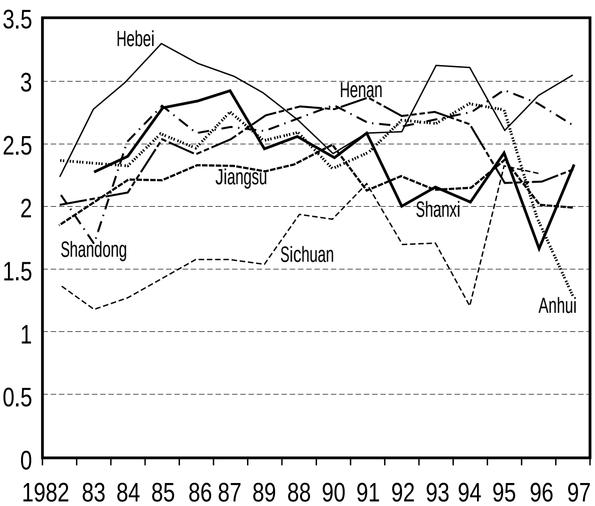

Figure 4. Shannon (evenness) index for wheat varieties grown in seven provinces of China, 1982-97.

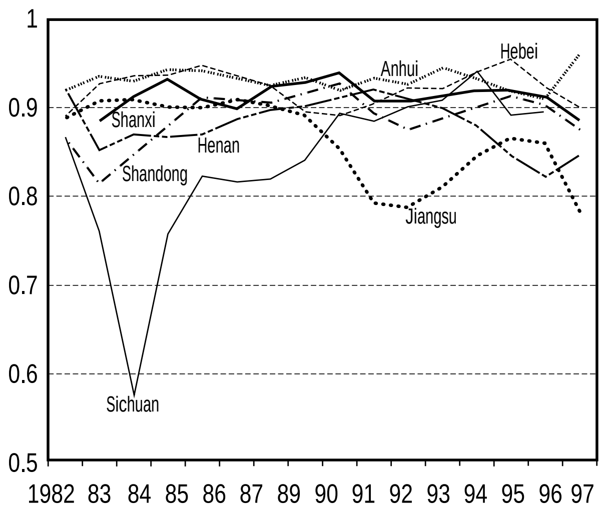

Figure 5. Simpson (evenness) index for wheat varieties grown in seven provinces of China, 1982-97.

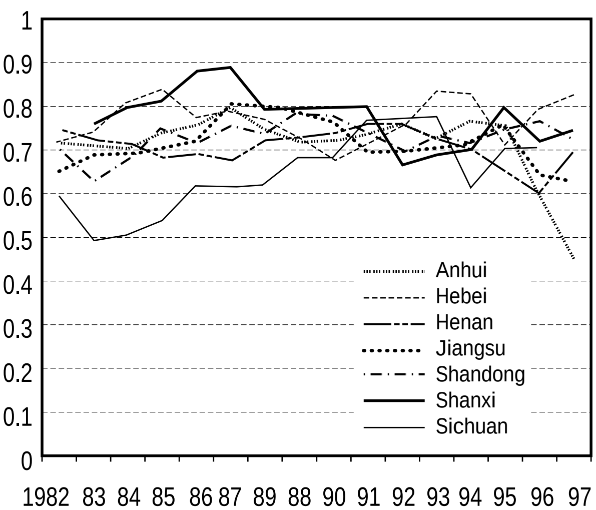

Figure 6. Pielou (evennes) index for wheat varieties grown in seven provinces of China, 1982-97.

thousand-kernel weight. The prevalence of these characteristics may be influenced by a combination of breeding decisions and the relatively short period of time available for tillering in Sichuan's wheat growing areas. The effective supply of wheat varieties in Sichuan could therefore be a factor in determining observed patterns of diversity.

The highest evenness indices are generally, but not always, found in Hebei Province. A possible explanation for the relative evenness among wheat varieties in Hebei may lie in its agroecological suitability for bread wheat varieties of all three growth habits—winter, spring, and facultative. We see similar evenness among wheat varieties and agroclimatic diversity in Shanxi Province, but to a lesser extent than in Hebei. The information provided on the relative evenness of wheat among provinces seems to be generally consistent among the three indices; the Simpson index varies less in relative magnitude, however, than either the Shannon or the Pielou index.

Figure 7 shows the national average of the diversity indices for China over the time period, illustrating their interrelationship. The large expanses of wheat area in China relative to Temora Shire in Australia mean that any single variety is less likely to occupy a high percentage of area. Levels of inverse dominance indices are therefore much higher, and the richness indices much lower, among the provinces of China relative to Temora Shire. The evenness indices, which account for both richness and relative abundance of wheat varieties, are more similar in overall magnitude between the Chinese provinces and Temora Shire. The Shannon index is slightly higher and more variable for the Chinese provinces than for Temora Shire, and the Simpson index is less variable. For the Chinese provinces, as for Temora Shire, evenness indices are interrelated, although much less so in China (Table 1, Table 3). Unlike Temora Shire, in the Chinese provinces the Shannon index is highly correlated with the Margalef index. While we expect evenness indices to be interrelated because of their construction, the relationship between the Margalef or Berger-Parker indices and evenness indices appears to be more of an empirical question.

Economic Factors Explaining Variation in Spatial Diversity

In a commercial cropping system, genetic diversity in a crop depends on the supply of diversity found in the varieties released by public and private breeding programs and farmers' demand for that diversity as expressed through their use of varieties. The variety choices of farmers are constrained by the supply of new varieties made available to them over time, and these choices are demonstrated through the mix of varieties and area sown to each in a given region and time period.

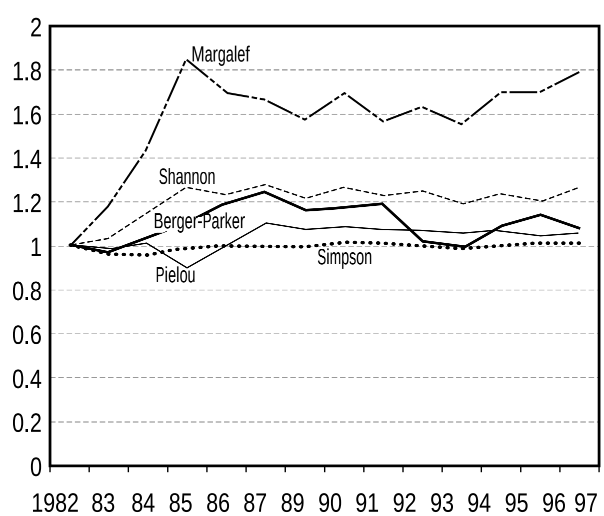

Figure 7. Average spatial diversity indices for wheat varieties grown in seven provinces of China, 1982-92.

The ecological indices adapted for the analysis of spatial diversity in wheat are constructed from variety area shares, which are determined by economic factors affecting the supply and demand of wheat varieties and their characteristics. Brennan et al. (1999) have shown that variety shares are a function of the parameters that determine the supply of and demand for farm products. Parameters that enter wheat production decisions of individual farmers enter the variety share equations for individual farms as well as the aggregates of these variety share equations. An increase in area sown may also change variety shares.

The supply of varieties in commercial wheat systems is determined by lagged investments in research, research spillins from other breeding programs, and legislation affecting variety release. The variables affecting farmer choice of varieties in such systems include variety-specific characteristics such as maturity, expected yield, yield variance, resistance to abiotic and biotic stresses, and resistance to lodging (Brennan 1988; Barkley and Porter 1996). Differences in the profitability of wheat as a crop may also be associated with cultivation patterns among varieties. While prices and costs may be the same for the same class of wheat, they are affected over time by changes in technology. Farmers' decisions are also conditioned by the agroecology and farming system in which they operate—both in terms of the demand for varieties that perform well and the supply of adapted varieties. While agroecological and farming systems are relatively uniform in Temora Shire, they vary by province in China. Marketing institutions affect the supply of seed and attractiveness of varieties, and the panel data from China cover major changes in policy regimes, including the periods of the household reform system and market liberalization.

Specification of Estimating Equations

Since the richness, inverse dominance, and evenness indices express different spatial diversity concepts, each was specified separately as a function of a set of related but distinct variables that determine the demand for and supply of varieties. This specification reflects the hypothesis that the economic determinants of spatial diversity operate differently depending on the diversity concept. In the most general form, the three equations in the systems can be represented as:

(1) $D^r = D^r(\mathbf{X}^r, \mathrm{P} \mid \mathbf{S}, \mathrm{A}, \theta, \mathbf{Z})$

(2) $D^d = D^d(\mathbf{X}^d, \mathrm{P} \mid \mathbf{S}, \mathrm{A}, \theta, \mathbf{Z})$

(3) $D^e = D^e(\mathbf{X}^r, \mathbf{X}^d, \mathrm{P} \mid \mathbf{S}, \mathrm{A}, \theta, \mathbf{Z})$

Table 3. Descriptive statistics for spatial diversity indices, seven major wheat-producing provinces in China, 1982-97

				Correlation				
Index	Mean	Standard deviation	Range	Margalef	Berger-Parker	Simpson	Shannon	Pielou
Margalef	1.91	0.769	0.431-3.90	1.00	0.434	0.449	0.884	0.372
Berger-Parker	5.88	2.16	1.58-10.25	–	1.00	0.778	0.559	0.583
Simpson	0.907	0.053	0.591-0.969	–	–	1.00	0.620	0.685
Shannon	2.41	0.443	1.18-3.30	–	–	–	1.00	0.740
Pielou	0.729	0.068	0.492-0.887	–	–	–	–	1.00

The richness (D^r), inverse dominance (D^d), and evenness (D^e) of the wheat varieties grown by farmers in a region over time is determined by the characteristics of the varieties (vector **X**), real prices and costs of wheat production as these change with technology (P), the supply of varieties and origin of the germplasm (vector **S**), the total area sown to wheat (A), parameters of the diffusion curve (q), and agroecological factors (**Z**). The vector **X** is superscripted because variety characteristics may be expressed or measured differently in the three equations, in part as a reflection of the data.[3]

The variables used in the regression models for Temora Shire and China are defined in Table 4. The dependent variables in both models are Margalef, Berger-Parker, and Shannon indices constructed from variety area share data, as defined in Table 1. Among the evenness indices, the Shannon index was chosen because its variation was greater in both data sets.

Specification for Temora Shire model

The variety characteristics hypothesized to be associated with the richness ($\mathbf{X}^r$) of the wheat varieties grown in Temora Shire are the variance of expected yield, maturity, height, straw strength, the number of genes conferring resistance to stem rust, and bread-making quality. Since maturity and straw strength classes were measured as qualitative variables, they are expressed in terms of a richness index. The bread-making score, a quantitative variable, was calculated by averaging over all scores for the varieties cultivated in a given year. The variance of expected yields was also included since it may be associated with the number of varieties grown by farmers.

The variety characteristics associated with the inverse dominance of a variety ($\mathbf{X}^d$) are its expected relative yield, maturity class, straw type, quality, and height, as well as the number of genes it carries for specific resistance to stem rust. Evenness among varieties, which by definition consists of elements of both richness and relative abundance, is expected to be associated with both sets of the factors ($\mathbf{X}^r$, $\mathbf{X}^d$). [4]

When the output price and input costs are assumed constant across varieties, relative yields are a good proxy for their relative profitability. Profits per ton are included to represent changes in technology and market conditions over time for wheat. The supply of wheat varieties (*S*) is measured by the total number of varieties released in the preceding five years, the number of varieties that are CIMMYT-derived semidwarf wheats, and the proportion originating in the Wagga Wagga research program.

Past area allocation decisions are expressed by the lagged area-weighted average age of varieties (q). On-farm seed supplies and variety choice are lagged responses to variety release. There is some inertia in changing varieties because most farmers save their seed from year to year and only purchase small quantities of new varieties. Diffusion curve

[3] Some of the variables are qualitative and some are quantitative.

[4] The straw strength of the dominant variety was highly (negatively) correlated with its height and was excluded from the analysis. Richness in height and straw type were highly correlated, and richness in height was not used. The number of genes for resistance to stem rust was also highly (positively) correlated with the number of CIMMYT-derived varieties, and was excluded from the inverse dominance equation. Similarly, not all of the characteristics variables could be included in the evenness equation because of collinearity problems.

Table 4. Definitions of variables used in regressions

Location and variable	Definition
Australia (per year)	
D^r	Margalef richness index of varieties for wheat varieties grown
D^d	Berger-Parker dominance index for wheat varieties grown
D^e	Shannon evenness index for wheat varieties grown
P	Real profits per ton (1987-88 A$)
X^r	Margalef richness index of maturity classes for wheat varieties grown Margalef richness index of straw types for wheat varieties grown; variance of expected yield among varieties grown in a given year; variance of bread-making score among varieties grown in a given year; average number of genes conferring resistance to stem rust/cultivated variety
X^d	Expected relative yield of variety with highest area share; maturity class of variety with highest area share; straw type of variety with highest area share; height class of variety with highest area share; bread-making quality of variety with highest area share; number of genes conferring resistance to stem rust in dominant variety
A	Total hectares sown to wheat
S	Number of varieties released in past five years; number of CIMMYT-derived semidwarf varieties in cultivation; proportion of area in varieties released by Wagga Wagga program; lagged area-weighted average age of varieties
China (province and year)	
D^r	Margalef richness index of varieties for wheat varieties grown
D^d	Berger-Parker dominance index for wheat varieties grown
D^e	Shannon evenness index for wheat varieties grown
X^r	Variance of expected yield among varieties grown in a given year; variance in days to maturity among varieties grown in a given year; variance in height among varieties grown in a given year
X^d	Expected yield of variety with highest area share; days to maturity of variety with highest area share; height of variety with highest area share; protein content of variety with highest area share
P	Ratio of real wheat price to total cost of wheat production, in yuan (1995=1)
A	Total hectares sown to wheat
S	Crop research expenditures, in million yuan (1985=1), lagged by four years
θ	Lagged area-weighted average age of varieties
Z	0,1 variables for Anhui, Hebei, Henan, Jiangsu, Shandong, Shanxi (Sichuan excluded); area in saline soils; area affected by drought; area affected by flood; area affected by erosion; multiple cropping index; ratio of irrigated area to total cultivated area; interaction term of ratio of irrigated to total cultivated area with maize-wheat region; 1=1982-84, household reform system; 1=1991-95, market liberalization

information, including the initial adoption lag and the length of the adoption period, is summarized in the area-weighted average age of varieties (Brennan and Byerlee 1991). Since Temora Shire is a very small geographical area with a relatively uniform wheat production system and agroecology, the vector **Z** was not included.

Specification for China model

For China, the vector of variety characteristics is represented by similar variables (length of season, height, protein content, expected yield, and yield variance). Profitability is expressed as the ratio of the real price of wheat to the per-hectare cost of production. The vector **Z** includes dummy variables for provinces, as well as factors describing the agroecology and farming system, such as the extent of land area affected by droughts, floods, erosion, and salinity; the coverage of irrigation systems; and cropping intensity. Dummy variables are used to mark changes in policy regimes with the household reform system and market liberalization. A variable for the overall level of government expenditure in crop research is used as an indicator of the supply of varieties (S). As in the Temora Shire model, the lagged area-weighted average age of varieties is included to express diffusion parameters (θ).

Data Sources

Data sources for both China and Australia are numerous. For Australia, data for the percentage share of area sown to each variety for each year between 1950 and 1988 were combined with data on percentage share of receivals at Temora grain silo (Temora Sub-Terminal) for 1990 to 1997.[5] To construct the area-weighted average age of varieties, the official year of release of each variety for commercial production was obtained from Macindoe and Walkden Brown (1968) and other sources. Profits per ton over the period since 1950 were calculated as the difference between the real local wheat price (in 1987-88 dollars) and the estimated real average costs per ton.

Yield data for each variety have been taken from trials of historical varieties and from selected annual variety trials. For convenience, they have been expressed as an index, with the yield of variety Banks set at 100. The yield of each variety in a given year was expressed as its yield relative to the unweighted average yields of all other varieties grown in that year (as a proxy for the yield levels of varieties available at that time). While the yield level of each variety was taken as fixed over its life, the yield advantage of a newly released variety tended to decline over time as the yields of more-recently released varieties trended upwards.

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[5] In the two years following the last recorded use of the variety, its area was listed as zero (that is, a definite decision was being made not to grow the variety). From the third year after its last use, the variety was considered not available (on the basis that there would have been no seed source), and so no observations were used. Missing variety share data for 1960 (no variety data collected) and 1989 (no data available) were interpolated from data on the preceding and following years. The minor varieties for which there were three or fewer observations, or for which the peak share was 3% or less, were excluded from the analysis. Of the total of 46 varieties, 13 were excluded on these criteria.

Data on other variety characteristics were drawn from multiple sources.[6] Height, maturity, and straw strength were each recorded on a scale of 1 to 6, with 6 corresponding to longest maturity period and greatest height or straw strength. Bread-making scores were developed by panel assessment.[7] Data on resistance mechanisms for rusts were compiled by Dante The and Colin Wellings of the National Rust Control Program, Sydney.

For China, panel data on input and output prices, expenditures, environmental conditions, and agricultural research investment have been assembled for the provinces of Anhui, Hebei, Henan, Jiangsu, Shanxi, Shandong, and Sichuan from 1982 to 1995. Data on the cost of wheat production come from a national Price Bureau data set collected over 20 years from a representative national sample of more than 400 counties and 20,000 households, combined with data from separate provincial surveys. Provincial input prices were also calculated from information provided in the *Agricultural Input Category Price Index*. China's statistical and agricultural yearbooks were the primary source for data on wheat area and production. Additional information on variety area shares was taken from relevant years of the publication *Agricultural Crop Sown Area by Variety* and from interviews with personnel at the Henan and Shandong Provincial Seed Management Stations. The national Science and Technology Bureau provided data on agricultural research investment. Total research expenditures were multiplied by the share spent on crops and lagged by four years, to represent the time spent finishing varieties. Yield and trait data refer to the time of release and were obtained by a thorough search of publications on wheat varieties and breeder surveys conducted by the Center for Chinese Agricultural Policy (CCAP). Finally, data on environmental variables were drawn from China's environmental yearbooks.

Econometric Results

Temora Shire model

Initially, the three equations were estimated separately with ordinary least squares. Since there is reason to believe that errors in area shares and the resulting diversity indices may be serially correlated or dependent on the levels of some of the explanatory variables, each was tested for first-order correlation with a Durbin-Watson test and for general heteroscedasticity using a Breusch-Pagan test. The Durbin-Watson statistic tests only for first-order intertemporal correlation in the error structure. The Breusch-Pagan tests the null hypothesis of homoscedasticity against the alternative hypothesis that variance is some function of more than one explanatory variable (Judge et al. 1982) All values of the test statistic lie in the inconclusive range for first-order autocorrelation. Based on the Breusch-Pagan test, the null hypothesis of homoscedasticity was rejected at the 5% significance level for the dominance and richness equations in the Temora Shire model. For the evenness equation, the null hypothesis of homoscedasticity could not be rejected.

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[6] Data were obtained with the assistance of John Woolston, CIMMYT, from a number of sources, including: Macindoe and Brown (1968); Ferns et al. (1975, 1978); Fitzsimmons et al. (1983 and n.d.); articles in journals including *Agriculture Gazette of New South Wales, Annual Wheat Newsletter, Australian Journal of Experimental Agriculture,* and *Plant Varieties Journal*; and from Cereal Communiques and registration documents provided by Michael C. Mackay, Australian Winter Cereals Collection, Tamworth NSW.

[7] Reported in Antony and Brennan (1988) and updated and extended by John Oliver and Helen Allen, NSW Agriculture, Wagga Wagga, NSW.

There is also reason to believe that the same errors that affect the richness of the varieties planted in any season may also affect their relative abundance and the equitability of their distribution in a geographical area. Zellner's seemingly unrelated regression (SUR) model exploits the underlying relationships in the errors among estimating equations by estimating them jointly in a generalized least squares procedure. When each dependent variable is a function of the same explanatory variables, the estimation is equivalent to ordinary least squares. When the three dependent variables are functions of different explanatory variables but are hypothesized to be related through their error structures, statistical efficiency gains may be made through SUR estimation. The greater the correlation of the disturbances among equations, the greater the efficiency gains from running the equations jointly (Greene 1997). The more distinct the matrices of explanatory variables, the greater the efficiency gain.

Results of the SUR estimation for Temora Shire are shown in Table 5.[8] All three equations are statistically significant at the 1% level, as indicated by the log-likelihood ratio test. Differences are apparent among the regressions in the significance and interpretation of the effects of individual explanatory factors.

The richness of the varieties grown by farmers in Temora Shire over the past 58 years has not been affected by the richness in maturity classes or straw strength. Neither the profitability of wheat production nor the variance of crop yield is significantly associated with variety richness. As varieties have carried larger numbers of resistance genes for stem rust, richness in varieties has declined. When a larger area is sown to wheat, variety richness is lower—since other factors held constant, the greater the scale of the area covered, the higher the numbers of varieties necessary to attain the given level of richness. The presence of older varieties, or slower diffusion and variety turnover, positively influences richness, as does the number of CIMMYT-related varieties. Except for Kite, Harrier, and Sunelg, all of the other varieties released since 1973 that were grown in Temora Shire have CIMMYT ancestry. Only 5 of the 24 varieties released since 1966 that were grown in Temora Shire were not released by the State. With the exception of Sunstar and Vulcan, all of these were also released locally, so that the proportion of area planted to Wagga Wagga releases and State releases is almost equivalent. The proportion of area planted to wheats released locally was not significantly associated with variety richness.

Since the Berger-Parker index of relative abundance/dominance is the inverse of the area share occupied by the dominant variety, a negative coefficient in the inverse dominance regression implies that the variable is positively associated with the popularity of the leading variety. The profitability of wheat production in Temora Shire is associated with greater concentration of area in the leading variety. The higher the relative expected yield of the leading variety, the greater its dominance. The longer the length of its growing season, the higher its area share. The better its bread-making quality, the more popular the variety

[8] Regressions were run using LIMDEP 7.0. No correction was made in the GLS estimation for the likely heteroscedasticity in the OLS regression of dominance on explanatory variables because it would complicate the diagnostics considerably. In the SUR (iterative GLS) regression, the test of significance of individual coefficients is the Z statistic. The significance of each equation was evaluated with a log-likelihood ratio test comparing regression on a constant with the hypothesized regression model.

is, as reflected in the amount of cultivated area. The number of varieties released reduces the dominance of the most popular variety, as does slower variety turnover.

The variables in the evenness regression do not include all of those in the richness and dominance regressions since some were highly correlated. The results demonstrate clearly, however, that variety characteristics are related to evenness. Evenness in the distribution of varieties, or "equity" among varieties in terms of the area they occupy, is affected by their relative yields, the length of growing period of the dominant variety, and the number of resistance genes for stem rust. The variation among the expected yields of the wheat varieties grown by farmers is positively associated with evenness in their distribution. Supply factors are also important. Greater area sown to wheat, or a larger scale of analysis, is associated positively with evenness in the spatial distribution of varieties. A higher rate of variety release and the continued presence of older varieties have the effect of distributing varieties more equitably. The number of CIMMYT-derived varieties is associated positively with evenness. The underlying data show that CIMMYT ancestry is also related to the number of resistance genes for stem, leaf, and stripe rust as well as resistance to septoria leaf blotch.

Table 5. Results of generalized least squares regression (SUR) of wheat diversity indices on explanatory factors, Temora Shire

	Richness		Dominance^{-1}		Evenness	
Explanatory variable	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Constant	3.83	.771	6.56	3.28	1.58	.506
Profitability of wheat production	.00126	.00112	–.00384 +	.00207	–.000169	.000355
Expected relative yield of dominant variety	–	–	-.0535 *	.0249	–.00717 *	.00368
Crop yield variance	-.00537	.00416	–	–	.00210 +	.00120
Longer season length of dominant variety	–	–	.228 *	.117	.0385 +	.0212
Richness in maturity class	–.0583	.241	–	–	–.0502	.0638
Richness in straw types	–.714	.651	–	–	–.0868	.189
Variation in bread-making quality	.0259	.0545	–	–	.00226	.0172
Bread-making quality of dominant variety	–	–	–.136 *	.0589	–	–
Average number of resistance genes for stem rust per variety	-.715 *	.189	–	–	–.256 *	.0584
Taller height of dominant variety	–	–	.000149	.000380	.000121	.0000957
Number of varieties released in past five seasons	.0223	.0395	.244 *	.0789	.0520 *	.0129
Number of CIMMYT-derived varieties	.294 *	.0618	.00636	.0651	.0856 *	.0172
Proportion of area in Wagga Wagga releases	–.119	.390	–.109	.533	–.162	.128
Total wheat area	–.0300 *	.0070	.0169	.0117	.00364 +	.00212
Lagged area-weighted average age	.0708 *	.0192	.0812 *	.0316	.0388 *	.00589
Value of log-likelihood ratio	59.38		27.11		67.76	
Number of observations	48		48		48	

Note: * indicates statistically significant at 5% level of significance with two-tailed Z statistic; + indicates statistically significant at 10% level with two-tailed Z statistic.

China model

Results of the SUR regression for seven major provinces in China are shown in Table 6. Log-likelihood ratio tests confirm that each individual regression is significant at the 1% level.[9] Similarly to the Temora Shire regressions, variety characteristics other than expected yield potential are associated with the diversity indices for richness, dominance, and evenness. Lower variance in expected wheat yields is associated with greater richness in (and a more equitable distribution among) the varieties grown by farmers. Variation in height and season length, both quantitative variables in the Chinese data, is positively associated with variety richness and evenness. The longer the season length of a dominant variety, the lower the percentage of wheat area it occupies, while the higher the protein content, the greater its area domination.

The ratio of wheat price to per-hectare total cost of production has a statistical relationship only with the evenness index, and the relationship is weak. Total area sown to wheat is not associated significantly with any of the diversity indices, which may reflect the large scale of analysis in China relative to Temora Shire. As in the Temora Shire relationship, however, the slower the turnover among wheat varieties, the greater their diversity in terms of any of three indices.

The regressions for China illustrate, as could not be demonstrated with data from a single shire in Australia, the importance of agroecological factors in determining the diversity of wheat varieties grown by farmers. The greater the saline area, the greater the dominance of the most popular variety, perhaps because of its comparatively better performance on this type of land. However, greater richness, less dominance, and more even distributions of wheat varieties are found where more eroded crop area exists. Perhaps there is no single variety that is better suited for production in these growing conditions. The greater the irrigated area as a proportion of all cultivated area, the more dominant the leading wheat variety. The interaction effect of this factor with the maize-wheat region enhances variety richness but dampens the dominance of the most popular wheat variety. The multiple cropping index is also associated with a higher level of diversity as represented by richness, inverse abundance, and evenness measures. Finally, the econometric results confirm that all provinces are significantly more diverse than Sichuan Province, in terms of any of the three diversity indices.

Policies also appear to influence the diversity of wheat varieties grown by Chinese farmers. In the early years of the household reform system (1982-84), farmers were free to sell surpluses and may have concentrated area on the highest-yielding variety or the variety most suitable for sale. The dominance of the leading variety was greater, and the distribution of varieties less even, from 1982-84. Market liberalization is expected to have improved the supply of seed relative to the 1985-90 period. Regression results are consistent with this hypothesis, indicating that variety richness was greater from 1991-95, other factors held constant. Expenditures on crop research are not associated statistically with any of the diversity indices—perhaps because the variable is measured too broadly and is therefore indirectly related to the supply of varieties.

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9 As was the case for Temora Shire, tests for autocorrelation in individual OLS regressions were inconclusive and Breusch-Pagan tests indicate the presence of general heteroscedasticity in one of the equations.

Conclusions

Results of SUR regressions demonstrate that diversity indices for wheat varieties grown in Temora Shire, New South Wales, are related strongly to economic factors affecting the demand for and supply of varieties, even when measured roughly with proxy variables. This makes sense given that the indices are composed of area shares which represent the outcome of farmers' choices in the aggregate, as these choices are constrained by the supply of modern wheat varieties and their characteristics as developed by breeding programs.

Table 6. Results of generalized least squares regression (SUR) of wheat diversity indices on explanatory factors, seven major wheat-producing provinces of China

Explanatory variable	Richness Coefficient	Richness Standard error	Dominance^{-1} Coefficient	Dominance^{-1} Standard error	Evenness Coefficient	Evenness Standard error
Constant	–27.61 *	7.72	–75.32 *	28.9	–17.5	4.59
Real wheat price/per ha production cost	636	800	2229	2798	755 +	450
Expected yield of dominant variety	–	–	.00207	.00227	–.000266	.000289
Crop yield variance	–.000168 *	.0000744	–	–	–.0000717 +	.0000412
Variation in season length	.000144 *	.0000518			.0000578 *	.0000284
Variation in height	.00614 *	.00284	–	–	.00431 *	.00161
Longer season length of dominant variety	–	–	.0437 *	.0230	–.00171	.00297
Protein content of dominant variety	–	–	–.241 +	.150	–.0334 +	.0198
Taller height of dominant variety	–	–	.0155	.0250	.00247	.00321
Salinity	.000214	.00338	–.0472 *	.0122	–.00374 +	.00194
Erosion	.000819 *	.000308	.00210 +	.00116	.000549 *	.000184
Flood	–.0000318	.0000709	.0000199	.000243	.0000189	.0000393
Drought	.0000350	.0000626	.000169	.000222	.0000275	.0000358
Multiple cropping index	2.64 *	.963	11.61 *	3.86	2.12 *	.595
Ratio of irrigated to total cultivated area	2.39 +	1.47	–18.96 *	4.99	–.542	.868
Interaction of irrigation ratio and maize-wheat region	3.73 +	2.31	16.87 *	7.23	2.73 *	1.32
Lagged crop research expenditures	–.000466	.000298	.000381	.00105	–.0000666	.000171
Total wheat area	.000418	.000406	–.000400	.00139	.0000322	.000227
Lagged area-weighted average age	.0835 *	.0414	.876 *	.136	.112 *	.0232
Household reform system	–.0475	.197	–1.48 *	.679	–.291 *	.112
Market liberalization	.321 *	.128	.0946	.454	.0758	.0737
Anhui	19.4 *	7.21	56.9 *	27.2	13.5 *	4.32
Hebei	15.3 +	8.27	87.2 *	30.8	14.5 *	4.92
Henan	14.0 +	7.88	71.9 *	29.2	13.0 *	4.68
Jiangsu	19.3 *	9.37	90.5 *	35.1	16.7 *	5.59
Shandong	15.2 +	8.88	85.7 *	32.9	14.9*	5.28
Shanxi	14.8 *	5.47	46.7 *	21.2	10.9 *	3.35
Value of log-likelihood ratio	97.9		80.8		105.0	
Number of observations	91		91		91	

Note: * indicates statistically significant at 5% level of significance with two-tailed Z statistic; + indicates statistically significant at 10% level with two-tailed Z statistic.

The importance of variety characteristics such as bread-making quality, protein content, maturity, and height in explaining the diversity of wheat varieties grown by farmers is evident both at a small scale of analysis (Temora Shire) and across a large wheat-producing area (the seven wheat-producing provinces in China). While profitability and expected yield may matter in Temora Shire, the effect of wheat price and total costs of wheat production is not statistically significant in the Chinese provinces.

The two sets of regressions provide some information of relevance to research policy in general. At both scales of analysis, ironically, a slower rate of variety turnover in the field is positively related to wheat diversity. On the other hand, the Temora Shire data demonstrate the positive effect on wheat diversity of a more rapid rate of variety release and the utilization of CIMMYT materials in the breeding programs. In the Chinese data, the effect of market liberalization on the richness of the wheat varieties grown by farmers is positive, while the period of the household reform system is associated with greater dominance of the leading variety and less evenness in the area distribution of varieties. The Chinese data also enable us to test the effects of agroecological and farming system variables across a larger wheat-growing area. Provincial effects are significant, as is the extent of erosion, salinity, and irrigation. The intensity of the cropping system, as measured by the multiple cropping index, also plays a role.

In future analyses, if data include more comprehensive information on policies affecting the supply of and demand for wheat varieties, more targeted policy implications may also be developed. When data can be analyzed at progressively larger "scales," as is recognized in the ecology literature, additional insights might be gleaned by comparing the impacts of certain policies at the shire, state, and national levels. Ideally, indices of spatial diversity in crops should be based on geographically referenced data to allow the pattern of varieties across landscapes and ecologies to be better represented. Aggregating across spatial scales may require specialized techniques that relate these indices to scale of measurement (see Kunin 1998). Comparison among different systems of landrace populations and modern wheats would provide another type of information, especially when the management of genetic resources in centers of crop diversity is the focus of the analysis. The methodology proposed in this paper may also be useful in socioeconomic studies of the spatial distributions of more gene-based definitions of varieties, such as varieties carrying certain types of genetic resistance to disease or transgenes.

References

Aguirre G., J.A., M.R. Bellon, and M. Smale. 1998. *A Regional Analysis of Maize Biological Diversity in Southeastern Guanajuato, Mexico.* CIMMYT Economics Working Paper 98-06. Mexico, D.F.: CIMMYT.

Antony, G., and J.P. Brennan. (1988), *Improvements in Yield Potential and Bread-Making Characteristics in Wheat in New South Wales 1925-26 to 1983-84*. Miscellaneous Bulletin 55. Division of Marketing and Economic Services, Department of Agriculture New South Wales.

Barkley, A.P., and L.L. Porter. 1996. The determinants of wheat variety selection in Kansas, 1974 to 1993. *American Journal of Agricultural Economics* 78: 202-211.

Begossi, A. 1996. Use of ecological methods in ethnobotany: Diversity indices. *Economic Botany* 50(3): 280-289.

Berger, W.H., and Parker, F.L. (1970). Diversity of planktonic Foraminifera in deep sea sediments. *Science* 168: 1345-7.

Brennan, J.P. 1988. *An Economic Investigation of Wheat Breeding Programs.* Agricultural Economics Bulletin No. 35. Department of Agricultural Economics and Business Management, University of New England, Adelaide.

Brennan, J.P., and D. Byerlee. 1991. The rate of crop varietal replacement on farms: measures and empirical results for wheat. *Plant Varieties and Seeds* 4: 99-106.

Brennan, J.P., D. Godden, M. Smale, and E. Meng. 1999. Variety choice by Australian wheat growers and implications for genetic diversity. Contributed paper, 43rd Annual Conference of the Australian Agricultural and Resource Economics Society, Christchurch, New Zealand, January.

Brennan, J.P., G.M. Murray, and B. Ballantyne. 1992. Private and social costs of growing cultivars susceptible to diseases. Contributed paper, Annual Conference of the Australian Agricultural Economics Society. Canberra, Australia.

Dempsey, G.J. 1990. Genetic diversity and disease resistance in crops: Two debates over the conservation and use of plant genetic resources. Ph.D. dissertation. University of Sussex.

Ferns, G.K., R.W. Fitzsimmons, R.H. Martin, D.H. Simmons, and C.W. Wrigley. 1975. *Australian Wheat Varieties, Identification According to Growth, Head and Grain Characteristics.* N.p.: Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Ferns, G.K., F.W. Fitzsimmons, R.H. Martin, and C.W. Wrigley. 1978. *Australian Wheat Varieties, Supplement No. 1: Eleven Recent Wheats, Grain Defects and Appendices on Foreign Seeds and Insects.* N.p.: Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Fitzsimmons, R.W., R.H. Martin, and C.W. Wrigley. 1983. *Australian Wheat Varieties, Identification According to Plant, Head and Grain Characteristics.* 2nd edition. East Melbourne, Victoria: Commonwealth Scientific and Industrial Research Organisation (CSIRO) Education and Publications Service.

Fitzsimmons, R.W., R.H. Martin, and C.W. Wrigley. N.d. *Australian Wheat Varieties, Supplement No. 1 to the Second Edition: Sixteen Recent Wheats and an Appendix on Australian Triticale Varieties.* East Melbourne, Victoria: Commonwealth Scientific and Industrial Research Organisation (CSIRO) Education and Publications Service.

Greene, W.H. 1997. *Econometric Analysis*. Third Edition. Upper Saddle River, New Jersey: Prentice-Hall.

Harper, J.L., and D. L. Hawksworth. 1995. Preface. In D. L. Hawksworth (ed.), *Biodiversity Measurement and Estimation.* London, U.K.: The Royal Society and Chapman and Hall.

Jain, S.K., C.O. Qualset, G.M. Bhatt, and K.K. Wu. 1975. Geographical patterns of phenotypic diversity in a world collection of durum wheat. *Crop Science* 15: 700-704.

Judge, C.G., R.C. Hill, W. Griffiths, H. Lutkepohl, and T.-C. Lee. 1982. *Introduction to the Theory and Practice of Econometrics.* New York and Toronto: John Wiley and Sons.

Kunin, W.E. 1998. Extrapolating species abundance across spatial scales. *Science* 281(4): 1513-1515.

Ludwig, J.A., and J.F. Reynolds. 1988. *Statistical Ecology: A Primer on Methods and Computing.* New York, New York: John Wiley.

Macindoe, S.L., and C. Walkden Brown. 1968. *Wheat Breeding and Varieties in Australia.* 3rd edition. Sydney, New South Wales: Division of Plant Industry, NSW Department of Agriculture.

Magurran, A. 1988. *Ecological Diversity and its Measurement*. Princeton, New Jersey: Princeton University Press.

Meng, E.C.H.1997. Land allocation decisions and *in situ* conservation of crop genetic resouces: The case of wheat landraces in Turkey. Ph.D. thesis. University of California, Davis, California.

NRC (National Research Council). 1972. *Genetic Vulnerability of Major Crops.* Washington, D.C.: National Academy of Sciences.

Pardey, P.G., J. M. Alston, J.E. Christian, and S. Fan. 1996. *Hidden Harvest: US Benefits from International Research Aid.* Washington, D.C.: International Food Policy Research Institute (IFPRI).

Pielou, E.C.1969. *An Introduction to Mathematical Ecology.* New York: John Wiley.

Priestley, R.H., and R.A. Bayles. 1980. Varietal diversification as a means of reducing the spread of cereal diseases in the United Kingdom. *J. National Institute of Agr. Botany* 15: 205-14.

Reid, W.V., J. A. McNeely, D.B. Tunstall, D.A. Bryant, and M. Winograd. 1993. *Biodiversity Indicators for Policy-Makers.* Washington, D.C.: World Resources Institute.

Rissler, J., and M. Mellon. 1996. *The Ecological Risks of Engineered Crops.* Cambridge, Massachussetts: MIT Press.

Simpson, E.H. 1949. Measurement of diversity. *Nature* 163: 688.

Smale, M., J. Hartell, P. W. Heisey, and B. Senauer. 1998. The contribution of genetic resources and diversity to wheat production in the Punjab of Pakistan. *American Journal of Agricultural Economics* 80: 482-493.

Smale, M., M. Bellon, and A. Aguirre. 1999. *Private and Public Characteristics of Maize Landraces and the Area Allocation Decisions of Farmers in a Center of Crop Diversity.* Economics Working Paper 99-08. Mexico, D.F.: CIMMYT.

Spagnoletti Zeuli, P. L., and C.O. Qualset. 1987. Geographical diversity for quantitative spike characters in a world collection of durum wheat. *Crop Science* 27: 235-241.

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

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