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The rate of crop varietal replacement on farms: measures and empirical results for wheat

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The rate of crop varietal replacement on farms is an important measure of the impacts of plant breeding programmes, the degree of varietal diversification over time, and the potential exposure to disease epidemics due to breakdown in disease resistance of older varieties. This paper proposes a simple measure, the weighted average age of varieties, for determining the rate of varietal replacement. This measure is used to compare the rate of wheat varietal replacement across countries/regions and over time in several developing and developed countries. The results indicate an average age of varieties of about 7 years, a figure close to the expected longevity of disease resistance of wheat varieties in many environments. However, the average age varies from less than 4 years in the Yaqui Valley in Mexico to over 10 years in the Punjab of Pakistan. Finally, the weighted average age is divided into the lag between varietal release and adoption initiation, and the speed of diffusion, once adoption is initiated. Differences in the relative sizes of these lags were noted between countries/regions, implying different policy interventions to increase the rate of varietal replacement.

INTRODUCTION

In countries where mature plant breeding programmes continuously release new varieties, it is useful to have a measure of the rate of varietal replacement for several reasons. First, the rate of varietal turnover indicates the impact of a plant breeding programme that has maintained a flow of improved varieties. For a given rate of varietal release, a rapid rate of varietal replacement in farmers' fields leads to higher returns to public plant breeding research because the lag between varietal release and adoption by farmers is reduced. Second, the rapid replacement of varieties over time can promote genetic diversification, especially if those varieties have diverse parentage (Duvick 1984). Third, for some crops (especially wheat), genetic resistance to diseases such as leaf rust continuously breaks down and varieties must be replaced periodically to maintain disease resistance. A measure of the rate of varietal replacement, when compared to the *expected* longevity of the disease resistance of a variety, is useful in assessing the vulnerability of a crop to disease epidemics. Finally, the desired rate of replacing varieties based on their expected longevity can also help plant breeders target how often they should release new varieties.

Although time–series data on varieties grown by farmers are often available, no single measure of the rate of varietal replacement is widely used to make comparisons over time and across regions. This paper proposes a simple measure for tracking varietal replacement. This measure, based on the weighted average age of varieties, is applied to compare rates of varietal turnover in wheat across countries and over time. The results are used to highlight policy implications for varietal development and seed multiplication and marketing systems, particularly in

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countries with largely public sector breeding programmes.

MEASURES OF VARIETAL REPLACEMENT

A number of measures of varietal replacement or turnover have been proposed. Johnson & Gustafson (1963) constructed an Index of Varietal Newness that compares the proportion of area covered by presently grown varieties with the proportion covered by the same varieties in earlier periods. This index is computed as follows:

$$Z_{it} = p_{it} - p_{i(t-n)} - 2p_{i(t-2n)} - 3p_{i(t-3n)} - \ldots \quad (1)$$

$$I_t = \sum_i Z_{it} \text{ for } Z_{it} > 0, \quad (2)$$

where p_{it} is the proportion of area sown to variety *i* in year *t*; *n* is the (arbitrary) desired number of years for varietal turnover; I_t is the index value in year *t*; and Z_{it} is an intermediate function for variety *i* in year *t*.

There are at least two problems with this index (Brennan 1984). First, it is sensitive to the choice of target period, *n*, for turnover of varieties. Johnson & Gustafson (1963) used a 5-year period largely because data were available in the USA at 5-year intervals; ideally, the choice of *n* would depend on the expected longevity of a new variety before it loses resistance to changing races of disease pathogens. Second, long time series of data are usually needed to construct the index for any given year.

An alternative Index, used by Brennan (1984) to analyse gains from wheat breeding in Australia, is the proportion of the area planted to varieties released in the past *m* years, where *m* is again (arbitrarily) defined to represent recently released varieties. The limitations of this index are similar to those of the Index of Varietal Newness, especially the sensitivity of the results to the choice of the parameter *m*. However, the proportion of area sown to recent varieties has a major advantage in that it is simpler to calculate and does not require long time series of data.

Both indices have the additional disadvantage of showing strong discontinuities in time–series estimates of the indices. For example, the indices for wheat varietal replacement in New South Wales (NSW), Australia, demonstrate sharp changes in 1965 and 1979, when successful new varieties were adopted rapidly after a period of relatively slow varietal turnover (Fig. 1). The years when these sharp discontinuities occur are also sensitive to the choice of the parameters *n* and *m*. In general, if $m = n$ the Index of Varietal Newness is somewhat higher, but follows with a short lag, the proportion of recently released varieties (see, for example, Fig. 1). This is because the Index of Varietal Newness measures varietal turnover from the time farmers first begin using a given variety, whereas the proportion of recent varieties uses the year of varietal release as the reference point.

To overcome the limitations of indices applied in the past, we propose a measure of the rate of varietal replacement that is based on the average age of varieties grown by farmers in a given year (measured in years since release), weighted by the area planted to each variety in that year. This measure, WA_t, is computed for a given year, *t*, as follows:

$$WA_t = \sum_i p_{it} R_{it} \quad (3)$$

where p_{it} is the proportion of the area sown to variety *i* in year *t*; and R_{it} is the number of years (at time *t*) since the release of variety *i*.

This measure is simple to calculate and avoids the use of an arbitrary definition of 'new' or 'recent' varieties. As a result, annual changes in this index are somewhat smoother than in the other two indices, since they are unaffected by the choice of 'target' period (see Fig. 1 for estimates for NSW, Australia, for example). This is the measure used in the following empirical analysis of wheat varietal turnover in different periods, regions, and countries.

For policy purposes it is useful to divide the Weighted Average Age (WA) into two

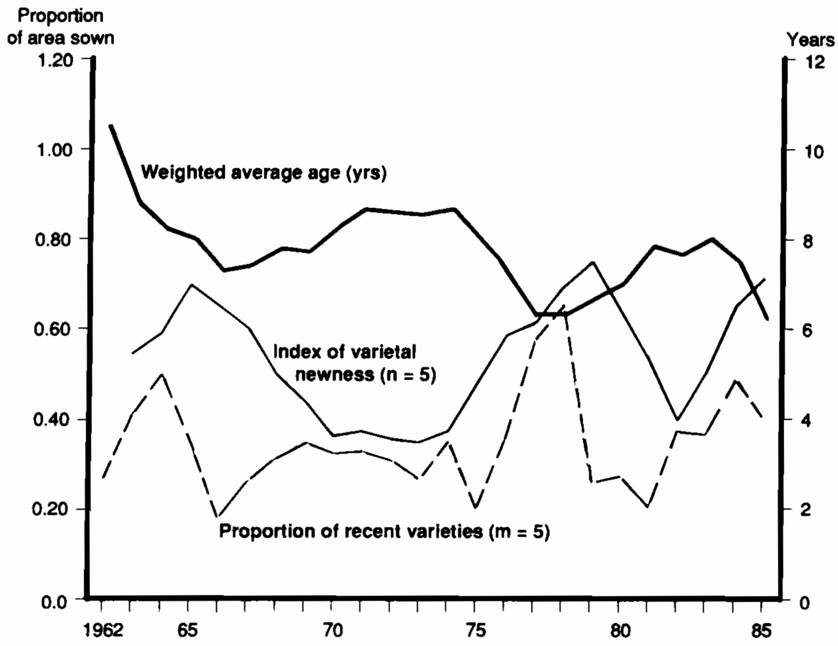

Figure 1. Comparison of measures of rate of varietal replacement, New South Wales, Australia.

components: (1) the average lag between varietal release and the initiation of adoption, WA^1 and (2) the average time for varietal adoption to occur once adoption has been initiated, WA^2. The first component reflects policies on seed multiplication and distribution, while the second is more likely to reflect the relative yield and other advantages of the variety as well as the effectiveness of the extension service. Conceptually these components can be separated as:

$$WA^1 = \sum_t \sum_i p_{it} S_i / n, \text{ and} \quad (4)$$

$$WA^2 = \left(\sum_t WA_t / n \right) - WA^1 \quad (5)$$

where S_i is the number of years from release of variety i to initiation of adoption, and n is the time period of analysis.

In practice, S_i is subjectively determined by how initiation of adoption is defined and by the precision with which varietal statistics are kept. Partially to overcome these problems, a logistic curve can be fitted to describe the adoption of varieties in a given country or region.[1] The logistic curve is defined, for the adoption phase only, by:

$$p_{it} = K_i / [1 + e^{-a - b(t - r_i)}] \quad (6)$$

where p_{it} is the proportion of area sown to variety i in year t; K_i is the maximum level of adoption of i; r_i is the year of release of variety i; and a and b are parameters of the curve. This curve can be fitted by OLS regression of pooled data on varietal use for a country or region by transforming as follows:

$$[-\ln(K_i/p_{it} - 1)] = a + bt^* \quad (7)$$

where $t^* = t - r_i$. From the curve, the two components of the adoption lag, averaged over the period of analysis, can be estimated as:

$$WA^1 = [-a - \ln(1/c - 1)]/b, \text{ and} \quad (8)$$

[1] A logistic curve is an S-shaped curve widely used to describe adoption of technologies (for example, see Griliches 1957). It allows a period of slow initial adoption, as farmers learn about a practice, followed by rapid adoption, followed by a slowing of adoption in the final phases when only laggard farmers continue using the old technology.

Table 1. Wheat area, yields and yield trends by region

Region/country	*Area (000 ha)*†	*Yield (t/ha)*†	*Yield growth rate (%/year)*‡
Punjab, Pakistan	5250	1.7	2.5**
Punjab, India	3020	3.3	2.6**
Yaqui Valley, Mexico	140	5.0	1.4**
Parana, Brazil	1380	1.6	5.1**
Argentina§	5390	1.9	1.9**
Kansas, USA	5020	2.5	0.8
NSW, Australia	3750	1.8	1.5
New Zealand	80	4.3	2.3**
The Netherlands††	130	7.5	3.4**

Source: Calculated from FAO data tapes and country statistical bulletins.
†Recent 3-year period, generally 1984–1986.
‡Estimated by time–trend logarithmic regression of yields for the period 1970–1986.
§Data for all of Argentina.
††Data for all wheat in The Netherlands.
**Denotes significance at the 5% level.

$$WA^2 = [-a - \ln(1/d - 1)]/b - WA^1, \quad (9)$$

where c defines the initiation of adoption, say $p = 0.10$; and d defines the completion of adoption, say $p = 0.95$.[1]

COMPARISON OF VARIETAL TURNOVER IN SELECTED COUNTRIES

Data sources

From published and unpublished sources, we assembled a data set on the area sown to wheat varieties for the following countries or regions and years: Punjab, Pakistan (1978–1986); Punjab, India (1970–1986); Yaqui Valley, Mexico (1972–1986); Parana, Brazil (1979–1985); Region II North, Argentina (1970–1980; Penna *et al.* 1983); Kansas, USA (1970–1986); New South Wales (NSW), Australia (1970–1985; Fitzsimmons 1987); New Zealand (1970–1986); and The Netherlands (1970–1986, winter wheat). Although not comprehensive in representing all the major wheat production areas, these countries and states/regions cover a wide range of production systems in developed and developing countries.[2] Some characteristics of wheat production in these various countries/regions are shown in Table 1.

Of the developing countries represented in the analysis, the regions of India, Mexico and Pakistan grow largely irrigated wheat in similar agro-ecological environments; these areas were the early beneficiaries of the 'Green Revolution' in wheat stimulated by the release of semi-dwarf varieties in the mid 1960s. The data analysed for these areas cover the period since the improved varieties were widely adopted. However, in these irrigated environments leaf rust is a major

[1] Note that the logistic curve is asymptotic to $p_i/K_i = 0$ and $p_i/K_i = 1$, so that arbitrarily small and large numbers of p_i/K_i have to be selected for defining initiation and completion of adoption.

[2] Although the wheat area represented by the data varies substantially between countries and regions/states, we have no reason to expect that the rate of varietal turnover is a function of the size of the wheat area sown.

Table 2. Weighted average age of wheat varieties

Region/country	*Data period*	*Age (years)* 1970s	*1980s*	*Mean*	*Time trend*†
Punjab, Pakistan	1978–1986	11.8	10.9	11.1	−0.12*
Punjab, India	1970–1986	5.4	5.3	5.3	0.05
Yaqui Valley, Mexico	1972–1986	2.6	3.7	3.1	0.13**
Parana, Brazil	1979–1985	7.3	10.5	9.9	0.50**
Region II North, Argentina	1970–1980	6.7	7.9‡	6.8	−0.06
Kansas, USA	1970–1986	6.6	6.9	6.7	0.06**
NSW, Australia	1970–1985	7.7	7.4	7.6	−0.11**
New Zealand	1970–1986	12.0	7.9	10.3	−0.46**
The Netherlands, winter wheat	1970–1986	5.4	7.6	6.6	0.29**
Mean§					
Developing countries	1970–1986	6.4	8.9	7.2	0.21**
Developed countries	1970–1986	7.1	6.7	7.1	−0.01
Overall	1970–1986	6.7	8.4	7.2	0.12*

†Estimated by a linear time–trend regression for the data period for that country/region.
‡Data for 1 year only (1980).
§Weighted by area sown (see Table 1).
**, *Denote significance at 5% and 10% levels, respectively.

problem and varieties should be replaced frequently to avoid losses from rust epidemics (Khan 1987). Yields in these areas range from 1.7 t/ha in the Punjab of Pakistan to over 5.0 t/ha in the Yaqui Valley, Mexico. In contrast, in the Argentinian and Brazilian regions wheat grows under rainfed conditions, often under considerable moisture stress; yields in these areas are generally lower. All of the developing countries represented are characterized by relatively strong wheat breeding programmes that release a steady stream of new varieties.

The areas selected from developed countries are mostly rainfed but range from dryland areas, such as NSW, Australia, where average yields are 1.8 t/ha, to high rainfall areas, such as The Netherlands, where average yields surpass 7.5 t/ha. In general, we expect varietal replacement to be somewhat more rapid in areas where yields are higher, because disease pressure is often more severe in those environments. All the regions have shown yield growth in the period examined, although the rate of yield improvement in Kansas and NSW is low and statistically non-significant.

Weighted average age of varieties

The Weighted Average Age (WA) of varieties ranges from 3.1 years in the Yaqui Valley of Mexico to 11.1 years in the Punjab of Pakistan (Table 2). Except for these two extremes, the WA is surprisingly consistent across regions and falls within a range of 5–10 years with an average of about 7 years.[1] The high rate of varietal turnover in Yaqui Valley, Mexico reflects several factors, including the rapid mutation of rust pathogens, the high rate of release of superior varieties, a well-developed seed production and wheat industry, and

[1] Differences in the size of wheat area in each country or region analysed may explain some variation in the estimated WA among countries. However, in most cases the country or region selected for analysis is a relatively homogeneous agro-climatic zone.

innovative farmers who continuously seek out new varieties. By contrast, the slow rate of varietal turnover in the Punjab of Pakistan reflects a poorly developed seed industry and extension service, and this has exposed the country to serious risks of a rust epidemic (Heisey 1990).

A WA of varieties of about 7 years appears to be consistent with expectations based on the economics of varietal replacement and the epidemiology of disease pathogens. A model of varietal replacement developed by Heisey & Brennan (1991) indicates that the optimal period for varietal replacement is a function of the rate of gain in yield potential of new varieties, the rate of deterioration of old varieties, the cost of seed, the cost of capital, and the minimum margin required to induce farmers to replace seed. Using this model, the calculated optimum period for varietal replacement in the Punjab of Pakistan is 13 years, close to the observed WA of 10.9 years in the 1980s. Optimal varietal replacement rates are lower for countries/regions with lower seed, capital and farmer learning costs.

The longevity of varieties in terms of rust resistance is expected to be highly environment specific.[1] However, Kilpatrick (1975) has assembled data from a number of countries on the estimated longevity of wheat varieties in terms of disease resistance. The overall average estimate of 5–6 years' varietal longevity for leaf and stripe rusts is close to the average WA of varieties across countries.

The WA for different decades and a linear time–trend regression on WA are also presented in Table 2. The WA has tended to increase in four of the nine countries/regions and to decline in three. The evidence suggests that the productivity of the wheat breeding programme explains the declining WA observed for NSW, New Zealand, and possibly the Punjab of Pakistan. For example, in NSW, where the WA shows a consistent decline over time, semi-dwarf varieties were first released in the 1970s and have been steadily adopted since then (Brennan 1986). The increasing WA in Yaqui Valley may reflect stabilization after the rapid varietal turnover stimulated by the adoption of semi-dwarf varieties in the 'Green Revolution' period of the late 1960s and early 1970s.

Long delays in diffusion of improved wheat varieties not only expose countries to the risk of a rust epidemic (Heisey 1990) but may also affect the returns to wheat breeding research. Although there are numerous examples of successful varieties that have survived for many years and provided high returns, where breeding programmes regularly release improved varieties, returns to the programme are increased by a more rapid rate of varietal replacement. For example, in the Punjab of Pakistan, given the rate of yield improvement in released varieties, the expected rate of return on investment in wheat breeding research would increase from 25 to 31%, if the WA in the Punjab of Pakistan were reduced from the current 11 years to the global average (in this sample) of 7 years (Byerlee 1990). Reducing the diffusion lag to a level comparable to the Yaqui Valley would increase returns to 41%.

Differences in the WA between countries and regions may also relate to differences in lags between varietal release and the initiation of adoption, or to differences in the speed of adoption. These time periods were estimated for each country or region by pooling varietal use data for all varieties that were sown on at least 10% of the wheat area in a minimum of 1 year, and fitting the regression of equation (7) above.[2] The parameter K_i was estimated as the maximum adoption level reached in the period for which data were available. The results presented in Table 3 indicate that the estimated time to reach 95% adoption is very close to the WA, with a correlation coefficient of 0.87. The very short

[1] The longevity of varieties may also be promoted by management, especially efforts to increase genetic diversity at the farm level by planting a mosaic of varieties with different resistance genes.

[2] In all cases, the logistic curve gave a very good fit with an $r^2 > 0.90$.

Table 3. Estimated lags and time for full varietal adoption

Country/region	*Estimated lags (years)* *WA*[1]	*WA*[2]	*Time to reach 95% adoption (years)*
Punjab, Pakistan	3.0	7.5	10.5
Punjab, India	−1.1	5.9	4.8
Yaqui Valley, Mexico	1.0	1.8	2.8
Parana, Brazil	4.5	3.8	8.3
Region II N, Argentina	−0.4	5.5	5.1
Kansas, USA	1.8	2.3	4.1
NSW, Australia	1.3	3.7	5.0
New Zealand	1.1	5.9	7.0
The Netherlands (winter wheat)	−1.2	8.2	7.0
Mean†			
Developing countries	0.8	6.1	6.9
Developed countries	1.5	3.0	4.5
Overall	1.1	5.0	6.1

*WA[1] is average time from varietal release to initiation of adoption (10% adoption) and WA[2] is average time from adoption initiation to full adoption (95% adoption).
†Weighted by area sown (see Table 1).

WA[1] and WA[2] for the Yaqui Valley indicate that seed multiplication and varietal diffusion are very efficient and that farmers are prepared to adopt improved varieties very rapidly. Kansas and NSW demonstrate similar characteristics. In contrast, the Punjab of Pakistan tends to be slow in initiating adoption, and especially slow in the rate of diffusion. In the case of Parana, Brazil, the lag before adoption is initiated tends to be very long, but once adoption begins, varieties diffuse rapidly. The reverse occurs in The Netherlands.[1] Overall, farmers in developing countries appear to initiate adoption as rapidly as those in developed countries. However, the period of varietal diffusion after adoption begins generally tends to be longer in developing countries (Table 3).

[1] For The Netherlands, the Indian Punjab, and Argentina, the estimated WA[1] is close to zero or even negative. The negative estimates suggest there is a need to treat the data with some caution. The negative value for the Indian Punjab may be explained by the fact that some varieties were grown commercially before their official release.

CONCLUSIONS

After considering alternative measures of the rates of varietal replacement, we have proposed the WA of varieties grown by farmers as a simple, unambiguous measure[2] and applied it to compare rates of varietal turnover in wheat across countries/regions and over time.

The increasing WA of varieties sown in farmers' fields in most of the developing countries in this analysis indicates that the rate of varietal turnover is declining. Decreasing turnover reflects the slower rates at which new varieties have diffused among farmers since 1970, which is partly the result of a return to normality after the introduction of semi-dwarf wheats in the sample of countries analysed in this paper.

[2] For the data sets analysed, there is nevertheless a high correlation between this measure and others previously applied. The correlation between the WA and the Index of Varietal Newness and the proportion of area sown to recent varieties is about 0.7 over the nine data sets.

For all countries and regions examined, the average age of varieties was about 7 years—close to the longevity of disease resistance in wheat varieties observed by Kilpatrick (1975) and Khan (1987) in many environments. However, countries and regions differ markedly in rates of varietal turnover. Regions such as the Punjab of Pakistan, where the weighted average age of varieties is high, probably run the risk of a rust epidemic and reduce their returns to wheat breeding research.

The variation between countries is also noteworthy when differences in varietal age are disaggregated into lags between varietal release and the initiation of adoption, and the speed of varietal diffusion once it begins to occur. These lags have somewhat different policy implications; the time from release to initial adoption reflects policies on seed multiplication and distribution and the existence of a group of innovative farmers, whereas the speed of diffusion is related to positive varietal characteristics and the effectiveness of extension.

This study demonstrates that countries with mature plant breeding programmes releasing a steady stream of new varieties need to collect statistics on the area planted to released varieties each year. Compiling and analysing these data can provide feedback on several issues related to the rate of varietal replacement. An analysis of the rate of varietal replacement on farms is useful to plant breeders in monitoring the impact of their research, to plant pathologists in assessing the risk of a disease epidemic and to policy makers in evaluating the effectiveness of the seed multiplication and marketing system and the role of extension services.

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