Articles

Production Risk and the Evolution of Varietal Technology

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A Just-Pope production function is used to estimate the effect of genetic improvement on the first two moments of wheat yield for the period 1950–86. The model characterizes the green revolution as the culmination of an era in which wheat breeders achieved rapid increases in yield potential accompanied by higher yield variances. To date, the post-green revolution has been an era of slower mean yield growth, but of relatively rapid improvement in yield stability. Overall, the analysis indicates steady progress in producing "better" varieties; successive releases have improved either stability, mean yield, or both.

Key words: genetic improvement, Just-Pope production function, post-green revolution, technical change.

Introduction of modern cereal varieties into developing country agriculture, commonly referred to as the green revolution, has been one of the most intensively studied agricultural phenomenon of recent times. Varietal technologies made available subsequent to the green revolution have received less scrutiny, despite tremendous changes in the global capacity to generate new technologies. International and national agricultural research systems have matured so that in most regions producers are the beneficiaries of regular—in some cases annual—release of new varieties. Yet existing studies simply classify varieties as either pre-green revolution "traditional" varieties or green revolution "modern" varieties (MVs) (e.g., Renkow; Coxhead; Evenson and Pray). A quantitative assessment of varietal technical change from pre-green through post-green revolution eras is merited because nearly thirty years have now passed since the initiation of the green revolution.

Peterson and Hayami state that "Comparison of the partial production parameters estimated on experimental data over time could be a promising approach to the measurement of technical change. Surprisingly little has been done along this line, however" (p.509). One advantage of using experimental rather than aggregate time series data is that the technology variable can be precisely defined, removing the need to rely upon a trend variable to proxy for "technical change." We examine the evolution of wheat varietal technology using data from a variety x nitrogen experiment conducted by the International Maize and Wheat Improvement Center (CIMMYT). The improved germplasm developed at CIMMYT is distributed to national agricultural research systems (NARSs) worldwide, so an examination of the varieties developed there has implications for wheat production in the developing world.[1]

Recognizing that plant breeders, as well as farmers, judge varieties using multiple criteria, we model the evolution of two important technical characteristics: mean yield and yield sta-

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[1] In 1990, 42% of the spring bread wheat area in developing countries was sown to varieties developed at CIMMYT (Byerlee and Moya).

bility.[2] The question of whether modern varieties (MVs) are less stable than traditional varieties (TVs) has already been addressed. Early studies (Mehra; Barker, Gabler, and Winkelmann; Hazell) associate green revolution technologies with decreased yield stability, while recent studies (Singh and Byerlee; Anderson, Findlay, and Wan) fail to establish a link. Our analysis suggests the reason for the apparent contradiction in previous studies is that yield stability decreased with the release of first generation MVs, but increased with subsequent releases.

We present a generalized least squares (GLS) production function approach to risk analysis using the econometric framework of Just and Pope to test the hypothesis that the evolution of varietal technology has increased yield variance. The model is then used to trace the evolution of mean yield and yield variance for the period 1950–85.

Analytical Framework

Just and Pope's econometric framework relaxes the second moment production function restrictions, providing a method for estimating the marginal risk effects of explanatory variables. The Just-Pope approach also facilitates direct econometric testing of risk-related hypotheses. Since it is a GLS procedure, efficiency gains in parameter estimates are also possible.

The general form of the Just-Pope production function is

$$(1) \qquad Y_i = f(\mathbf{X}_i, \boldsymbol{\beta}) + g(\mathbf{X}_i, \boldsymbol{\alpha})\varepsilon_i$$

where Y_i is yield or output, the $\mathbf{X}_i$ are explanatory variables, $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}$ are parameter vectors, and ε_i is a random variable with zero mean. The production function $f(\mathbf{X}_i, \boldsymbol{\beta})$ relates explanatory variables to mean output, while the function $g(\mathbf{X}_i, \boldsymbol{\alpha})\varepsilon_i$ relates explanatory variables to the variance of output.

The premise of the Just-Pope model is that the variance of the production function error term may be related to some or all explanatory variables, implying it is a multiplicative heteroskedasticity model (Judge et al., Harvey). Our multiplicative heteroskedastic model is estimated using the three-stage estimation procedure described in Judge et al. If variance is an exponential function of K explanatory variables, a general model with heteroskedastic errors can be expressed as

$$(2) \qquad Y_i = X_i'\beta + e_i, \; i = 1,2, \ldots, N$$

$$(3) \qquad \mathrm{E}(e_i^2) = \sigma_i^2 = \exp[\mathbf{Z}_i'\boldsymbol{\alpha}]$$

where $\mathbf{Z}_i' = (z_{1i}, z_{2i}, \ldots, z_{ki})$ is a vector of observations on the K independent variables, $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \ldots \alpha_k)'$ is a $(K \times 1)$ vector of unknown coefficients, and $\mathrm{E}(e_i) = 0$, $\mathrm{E}(e_ie_s) = 0$ for $i \neq s$. In our empirical model, the $\mathbf{Z}$ matrix is specified as the $\mathbf{X}$ matrix.

Equation (3) can be rewritten as $\ln \sigma_i^2 = \mathbf{Z}_i'\alpha$. The σ_i^2 are not known, but the least squares residuals from (2) can be used to estimate the marginal effects of explanatory variables on the variance of production. Therefore,

$$(4) \qquad \ln e_i^{*2} = \mathbf{Z}_i'\alpha^* + u_i$$

where $u_i = \ln(e_i^{*2}/\sigma_i^2)$. Although u_i has a nonzero mean, the mean and the variance of the limiting distribution of $\boldsymbol{\alpha}^*$ is known. Harvey has shown that asymptotically the u_i will be independent with mean of $\mathrm{E}[u_i] = -1.2704$, and with asymptotic covariance matrix $\boldsymbol{\Gamma}_{\alpha'} = 4.9348(\mathbf{Z}'\mathbf{Z})^{-1}$. These results permit asymptotically valid hypothesis tests about marginal risk effects. Predicted values from equation (4) are used as weights for generating GLS estimators for the mean output equation.

Data

Data come from trials by the International Center for Improvement of Wheat and Maize (CIMMYT) in the Yaqui Valley of Sonora, Mexico. Ten wheat varieties, released in Mexico from 1950 to 1985, were grown during three crop cycles: 1987, 1988, and 1989. Five levels of nitrogen fertilization (0, 75, 150, 225, and 300 kg/ha) were applied in 1987 and 1988, and all but the 300 kg/ha treatment were applied in 1989. Each variety by nitrogen treat-

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[2] Rajaram, Skovmand, and Curtis list the following germplasm traits as long-term objectives of the CIMMYT wheat improvement program: "high yield potential, stable yield, wide adaptation, semi-dwarf characteristics, photoperiod insensitivity, and disease resistance" (p. 37). We examine the first two of these traits. Stability is genotype performance with respect to environmental factors that change across time within a given location, while adaptability is performance with respect to environmental factors that change across locations (Evenson et al.). Binswanger and Barah, and Evans (p.164) argue that stability is the relevant concern for farmers because it deals with performance within their decision environment.

Table 1. Year of Release and Summary Statistics by Variety

Variety	Year of Release	Mean Yield (kg/ha)	Std. Dev. (kg/ha)	Min. Yield (kg/ha)	Max. Yield (kg/ha)
Yaqui[a]	1950	3,478	1,055	1,239	6,256
Nainari[a]	1960	4,964	1,315	1,518	6,662
Pitic	1962	5,268	1,497	1,366	7,972
Siete Cerros	1966	5,552	1,557	1,947	7,375
Yecora	1970	5,835	1,852	1,698	8,247
Jupateco	1973	5,431	1,572	1,776	8,230
Ciano	1979	5,960	1,757	1,384	8,447
Genaro	1981	6,324	1,719	2,015	8,651
Opata	1985	6,029	1,587	1,826	7,905

[a] Tall variety

ment contained three replicates. Hence, the data set has nine yield values for each treatment, except for 300 kg/ha which has six replicates. Water and other nutrients were provided at nonlimiting amounts and fungicides were used to protect against rust. Summary statistics for each variety are given in table 1.

All of the varieties were grown by farmers in the Yaqui Valley between 1950 and 1990. Most varieties also were distributed to wheat breeders in other developing country research systems for release or for use as breeding material. One variety grown in the trials, INIA 66, was not included in our analysis to avoid having two varieties released in 1966. The oldest varieties, Yaqui and Nainari, are improved tall varieties. Pitic was the first variety containing the dwarfing gene (Hanson, Borlaug, and Anderson). Siete Cerros is the major Green Revolution variety that, along with sister varieties, was planted to some thirteen million hectares worldwide in the early 1970s. Genaro is a "Veery" variety that is the result of crossing spring and winter wheat lines. In the early 1990s, Genaro and its sister lines were sown on about four million hectares worldwide.

Empirical Model

Isolating the impact of varietal technology on mean and variance of production is difficult because of the confounding effects of production changes accompanying MV diffusion. Studies with national, state, or district level aggregate time series data use time as a proxy for technical change, but they are unable to separate the effect of varietal technology from improvements in management efficiency, the expansion of production to marginal lands, or increased use of chemical and other inputs (Eisgruber and Schuman; Barker, Gabler, and Winkelmann; Hazell 1984, 1989; Singh and Byerlee).

Studies have employed data from controlled experiments to isolate either the mean yield or stability differences between varieties (e.g., Pfeiffer and Braun, Brennan). However, when variety is the only experimental factor, there is no insight into relative varietal performance beyond the experimental input level, thereby limiting applicability of the findings. Our data set allows varietal progress to be traced at several nitrogen levels. Nitrogen and improved irrigation were the major technological components combined with improved varieties to produce the green revolution.

The mean and variance of response were specified as functions of nitrogen (X) and technology (v). The estimated equations for yield, (Y_i) in kg/ha, and the log of the variance of yield (e_i^2) are specified as quadratic functional forms with the same regressors

$$(5) \quad Y_i = \alpha_0 + \alpha_1 X_i + \alpha_2 X_i^2 + \alpha_3 v_i + \alpha_4 v_i^2 + \alpha_5 X_i v_i + \alpha_6 D87_i + \alpha_7 D88_i + \varepsilon_i$$

and

$$(6) \quad \ln e_i^2 = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + \beta_3 v_i + \beta_4 v_i^2 + \beta_5 X_i v_i + \beta_6 D87_i + \beta_7 D88_i + \mu_i$$

where X_i = nitrogen (kg/ha), v_i = year of release of the variety minus 1949 (1950 = 1), $D87_i$ = dummy variable for trials conducted in 1987, and $D88_i$ = dummy variable for trials conducted in 1988.

The technology variable is not a time trend, but is modeled similar to the way that growth

Table 2. Econometric Results

Explanatory Variables	Yield[a]	Variance of Yield
X	18.47	−0.0023
	(12.39)**	(−0.53)
X^2	−0.09	0.000015
	(−10.75)**	(1.15)
v	147.08	0.11
	(11.54)**	(2.60)**
v^2	−3.06	−0.0017
	(−9.33)**	(−1.70)*
Xv	0.25	−0.00028
	(6.67)**	(−2.65)**
D87	1368.70	−0.027
	(13.41)**	(−0.09)
D88	1006.90	−0.021
	(9.86)**	(−0.07)
CONSTANT	1398.30	11.61
	(10.68)**	(21.50)**
R^2	0.81	0.069
n	378	378

[a] Weighted least squares results.
Note: t-ratios are presented in parentheses.
* coefficient statistically different from zero at 10% level (two-tailed t-test).
** coefficient statistically different from zero at 1% level (two-tailed test).

Table 3. Results of Variance Model Hypothesis Tests

Null Hypothesis	Parameter Restriction	Test Statistic
Variance not influenced by varietal development	$\beta_3 = \beta_4 = 0$	F = 5.22[a]
Variance not influenced by nitrogen use	$\beta_1 = \beta_2 = 0$	F = 1.09
Interaction between varietal development and nitrogen use	$\beta_5 = 0$	t = −2.65[a]

[a] Reject H_0 at 1% significance level.

models by Arrow and others denote embodied technology. The growth models assign "serial numbers" of ordinal significance to each technological vintage of capital. In our model, the technology variable, v, represents the year of release of the trial variety. Hence, the value taken by v has cardinal as well as ordinal importance to specify the spacing as well as the sequencing of releases.

The varietal development component of technological change presents a unique opportunity to depart from the conventional trend specification. For most processes and data sets, it is not possible to identify the precise manner in which research output is embodied, to accurately measure the direct productivity impact of a research discovery, or to relate sequential research discoveries to time.

Econometric Results

Econometric results are presented in two parts. The GLS mean yield equation is discussed first, followed by discussion of the yield variance model.

Mean Output Response

The quadratic GLS mean response equation fits the data well, as shown in table 2. All coefficients have the anticipated signs, are significant at the 1% level, and the production technology is estimated to be strictly concave. At the mean nitrogen level (140 kg/ha), year of release (v) has a positive effect on mean yield until 1979, with yield reaching a plateau after 1979. While the model clearly indicates a slowing in the rate of yield improvement in the post-green revolution years, the conclusion that a plateau has occurred is not robust. The model is estimated based upon data including just one variety released subsequent to the "plateau" period. The positive interaction coefficient for the variable Xv implies that yield improvement has been greater at higher nitrogen levels.

Output Variance Response

A Breusch-Pagan test statistic value of 46.78, obtained from the first-stage OLS mean yield regression, indicates the hypothesis of homoskedastic errors is rejected. The variance response model (table 2) was used to conduct three hypothesis tests as shown in table 3. The first hypothesis is that varietal development had no independent effect on output variance; it was tested using the joint F-test that the coefficients $\beta_3 = \beta_4 = 0$. The estimated F-value of 5.22 ex-

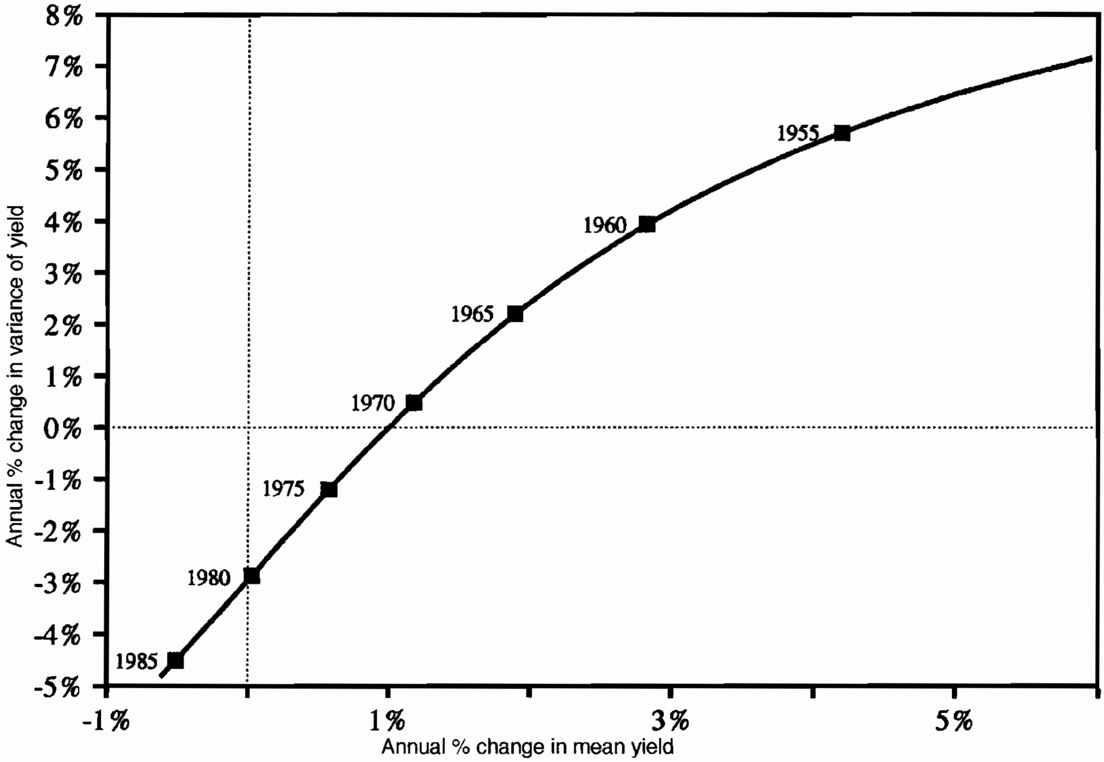

Figure 1. Mean yield–yield stability frontier (N = 140 kg/ha)

ceeds the 1% critical $F_{(2,370)}$ of 4.61, indicating rejection of the null hypothesis. The null hypothesis that variance is not affected by nitrogen use ($\beta_1 = \beta_2 = 0$) results in an estimated F-value of 1.09 which does not exceed the critical value.[3] Finally, a t-test of $\beta_5 = 0$ indicates rejection of the null hypothesis of no interaction between varietal development and nitrogen use.

The analysis suggests that at the mean nitrogen level of 140 kg/ha, varieties released prior to 1971 increased yield variance, but that varieties released subsequent to 1971 were variance reducing. Although we found no independent effect of nitrogen use on variance, the negative interaction coefficient implies that the nitrogen response of newer varieties is less variable than that of older varieties.

[3] Roumasset et al. review a number of studies which used farm survey data to estimate the risk effect of nitrogen fertilizer use. Most of the studies found nitrogen to be modestly risk-increasing. Antle and Crissman found nitrogen use to be risk-reducing when used by experienced farmers planting modern rice varieties.

Mean-Variance Trade-Off in Varietal Development

Figure 1, the evolution of varietal technology from 1950–85, was constructed using the mean and variance response functions to calculate the annual percentage change in yield and the annual percentage change in variance for each year, holding nitrogen fixed at 140 kg/ha. The figure shows that in the years in which the most rapid yield increases were achieved, yield variance also increased. On the other hand, in the period when progress was made in reducing yield variance, mean yield improvement was slower. Figure 1 suggests that a tradeoff exists between selection for high yield and selection for yield stability; given the appropriate data, analogous curves could be drawn for characteristics such as disease resistance or grain quality. The curve reflects the historical mean-stability tradeoff, but it is likely that the curve has shifted over time—so reducing stability would not guarantee returning to a 4% per annum rate of yield gain. It is likely that the long-run rate of yield gain would increase if selection for secondary plant characteristics were de-emphasized.

Summary and Conclusions

A heteroskedastic production function was used to model the effect of varietal technical change on the first two moments of wheat yield. The model characterizes varietal traits as arising from an ongoing, dynamic plant breeding research effort. The quadratic model indicates that mean yield potential increased steadily between 1950 and 1980, but reached a plateau in the 1980s. The variance of output is estimated to have peaked around 1970, but decreased after that year. Overall, the analysis indicates steady progress in producing "better" varieties; successive releases have improved either stability, mean yield, or both.

Our model characterizes the green revolution as the culmination of an era in which wheat breeders achieved rapid yield increases accompanied by higher yield variances. To date, the post-green revolution has been an era of slower mean yield growth but of relatively rapid improvement in yield stability. The International Rice Research Institute's (IRRI) rice breeding experience has been qualitatively similar to CIMMYT's wheat breeding experience. The first rice MV to be widely grown in Asia, IR 8, was released in 1966. Subsequent rice varieties do not yield more than IR 8, but as with wheat, steady improvement has been achieved in secondary characteristics such as increasing insect and disease resistance, and shortening the crop duration (Pingali, Moya, and Velasco; Herdt).

Genetic improvement is the major source of yield increases for major crops in the United States during this century (Huffman and Evenson, Schmidt), and the same is undoubtedly true for developing countries (Heady and Auer, Evans). Developing country cereal yields increased at a 2.6% annual rate between 1969 and 1989 (CIMMYT), but concern exists about the momentum of the existing system for technology generation and prospects for continued yield growth (Herdt; Pingali, Moya, and Velasco; Byerlee). A basic principle of plant breeding is that the success rate for developing higher yielding varieties is reduced as objectives are added to a breeding program (Evans, p. 311; Fehr, p. 120). In recent times, plant breeders have been asked to embrace an expanded set of breeding objectives as a way to overcome an assortment of challenges (Anderson 1991; Lipton with Longhurst), but economists have offered little practical guidance in weighting these objectives. A few studies have examined the benefits accruing to improvement in secondary breeding objectives (Voon and Edwards, Unnevehr), but no attempts have been made to estimate the opportunity cost of the slower rate of yield growth inherent in incorporating additional objectives. As a result, the process for setting breeding objectives often remains informal (Bingham and Lupton). Therefore, research aimed at quantifying the opportunity cost of directing research at improvement of secondary plant traits would be valuable.

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