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Determinants of spatial diversity in modern wheat: examples from Australia and China

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Abstract

The spatial distribution of modern varieties, and the genes they embody, has economic value because it affects crop productivity from year to year. Since farmers choose varieties based on observable traits rather than the genes they cannot see, a first step in understanding the spatial distribution of genes is to better understand the determinants of the spatial distribution of varieties. In this paper, we have constructed spatial diversity indices from area distributions of modern wheat varieties in Australia and China. We hypothesise that factors explaining variation in these indices are related to farmers' demand for traits and the supply of varieties, given physical features of the production environment. We test these hypotheses using reduced form equations for three concepts of spatial diversity, richness, abundance and evenness, using Zellner's seemingly unrelated regression (SUR). Spatial diversity indicators and analyses of this type, if more fully developed and targeted to address specific policy issues, may assist in monitoring crop genetic diversity or 'refuge' targets associated with the diffusion of some genetically modified crops.

Keywords: Wheat; Biodiversity; Variety choice

1. Introduction

Biodiversity conservation in a broad sense encompasses the diversity among and within wild and domesticated species, including crop plants that continue to evolve under natural and farmer-selection pressures. Mistakenly, managing crop genetic diversity in farmers' fields has become synonymous with landrace cultivation. Crop genetic diversity serves a purpose in areas favourable to the production of modern varieties as well as those still dominated by landraces.

With modern varieties of a self-pollinating species such as wheat, as compared with either more heterogeneous landraces or open-pollinated varieties, crop genetic diversity is expressed among rather than within varieties. The spatial pattern of the varieties grown by farmers affects annual yields and production risks in a crop-producing area. Though these effects may be more pronounced in landrace systems with fewer external inputs, the area distribution of modern varieties over a landscape and the genes they carry has economic value.

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For example, plant pathologists have long been concerned about the spatial distribution of resistance genes across areas of cultivation. Attempting to influence the distribution of varieties over space is one avenue for preventive control of plant disease epidemics. Priestley and Bayles (1980) describe efforts to enhance the diversity of genetic resistance to disease in the United Kingdom by encouraging farmers to grow a mosaic of varieties 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). 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 US corn (NRC, 1972). As some forms of genetically modified crops gain popularity, the need to preserve genetic 'refuges'—crop areas planted to varieties not carrying the transgene—has also emerged (Rissler and Mellon, 1996).

One way to monitor spatial distributions of crop varieties is through an index of spatial diversity. Ecologists have used indices of spatial diversity to describe in a compact form the richness, abundance and evenness among species in defined geographical areas. For crop varieties as compared with species, indicators of spatial diversity can be constructed by grouping the varieties cultivated in a specific geographical unit and time period based on the names given to them by farmers or plant breeders, the genes they contain, their agro-morphological descriptors, or other attributes.

To influence the spatial distributions of crop varieties and the traits or genes they embody through policy, however, we need first to identify the factors that cause these distributions to vary. The spatial distribution of varieties reflects farmers' variety choices. Farmers choose varieties based on observable traits or genetic expression—rather than on genetic composition at a molecular level, which they cannot see. Those who grow modern varieties are more reliant on the supply provided through plant breeding programs than those who cultivate landraces. As the economy develops and agriculture is commercialised, farmer demand for specific varieties shifts in focus from their own needs as consumers toward a demand derived from the requirements of industrialised grain processors, export markets and the preferences of more distant, urban consumers. In any crop production system, agro-ecological features of the production environment condition farmers' decisions by affecting the performance of varieties differentially. The variety choices of farmers are also constrained by government policies that affect the research and development of varieties, as well as the performance of seed markets and the information that they receive.

In this paper, we have constructed time series for spatial diversity indices from panel data on the area shares sown to wheat varieties in eight representative shires (local government areas) in the state of New South Wales (NSW), Australia (1983–1997) and seven major wheat-producing provinces in China (1982–1995). We hypothesise that the variation in these indices—richness, dominance and evenness—is affected by the same factors determining the variety choices of farmers, and test our hypotheses econometrically using Zellner's seemingly unrelated regression (SUR).

The two regions of study provide some essential points of comparison. The wheat varieties grown in China 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 has facultative and winter growth habit, although wheat varieties with spring habit are cultivated in parts of Anhui and Jiangsu provinces and most of Sichuan province, where they are planted in the autumn.[1]

The wheat varieties grown on about 2.8 million hectares in NSW are generally bread wheats with spring growth habit that are grown exclusively for sale. In the early 1990s, NSW produced over 25% of Australia's total wheat crop on about 22% of national wheat area. The average area of wheat grown on specialist cropping farms was over 400 ha, and on mixed livestock and cropping farms, slightly under 150 ha. Specialist cropping farms produce a number of crops in addition to wheat on large areas, as well as some livestock.

[1] Facultative wheats are intermediate in vernalisation requirements to spring and winter wheats. They are often planted in autumn, like winter wheats, in areas where winter temperatures are relatively warm.

Section 2 discusses the spatial diversity indices used by ecologists and adapted here to the study of wheat varieties. Indices calculated from the Australian and Chinese data are presented. The conceptual basis for the reduced-form estimation used to explain their variation is described in subsequent section, along with a description of data sources and variables. Regression results are then presented and interpreted, followed by conclusions and recommendations for further research.

2. Diversity indices

There are many types of diversity indicators that can be adapted for use in applied economic analysis. Each indicator has advantages and disadvantages, and the choice of indicators depends on the hypothesis to be tested, whether the crop is predominantly self- or open-pollinating, and whether the unit of observation in the data to be analysed is the plant, field, household, or region (Meng et al., 1998). We chose to use spatial diversity indices in this analysis for several reasons. First, spatial diversity is probably the most generally recognised concept of diversity in the literature. Second, our analysis is conducted with panel data assembled at the regional level. Third, we are analysing modern varieties of a self-pollinating crop species whose diversity is expressed among rather than within varieties. Moreover, we have constructed the spatial diversity indices from area shares planted to varieties. Since area shares planted to varieties are the outcome of farmers' variety choices, we can use microeconomic principles to explain variation in spatial diversity.

The spatial diversity indices we employ are adapted from those used by ecologists to measure ecosystem well-being in conservation projects and to monitor the environment. 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) equality of abundance, or evenness.

A count of species reported or collected in an area, although usually simplest to implement, assumes that all species at a site contribute equally to its biodiversity (Harper and Hawksworth, 1995). Since this is often not the case, frequency counts of individuals within a species provide more information. The Margalef richness index adjusts the number of species sampled in a reference area by the logarithm of the total number of individuals sampled, summed over species. The higher the Margalef index, the richer the diversity of the population.

Indices of abundance detect whether or not certain species dominate others. The Berger–Parker index (Berger and Parker, 1970) expresses the relative abundance of the dominant species and is computed as the inverse of the number of individuals of that species relative to the total number of individuals sampled across species. Effectively, the Berger–Parker index measures inverse dominance, so that the more dominant the most abundant species, the lower the index.

The third category, which combines the richness of species with a measure of their relative abundance, includes the widely used Shannon index.[2] '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, 1988). The Shannon index has been called a 'non-parametric index' because it accounts for the distribution of species without making assumptions about its shape. The Shannon index was originally used in information theory but has been commonly employed to evaluate species diversity in ecological communities.

Each index is described in Table 1 according to the concept it measures, its mathematical construction and its adaptation in this paper. Fig. 1 shows the relationship in terms of scale and relative variation between the richness (Margalef), inverse dominance (Berger–Parker) and relative abundance or evenness (Shannon) indices for the wheat varieties grown by farmers in selected shires of NSW from 1983 to 1997. The inverse dominance and evenness indices vary in similar ways, both reaching peaks in 1987, declining in the last few years of the 1980s and remaining at lower levels during the 1990s. Richness varies more over the period, in some cases moving in the opposite direction from the inverse dominance and evenness indices. Both relatively large numbers of varieties (a

[2] Shannon and Wiener independently derived the function that is commonly known as the Shannon index (Magurran, 1988).

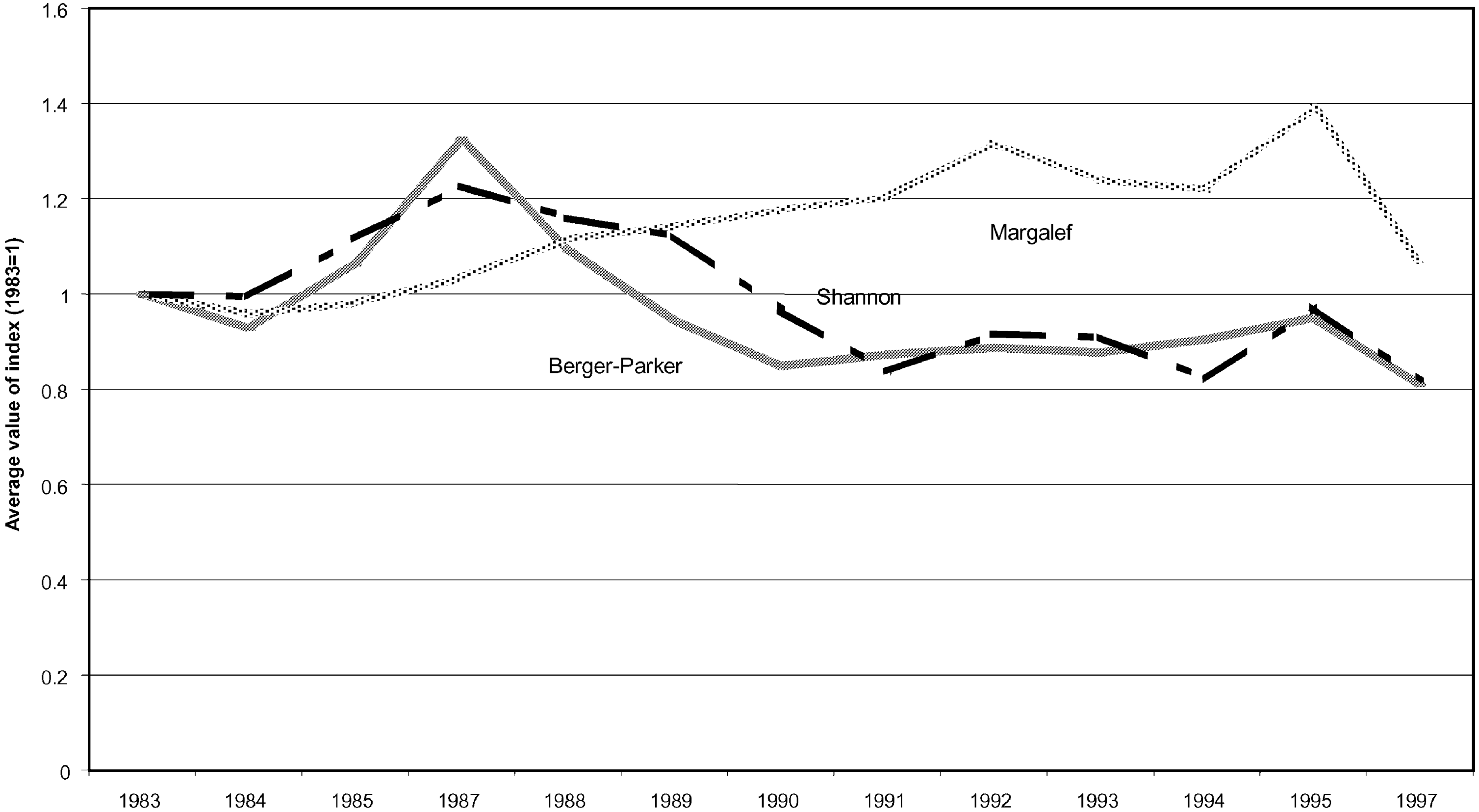

Fig. 1. Spatial diversity indices for wheat varieties grown in NSW, Australia, 1983–1997 (average of eight shires, 1983 = 1).

Table 1
Definition of the 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 is the number of wheat varieties grown in a season, N the total hectares of wheat in that season
Berger–Parker	Inverse dominance or relative abundance	$D = 1/(N_{max}/N)$ $(D \geq 1)$	The more dominant the most abundant species, the lower the index value	Inverse of maximum area share occupied by any single wheat variety
Shannon	Both richness and relative abundance	$D = -\Sigma p_i \ln p_i$ $(D \geq 0)$	The p_i is the proportion, or relative abundance of a species	The p_i is the area share occupied by the ith variety

Source: Authors' adaptation of mathematical construction as defined by Magurran (1988).

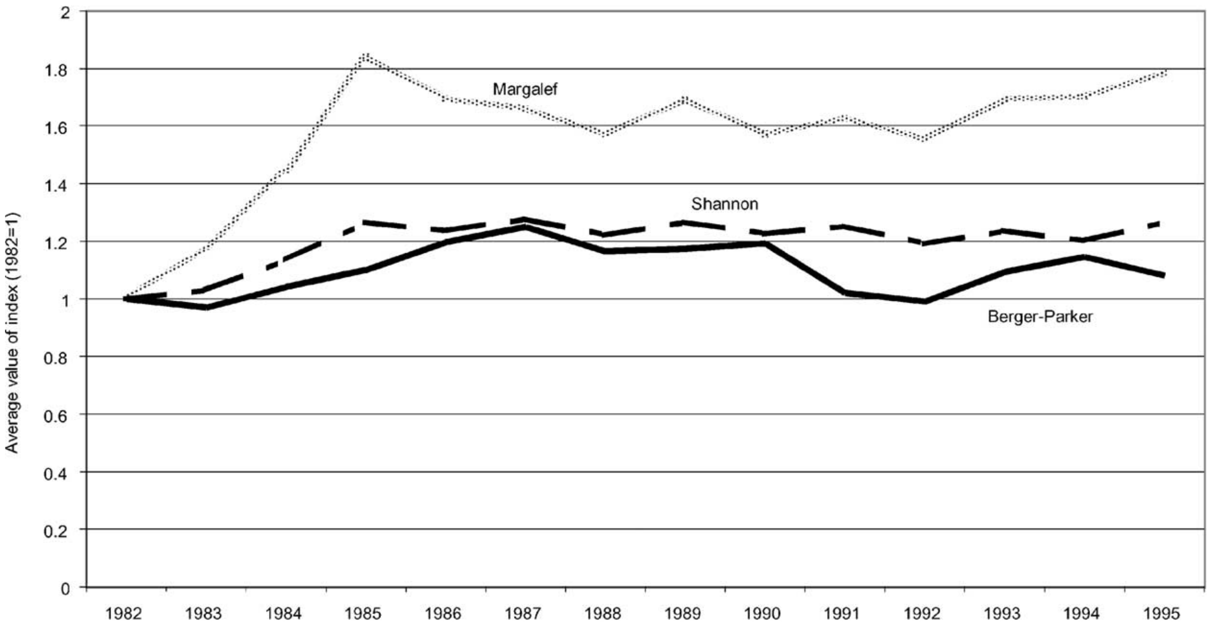

Fig. 2. Spatial diversity indices for wheat varieties grown in China, 1982–1995 (average of seven provinces, 1982 = 1).

peak in the Margalef index) and dominance of a single variety (a low point in the Berger–Parker index) can occur at the same time.

Minima, maxima, means and standard deviations of the indices are shown in Table 2 for eight shires of NSW from 1983 to 1997. The Berger–Parker and Shannon indices approach their absolute minima (1 and 0, respectively) in one shire during a year when a single variety was cultivated on 98% of the wheat area. In NSW, the coefficient of variation is greatest for the Margalef index of richness—in other words, there is greater variability in the number of

Table 2
Descriptive statistics for indices of the spatial diversity of the wheat varieties grown in eight shires of NSW, 1983−1997

Index	Mean	S.D.	Minimum	Maximum
Margalef	0.865	0.321	0.108	1.72
Berger–Parker	2.83	1.03	1.02	5.77
Shannon	1.68	0.439	0.087	2.43

Note: The eight shires are Carrathool, Coonabarabran, Cowra, Gunnedah, Lachlan, Narrabri, Temora and Wagga Wagga.

Table 3
Descriptive statistics for indices of the spatial diversity of the wheat varieties grown in seven provinces in China, 1982−1995

Index	Mean	S.D.	Minimum	Maximum
Margalef	1.91	0.769	0.43	3.90
Berger–Parker	5.88	2.16	1.58	10.25
Shannon	2.41	0.443	1.18	3.30

Note: The seven provinces are Anhui, Jiangsu, Hebei, Henan, Shandong, Shanxi and Sichuan.

varieties per unit of wheat area than in the extent to which one variety dominates or in the evenness of their area share distribution.

Fig. 2 shows the average of the diversity indices for seven provinces of China. The three indices move in similar directions—illustrating a pattern that is different from that found in NSW over almost the same time period. The large expanses of wheat area in the provinces of China relative to the shires of NSW mean that any single variety is less likely to occupy a high percentage of area. The mean and range of the inverse dominance index are therefore much higher, and those for the richness indices on average lower, in the data from China. The Shannon index of evenness is generally higher and less variable in the Chinese provinces than in NSW (Tables 2 and 3).

3. Hypothesised determinants of spatial diversity

The genetic diversity in the modern wheat that grows in farmers' fields is the outcome of how farmers allocate wheat area among varieties. Our approach follows models of consumer demand for characteristics as applied to variety choice (Adesina and Zinnah, 1993; Barkley and Porter, 1996). The proportion of wheat area a farmer chooses to plant to each variety is an indirect realisation of his or her demand for traits embodied in the varieties. These traits are 'fixed' or predetermined from the farmers' viewpoint, though they are malleable to change over time through modern plant breeding.

In a fully commercial wheat production system, the traits farmers demand are those that determine expected profits. When varieties are exclusively of one type (modern or traditional), and costs of production and output prices are similar among them, seed-to-grain price ratios have little significance and levels of other inputs are exogenous to variety choice. Relative profitability is then determined by yield differences. For example, the traits considered by farmers in Australia include agronomic features such as expected yield, days to maturity, and resistance to lodging, as well as bread-making quality, which may earn a price premium. In a semi-commercial system such as that found in China, yield differences are important in determining the utility that households derive from wheat production. There, the implicit value of wheat output depends on whether farm households are net sellers or net purchasers of wheat, and on the socio-demographic characteristics that affect their on-farm wheat consumption, access to markets and information. Some varieties, such as those with more protein content, may have a higher implicit value than others.

Farmers' choices are constrained by the supply of distinct varieties and seed. With a predominantly self-pollinating crop such as wheat, and in a modern production system such as those under study, new germplasm is supplied to farmers as the product of public and private breeding programs rather than their own on-farm selection practices. The supply of varieties is determined by a complex of factors, including lagged investments in research, the flow of germplasm and varieties from other programs, legislation affecting variety release and policies influencing seed sales or distribution.

Agro-ecological features of the crop production zone, such as soils and rainfall, condition farmers' variety choices. Though systems of modern wheat varieties do not respond to the selection pressures of the environment as would systems composed of landraces, the heterogeneity of the production environment influences the performance of the genetic materials that the seed system provides. We might hypothesise, for example, that difficult growing conditions leads farmers to choose a broader set of varieties to suit multiple classes of soil and seasonal niches. A more heterogeneous, variable environment would display a greater mix of varieties in which no single variety tends to dominate unless that variety is widely adapted. Features of the production environment generally are not affected by the specific conditions of any one farm or by the deliberate actions of any one farmer.

The indices we use to measure spatial diversity are constructed from the proportional distributions of area by variety, or area shares. We therefore hypothesise that the determinants of variety choice influence the variation in spatial diversity indices. Agro-ecological features of the crop production zone, the supply of variety-specific traits that can be observed by farmers, and the policies that affect the distribution of new wheat varieties to farmers are exogenous variables that we use in regression equations to explain spatial diversity among modern wheat varieties in Australia and China. The specifications of these regressions are described in Section 3.1.

3.1. 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 constrained demand for and supply of varieties. This specification reflects the hypothesis that 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:

$$D^{\mathrm{r}} = D^{\mathrm{r}}(\boldsymbol{X}^{\mathrm{r}}|\boldsymbol{S}, \theta, \boldsymbol{Z}) \tag{1}$$

$$D^{\mathrm{d}} = D^{\mathrm{d}}(\boldsymbol{X}^{\mathrm{d}}|\boldsymbol{S}, \theta, \boldsymbol{Z}) \tag{2}$$

$$D^{\mathrm{e}} = D^{\mathrm{e}}(\boldsymbol{X}^{\mathrm{r}}, \boldsymbol{X}^{\mathrm{d}}|\boldsymbol{S}, \theta, \boldsymbol{Z}) \tag{3}$$

The richness (D^{r}), inverse dominance (D^{d}), and evenness (D^{e}) of the wheat varieties grown in by farmers in a region over time is determined by the observable characteristics of the varieties that have economic value to farmers (vector $\boldsymbol{X}$), factors that affect the supply of varieties and germplasm (vector $\boldsymbol{S}$), parameters of the diffusion curve (θ) and agro-ecological factors ($\boldsymbol{Z}$).

The variables used in the regression models for NSW and China are defined in Table 4. The dependent variables in both models are the Margalef, Berger–Parker and Shannon indices as defined in Table 1. Indices were constructed from data on percentages of area planted by variety, by province or shire and year.

The variety traits that we hypothesise to be associated with spatial diversity are relative yield potential, maturity, height and grain quality. The vector $\boldsymbol{X}$ is superscripted because variety characteristics may be expressed or measured differently in each of the three equations, in part because each equation represents a different concept and in part as a reflection of the fact that the variety-specific data used to construct the variables may be either qualitative or quantitative. We have specified evenness, which by definition consists of elements of both richness ($\boldsymbol{X}^{\mathrm{r}}$) and relative abundance ($\boldsymbol{X}^{\mathrm{d}}$), as being associated with both sets of variety-specific factors ($\boldsymbol{X}^{\mathrm{r}}$, $\boldsymbol{X}^{\mathrm{d}}$).

For example, in the data from NSW the height and maturity of varieties is recorded as a class, while relative yield potential and bread-making quality are quantitative variables. Since there is no meaningful way to summarise height and maturity classes across varieties, these variables are not included in the richness and evenness equations. The height and maturity class of the dominant variety are included in the inverse dominance equation. In China, by comparison, maturity and height variables are quantitative and their ranges are included as explanatory variables in the richness equation. Protein content was not available for most varieties studied in China and is included only for the leading variety in the inverse dominance equation.

The supply of wheat varieties (S) is measured in NSW by the total number of varieties released in the preceding 5 years, and by the proportion that were bred locally. Other supply-related variables are the proportion of varieties grown that are recommended or approved by the NSW department of Agriculture, and a dummy variable to capture the change in policy regime from the regulated to the deregulated period. From 1983 to 1989, the Australian Wheat Board (AWB) controlled the marketing of all Australian wheat, but control was restricted to exports in 1990. For China, dummy variables are used to mark changes in policy regimes with the household reform system (1982–1984) and market liberalisation (1991–1995) relative to the intervening period. A variable for the overall level of government expenditures in crop research is used as an indicator of the supply of varieties (S).

The vector $\boldsymbol{Z}$ includes 0–1 variables for shires and provinces, as well as variables representing agro-ecological features and farming systems. In NSW, an index of the evenness in soil classes relevant for wheat production was constructed from geographically referenced data. Moisture regimes are

Table 4
Definitions of variables used in regressions

Variable	Definition
Australia (shire and year)	
D^r	Margalef richness index for wheat varieties grown
D^d	Berger–Parker dominance index for wheat varieties grown
D^e	Shannon evenness index for wheat varieties grown
$\boldsymbol{X}^r$	Average relative yield potential of wheat varieties
	Average bread-making score of wheat varieties
$\boldsymbol{X}^d$	Relative yield potential of variety with highest area share
	Maturity class of variety with highest area share
	Height class of variety with highest area share
	Bread-making quality of variety with highest area share
S	Number of varieties released in past 5 years
	Recommended varieties as proportion of varieties grown
	Varieties bred locally as proportion of varieties grown
	Regulated market period to 1989 = 1, 0 thereafter
$\boldsymbol{Z}$	Shannon evenness index of soil types relevant to wheat production
	Average rainfall (mm) from April to October
	Probability of being able to sow early = 1 if rainfall from April 10−30 >30 mm, 0 otherwise
	Probability of having to sow late = 1 if rainfall from April 10−30 <30 mm and rainfall in June >15 mm, 0 otherwise
	Variables for shires = 0–1 (Carrathool, Coonabarabran, Cowra, Lachlan, Narrabri, Temora and Gunnedah)
China (province and year)	
θ	Lagged area-weighted average age of varieties
D^r	Margalef richness index for wheat varieties grown
D^d	Berger–Parker dominance index for wheat varieties grown
D^e	Shannon evenness index for wheat varieties grown
$\boldsymbol{X}^r$	Average yield potential of wheat varieties
	Range in days to maturity among wheat varieties
	Range in height among wheat varieties
$\boldsymbol{X}^d$	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
S	Crop research expenditure lagged by 4 years, in million yuan (1985 = 1)
$\boldsymbol{Z}$	Variables for provinces = 0–1 (Anhui, Hebei, Henan, Jiangsu, Shandong and Shanxi)
	Saline area, area affected by drought, area affected by flood and eroded area
	Multiple cropping index defined as ratio of total area cropped to cultivated land area, ratio of irrigated area to crop area, interaction term of ratio of irrigated to crop area with dummy variables representing the maize–wheat region
	1 = 1982–1984 (household reform system), 0 otherwise
	1 = 1991–1995 (market liberalisation), 0 otherwise

measured with three variables constructed from rainfall data: (1) average growing-season rainfall from April to October; (2) the possibility of being able to sow early; and (3) the possibility of having to sow late. In China, agro-ecological variables include the extent of land area affected by droughts, floods, erosion and salinity, the coverage of irrigation systems and cropping intensity.

In both Australia and China, past area allocation decisions are expressed by the lagged area-weighted average age of varieties (θ). 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 information, including the initial adoption lag and the length of the adoption period, is summarised in the area-weighted average age of varieties (Brennan and Byerlee, 1991). This variable is lagged to ensure exogeneity.

3.2. Data sources

Data sources for both China and Australia are numerous. In NSW, eight shires were selected to represent farming systems across the region: Wagga Wagga, Temora, Cowra, Carrathool, Lachlan, Coonabarabran, Gunnedah and Narrabri. From 1983 to 1989, the data source for variety area shares is Fitzsimmons (1991), a compilation of annual farm census data from the Australian Bureau of Statistics (ABS). From 1989 to 1997, data were calculated from wheat receipts at representative local silos, as recorded by the Australian Wheat Board (AWB).

Data on the year of release of each variety and the breeding program that developed the variety were obtained from Fitzsimmons (1998). Variety yield data from all advanced trials conducted in the selected shires by NSW Agriculture from 1982 to 1998 were analysed. Yields were ranked against a standard, and relative yields were then expressed as a percentage of the yield of Banks, a widely grown variety released in 1979.

The recommendation status of varieties in each shire in each year was taken from NSW Agriculture's *Winter Cereal Sowing Guide*. Based on the same source, varieties were classified into three maturity classes (late, medium, and early). Bread-making scores were drawn from Antony and Brennan (1988) and Oliver and Allen (2000), and are measured on a 1–10 scale. Data on the agro-morphological characteristics of varieties, such as height, were obtained from the variety registration papers and in some cases the published records of new varieties. The soil types present in the arable portions of the shire were identified using spatial imaging, and the area and percentages of each type was obtained for each shire (Freckleton, 2000).

China's statistical and agricultural yearbooks were the primary source for data on area sown to wheat and wheat production in Anhui, Hebei, Henan, Jiangsu, Shanxi, Shandong and Sichuan from 1982 to 1995. Additional information on variety area shares was drawn from relevant years of the publication *Agricultural Crop Sown Area by Variety*, supplemented by 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 4 years, to represent the time spent finishing varieties. Yield and trait data refer to the time of release and were obtained from publications on wheat varieties and breeder surveys conducted by the Chinese Academy of Agricultural Sciences Center for Chinese Agricultural Policy (CCAP). Data on environmental variables were compiled from China's environmental yearbooks.

4. Econometric results

4.1. Model for New South Wales, Australia

The same errors that affect the richness of the varieties planted in any season may also affect their relative abundance and the evenness of their distribution over a geographical area. Zellner's seemingly unrelated regression (SUR) model exploits the underlying relationships in the errors among equations by estimating them jointly. The greater the correlation of the disturbances among equations, and the more distinct the matrices of explanatory variables, the greater the efficiency gains from running the equations jointly (Greene, 1997, p. 694).

Results of the SUR estimation for shires in NSW are shown in Table 5.[3] All three equations are statistically significant at the 1% level, as indicated by the tests of log–likelihood ratios. Differences are apparent among the regressions in the significance and interpretation of the effects of individual explanatory variables. While economic concepts have been used to motivate the specification of the regression equations, the direction of marginal effects is not predicted a priori by theory. Hence, all hypothesis tests were conducted with two tails.

No trade-off is apparent between any of the diversity indices and the yield potential of varieties. In fact,

[3] Regressions were run using LIMDEP 7.0. 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 hypothesised regression model.

Table 5
Results of generalised least squares regression (SUR) of wheat diversity indices on hypothesised determinants of diversity, NSW

Explanatory variable	Richness coefficient	S.E.	Dominance^{-1} coefficient	S.E.	Evenness coefficient	S.E.
Constant	−0.00440	0.862	0.894	1.77	−0.166	0.840
Average relative yield potential	0.0114*	0.00622			0.00907*	0.00523
Relative yield of dominant variety			0.00222	0.00450	−0.00165	0.00112
Average bread-making quality	−0.0416	0.519			−0.328	0.0442
Bread-making quality of dominant variety			−0.267*	0.163	−0.086**	0.0429
Later maturity of dominant variety			−0.00497	0.145	0.0732**	0.0360
Taller height of dominant variety			0.109*	0.0610	0.0259	0.0174
Proportion locally bred	0.395*	0.206	0.471	0.723	0.528**	0.232
Proportion recommended	−0.403**	0.0651	−0.681**	0.244	−0.399**	0.0763
Varieties releases in last 5 years	0.0202**	0.00981	−0.0106	0.0355	0.0465**	0.0113
Regulated market period	−0.105**	0.0579	0.696**	0.215	0.132**	0.0673
Rainfall	−0.000491**	0.000233	−0.000746	0.000807	−0.000337	0.000270
Soil type evenness	−0.00994	0.299	1.72*	1.02	0.868**	0.335
Sow early	0.00735	0.0403	−0.264*	0.146	0.00148	0.0462
Sow late	−0.102*	0.0649	0.176	0.239	0.0129	0.0750
Lagged area-weighted average age	0.00725	0.0194	0.113*	0.0674	0.0369*	0.0220
Carrathool	0.0929	0.0853	−0.115	0.313	−0.000892	0.0987
Coonabarabran	0.452**	0.112	−0.977	0.342	0.622**	0.121
Cowra	−0.119	0.146	0.538	0.455	0.109	0.160
Gunnedah	0.381**	0.158	10.89**	0.423	0.846**	0.164
Lachlan	0.453**	0.0875	0.823**	0.331	0.402**	0.103
Narrabri	0.191	0.133	1.91**	0.345	0.494**	0.138
Temora	0.214	0.161	1.19**	0.564	0.578**	0.182
Value of log–likelihood ratio	86	86	57	57	99	99
Number of observations	104	104	104	104	104	104

* Statistically significant at the 10% level with two-tailed *Z* statistic.
** Statistically significant at the 5% level with two-tailed *Z* statistic.

the richness and the evenness in the spatial distribution of the varieties grown are positively related to their average relative yield potential. Though we might hypothesise that higher yields are associated with the cultivation of fewer, higher-yielding varieties over a larger proportion of area, no annual yield losses appear to be associated with greater spatial diversity of modern varieties over the past 15 years in NSW. Breeding for successive improvements in yield performance in trials while seeking to ensure a rich and even distribution of varieties from year to year do not appear to be conflicting goals. This result implies either that many of the varieties have similar yield potentials, or that farmers are also interested in traits other than yield, i.e. that regional acreage portfolios are not heavily skewed in favour of varieties with large relative yield advantages.

Other variety traits appear to explain variation in the spatial diversity of wheat varieties grown in NSW. The higher the bread-making quality (related to price premia) and the shorter the height (implying less lodging) of the most popular variety, the greater the extent of its dominance. The later its maturity and the lower its bread-making quality, the more equitable the spatial distribution of varieties.

Variables related to the supply of varieties are also important determinants of spatial diversity among the modern wheats grown in NSW. The greater the relative proportion of locally bred varieties, the greater the richness and evenness among varieties—and the magnitude of these effects is relatively large. A more active local breeding program infuses new germplasm into an area—increasing the number of varieties and smoothing their distribution across a crop-producing area. A higher proportion of recommended varieties among those grown by farmers is associated with greater dominance in the leading variety and less equity in variety area shares—suggesting that farmers follow recommendations. Similarly, the lagged area-weighted average age of varieties reduces the dominance of any single variety and improves spatial evenness among varieties. These results are intuitive when we think about how the variables are constructed; as older varieties or varieties that are no longer recommended shift gradually out of production, the minor areas they occupy serve to enhance diversity from a spatial perspective. A higher rate of variety release enhances richness and offsets the negative effects of recommended varieties on the equity of their spatial distribution. Prior to the deregulation of the wheat market in 1990, the richness of the variety mix was lower and the inverse dominance and evenness higher than they have been in the period since.

Physical features of the production environment also contribute to explaining variation in the spatial diversity of the wheat varieties grown in NSW. A higher average level of precipitation is negatively associated with richness of wheat varieties, as is the possibility of having to sow late. A better moisture regime may mean that more farmers choose to grow fewer varieties, while a delay in the onset of the rainy season implies that fewer varieties are suitable since the growing period will be shorter. Increasing evenness of the distribution of soil types relevant to wheat production reduces the dominance of the leading variety and enhances the equitability of variety area shares. This finding is consistent with the fact that the performance of varieties is often soil-specific. Wheats grown in the shires of Gunnedah, Lachlan, Narrabri, Temora and Coonabarabran are in one respect or another more spatially diverse than those grown in the shires of Carrathool and Wagga Wagga.

4.2. China Model

Results of the SUR regression for seven major provinces in China over the time period 1982−1995 are shown in Table 6. Tests of log–likelihood ratios confirm that each individual regression is significant at the 1% level. As in NSW, variety characteristics other than yield potential are significantly associated with the richness, dominance and evenness in the spatial distribution of wheat varieties grown by farmers. The greater the range in the maturity period and height of the varieties sown, the greater the richness and evenness of their spatial distribution. Later maturity, however, is associated with a lower area share of the dominant variety.

The average yield potential of the wheat varieties sown is negatively associated with richness in China. When fewer varieties were grown per unit of area, these varieties had higher yield potentials. It would be incorrect to assume, however, that this pattern reflects government controls over the dissemination of materials rather than the choices of individual farmers. In the period covered by the data, the relationship between government policies and farmers' variety choices had already become more complex.

For example, the household reform policies instituted in the late 1970s allowed farmers the flexibility to sell surplus output after the fulfilment of their official production quotas. Regression results demonstrate that the dominance of the leading variety was greater, and the distribution of varieties less even, during the household reform period (1982−1984). With the new incentives and income opportunities, farmers may have concentrated the area sown on the highest-yielding variety or the variety most suitable for sale. The seed market liberalisation that has occurred since 1990 is believed to have improved the supply of seed. Regression results are consistent with this hypothesis, indicating that richness, or the number of varieties per unit of area, was greater in the most recent period relative to the intervening, 1985–1990 period. Expenditures on crop research are not associated statistically with any of the diversity indexes—perhaps because the variable is measured too broadly and is only indirectly related to the supply of varieties. In China as in Australia, older area-weighted age of varieties contributes to greater spatial diversity since older varieties continue to occupy minor areas as farmers gradually discard them in favour of newer materials.

As in the case of NSW, agro-ecological factors explain the spatial diversity among modern wheat varieties in China. The greater the area affected by salinity, the greater the dominance of the most popular variety, perhaps due to its comparatively better performance on this type of land. However, greater richness, less dominance and more even distributions of wheat varieties are found where there is more eroded crop area. Perhaps, no single variety is best suited for production in fragile growing conditions. The greater the irrigated area as a proportion of all cultivated area, the more dominant the leading variety. The interaction

Table 6
Results of generalised least squares regression (SUR) of wheat diversity indices on hypothesised determinants of diversity, China

Explanatory variable	Richness coefficient	S.E.	Dominance^{-1} coefficient	S.E.	Evenness coefficient	S.E.
Constant	−21.943	7.37	−73.77**	28.89	−15.08	4.56
Average yield potential	−0.00434*	0.00246	–	–	−0.00231	0.00152
Yield potential of dominant variety	–	–	0.00229	0.00223	0.000272	0.000300
Range in maturity	0.00284*	0.00994	–	–	0.000575	0.000582
Range in height	0.0205**	0.00537	–	–	0.0128*	0.00311
Later maturity of dominant variety	–	–	0.0383*	0.0214	0.0000650	0.00292
Protein content of dominant variety	–	–	−0.212	0.148	−0.0205	0.0192
Taller height of dominant variety	–	–	0.0163	0.0248	0.00160	0.00321
Salinity	0.00309	0.00319	−0.0460*	0.0120	−0.00252	0.00191
Erosion	0.000605*	−0.000291	0.00209*	0.00115	0.000475*	0.000181
Flood	−0.0000151	0.0000647	0.000143	0.000239	0.0000245	0.0000377
Drought	0.0000369	0.0000580	0.000148	0.000222	0.0000273	0.0000347
Multiple cropping index	3.63*	0.806	10.97*	3.51	2.47*	0.528
Ratio of irrigated to total cultivated area	2.22**	1.26	−19.80*	5.00	−0.615	0.797
Interaction of irrigation ratio and maize–wheat region	1.18	1.82	17.1*	6.99	0.973	1.09
Lagged crop research expenditures	−0.000385	0.0278	−0.000323	0.00105	0.0000222	0.000167
Lagged area-weighted average age	0.0985*	0.0355	0.876*	0.134	0.113*	0.0211
Household reform system	0.0561	0.177	−1.59*	0.645	−0.259*	0.106
Market liberalisation	0.261*	0.119	−0.165	0.440	−0.066	0.0718
Anhui	14.18*	6.82	56.64*	27.17	11.84*	4.25
Hebei	10.09	7.768	85.39*	30.61	13.00*	4.81
Henan	10.21	7.35	70.50*	29.00	11.83*	4.55
Jiangsu	12.37	8.86	89.54*	34.99	14.23*	5.49
Shandong	10.87	8.29	84.18*	32.76	13.58*	5.13
Shanxi	11.25*	5.12	45.64*	20.847	10.13*	3.24
Value of log–likelihood ratio	103	103	79	79	105	105
Number of observations	91	91	91	91	91	91

* Statistically significant at the 5% level with two-tailed Z statistic.
** Statistically significant at the 10% level with two-tailed Z statistic.

effect of this factor with the dummy variable representing the maize–wheat producing region dampens the dominance of the most popular wheat variety. The maize–wheat region is ecologically distinct, and spring wheat varieties are grown there with shorter duration. Similarly, the multiple cropping index, which reflects the intensity of the farming system, is also associated with a higher level of spatial diversity. The multiple cropping is defined as the ratio of the total area cropped (in successive crops) to cultivated area. Finally, the econometric results confirm that all provinces are significantly more diverse than Sichuan province, both in terms of the inverse dominance and evenness.

4.3. Diversity indices

Finally, recalling the mathematical construction of the spatial diversity indices and observing the patterns they assume when applied to area share data provides some additional policy relevant information. For example, in NSW, though the area sown to wheat varies more temporally than does the number of varieties (measured in coefficients of variation), the Margalef index is highly correlated with the number of varieties (0.98), and not at all with hectares sown to wheat (0.09). The number of varieties grown in any one shire and year ranges from 2 to 19, with an average of 10. The temporal change in the number of modern varieties grown, and the extent to which promoting variety release can enhance spatial richness, will nevertheless depend very much on the zone of study and the seed system.

Neither the Margalef nor the Berger–Parker indices tells us much about the pattern of varieties across space. An inverse dominance index like the Berger–Parker, which is constructed with only the area share of the leading variety, might be most useful when a particular variety with a specific gene or trait is the target of policy, or when policymakers are concerned that the leading variety is too widely grown. The Shannon index summarises the complete area distribution by variety in a single number, approaching zero as one variety dominates to the exclusion of others and rising with an increasingly uniform distribution. As suggested by its construction, the Shannon index for shires in NSW is also highly correlated with the number of varieties grown (0.73), so that in this case both richness and evenness could be addressed by the same policy.

5. Conclusions

The spatial diversity of crop varieties has economic value because it affects crop productivity—in systems of either landraces or modern varieties. In the case of modern varieties of a self-pollinating crop such as wheat, diversity is expressed more among than within varieties. The ecology literature on spatial diversity of species is a good source of indicators that can be adapted to the analysis of area distributions of crop varieties. Here, we have constructed indices for three concepts of spatial diversity—richness, inverse dominance and evenness—from data on area shares sown to modern wheat varieties in Australia and China.

When spatial diversity indices are constructed from variety area shares, we hypothesise that their variation can be explained by economic factors related to the supply of and demand for varieties as well as the physical features of the production environment. Farmers choose varieties based on traits that are valuable to them, given the supply of varieties available and their growing environment. These choices are reflected in area shares planted to the individual varieties that embody the traits. In a commercialised production system, the traits they demand relate to profitability and they rely on crop breeding programs for their supply of new germplasm. In a partially commercialised system, traits that provide utility in home consumption, such as specific tastes, may also be important.

SUR estimation of reduced form equations supports these hypotheses for two contrasting production systems in China (1982–1995) and Australia (1983–1997). The importance of traits such as bread-making quality, maturity and height in explaining the diversity of wheat varieties grown by farmers is evident in both systems. While there is an apparent trade-off between yield potential and the richness of wheat varieties grown in China, breeding for higher yield potential does not conflict with greater richness and evenness in the spatial distribution of wheat varieties grown in NSW.

The two sets of regressions provide information of general relevance to agricultural research policy and the study of crop biodiversity. In both the Australian and Chinese cases, a slower rate of variety turnover in the field is positively related to wheat diversity since older varieties occupy minor shares as farmers gradually replace them with newer germplasm. This result suggests a possible yield trade-off over the longer term, since variety turnover is a principal defense mechanism against the depreciation of genetic resistance to pathogens in systems of modern varieties. In NSW, a more rapid rate of variety release and a higher proportion of locally bred material enhances spatial diversity. The deregulation of the Australian wheat market has been associated with a reduction in richness of the variety mix, but an increase in the level of spatial diversity by other measures. In the Chinese data, the effect of market liberalisation 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 more uneven distribution of variety area shares.

Both sets of regressions confirm that environmental variables are significant determinants of spatial diversity. Rainfall levels and distribution during the planting season influence the number of varieties grown per unit of area in NSW. The evenness of area distributions among wheat varieties, and the extent to which the most popular variety dominates wheat area, is related to the evenness in the distribution of soil types in a region. Erosion, salinity, irrigation and cropping intensity affect the spatial diversity of modern varieties of wheat in China.

If it becomes possible to draw on more detailed data and design a model with a fuller empirical specification of economic behaviour, hypothesis tests may be conducted for more targeted policy issues. When data can be analysed at progressively larger ‘scales’, as is recognised in the ecology literature, additional insights might be gleaned by comparing the impacts of the same policies at the local, regional and national levels. The methodology proposed in this paper may also prove useful for the analysis of the spatial distributions of varieties carrying certain types of genetic resistance to disease or transgenes. For example, suppose it is desirable to target a maximum area share (dominance level) for a variety or set of varieties embodying a certain gene, or a given level of 'equity' (evenness) in the area distribution of varieties carrying and not carrying that gene. Using the approach described above, we can identify determinants of the probability of achieving such a target, as well as ranges in the values of these determinants that would be compatible with reaching this target.

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