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# Wheat breeding, productivity and slow variety change: evidence from the Punjab of India after the Green Revolution*

Melinda Smale, Joginder Singh, Salvatore Di Falco and Patricia Zambrano†

Variety change and genetic diversity are important means of combating crop losses from pests and diseases in modern agricultural systems. Since the Green Revolution, genetic diversity among wheat varieties released in India has increased but variety change on farms continues to be slow. In this article, we define and summarise indices of variety change and genetic diversity for the wheat varieties released and grown in Indian Punjab during the post-Green Revolution period. We evaluate the effect of each index on technical efficiency with a Cobb-Douglas yield model after testing for exogeneity. Findings support the hypothesis that slow variety change has offset the positive productivity effects of diversifying the genetic base in wheat breeding during the post-Green Revolution period. Policies that speed the rate of variety change and contribute to a more equitable spatial distribution of modern varieties could support wheat productivity in the Punjab of India, reinforcing plant breeding successes.

**Key words:** genetic diversity, plant breeding, productivity, Punjab of India, wheat.

## 1. Introduction

The centre of origin of wheat is 'diffuse' (Harlan 1992). Though India is not considered as a primary centre of diversity, evidence suggests that farmers have cultivated wheat in the subcontinent since 3000 BC (Tomar *et al*. 2004). Until the early-1900s, farmers grew heterogeneous landraces and landrace mixtures, known as 'sorts' (Pal 1966). Some of these served as the basis for the Indian breeding program, initiated with the establishment of the Agricultural Research Institute at Pusa in 1905. Since then, India has contribute key wheat genetic resources to modern plant breeding programs in numerous countries, as demonstrated in the recorded pedigrees of modern wheat varieties (see, for example, Zeven and Zeven-Hissink 1976). India is second only to China in terms of scale of wheat production.

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The Green Revolution in wheat began in the Indian Punjab during the late-1960s, as did the concern for genetic erosion caused by the displacement of local landraces (Frankel 1970; Hawkes 1983; Harlan 1992). Genetic erosion is not easy to quantify, however (Smale 1997). One of the most comprehensive sources of information on the topic is the 'The State of the World's Plant Genetic Resources for Food and Agriculture,' published by the Food and Agriculture Organisation of the United Nations (FAO) in 1997. The report synthesises information provided by representatives in 143 participating countries, but data sources were largely anecdotal or descriptive. FAO concluded that 'there have been few systematic studies of the genetic erosion of crop genetic diversity which have provided quantifiable estimates of the actual rates of genotypic or allelic extinction' (FAO 1997: 35), calling for better measurement (p. 41).

In regions with high productivity potential like the Indian Punjab, much of the area was already planted with earlier products of modern plant breeding programs when the Green Revolution began (Jain 1994). These cultivars were more genetically similar and less productive than the semi-dwarf wheat varieties that succeeded them, as evidenced by their pedigrees and yields. They were also taller in stature.

Seeking resistance to wheat diseases was a central motivation for early plant breeding programs. Since the Green Revolution, plant breeders have sought to diversify genetic resistance to diseases in modern wheat varieties to reduce the vulnerability of the crop to epidemics. Increasing the 'latent' diversity (unexpressed until challenged by stress) through breeding multiple sources of genetic resistance into varieties grown by farmers reduces the probability that resistance will be overcome by mutation as well as the incidence of disease should mutation occur. However, it may not enhance annual crop yields because disease incidence and severity vary over seasons and areas. For example, Heisey *et al.* (1997) showed that maximising the genetic diversity of modern varieties grown in the Punjab of Pakistan would have generated costs in terms of annual yield losses, especially in favoured environments.

Plant breeders use the genetic diversity of their materials to enhance the disease-free yield potential of a crop and protect yield through conferring genetic resistance to pests and diseases. Genetic resistance can reduce the yield variability on farms. By definition, the spatial and temporal configuration of modern varieties across a wheat-producing landscape determines annual crop yields. That configuration is the consequence of farmer demand for continually higher-yielding, resistant varieties and of the capacity of the seed system to supply them.

In this article, we define and summarise indices of variety change and genetic diversity for the modern wheat varieties released and grown in Indian Punjab since 1970. The first index is the average of varieties grown. Each variety age in a group of varieties grown by farmers is weighted by the proportion of the wheat area sown to the variety. This index measures the inverse of the rate of variety change over time, adjusting for the spatial distribution of varieties. In modern, intensified farming systems, the speed of variety change substitutes to some extent for the spatial heterogeneity found in landrace systems, and is an important means of counteracting the uniformity that can lead to pathogen mutation and plant diseases. The rate of variety change is influenced directly by variety release and seed industry policies.

The second index is the average coefficient of diversity among varieties grown by farmers, calculated from pair-wise coefficients of parentage. This index measures the extent of dissimilarity among wheat varieties conferred by inheritance, or plant breeding. The average coefficient of diversity is influenced by the search for new sources of traits, such as resistance to pests and diseases. The broader and more diverse the ancestry of genetic materials used to breed a set of varieties, the lower is the average coefficient of parentage (COP) and the higher is the average coefficient of diversity among them.

We use panel data to test the direction of effect of the two indices on wheat productivity in the post-Green Revolution period. A Cobb-Douglas yield model is estimated with the indices specified as technical efficiency parameters, after testing the exogeneity of each.

The next section provides essential background information about wheat breeding in India. Methods used to measure diversity and estimate the econometric model are the presented. The findings section includes descriptive analysis of diversity indices and variables, followed by regression results. Conclusions and policy implications are drawn in the final section.

## 2. Wheat breeding in India

Before modern plant breeding programs in India, farmers classified ‘sorts’ on the basis of grain characters, such as red or amber colour, or hard or soft grain texture, rather than botanical characters (Pal 1966). The history of wheat breeding in India between 1905 and 1962 has been classified into three phases (Indian Council for Agricultural Research 1978). In the first phase, pure lines were selected from local mixtures. Some of these were known for excellent grain type and quality. In the second phase, breeders attempted to combine different characters in one cultivar through hybridisation. In the third phase, breeders sought to develop disease-resistant cultivars. In none of these phases were significant yield gains achieved.

Almost all of the wheat varieties bred during this 60-year period were tall with weak straw, which meant they were unsuitable for intensive agriculture. After 1962, breeders realised the importance of strong straw and began to develop varieties resistant to lodging. Some Italian wheat varieties with these characteristics were identified (e.g. Funo), but they were susceptible to the rust diseases (Indian Council for Agricultural Research 1978). Despite these shortcomings, point estimates suggest that by the beginning of the Green Revolution in the mid-1960s, much of the wheat area in irrigated zones and some of the rain-fed areas were already planted to improved, tall varieties (Pray 1983; Dalrymple 1986). Sukhatme (1945) estimated that more than 50 per cent of the irrigated area and about 31 per cent of the unirrigated area in the Punjab of India was planted to C591 in the early 1940s. Pal (1966) reported that by 1955, C591 occupied nearly 80 per cent of the area in the Indian Punjab.

The Green Revolution in wheat refers specifically to the rapid adoption of varieties with semi-dwarf stature (conferred by Rht1 and Rht2 genes) during the late-1960s and early-1970s.[1] When grown with increased rates of fertiliser application and a controlled water supply, semi-dwarf varieties performed significantly better than the varieties they replaced. Initially, they spread rapidly throughout many of the irrigated zones of the developing world where wheat cultivation was concentrated and where population densities were high – often replacing improved varieties with tall stature. Later, more widely-adapted descendants of these varieties spread gradually into less favourable environments, including rainfed areas with relatively modest production potential – often replacing landraces.

The semi-dwarf materials of the Green Revolution were more resistant to both lodging and rust diseases. After the introduction of the first semi-dwarf varieties, the area sown to leading wheat varieties decreased initially and then rose as they gained in popularity (Punjab Agricultural University, unpublished data). The most famous and extensively grown of these, Mexipak and Sonalika, continued to occupy three and 13 per cent (respectively) of the area sown to bread wheat in developing agricultural economies in 1990, although they were released in India in 1966 (Smale 1996: 36). Since then, the Veery cross and the Attila cross have been major progenitors of the varieties of bread wheat that are extensively grown in India and globally.

Byerlee and Traxler (1995) estimated yield gains during the first phase and second phases of technical change in the Green Revolution. They modelled the first phase of adoption of modern varieties, which involved the replacement of taller varieties by semi-dwarf varieties, as a one-time increase in productivity. They estimated that yield gains in this phase were 25 per cent in irrigated areas, 20 per cent in wetter rainfed areas, and 10 per cent in dry areas. The next phase of genetic technical change occurred when farmers replaced the modern varieties they had already adopted with newer modern varieties. This second type of genetic technical change protects yield from evolving diseases and steadily improves yield potential. In a 2001 paper that focuses on this second type of change, Traxler and Byerlee used a vintage model (Godden 1998) to estimate the rate of genetic progress. They found a rate of yield gain of one per cent per year in the irrigated areas, and nearly zero in some rainfed areas.

The analysis presented in this paper also focuses on the second type of technical change during the post-Green Revolution period.

[1] It may be useful to note that other dwarfing genes and other cultivars of short stature exist in wheat, and taller varieties produced by modern plant breeding programs were released before 1960 and have been released since.

## 3. Methods

### 3.1 Measuring diversity in modern wheat systems

Meng *et al*. (1998) summarise the issues related to measurement of diversity for economic analysis. A panoply of diversity indices are found in the crop science and ecological literature. No single index of diversity is inherently superior to another. Different indices represent different concepts and can be constructed with various types of raw data. Meng *et al*. (1998), and an extensive technical literature in the crop sciences, discuss the advantages and disadvantages of various indices employed to study the genetic diversity of crop plants. More recently, Brock and Xepapadeas (2003) have also analysed more generalised classes of diversity indices from the perspective of a unified framework based on economic theory.

To characterise the diversity on farms in production systems dominated by modern varieties, both spatial and temporal concepts are relevant. Spatial diversity refers to the distribution of varieties across a crop-producing landscape. The rate of variety change substitutes to some extent in modern systems for the spatial diversity found in landrace systems (Apple 1977; Plucknett and Smith 1986). Typically, landraces are locally adapted and genetically heterogeneous across space. Spatial diversity and variety change among modern varieties are determined in large part by the economic factors affecting the relative profitability of individual varieties, the structure and performance of the seed industry and price policies. Heisey (1990) and Heisey and Brennan (1991) have analysed and modelled variety change in modern wheat systems have. Brennan and Byerlee (1991) developed and applied the index of variety change used here, the area-weighted average age of varieties grown by farmers. This index combines spatial and temporal data, and is negatively related to variety change.

Pedigree analysis has been used by crop scientists to assess the latent genetic variability among modern varieties. A practical method for incorporating pedigree information into a usable form is through calculating a coefficient of diversity, equivalent to one minus the COP. In wheat, the COP measures the probability that two cultivars are identical by descent for a character that varies genetically (Malecot 1948). In calculating the average COP for a set of cultivars, each pair has equal weight. Average coefficients of parentage plotted over time provide an indication of the relative change in the diversity conferred through plant breeding. The average coefficient of diversity was developed and applied to analysis of wheat varieties in the Punjab of Pakistan by Souza *et al*. (1994), and is applied here.

### 3.2 Econometric estimation

Initial attempts to link diversity in modern cultivars to productivity are found in Gollin and Evenson (1998); Smale *et al*. (1998) and Widawsky and

Rozelle (1998). Widawsky and Rozelle applied a generalised Cobb-Douglas yield model with a stochastic specification to test the effects of diversity on mean and variance of rice yields, using township data for Zhejiang and Jiangsu Provinces. They measured diversity with a Solow/Polasky distance index constructed from pedigree data, and the diversity index was entered as an intercept shift in the regression equation. Smale *et al.* (1998) used a Cobb-Douglas function with a Just and Pope (1979) specification to test the effects of wheat diversity on mean and variance of yields in the irrigated and rainfed districts of the Punjab of Pakistan from 1979 to 1985.

Our focus in this study is on the estimated coefficients for the area-weighted variety age, the average coefficient of diversity, and the interaction between them. To maintain consistency with these studies we test the effects of these factors on partial productivity by applying a Cobb-Douglas yield model. Thus:

$$y_{it} = A_{it}x^{\beta}u_{it}, \tag{1}$$

where $y_{it}$ is yield of wheat per hectare in district $i$ in year $t$, $A_{it}$ is an index of technology in district $i$ in year $t$ and $x_{it}$ is expenditure on conventional inputs per hectare in district $i$ in year $t$. Taking logarithms of both sides of Equation (1) we obtain,

$$\ln y_{it} = \ln A_{it} + \beta \ \ln x_{it} + \ln u_{it}. \tag{2}$$

The technology index includes the effects of weather ($w$), disembodied technological change proxied by a time trend ($T$), the area-weighted average age of varieties (d$t$) and the average coefficient of diversity (d$g$). We allow for an interaction between the effects of variety age and diversity in logarithms.

$$\ln A_{it} = \alpha_0 + \alpha_1 T_t + \alpha_2 \ln \mathrm{d}t_{it} + \alpha_3 \ln \mathrm{d}g_{it} + \alpha_4 \ln \mathrm{d}t_{it} \times \ln \mathrm{d}g_{it} + \alpha_5 \ln w \tag{3}$$

In addition, we allow for a district-specific fixed effects structure to the error terms, such that

$$\ln u_{it} = v_i + \varepsilon_{it} \tag{4}$$

where $\upsilon_i$ is the district-specific residual $\varepsilon_{it}$ are independently and identically distributed with a mean of 0 and variance $\sigma^2$. Combining all these elements the regression model becomes

$$\ln y_{it} = \alpha_0 + \beta \ln x_{it} + \alpha_1 T_t + \alpha_2 \ln \mathrm{d}t_{it} + \alpha_3 \ln \mathrm{d}g_{it} + \alpha_4 \ln \mathrm{d}t_{it} \times \ln \mathrm{d}g_{it} + \alpha_5 \ln w + v_i + \varepsilon_{it} \tag{5}$$

The estimated coefficients for the two indexes can be interpreted as yield elasticities in this specification. We applied a panel data estimator with fixed effects to control for district characteristics. This estimator effectively controls for all district-specific characteristics.

### 3.3 Data sources

The Farm Management Extension Wing of Punjab Agricultural University regularly collects data regarding the wheat varieties planted from a sample of 600–700 farmers distributed among 12 districts of Punjab, with a rotating statistical sample that varies in size by year. Districts represented are: Amritsar, Bhatinda, Faridkot, Ferozpur, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhinana, Ptiala, Ropar, and Sangrur. This series runs from 1964–1965 to 2000–2001, and was used to compile district-level variety information for the period 1981–1982 to 2000–2001 A separate data series was compiled for input costs and production, based on annual surveys conducted with a statistical sample of 300 farmers in Punjab. The second series spans only the years 1980–1981 to 2001–2002. Sponsored by the Government of India, this national series is called the 'Comprehensive Scheme of Cost of Cultivation of Major Crops.' The two data series were combined for the purposes of this analysis, resulting in 98 district-by-year observations. In a number of years, data were missing for one variable or another.

## 4. Findings

### 4.1 Description of wheat diversity in Indian Punjab

The number of different parental combinations and the number of distinct landrace ancestors in the pedigrees of modern wheat varieties grown in Indian Punjab from 1970 are shown in Table 1, ordered by date of release and variety name. There is a positive, step trend in the number of different parental combinations, illustrating the role of plant breeders in continuing to bring in new materials and make new crosses. The number of different landrace ancestors in the pedigrees of the varieties has a statistically significant, but imperceptible trend. Comparing the ratios of the figures at different time periods suggests that a declining number of new landraces are used in parental combinations. For example, the ratio of unique landraces to unique parental combinations is nearly two-thirds in 1966, as compared to one-third after three decades.

The average and area-weighted average age of wheat varieties are shown for Indian Punjab from 1970 to 2001 in Figure 1. In this generally high potential production environment, the un-weighted and weighted average ages move closely together in a cyclical pattern, suggesting that varieties are fairly uniformly distributed spatially over the time period as they are introduced into the system and others are discarded by farmers. The exception to this pattern is visible from about 1998, when fewer varieties are grown and they tend to be older, leading to an increase in the average age.

**Table 1** Pedigree characteristics of modern wheat varieties grown in Indian Punjab from 1970

| Name | Release year | Number of different parental combinations in pedigree | Number of different landrace ancestors in pedigree |
|---|---|---|---|
| PV18 | 1966 | 58 | 37 |
| S 308 | 1966 | 90 | 39 |
| HD 1553 | 1967 | 90 | 39 |
| Kalyan Sona | 1967 | 58 | 37 |
| Sonalika | 1967 | 90 | 39 |
| WG 357 | 1973 | 61 | 40 |
| WG 377 | 1973 | 60 | 39 |
| WL 1562 | 1979 | 88 | 43 |
| WL 711 | 1979 | 106 | 45 |
| DWL5023 | 1982 | 91 | 40 |
| PBW 120 | 1982 | 150 | 55 |
| PBW54 | 1983 | 121 | 52 |
| HD 2285 | 1985 | 188 | 59 |
| HD 2329 | 1985 | 153 | 58 |
| PBW 34 | 1985 | 65 | 38 |
| PBW 138 | 1986 | 112 | 51 |
| HD 2428 | 1989 | 109 | 46 |
| PBW 154 | 1989 | 144 | 54 |
| PBW 226 | 1989 | 74 | 42 |
| PBW 222 | 1990 | 112 | 48 |
| PDW 215 | 1991 | 70 | 39 |
| CPAN 3004 | 1992 | 164 | 57 |
| HD 2009 | 1993 | 71 | 37 |
| WH 542 | 1993 | 163 | 52 |
| WH 542 | 1993 | 163 | 52 |
| PBW 343 | 1995 | 192 | 65 |
| PBW 373 | 1995 | 192 | 65 |
| PDW 233 | 1996 | 103 | 41 |
| UP 2338 | 1997 | 140 | 49 |

Source: Variety names from Punjab Agricultural University, pedigrees from CIMMYT Wheat Impacts database and Pedigree Management System.

The average and area-weighted average coefficients of diversity (for brevity we refer to them in the remainder of the paper as genetic diversity conferred through breeding) constructed from the pedigree data are shown in Figure 2. The pattern in the area-weighted indices echoes that observed for area-weighted variety age, but with sharper peaks and troughs, diverging more in direction from about 1990. A downturn is evident at the end of the period, rather than the upturn that is observed in the rate of variety change. Hence, in the final years of the 1990s, the relatively fewer varieties grown were not only older in age, but more similar in parentage than those of the first half of the decade. The area-weighted coefficient of diversity lies everywhere below the un-weighted average, and is at its lowest since the early 1970s in 2000–2001. The fact that Indian wheat breeders drew in more dissimilar parentage over the 1970–2000 period is also apparent, since the average coefficient of

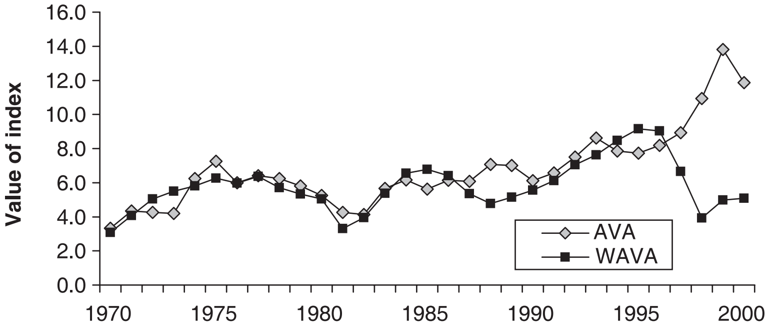


**Figure 1** Average and area-weighted average age of wheat varieties grown in Indian Punjab, 1970–2001.
Source: Data from Punjab Agricultural University. Calculations based on Brennan and Byerlee (1991).

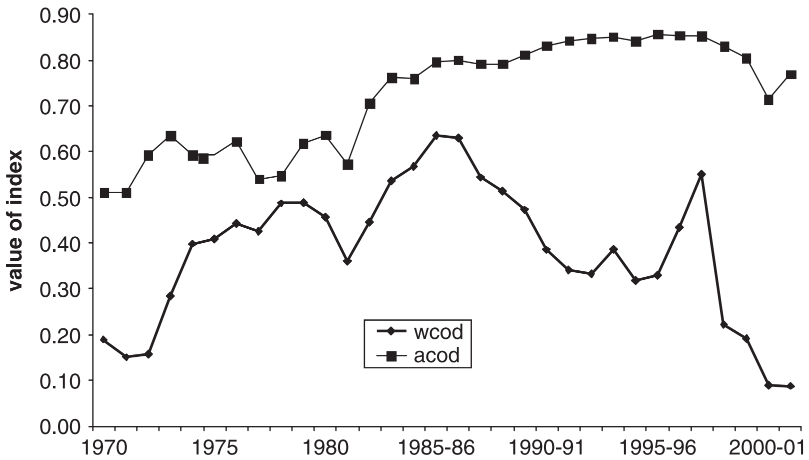


**Figure 2** Average and area-weighted average coefficient of diversity for wheat varieties grown in Indian Punjab, 1970–2001.
Source: Data from Punjab Agricultural University. The average coefficient of diversity is the average of 1-cop(ij) where cop(ij) is the pairwise coefficient of parentage between any two varieties of the j varieties grown in each year. The area-weighted average coefficient of diversity is the average of 1-cop(ij) where cop(ij) is the pairwise coefficient of parentage between any two varieties of the j varieties grown in each year, weighted by the areas planted to them (Souza *et al.* 1994).

diversity among all varieties grow in Indian Punjab has generally floated upward to over 85 per cent. For purposes of comparison, the coefficient of diversity between a parent and offspring would be 25 per cent, and would be close to 50 per cent for a sibling, while the coefficient of diversity for varieties with no ancestors in common would be one.

Table 2 reports the descriptive statistics of the variables used in the regression analysis. We discussed the definition of the diversity indices in the section on methods. We use the area-weighted average age as a proxy for variety change, and the average coefficient of diversity as an indicator of genetic diversity

**Table 2** Descriptive statistics for explanatory variables

| Variables | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|
| Genetic diversity Average coefficient of diversity | 0.733 | 0.124 | 0 | 0.848 |
| Area-weighted average age of varieties | 7.5 | 2.53 | 2.136 | 13.73 |
| Conventional inputs (RS/ha) | 3591.86 | 822.89 | 2075.37 | 10 281.73 |
| Rainfall (mm per year) | 162.69 | 152.56 | 0 | 558.07 |
| No use of bullocks Dummy variable 1 = Yes 0 = Otherwise) | 0.2 | 0.4 | 0 | 1 |
| Yields (Tonnes/ha) | 18.33 | 10.44 | 7.28 | 46.76 |

conferred through breeding. The area-weighted average age accounts for spatial distributions and is negatively related to variety change. Each index is calculated per district per year. Rainfall is recorded in mm per year.

To measure the impact of conventional inputs on productivity we used the total cost of hired labour, machinery costs per hectare, and costs of chemicals. All data on cost items are expressed in Rs/ha (in real terms 1993 = 100). Screening the database, we also found that in later years, in some districts, farmers had shifted entirely from bullock traction to mechanisation. To control for this source of heterogeneity, we introduced a dummy variable to measure the complete shift to mechanisation, treating it as a shift variable among conventional inputs. Initially, we estimated a production function with conventional inputs specified separately, which resulted in severe multicollinearity problems. The aggregation allows data parsimony and reduces the multicollinearity problems among conventional inputs.

### 4.2 Regression analysis

The potential endogeneity of diversity indices has been identified as a limitation that was not addressed in previous studies. If diversity indices were correlated with the error term, the least-squares estimates of the effects of indices on wheat yield would be biased. The endogeneity of each index was evaluated with a Durbin-Wu-Hausman test. The test compares ordinary least squares (OLS) estimates with estimates obtained from an instrumental variable estimator. Lagged values of the diversity indices were used as instruments in an instrumental variables regression and the statistical results were compared to the same model estimated with OLS. The $F$-statistic of the Durbin-Wu-Hausman was 0.508, corresponding to a $P$-value of 0.603, which led to failure to reject the null hypothesis. Thus, in this empirical context, data provide no support for the hypothesis that diversity indices are endogenous. Rather than an instrumental variables method, OLS was applied to estimate the Cobb-Douglas yield model.

Consistent with economic theory, conventional inputs are hypothesised to be positively related to wheat yields per hectare. These include machinery

**Table 3** Production function with temporal and genetic diversity. Fixed effects panel data estimator

| Variables | Coefficients | Standard errors |
|---|---|---|
| Average coefficient of diversity | 1.4*** | 0.24 |
| Average coefficient of diversity × Area-weighted average age of varieties | –0.7*** | 0.14 |
| Area-weighted average age of varieties | –0.19*** | 0.06 |
| Conventional inputs | 0.11* | 0.06 |
| Rainfall | –0.034 | 0.048 |
| Dummy for no use of bullocks | 0.11*** | 0.03 |
| Time trend | 0.03*** | 0.003 |
| Constant | 2.4*** | 0.49 |

*N*: 98; $R^2$: 0.57; *F*-Test: 22.47; Significance code: *** = 1%; **5% and *10%.
All conventional inputs are in Rupees/ha. All variable in logs. Robust standard errors have been used.

costs per hectare, costs for chemicals per hectare, and costs for hired labour. A lower variety age, suggesting more rapid variety change on farms, is thought to contribute positively to wheat productivity through mitigating the buildup of biotic pressures and bolstering yield potential. When weighted by area, the index also accounts for relative abundance of some newer releases. The average coefficient of diversity, calculated from the coefficients of parentage, is expected to positively affect wheat productivity through breeding advances.

Regression parameters and statistics are presented in Table 3. The sign and significance of conventional inputs is as expected, contributing positively to marginal productivity. The size of the coefficient is quite low (0.11). Note, however, that the output share of conventional inputs 0.14, which is quite close to value of the estimated coefficient. Non-genetic, disembodied technical change, which is expressed in the time trend, is positively correlated with wheat yields. The coefficient for rainfall is not statistically significant. This finding probably reflects the fact that nearly all the farms in the sample have access to irrigation.

Dissimilarity of parentage in wheat varieties, augmented through successful breeding, clearly enhanced wheat productivity in Indian Punjab from 1980 to 2000. Older area-weighted age of varieties, indicating slower variety change, decreased productivity. The negative coefficient on the interaction effect also shows that slower variety change offsets breeding successes. To illustrate this point, consider the estimated marginal productivity of genetic diversity. The sample mean for variety longevity in farmers' fields is seven years. Evaluated at the sample mean, the marginal productivity of genetic diversity is extremely small. However, the magnitude of the effect becomes relatively more important when the index for variety change is smaller. Thus, the marginal productivity imputed to genetic diversity is equal to 0.35 when variety change occurs every 4.5 years, and 0.65 when variety change occurs every three.

## 5. Conclusions

The Punjab of India is an historical source of key wheat genetic resources in national and global plant breeding. This region has also been a focus of concerns about some of the negative effects of the Green Revolution, including the abandonment of local varieties and genetic erosion.

We have used a yield model to test the effects of genetic diversity conferred through plant breeding and the area-weighted average age of varieties, which is negatively related to variety change, in the Indian Punjab during the post-Green Revolution period. The analysis is one of a few that tests related hypotheses using a combination of diversity indices constructed from detailed pedigree data, variety area data, and data on conventional inputs. Econometric findings demonstrate that continued infusion of diverse genetic materials through planting breeding has enhanced productivity in the wheat fields of Punjab in the post-Green Revolution period. Older variety ages on farms (slower variety change) dampen productivity, and also offset the positive impact of diversifying the genetic base through plant breeding. Clearly, policies that speed up variety change on farms, and encourage more diverse spatial distributions, would reinforce the advances made due to genetic diversity conferred through plant breeding. Even within a system that is characterised by modern varieties, continued investments in breeding and seed supply are critical to sustain crop productivity. While long recognised by practitioners, this paper tests this point more formally.

The implications of these findings are intuitive. Continued investments in wheat genetic improvement are fundamental to sustaining yield growth in the Indian Punjab. In particular, ensuring access of breeders to diverse germplasm obtained from an array of national and international sources continues to play a major role in this improvement, despite an increasingly proprietary environment. Genetic diversity cannot be exploited without access to diverse germplasm. Furthermore, efforts to speed the development and release of varieties and support dissimilar materials in a spatially heterogeneous way could have a positive impact. These points echo those made by others for earlier periods of plant breeding (Heisey 1990; Brennan and Byerlee 1991; Heisey and Brennan 1991).

The policy issue that remains unresolved is how best to support spatial heterogeneity. The performance of seed supply institutions and local channels are obvious aspects to examine. Decentralised breeding has been recommended, but there is disagreement about its costs and benefits. Witcombe (1999) has challenged the efficacy of centralised breeding programs, arguing that productivity gains might be achieved by delivering more diverse varieties to farmers, even in high potential production environments such as the Punjab of India. India follows China in terms of scale of wheat production. The Indian wheat breeding program is composed of 20 breeding programs. The size of the mandated production environment for these programs varies from 0.1 million ha (irrigated durum wheat, Central) to 4.9 million ha (irrigated, timely sown, bread wheat, Northern) (Traxler and Byerlee 2001: 237). Using a technology spillover matrix, Traxler and Byerlee (2001) examined the relative returns to programs. They concluded that although the overall rate of return to wheat research in India was 55 per cent, a number of programs earned negative rates of return.

Further research should consider wheat variety change and diversity within the broader context of current evidence regarding the degradation of water and land resources in the Punjab. Increasingly, non-seed technical change will be necessary to maintain total factor productivity in wheat against environmental degradation as documented in the Ali and Byerlee (2001) analysis for the Punjab of Pakistan & Murgai (2001) of the Indian Punjab. Unfortunately, the dataset used in this analysis precluded more advanced modelling of the relationship between genetic improvement, variety change, conventional inputs, soil, and water resources. Related research is now underway at the Punjab Agricultural University (Bhullar *et al.* 2006).

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