Impacts of International Research on Intertemporal Yield Stability in Wheat and Maize: An Economic Assessment

Douglas Gollin

Department of Economics
Williams College
Williamstown, Massachusetts

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CIMMYT

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This study makes extensive use of a data set on the diffusion of modern crop varieties compiled by Bob Evenson. I gratefully acknowledge the permission to work with these data. This study was initiated by Michael Morris and supported successively by Erika Meng and John Dixon. This study also draws, albeit indirectly, on my interactions over the years with many outstanding social scientists who have been based at CIMMYT, including Mauricio Bellon, Paul Heisey, Prabhu Pingali, and Melinda Smale. I have also appreciated the patience and cooperation of many other current and former CIMMYT scientists, who have attempted to explain breeding strategies and scientific concepts to me. This list includes (but is not limited to): David Beck, Norman Borlaug, Maarten van Ginkel, David Hoisington, Masa Iwanaga, Dan Jeffers, Bent Skovmand, Suketoshi Taba, and Marilyn Warburton. CIMMYT science writer Mike Listman provided editorial support and designer Antonio Luna did the layout. And although they have not directly commented on this manuscript, my writings reflect input from Cheryl Doss and Bob Evenson. Stefan Krieger provided helpful comments and suggestions on calculating the benefits of variance reduction. Portions of this research were carried out while I was visiting the Centre for Study of African Economies, Oxford University. I gratefully acknowledge the support of CSAE, and its staff.

Author's contact information: Department of Economics, Williams College, Fernald House, Williamstown, MA 01267 USA. Currently on leave at Economic Growth Center, Yale University, 27 Hillhouse Ave., PO Box 208269, New Haven, CT 06520-8269. Phone: 203-432-3638. Fax: 203-432-3635. E-mail: *Douglas.Gollin@williams.edu*.

CIMMYT® (www.cimmyt.org) is an international, not-for-profit organization that conducts research and training related to maize and wheat throughout the developing world. Drawing on strong science and effective partnerships, CIMMYT works to create, share, and use knowledge and technology to increase food security, improve the productivity and profitability of farming systems, and sustain natural resources. CIMMYT is one of 15 Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org). Financial support for CIMMYT's work comes from the members of the CGIAR, national governments, foundations, development banks, and other public and private agencies.

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Abstract: Critics of modern maize and wheat varieties (MVs) have suggested that, in developing countries, yields of these varieties vary more from season to season than yields of farmers' traditional varieties, thereby exposing consumers and producers to greater risk. Drawing on country-level data for MV diffusion, as well as aggregate data on production and yields from FAOSTAT, this study makes novel use of the Hodrick-Prescott filter to disentangle changes in trend from annual fluctuations. The outcomes suggest that, over the past 40 years, the relative variability of grain yields—that is, the absolute magnitude of deviations from the yield trend—has declined for both wheat and maize in developing countries, and that the reduction is statistically associated with the spread of MVs, even after controlling for expanded use of irrigation and other inputs. At appropriate world prices, the annual benefits from improved yield stability alone are about US$143 million for wheat and about US$149 million for maize.

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Contents

Tables and Figures

1. Executive Summary

Modern crop varieties developed through scientific crop breeding clearly produce higher yields than farmers' traditional varieties. But critics have long suggested that, in developing countries, yields of modern varieties vary more from season to season than farmers' traditional varieties, thereby exposing consumers and producers to greater risk.

Drawing on country-level data for the diffusion of modern wheat and maize varieties (MVs) compiled by Robert Evenson of Yale University, as well as aggregate data on production and yields from FAOSTAT, this study makes novel use of the Hodrick-Prescott filter to disentangle changes in trend from annual fluctuations. The results depict changes in national-level yield stability for wheat and maize across developing countries and relate them directly to MV diffusion. The outcomes strongly suggest that, over the past 40 years, there has actually been a *decline* in the relative variability of grain yields—that is, the absolute magnitude of deviations from the yield trend—for both wheat and maize in developing countries. This reduction in variability is statistically associated with the spread of MVs, even after controlling for expanded use of irrigation and other inputs.

Valuing these reductions in yield variability requires assumptions about society's willingness to trade off risk against return. Using a standard analytic framework, the study finds that the realized reductions in variability are worth the same as small increases in average yield. Assuming a moderate level of risk aversion on farmers' part and taking the preferred coefficient estimates for the magnitude of reductions in yield variability, the results suggest that the realized reductions in yield variability due to MVs are worth about 0.3% of annual production in the case of wheat and 0.8% of production in the case of maize. These appear to be small effects, but the sheer scale of wheat and maize production in the developing world means that the benefits from improved yield stability are large in absolute terms. At appropriate world prices, the benefits are about US $143 million for wheat and about US $149 million for maize, on an annual and recurring basis.

The benefits are not attributed to any particular research theme or program. Instead, they reflect longstanding efforts in breeding for disease and pest resistance, drought tolerance, and improved cropping systems, to name a few. By reducing the fluctuations in maize and wheat grain yields, scientists have played a vital role in making modern crop technology attractive, accessible, and beneficial to farmers and consumers around the globe.

2. Introduction

This study asks whether agricultural research has affected the yield stability of wheat and maize production in the developing world. This is not a new question. Since at least the 1970s, researchers have asked whether the "improved" crop varieties developed by international research centers might heighten the production risks faced by producers and consumers. Critics have long suggested that modern varieties have the potential to raise the variability of yields, possibly leaving poor consumers and producers worse off than with "safer" traditional varieties.

This study will make use of aggregate data on production and yields to tell a different story. The data suggest strongly that, over the past 40 years, there has been a striking *decline* in the relative variability of grain yields in wheat and—to a lesser extent—maize, in developing countries. The term "relative variability" refers to the variability of production as a fraction of total output. Another way to say this is that increases in yield *levels* have been greater in magnitude than the corresponding increases in yield *variation*, as measured in several different ways.[1]

The study reaches this conclusion based on analysis of new data using new techniques. The new data set, compiled by Robert Evenson of Yale University, reports country-level diffusion of modern varieties by crop for the period 1960-2000. This data set makes it possible for the first time to address changes in yield stability for wheat and maize across all developing countries and to relate them directly to modern variety diffusion. The study also introduces a new technique for measuring yield variance. Specifically, it uses a Hodrick-Prescott filter to disentangle changes in trend from annual fluctuations. This technique is particularly well suited to working with the data available. It has been widely used in other areas of macroeconomics and statistics (Hodrick and Prescott 1981; 1997), but does not appear to have been used previously in computing crop yield variability.

The study's results show that the diffusion of modern varieties has been accompanied by declines in yield variability. But how much of this change can be attributed to changes in the genetic resources used by farmers? In other words, how much of the decline in yield variability is due to changes in crop varieties? This is a difficult question, because it is hard to separate the impact of changes in genetic resources from other changes in farming systems, infrastructure, or markets, to name a few factors. This paper will describe correlations between the diffusion of modern crop varieties and the reduction of yield variability, but the data do not (and cannot) support a definitive claim of causation.

A further limitation of the paper is that there is no clear way to disentangle the impact of agricultural research carried out by individual

[1] For simplicity, most of this paper will use the terms "yield variability" and "yield stability" in their relative sense. In other words, "yield variability" will be measured as the coefficient of variation (standard deviation divided by mean) or a similar measure that controls for mean values.

agricultural research programs. Although the paper will show that increases in intertemporal yield stability have accompanied the diffusion of modern varieties, it is beyond the scope of this study to attribute the impact to specific research programs or to weigh the impact (for example) of different breeding strategies.

This paper will instead argue that the observed impact of modern varieties on yield stability is the *net effect* of a multitude of separate research efforts. Some of these efforts have targeted stability directly. For example, breeders have often sought to select varieties that performed well in multilocation trials, taking this as an indication of robustness (assuming that yield stability across regions is a good proxy for stability over time). In many other instances, breeders and other scientists have targeted the incorporation of traits that would be expected to confer greater stability. For example, major breeding efforts have targeted the improvement of disease and pest tolerance or resistance and greater adaptation to abiotic stresses.

To assess the contribution of research to the reduction in yield variability, this study uses cross-country data on wheat and maize yields and the diffusion of modern varieties. It finds that variability decreases with the diffusion of modern crop varieties, a pattern more strongly evidenced in wheat than in maize. Because genetic improvements are not the only cause of reduced yield variability, the analysis controls for changes in irrigation and also for time trends, effectively taking into account other inputs or conditions that are increasing in a linear fashion over time.

To use an econometric term, the identification strategy for the paper is to take advantage of the fact that modern varieties (MVs) were developed and introduced at different times and with different degrees of success in different countries. An underlying assumption is that the diffusion of modern varieties was effectively exogenous to individual countries. This is not a perfect assumption, but from the perspective of many small countries that received modern varieties only when the international research system delivered them, it is a reasonable approximation of reality. Even for large countries (India, China, Brazil), the assumption only requires that the timing of MV diffusion is not influenced specifically by a country's efforts to reduce yield variability. Since most countries were far more concerned with yield levels than with yield stability, this seems like a defensible proposition, though certainly not an irrefutable one.

The conclusion of the analysis is that there has been a significant and valuable improvement in yield stability. Although much attention has been given to international agricultural research and its achievements in boosting the yield *levels* of wheat and maize in the developing world, its impact on yield *stability* has been equally remarkable. By reducing the fluctuations in grain yields, scientists have played a vital role in making modern crop technology attractive and accessible to farmers around the globe.

What is the dollar value of this contribution? This is difficult to estimate in a careful way, but it is possible to arrive at some informative "back-of-the-envelope" calculations. One way to approach this question is to use a theoretical framework taken from the financial literature. Typically we model individuals as willing to trade off risk against return. Most individuals would be willing to sacrifice some level of return to reduce their exposure to risk. Using some standard values from the finance and macro literature, we can ask how much we would need to compensate farmers today to force them to assume the yield variability levels that they faced in 1970. Almost equivalently, we can ask them how much they would be prepared to pay to *avoid* going back to historic levels of yield variability.

These measures are crude and require strong assumptions about the nature of farmer preferences. They offer a useful starting point, however, for thinking about the impact of research on crop improvement. Compared with the costs of research at these institutions, the benefits are extremely large. Even if the estimation procedures are crude, it suggests a high historic payoff to research targeted to disease and pest problems, stress tolerance, and similar variability reduction factors.

The remainder of the paper is organized as follows. Section 2 reviews different measures of yield stability, discusses the strengths and weaknesses of different approaches, and reviews the literature on yield stability and MV diffusion. Section 3 describes the data used in the analysis and details the methodology followed in constructing measures of yield stability. Section 4 provides an overview of regional patterns and major trends in the diffusion of modern varieties and the corresponding reduction in yield stability, with a graphic presentation of major patterns. Section 5 takes the analysis to the country level and reports the results of regression analysis using country-level data. Section 6 offers some rough and ready benefit calculations, and Section 7 provides concluding comments.

3. Defining Yield Variability: Concepts and Measurements

As noted above, this study focuses on reductions in the relative variability of yield: variability in relation to mean yields. There is a long literature discussing yield variability and more generally discussing variability in time series data (Cuddy and Della Valle 1978), and there are many different definitions and concepts used. In some literature, it is common to focus on *absolute* variability in yields (the standard deviation of yield, measured in kg/ha). This is a useful measure for certain purposes. Also, in some literature, it is common to focus on yield variability across locations. For example, specific crop varieties are said to have "more stable" or "less stable" yields based on their performance across locations.

These are all useful measures of yield variability. In this study, however, the focus is on intertemporal variability of aggregate yields, at the levels of countries or country groups. There are several reasons why this is a relevant measure. One is that the variability of aggregate yields has important implications for domestic food markets and food prices. Both consumers and producers are made better off by stable prices, which are generally related to reduced yield variability. Another reason is that yield stability at the aggregate level incorporates the adoption decisions of many individual farmers. In measuring yield variability at this level, we are effectively considering the impact of research on yield *outcomes*. National and international research institutions have collectively transformed the portfolio of crop variety choices available at different times and places. The impact of their research is in part measured by the realized performance of this portfolio. The measure used here is thus, in some sense a measure of the portfolio of varieties available during a period in time for a particular region.

Unlike measures of variability by variety, this study looks at the full range of variety choices available to farmers. Looking at aggregate variability also avoids some of the problems that arise with farm-level measures of yield stability. At the level of the individual farm, all choices of varieties and inputs are endogenous, so it is difficult to know whether yield variability from one year to the next reflects farmers' choices or unanticipated shocks.

In contrast, yield variability at the aggregate level is an *outcome*, not a choice variable. It makes sense, then, to treat it as a measure that evolves over time in response to the changing array of varieties made available by research institutions. No research institution effectively controls the mix of varieties planted by farmers, but by making available new varieties that are targeted to specific niches, these research institutions do affect the aggregate yield variability.

Declines in yield variability over time may reflect research successes of several types. First, they may arise from improved disease or pest resistance within a prevailing group of improved varieties—the replacement of susceptible MVs by resistant ones. Second, they may arise from the diffusion of multiple varieties that differ in their susceptibilities and resistances; although individual varieties may be no more resistant than previous varieties, the aggregate portfolio will generally display lower overall variability than any single variety. Third, the replacement of traditional varieties by higher-yielding varieties that may have higher *absolute* but lower *relative* yield variability will tend to decrease the aggregate variability. All these mechanisms—and perhaps others—appear to be at work in the data.

Of course, declines in yield variability may have little or nothing to do with agricultural research. Yield variability may decline due to increases in irrigation, pesticide use, or crop management practices. Changes in variability may also reflect changes in the type of land devoted to a particular crop—perhaps in response to changes in market conditions or relative prices.[2] They may also reflect changes in markets conditions, infrastructure, or policies. Thus, we need to be careful not to assume that all changes in yield variability are necessarily induced by changes in production technology.

Not only must we be careful when interpreting changes in yield variability, but we must be aware of the implications of different measures of variability. In discussing changes in yield variability over time, this study uses several different measures. All are aggregate—at the level of countries or regions, rather than farms or varieties. All are intertemporal, rather than cross-locational. In general, the different measures give comparable results. However, different measures also have properties that may tend to skew our interpretations. The measures are as follows.

Changes in the coefficient of variation of yields

One measure of yield variability is the coefficient of variation of yield. This is defined as the standard deviation of yield over some time period divided by the mean yield over the same period. Specifically, let y_{it} be the yield realized in region *i* at date *t*.[3] Consider, say, a 10-year period leading up to date *t*. The average yield for this period is simply

$$\bar{y}_{it} = \frac{1}{10} \sum_{k=t-9}^{t} y_{ik}$$

where *k* indexes time. The intertemporal variance of these yields is given by

$$s_{it}^2 = \frac{1}{10} \sum_{k=t-9}^{t} (y_{ik} - \bar{y}_{ik})^2 .$$

The standard deviation of yields is simply the square root of the variance, and is denoted by s_{it}. This measure reflects yield variability over time. Now define the coefficient of variation of yields in region *i* at date *t* as

$$CV_{it} = \frac{s_{it}}{\bar{y}_{it}}.$$

This measure will vary across regions and over time.[4]

One disadvantage of the measure is that it does not account for any trend in yields. For instance, suppose yields were to grow at a steady rate *g* over the 10-year period. The faster the growth rate, the greater would be the dispersion in observed yields over the period, and hence the measured CV for the period would be higher. Thus, this measure tends to show higher variability in countries with rapid yield growth than in countries with slower yield growth.

Correspondingly, if growth rates were changing over time, this measure would show changes in yield variability that would, in some sense, be spurious.

Consider a country where wheat yields were growing over time at a positive but declining rate, with no variability whatsoever from this growth

[2] For example, a decline in the relative price of maize might lead to the substitution of sorghum for maize in some areas with low or erratic rainfall. This might tend to lead to a reduction in the observed yield variability of maize, even though there has been no change in its variability at any given location.

[3] This region-specific yield is simply total production divided by total area harvested. Note that it is not the yield of an "average" or median farm, nor is the regional yield the average of farm-level yields.

[4] Note that this measure is not well suited for sets of numbers with a mean value close to zero. For the current application, however, this is not a concern.

trend. Using a CV measure, it would appear that variability was initially high but falling over time, suggesting a decline in yield variability where the driving force was in fact a declining rate of yield increase.

To avoid this problem, an alternative approach is to use measures that attempt to control for trends in the data. Two such measures are used in this study.

Percent deviation from geometric growth trend

An alternative measure of yield variability is the average percent deviation from a geometric trend in yields. This is a measure that explicitly addresses the problem of computing variability in a trending data series. Suppose analysis reveals that growth in yields is occurring at approximately a constant rate g, such that $y_t = y_{t-1}(1 + g), \forall t$. As is well recognized, we could arrive at an estimate of g by regressing the log of yield on a time trend variable. In this case, we could observe, for each date t, the actual yield, y_t and compare it to the predicted yield, which might be estimated as $\hat{y}_t = y_0(1 + g)$. (There are other slightly different ways of estimating predicted yield, using different base years and functional forms.) The percent deviation from trend is thus:

$$\frac{y_t - \hat{y}_t}{\hat{y}_t} \text{ x } 100.$$

Denote this measure as δ_t. Because these deviations are in percentage terms, they are comparable across time, even in a context of rising yields.

To compare yield fluctuations across time, we could compare the average of these deviations over some number of years. For example, define the five-year average percent deviation from trend at date t as:

$$\Delta_t = \frac{1}{5}\sum_{s=t-4}^{t} \delta_s .$$

If we found that this value appeared to be falling over time, we might conclude that yields were growing ever closer to a trend growth rate.

A difficulty with this measure, of course, is that it makes sense only when a strong and relatively constant trend growth rate is present. If growth rates are rising or falling markedly, the deviations from trend growth will be inaccurately estimated, and it may appear that deviations are rising or falling when in fact the trend growth rate is rising or falling. Moreover, if the movements around the trend are sufficiently noisy, then this may not be a very useful measure.

Percent deviation from varying trend

An alternative approach involves measuring the percent deviation from trend, using a non-geometric approach to computing the trend. There are many widely used statistical approaches for deriving a trend from a noisy data series, including exponential smoothing, Kalman filtering, and others. Perhaps the most widely used in many branches of economics is the Hodrick-Prescott filter, which is a technique for separating a trend from fluctuations in a noisy data series (Hodrick and Prescott 1981; 1997). The underlying assumption of HP filtering is that we observe a time series such as realized crop yield, which embodies both a trend and a shock. Thus, imagine that y_t is a time series for yield. We believe it to consist of a non-stationary growth trend (denoted g_t) and a stationary residual (denoted c_t) so that $y_t = g_t + c_t$. Neither g_t nor c_t is directly observed, so the challenge is to take the observed series y_t and to separate it into its components. Since c_t is assumed to be stationary, we can take y_t as a noisy signal of g_t. How do we allocate the observed fluctuations to "signal" and "noise"? The HP filter allows for a continuum of possible weights, denoted by λ, in interpreting fluctuations as signal. The two extreme cases are those in which all the observed fluctuations are thought to represent changes in trend (*i.e.*, $y_t = g_t$) and the alternative extreme in which all the change is taken to be noise, in which case the filter generates a least squares line through the data, with zero time trend. These two cases correspond to and $\lambda = 0$ and $\lambda = \infty$, respectively. In general, the choice of λ reflects the properties of the data and the "true" characteristics of the noise. For annual data series, it is common to set $\lambda = 100$ (Backus and Kehoe 1992), although much lower values have also been proposed (about 6.5 to 8.5, according to Ravn and Uhlig 1997).

Using the HP filter, it is possible to decompose time series data for yields into a trend component and a fluctuation component. We then want to measure the magnitude of the fluctuations, relative to the trend. The procedure for this follows exactly the procedure described above for computing the magnitude of deviations from a geometric trend. The only difference is that the trend component is now given by the HP filtered data. Thus, $\hat{y}_t = HP(y_t)$, where $HP(y_t)$ is the HP-filtered estimate of trend yield at date t. As before, the percent deviation from trend is thus:

$$\frac{y_t - \hat{y}_t}{\hat{y}_t} \times 100.$$

Denote this measure as δ_t. To compare yield fluctuations across time, we could compare the average of these deviations over some number of years. For example, define the five-year average percent deviation from trend at date t as:

$$\Delta_t = \frac{1}{5} \sum_{s=t-4}^{t} \delta_s .$$

The advantage of using the HP filter is that it allows us to handle time series for yield that display changes in the trend growth rates. In this sense, it is superior to assuming that the data reflect a single geometric growth rate over an entire 40-year time period. However, the filtering procedure imposes some structure and assumptions that we might be concerned about. In particular, an extended period of bad yields might be interpreted as a change in the trend, rather than as a sign of high variability. Thus, the "trend" might in fact be misidentifying persistent shocks as changes in trend.

An assessment

The bottom line for this discussion is that there is no single measure of yield variability that is unproblematic. The three measures described here all have advantages and disadvantages. To make sure that the results are not driven primarily by the chosen method of computing variability, this study has attempted to use more than one measure for each set of results. For the most part, the results reported below are quite robust to changes in the method of measuring variability.

Spatial issues in measuring variability

As noted above, this study will focus on yields aggregated at the level of a region or country group. Within the region, there may be an entirely different level of variance across farms or plots, and changes in the aggregate variability may be entirely different from changes in the spatial variability. For example, we can imagine a situation in which average yield remains constant over time in a region (and thus the variance is zero) but the variance of yields across farms is increasing, as (for example) productive farms achieve ever-higher yields and unproductive farms achieve ever-lower yields. In the same way, it is possible for spatial variance to be zero (all farms have the same yield in a given time period), even though aggregate variance over time is very high; for example, if all farms are identical and receive the same weather shock each period. Aggregate yields will vary greatly, but cross-section yields will not vary at all.

These numerous approaches to measurement remind us that there is no single "correct" way of measuring variability, but we can nonetheless gain insights from approaching the data carefully and cautiously.

Previous literature

Since the initial development of improved varieties for the tropics in the 1960s, researchers have sought to assess the yield stability of farming systems that use these varieties. A substantial literature has accumulated over time. Several useful surveys of concepts and measurement approaches have been published, beginning with Anderson, et al. (1977) and extending to Barry (1984); Hardaker et al. (1997); Harwood et al. (1999); and Hardaker et al. (2004). Other works focus on risk aversion in decision-making in non-agricultural contexts (Anderson and Hardaker 2003).

A small set of works has examined patterns of yield variability at the country or global levels. An important and comprehensive review was provided in a volume edited by Anderson and Hazell (1989), which included analyses of variability across numerous crops, countries, and regions. The introduction by the editors noted changing patterns of variability in world grain production and worked through the methodology of attributing the change in production variance to changes in the variance of area, changes in the variance of yield, and assorted covariance terms. A subsequent chapter by Hazell (1989), echoing Hazell (1985), suggested that world cereal production, in aggregate, had displayed increasing variability around a linear trend from 1960/61 to 1982/83. Hazell left open, however, the question of whether the adoption of modern varieties would increase or decrease yield variability in the future; too little information was available at the time to provide any quantitative analysis of the question. Although many papers in this volume included discussion of MV impacts on yield variability at the country or farm level, data did not permit much quantitative analysis.

In more recent years, Naylor et al. (1997) explored changes in the variability of grain yields over 1950-94, but these authors were not able to look for any specific effect of modern varieties. Instead, they documented changes at the regional level in grain yield variability, with some additional attention to US data.

Other work has explored changes in variability at the level of individual countries or regions, or at the farm level within countries. Studies by Byerlee and Moya (1992; 1993), Singh and Byerlee (1990), and others have attempted to examine the impact of plant breeding on aggregate production patterns, though with relatively little attention to variability. Traxler et al. (1995) examine changes in yield variability in experimental data for specific modern varieties, but this is different from analyzing the realized portfolio of varieties.

4. Data and Methods

The data used to measure variability are annual country-level yield data compiled and published by the Food and Agriculture Organization (FAO) of the United Nations. These data are available in digital form through the FAO website (http://faostat.fao.org/), where notes are also provided on the original sources of the data. This paper uses FAOSTAT data on a subset of 91 countries for which Evenson provides estimates of MV diffusion (as described below). The FAOSTAT data include detailed notes about country definitions and adjustments for changes in borders, new countries, etc. Yield data are provided directly by FAO for 1961-2005, although not all countries have complete data for these time periods. Where necessary, this study has dropped missing years for individual countries.

The FAOSTAT data also include figures on agricultural area and agricultural area under irrigation, on an annual basis over approximately 1961-2005. These were combined to create a measure of the percentage of agricultural area under irrigation, which is used in the analyses below.

The regional analysis of Section 5 is based on aggregates provided and defined by FAO. As a result, this analysis considers essentially all countries of the developing world. The country-level analysis of Section 6, by contrast, focuses on a set of 91 countries for which Evenson offers estimates of MV diffusion.

The Evenson data are available from the author and through the National Bureau of Economic Research (NBER) Historical Cross-Country Technology Adoption data set (available at http://www.nber.org/hccta/). The Evenson data include estimates of the area planted to modern crop varieties for 11 food crops at 5-year intervals from 1960 to 2000. The data are drawn from a variety of published and unpublished sources, including extensive extrapolation and interpolation, and they reflect Evenson's "studied best estimates" for area under MVs at different moments in different countries.[5]

It is worth noting that Evenson's estimates differ in some instances from more detailed point estimates of MV adoption available for individual crops, countries, and years. For example, Evenson's data on maize MV diffusion differ markedly in some instances from CIMMYT's data on maize MVs, which are available for selected years between 1985-86 and 1999. The source of the differences is not clear, nor is it clear whether modern varieties are being defined in comparable ways across the two data sets. Evenson's estimates tend to show relatively smooth diffusion curves for most crops in most countries. By contrast, the CIMMYT maize data show fairly large fluctuations in modern variety use, for some countries.

For the most part, however, both the levels and patterns of MV diffusion in the Evenson data appear to follow quite closely the limited data available from other sources. Since no other data set available provides comprehensive cross-

[5] Evenson, personal communication.

country and time-series estimates of MV diffusion, this study has made use of Evenson's estimates. Producing a reconciled version of maize MV data from CIMMYT and Evenson would be useful, but lies beyond the scope of this study.

The Evenson data include 91 developing countries; however, smaller samples are used in specific analyses described below, due to data limitations. The total number of wheat-producing countries in the data is 58, and there are 85 maize producers. For portions of the analysis, it furthermore makes sense to split the sample into those which have some MV adoption of modern varieties and those which do not. For wheat, the sub-sample of the former for which there were data included 30 countries.[6] The corresponding sub-sample for maize included 27 countries.[7]

The methodology for computing measures of variability is as described above. For measures of the coefficient of variation (CV), this paper uses a 10-year moving time period, centered on the date in question. Thus, the CV reported for 1970 is based on the average yield and standard deviation for the years 1966-75. Measures of average deviation from trend are based on the five previous years. A quick check of the results suggests that they are quite robust to small changes in these measures.

[6] For wheat, Evenson's data show that the following countries used modern varieties in 2000: Algeria, Argentina, Bangladesh, Brazil, Chile, China, Colombia, Ecuador, Egypt, Ethiopia, Guatemala, India, Iran, Kenya, Lebanon, Mexico, Morocco, Nepal, Nigeria, Pakistan, Paraguay, Peru, Saudi Arabia, Sudan, Syria, Tanzania, Tunisia, Turkey, Uruguay, and Zimbabwe.

[7] For maize, Evenson's data show that the following countries used modern varieties in 2000: Argentina, Benin, Brazil, Burkina Faso, Cameroon, Chad, Chile, China, Congo DR, Costa Rica, Ghana, Guinea, India, Indonesia, Kenya, Mali, Mexico, Nepal, Nigeria, Paraguay, Peru, Philippines, Senegal, Thailand, Togo, Venezuela, Viet Nam.

5. Changes in Yield Variability: Descriptive Analysis

As noted in the introduction, one widely articulated goal of CIMMYT's crop improvement efforts since the 1960s has been to reduce the variance of yields, or equivalently to increase yield stability.[8]

Have breeders been successful in this effort? We know that new varieties of CIMMYT-derived wheat and maize have been adopted extensively across all regions of CIMMYT's mandate area. Presumably this reflects farmers' choices and revealed preference for the new varieties. But do we observe increased yield stability in the data?

Regional measures of yield stability

Table 1 reports yields of wheat and maize for 10-year intervals over 1960-2000, taken from FAOSTAT online data. The data are disaggregated by region using FAO classifications. It is clear from even a brief examination of the data that yields of both wheat and maize have increased dramatically over the period in question in nearly all regions (Figures 1 and 2). These data have been widely reported elsewhere, and no further comment is required, except to note that the gains have been widespread. Maize yields appear to have risen somewhat later than wheat yields, and with somewhat greater variation across regions. The only clear exception to the rule of rising yield gains has been the performance of maize in developing Africa, which saw essentially flat maize yields over 1961-2003.

At the level of aggregation reported here, yield variability has not changed much; there is no obvious visual pattern in the magnitude of the fluctuations. We can quantify this observation by looking at several measures of yield stability.

Table 1. Wheat and maize yields (kg/ha), selected years and country groupings.

Wheat	**1961**	**1970**	**1980**	**1990**	**2000**
World	1,089	1,494	1,855	2,562	2,719
Developing countries	775	1,124	1,565	2,289	2,698
Least developed countries	935	899	1,275	1,279	1,288
Africa developing	710	909	1,150	1,714	1,655
Eastern Africa	748	892	1,399	1,755	1,380
Southern Africa	870	665	1,044	933	1,773
Latin America and Caribbean	1,191	1,446	1,498	1,946	2,564
South America	1,136	1,250	1,315	1,728	2,368
Central America	1,638	2,950	3,720	4,172	4,905
Asia developing	727	1,110	1,608	2,379	2,802
East and Southeast Asia	678	908	8,490	1,111	892
South Asia	845	1,196	1,470	2,025	2,683
Near East	912	1,005	1,454	1,898	2,022
Maize	**1961**	**1970**	**1980**	**1990**	**2000**
World	1,944	2,352	3,154	3,679	4,288
Developing countries	1,128	1,495	1,968	2,447	2,856
Least developed countries	963	938	1,140	1,143	1,315
Africa developing	957	1,050	1,267	1,351	1,503
Eastern Africa	1,006	959	1,257	1,343	1,468
Southern Africa	703	552	968	1,054	684
Latin America and Caribbean	1,213	1,474	1,809	1,994	2,860
South America	1,373	1,636	1,858	2,038	3,174
Central America	974	1,196	1,743	1,954	2,314
Asia developing	1,136	1,699	2,325	3,307	3,571
East and Southeast Asia	1,034	1,250	1,567	2,065	2,544
South Asia	1,044	1,301	1,200	1,511	1,710
Near East	1,751	2,296	2,707	4,217	5,460

Source: FAOSTAT online data, July 2004.

[8] Obviously this reflects a desire to reduce negative yield shocks, rather than to constrain increases in yield.

As noted above, one such measure is the coefficient of variation of yields; that is, the standard deviation divided by the mean.

Table 2 summarizes changes over time in the CV for wheat for a number of regions; Table 3 shows the same data for maize. The standard deviation used for each year is the computed standard deviation of yields within each region over the preceding 10-year period.[9] This is divided by the mean yield within each region over the same 10-year period. The CV is computed for each year from 1970 to 2003. The values for 1970, 1980, 1990, and 2000 are shown in the tables. The tables also reports the coefficient on a linear time trend of CV. This time trend was estimated for the entire 33 years for which data were available. Both the coefficient and the associated *t*-value are shown in the tables.[10] A negative coefficient implies a declining coefficient of variation over time; in other words, a reduction in yield variability.

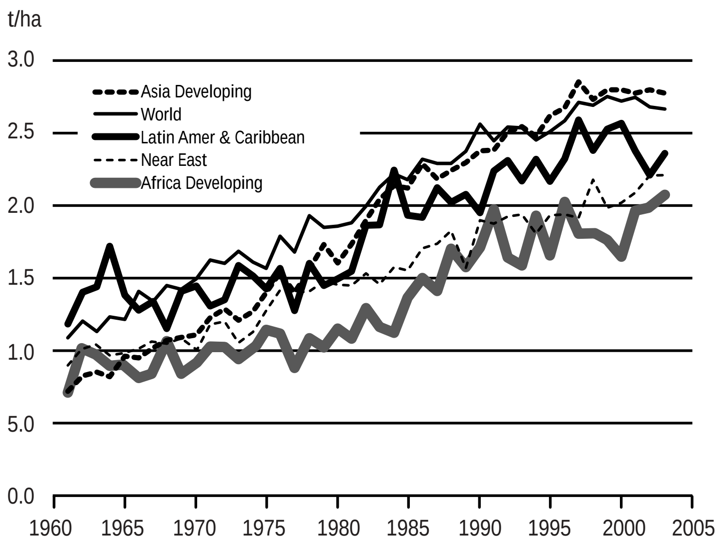

Figure 1. Wheat yields, 1961-2003.

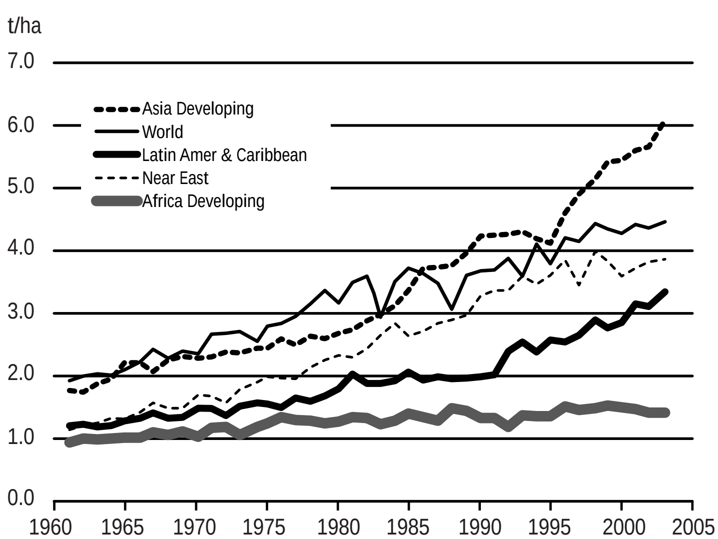

Figure 2. Maize yields, 1961-2003.

Common perceptions hold that the introduction of high-yielding varieties also led to growing instability in yields. The data suggest otherwise. The CV for wheat yields in almost all regions fell significantly from 1970 to 2000. For developing countries overall, the CV fell from 0.108 in 1970 to 0.055 in 2000. In both Asia and Latin America, the CV fell rapidly and remarkably. It is evident that the CV fell across almost all areas of the developing world, with the exception of Africa, where essentially no sub-region showed strongly significant declines in CV. (Overall, sub-Saharan Africa showed a weak decline, led by East Africa; but in fact Southern Africa showed a significant *increase* in the CV of wheat yields.) Somewhat surprisingly, the other area showing no significant decline in the CV of wheat yields was East and Southeast Asia, where the decline was not strong.

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[9] In other words, the standard deviation used for 1970 is the standard deviation of yields in 1961-70.

[10] The *t*-value is of interest here, but technically speaking, the sampling distribution for the CV is not normal, and so the *t*-value does not imply true statistical significance.

For maize, the picture is less clear. For the developing countries overall, the coefficient of variation fell from 0.093 in 1970 to 0.056 in 1990. The figure for 2000 was somewhat higher, at 0.073, reflecting a slight rise in the CV in the late 1990s, but the figures fell again in 2001-03. The time trend is strongly and significantly negative. The patterns *within* the group of developing countries were far more varied, however. The one region that observed clearly negative time trends in the CV was developing Asia, where the CV fell from 0.129 in 1970 to 0.062 in 2000. Two other large regions of the developing world actually witnessed increases in the CVs of maize yields: the Near East and Latin America and the Caribbean.

As noted above, however, the changes in the CV of wheat and maize yields are not necessarily the most useful measures of yield variability. In particular, changes in the CV may be a difficult measure to interpret in a data series that has a strong trend. A different approach is to look at the deviations from trend—in other words, to look at the variability of de-trended yield data. As discussed above, this approach requires fitting a trend to each data series.

Figures 3 and 4 display deviations from a geometric trend for wheat and maize yields, respectively. Each figure displays deviations for the four major geographic regions under consideration. The figures show, in

Table 2. Coefficient of variation of wheat yields, 10-year moving coefficient of variation.

	1970	1980	1990	2000	Time trend coefficient	t-stat.
World	0.109	0.074	0.087	0.045	-0.0021	-9.4602
Developing countries	0.108	0.112	0.091	0.055	-0.0023	-5.3597
Least developed countries	0.071	0.136	0.032	0.073	-0.0016	-2.8926
Low-income countries	0.147	0.083	0.083	0.051	-0.0026	-7.4609
Low-income food deficit	0.157	0.122	0.096	0.056	-0.0035	-8.4079
Africa developing	0.113	0.083	0.165	0.086	0.0002	0.3826
Africa South of Sahara	0.055	0.138	0.083	0.074	-0.0008	-1.8387
Eastern Africa	0.071	0.165	0.098	0.085	-0.0011	-1.8905
Southern Africa	0.107	0.436	0.143	0.384	0.0041	2.1684
Latin America and Caribbean	0.114	0.080	0.096	0.065	-0.0012	-2.2755
South America	0.129	0.083	0.106	0.080	-0.0011	-2.0269
Central America	0.175	0.113	0.061	0.087	-0.0024	-5.9943
Asia developing	0.139	0.126	0.092	0.060	-0.0031	-8.5892
East and Southeast Asia	0.115	0.151	0.147	0.071	-0.0005	-0.5172
South Asia	0.167	0.082	0.087	0.068	-0.0032	-7.6860
Near East	0.052	0.116	0.094	0.051	-0.0009	-2.1681
Near East in Africa	0.094	0.118	0.198	0.138	-0.0006	-0.9825
Near East in Asia	0.061	0.130	0.088	0.046	-0.0013	-2.9714

Source: Author's calculations from FAOSTAT online data, July 2004.

Table 3. Coefficient of variation of maize yields, 10-year moving coefficient of variation.

	1970	1980	1990	2000	Time trend coefficient	t-stat.
World	0.086	0.092	0.073	0.071	-0.0010	-5.1189
Developing countries	0.093	0.098	0.056	0.073	-0.0007	-3.3391
Least developed countries	0.020	0.068	0.037	0.108	0.0016	4.1526
Low-income countries	0.036	0.064	0.060	0.059	0.0002	1.2261
Low-income food deficit	0.105	0.122	0.068	0.068	-0.0015	-6.1331
Africa developing	0.049	0.066	0.058	0.078	0.0000	-0.1445
Africa South of Sahara	0.047	0.069	0.070	0.081	0.0000	0.0790
Eastern Africa	0.062	0.086	0.070	0.112	0.0002	0.4151
Southern Africa	0.082	0.137	0.150	0.212	0.0007	1.0892
Latin America and Caribbean	0.069	0.076	0.029	0.103	0.0013	3.0428
South America	0.073	0.070	0.042	0.133	0.0019	4.4295
Central America	0.076	0.138	0.048	0.049	-0.0001	-0.1492
Asia Developing	0.129	0.122	0.102	0.062	-0.0016	-6.4007
East and Southeast Asia	0.063	0.088	0.081	0.059	-0.0002	-0.5824
South Asia	0.077	0.074	0.122	0.084	0.0004	1.2394
Near East	0.109	0.054	0.143	0.112	0.0016	3.0295
Near East in Africa	0.180	0.046	0.115	0.119	0.0007	1.2320
Near East in Asia	0.062	0.075	0.184	0.103	0.0017	2.1211

Source: Author's calculations from FAOSTAT online data, July 2004.

general terms, that deviations from trend yields have been relatively constant in magnitude across region and time. There is some evidence that deviations are persistent: an increase above trend in one year is likely to be followed by another positive deviation in the succeeding year. But there is no strong suggestion for either crop that deviations from trend are becoming larger over time.

Consider first the case of wheat. For Latin America and the Caribbean (top left panel of Figure 3), deviations from trend appear to have become smaller since the early 1980s. Deviations for developing Africa (top right panel) have tended to be large, with the exception of a few years around 1980, but there has been no secular trend (a long-term upward or downward trend in the numbers, as opposed to a smaller cyclical variation with a periodic and short-term duration) in the absolute value of these deviations over time. For the Near East (bottom left panel), deviations from trend have been very small. If anything, they have been smaller since 1980 than before, but there is little pattern over time. Finally, for developing Asia (bottom right panel), the magnitude of the deviations has risen and then fallen. The pattern is almost certainly not reflecting random variation around a trend; instead, the trend is overestimating yield levels in the early years (i.e.,

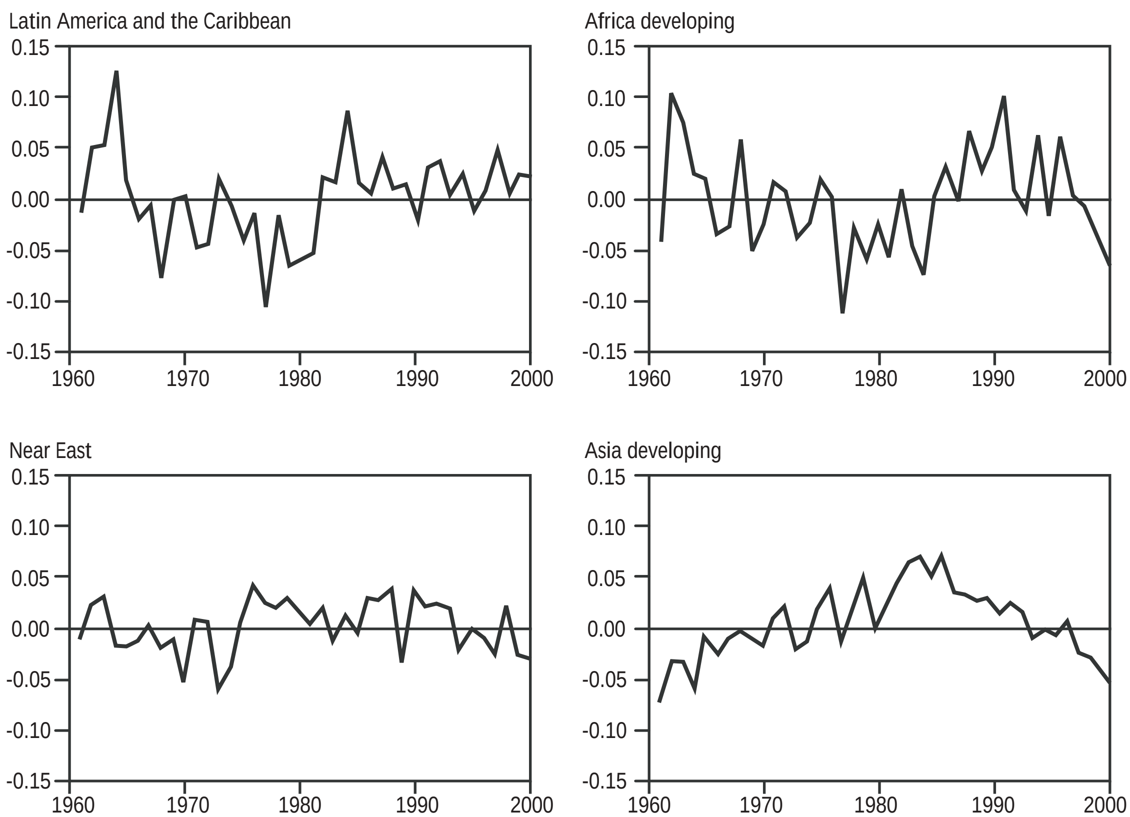

Figure 3. Percent deviations from trend wheat yield, by region, 1961-2003.

underestimating actual growth) and underestimating them in the middle years (i.e., overestimating actual growth). The trend and the actual yield are coming together in the end of the period.

For maize, the story is similar. For Latin America and the Caribbean (top left panel of Figure 4), deviations from trend appear to have risen slightly over 1980-1990, but more recently they have been quite modest. In developing Africa (top right panel), deviations from trend also appear to have been largest in the middle of the period, while in developing Asia (bottom right), the deviations are largest at the end of the period. For several regions, there seem to be systematic movements in actual yields relative to data—consistent with breaks in the actual trend. When irrigated area is omitted, MV coverage is significantly correlated with a reduction in CV; when irrigation is included, the significance of the MV variable tends to disappear (Tables 4 and 5).

Summing up, this measure of variability, like the coefficient of variation, supports the notion that the yield increases in wheat and maize have come without any evident increase in the frequency or magnitude of yield shocks. Aggregated across the entire developing world, variability of maize and wheat yields seems to be falling, if anything.

Table 4. Regression results with irrigation control, dependent variable: Maize, coefficient of variation.

Regression statistics	
Multiple R	0.1306
R square	0.0171
Adjusted R square	0.0078
Standard error	0.0803
Observations	216

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.02387	0.01194	1.84929	0.15987
Residual	213	1.37486	0.00645		
Total	215	1.39873			

Variables	Coefficients	Standard error	t stat	P-value	Lower 95%	Upper 95%
Intercept	-1.2160	1.3654	-0.8906	0.3742	-3.9074	1.4754
Year	0.0007	0.0007	0.9911	0.3227	-0.0007	0.0020
lnMV	-0.0090	0.0049	-1.8548	0.0650	-0.0187	0.0006

Table 5. Regression results without irrigation control, dependent variable: Maize, coefficient of variation.

Regression statistics	
Multiple R	0.1690
R square	0.0286
Adjusted R square	0.0148
Standard error	0.0801
Observations	216

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.03997	0.01332	2.07886	0.10403
Residual	212	1.35876	0.00641		
Total	215	1.39873			

Variables	Coefficients	Standard error	t stat	P-value	Lower 95%	Upper 95%
Intercept	-1.0235	1.3660	-0.7493	0.4545	-3.7161	1.6691
Irrigated area	-0.1081	0.0682	-1.5848	0.1145	-0.2426	0.0264
Year	0.0006	0.0007	0.8526	0.3948	-0.0008	0.0020
lnMV	-0.0070	0.0050	-1.3820	0.1684	-0.0169	0.0030

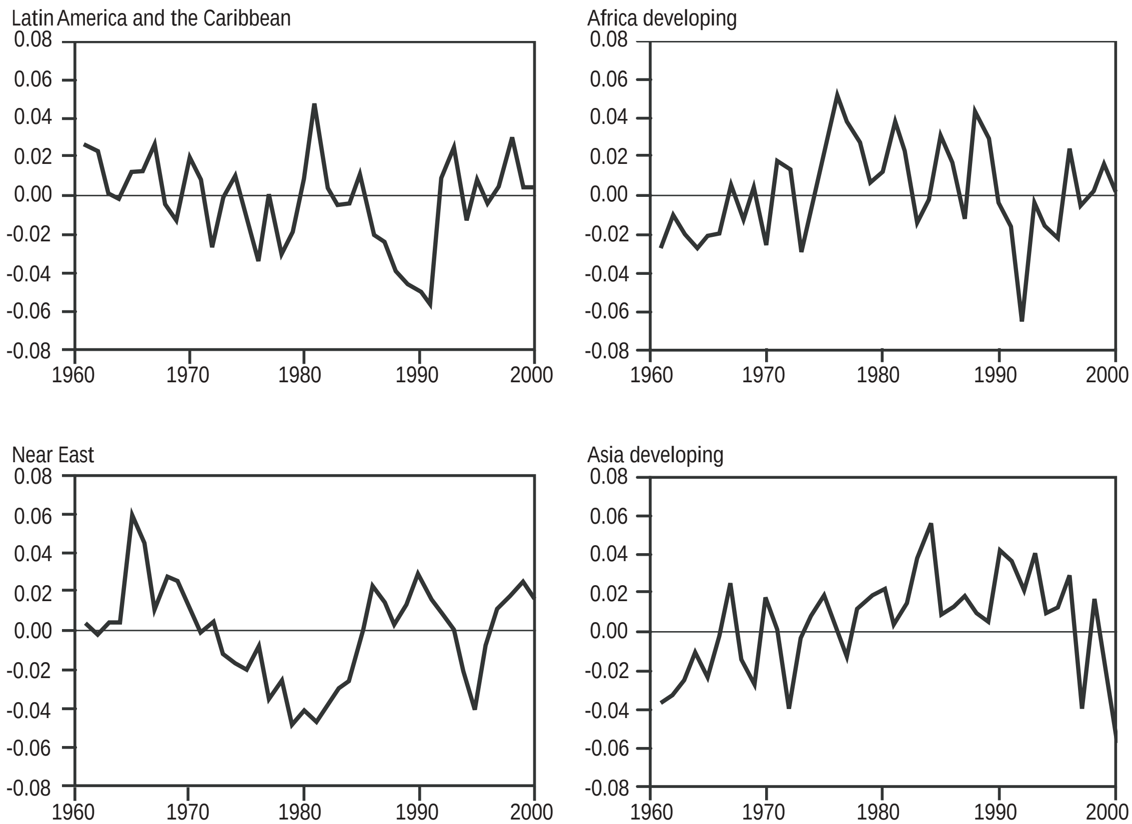

Figure 4. Percent deviations from trend maize yield, by region, 1961-2003.

6. Changes in Yield Variability: Regression Analysis

The descriptive analysis of yield variability at the regional level is informative, but cannot shed much light on the sources of variability reductions. Are these being driven by the diffusion of modern varieties, or by greater use of inputs, such as irrigation? Do these region-level aggregates accurately describe what is happening at the country level?

To address these questions, it is useful to consider country-level data. As noted above, the data for this analysis consists of observations at five-year intervals for a number of countries. For each crop and for each country at each date, we observe the yield variability—measured either by a CV or an average percent deviation from trend—along with the proportion of MV area for that crop and the proportion of the country's agricultural area under irrigation.

Wheat

Consider first the case of wheat. As noted above, of the 91 countries in the Evenson data, 58 cultivate wheat. For each of these countries, a smooth yield data series was computed using a Hodrick-Prescott filter with the smoothing parameter set to 100, the standard value for annual data series. (See Figure 5 for an illustration of how the HP filter with this degree of smoothing addresses a noisy data series. Figure 6 shows the deviations from trend that result from this analysis.) The deviations from this trend were then computed for each year, as a percentage of the trend value. For each five-year period, the average percent deviation was computed; thus, for 1965, the average percent deviation over 1961-65 was used as a measure of yield variability in 1965.

In a series of regressions, these average deviations were taken as the independent variables and were regressed on a set of independent variables that included the fraction of national wheat area planted to modern varieties at the start of the five-year period and the contemporaneous fraction of agricultural area under irrigation.

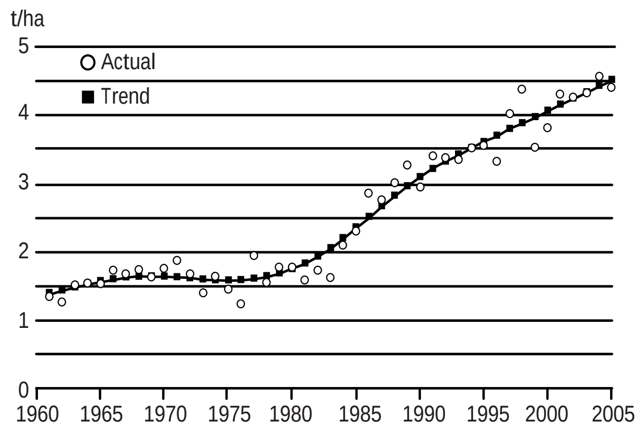

Figure 5. Wheat yields, actual and trend, Chile, 1961-2005. (Computed with HP filter, λ =100.)

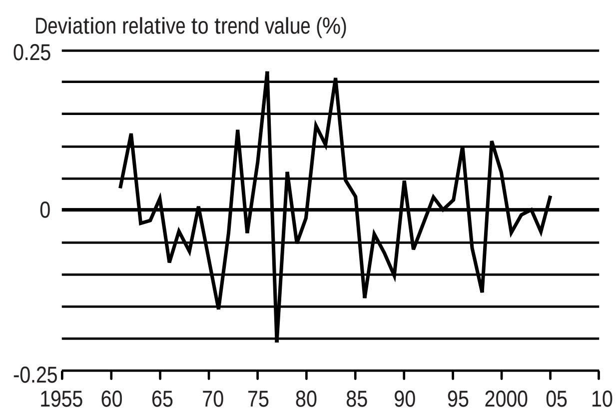

Figure 6. Chile's wheat yields, 1961-2005: deviation from HP trend.

Because data were not available for other inputs nor for infrastructure or policy, a time trend was also used as a right-hand variable. This time trend would be expected to capture any factors that are increasing or decreasing in a linear fashion over time and that are affecting yield variability. In some of the regressions, a squared time trend was also included to capture changes that were growing over time in a geometric pattern.

Finally, a dummy variable was included for countries that produce very small volumes of wheat; such countries might face production constraints that differ from those confronting larger volume wheat-producing countries. In most regression runs, the dummy variable was set to distinguish between countries with more than 50,000 hectares of wheat area and those with less. In some runs, it was set for a cutoff of 100,000 hectares.

In all the regression runs the fraction of MV wheat area was negatively associated with yield variability. In other words, the higher the fraction of wheat area planted to modern varieties, the lower the deviations from trend yield. As expected, irrigation also leads to smaller deviations from trend. In some specifications, the time trend is also associated with a smaller deviation from trend, indicating that yield variability is getting smaller over time, even after controlling for irrigation and modern varieties. The dummy variable for "small producers" also shows up fairly consistently as significant.

Consider Table 6, which lists the results of one regression. In these results, the coefficient on the percent of wheat area planted to MVs is -0.00036, which is strongly statistically significant (at the 5% level). Evaluated at the mean, this implies that the diffusion of modern varieties onto an additional 20% of wheat area in a country is associated with a 6.4% reduction in average deviation from trend yield. This is a substantial reduction in yield variability, though not as large a reduction as would be achieved by a major increase in irrigation: the results suggest that irrigating an additional 10% of agricultural area would be associated with a 10% reduction in average deviation from trend yield.

Table 7 shows a similar regression, in which a squared time trend is included to capture any effects on variability that are growing at a geometric rate. Both the linear time trend and the squared time trend show up as strongly statistically significant, as do the irrigation variable, the dummy for small producers, and the MV variable. Quantitatively, the coefficient on the MV term is little changed by adding the square term.

Table 6. Regression results, dependent variable: Wheat, average deviation from trend yield.

Regression statistics	
Multiple R	0.2384
R square	0.0569
Adjusted R square	0.0496
Standard error	0.0890
Observations	522

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	4	0.2471	0.0618	7.7911	0.0000
Residual	517	4.0991	0.0079		
Total	521	4.3462			

Variables	**Coefficients**	**Standard error**	**t stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	-0.00070	0.68610	-0.00102	0.99919	-1.34859	1.34719
Irrigation (Pct)	-0.11475	0.02586	-4.43814	0.00001	-0.16555	-0.06396
Year	0.00006	0.00035	0.17464	0.86143	-0.00062	0.00074
Wheat MV area	-0.00036	0.00016	-2.31446	0.02103	-0.00066	-0.00005
Large	0.01928	0.00875	2.20450	0.02793	0.00210	0.03646

Note: Large implies wheat area > 100,000 hectares.

Table 8 shows that the same general story holds when the coefficient of variation is used in place of the deviation from trend. In this particular regression run, the sample is restricted to those countries with non-zero area planted to wheat MVs in 2000. The result is not as strong when the entire sample of countries is used.

The overall implications of this analysis are clear. There is a negative statistical relationship between the levels of wheat MV use and the variability of wheat yields. In general, the higher the level of MV use in wheat, the lower the intertemporal variability of wheat yields. This result holds even when we control for other possible causes of declining yield variability: specifically, irrigation expansions and any kind of input use that might track a time trend or a squared time trend. From this analysis, it appears clear that wheat breeding research for developing countries—such as that pursued by CIMMYT and other institutions—has succeeded in one of its main goals.

Maize

Do the same results hold for maize? The data suggest that the relationship between maize MV diffusion and yield stability is weaker than for wheat. Table 9 shows the results of a regression in which the dependent variable is the average deviation of maize yields from trend. Independent variables are MV diffusion (measured on a log scale), a time trend, and an irrigation variable. The MV variable is not significantly different from zero in

Table 7. Regression results, dependent variable: Wheat, average deviation from trend yield.

Regression statistics	
Multiple R	0.3015
R square	0.0909
Adjusted R square	0.0821
Standard error	0.0875
Observations	522

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	5	0.3950	0.0790	10.3168	0.0000
Residual	516	3.9512	0.0077		
Total	521	4.3462			

Variables	**Coefficients**	**Standard error**	**t stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	-433.889	102.715	-4.22420	0.00003	-635.680	-232.097
Irrigation (Pct)	-0.11326	0.02524	-4.48746	0.00001	-0.16285	-0.06368
Year	0.43829	0.10375	4.22445	0.00003	0.23446	0.64212
Year Sq	-0.00011	0.00003	-4.22352	0.00003	-0.00016	-0.00006
Wheat MV area	-0.00040	0.00015	-2.60698	0.00940	-0.00070	-0.00010
Large	0.02178	0.00849	2.56541	0.01059	0.00510	0.03847

Note: Large implies wheat area > 50,000 hectares.

Table 8. Regression results, dependent variable: Wheat, coefficient of variation.

Regression statistics	
Multiple R	0.5195
R square	0.2698
Adjusted R square	0.2588
Standard error	0.1629
Observations	270

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	4	2.5975	0.6494	24.4836	0.0000
Residual	265	7.0286	0.0265		
Total	269	9.6261			

Variables	**Coefficients**	**Standard error**	**t stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	-22.50649	2.92284	-7.70021	0.00000	-28.26144	-16.75155
Irrigation (Pct)	-0.08209	0.04823	-1.70188	0.08995	-0.17706	0.01288
Year	0.01152	0.00149	7.74821	0.00000	0.00859	0.01445
Wheat MV area	-0.00201	0.00057	-3.50166	0.00054	-0.00314	-0.00088
Large	0.00490	0.02468	0.19846	0.84284	-0.04369	0.05349

Note: Large implies wheat area > 50,000 hectares.
Sample includes only those countries with positive MV area in 2000.

a statistical sense (significant only at the 11% level). Nevertheless, the sign of the coefficient is appropriately negative and of a reasonable magnitude: it suggests that a 20% increase in maize MV coverage in a country would reduce the average deviation from yield by 21.2%.

The lack of significance in the coefficient estimate appears to come in part from a degree of collinearity between maize MV diffusion and irrigation; when the irrigation variable is dropped, the maize MV variable carries a strongly significant (and appropriately negative) sign, even after controlling for a time trend and a squared time trend term (Table 10). Similar results pertain when the coefficient of variation is used as a dependent variable, instead of the deviation from trend yield. When irrigated area is omitted, MV coverage is significantly correlated with the reduction in the CV; when irrigation is included, the significance of the MV variable tends to disappear.

In general, the results for maize are less robust than the results for wheat. It is unclear whether this reflects the lower quality of the maize MV data, a stronger collinearity between irrigation and maize MV diffusion, or simply a weaker underlying relationship between maize MVs and reductions in yield variability. Nevertheless, the results do suggest that there is at least a weak correlation between maize MV diffusion and a reduction in maize yield variability in developing countries.

Table 9. Regression results, dependent variable: Maize, average deviation from trend yield.

Regression statistics	
Multiple R	0.293417232
R square	0.086093672
Adjusted R square	0.074622045
Standard error	0.053725523
Observations	243

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.0649873	0.021662	7.5049222	8.04897E-05
Residual	239	0.6898572	0.002886		
Total	242	0.7548446			

Variables	Coefficients	Standard error	t stat	P-value	Lower 95%	Upper 95%
Intercept	-0.5017	0.8484	-0.5913	0.5549	-2.1731	1.1697
Irrigated area	-0.1548	0.0420	-3.6842	0.0003	-0.2376	-0.0720
lnMV	-0.0052	0.0033	-1.5635	0.1193	-0.0117	0.0013
Year	0.0003	0.0004	0.6948	0.4879	-0.0005	0.0011

Table 10. Regression results, dependent variable: Maize, average deviation from trend yield.

Regression statistics	
Multiple R	0.2078
R square	0.0432
Adjusted R square	0.0312
Standard error	0.0550
Observations	243

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.03259	0.01086	3.59499	0.01429
Residual	239	0.72225	0.00302		
Total	242	0.75484			

Variables	Coefficients	Standard error	t stat	P-value	Lower 95%	Upper 95%
Intercept	-144.9871	96.2034	-1.5071	0.1331	-334.5020	44.5277
lnMV	-0.0075	0.0033	-2.2697	0.0241	-0.0140	-0.0010
Year	0.1458	0.0970	1.5031	0.1341	-0.0453	0.3368
Year squared	0.0000	0.0000	-1.4982	0.1354	-0.0001	0.0000

7. Benefit Calculations

What are the economic benefits resulting from this decline in yield variability? To address this question, it was necessary to make some assumptions and impose some strong theoretical structure on the problem.

The approach taken in this paper is as follows. First, for each country and crop, it is possible to use the estimates described above to compare the current level of yield variability with an alternative scenario in which modern varieties had not reduced yield variability at all. In other words, suppose that modern variety adoption had occurred but had not influenced deviations from trend yield. People in this scenario would prefer either a less risky production system or one with a higher average yield. There is an equivalence between these two *desiderata*: a variance reduction is as good as an increase in mean yield. We can measure the value of the less risky scenario fairly precisely by asking how much additional yield would be needed to compensate people for the higher variance associated with the risky scenario.

This is the approach followed here to compute the benefits of MV-induced reductions in yield variability. Thus, the question we can ask for each country is: if modern varieties had not been accompanied by declines in yield variability, how much worse off would people be today?

Using a mean-variance utility specification, it is possible to translate reductions in yield variance into the equivalent increases in mean yield that would leave people comparably well off. These country-level mean yield gains can in turn be aggregated and averaged in various ways.

Specifically, suppose that countries have preferences over yield levels and yield variance that take a standard exponential form, such that $u(x) = a + be^{-\gamma x}$, where γ is a risk aversion parameter. This specification implies that where x is drawn from a distribution, we can calculate the "certainty equivalents" of $CE(x) = \bar{x} - \gamma\frac{\sigma^2}{2}$, where the first term is the mean of the distribution and the second term includes both the risk aversion parameter and the variance of the distribution.[11]

Next, note that the analysis of Section 6 suggests that for each country and crop, we observe the variance of production from its trend. Let s_i^2 denote this variance for country i, as measured for the year 2000. We know from the regression results of Section 6 that MV diffusion is associated with reductions in the deviations from trend yield for wheat and maize. Using the regression coefficients, it is possible to compute an estimate of the variance that would have pertained in 2000 for each country and crop, in the absence of modern varieties. Note that this approach ignores the impact of MVs on the *levels* of yield, focusing instead on the *variance* of yield.

[11] It is not entirely clear what it means in this context to specify a single social utility function; this study assumes that it is possible to characterize aggregate utility in this way, or perhaps to think of the utility of a representative household. But producers and consumers may have very different views towards yield variability, and thus some standard aggregation results may not apply neatly. Nevertheless, for the purposes of this study, we abstract from such conceptual dilemmas.

In particular, let this estimated alternative variance be computed as $\hat{s}_i^2 = s_i^2 - \hat{\beta} MV_i$, where MV_i is a country-level estimate of MV coverage in the crop under consideration.[12] In other words, the alternative variance is that which would have applied in the absence of the variance-reducing effects of MVs. Assume that the mean yields would have remained the same; then the difference in certainty equivalents associated with the diffusion of MVs is given simply by $CE_i = \frac{\gamma}{2}(s_i^2 - \hat{s}_i^2)$. This measure is interpreted as a percentage increase in the mean that would give the same utility as the realized reduction in yield variance. These numbers are interpreted as increases in mean yield; thus, we convert them into output equivalents by multiplying by yield and area (or equivalently, by production) to get the additional quantities of output that correspond in utility value to the variance reductions. Let $\tilde{Y}_i = CE_i Y_i$ denote the output equivalent in country i of the realized variance reductions, where Y_i is the output of the crop in country i. Then $\tilde{Y}_i = \sum_i \tilde{Y}_i$ is the total across all countries of these output equivalent benefits, and $\tilde{Y}/Y$ is the aggregate output equivalent gain that is derived from reductions in yield variance. It is straightforward to report these gains as tons of grain or as dollar values.

Table 11 reports the results of these calculations for wheat. The table summarizes calculations using an estimate for β that averages the values found in Tables 6 and 7 (0.00038). It also reports estimates using values of this coefficient that are one and two standard errors higher and lower, based on the regression results. Table 11 also shows results for three different values of the risk aversion parameter γ, with the middle value $\gamma = 5$ representing a moderate level of risk aversion, and the alternatives $\gamma = 2$ and $\gamma = 10$ corresponding, respectively, to low risk aversion and high risk aversion.

The first block of numbers in this table shows estimates of the yield increase that would have delivered utility benefits equivalent to the realized decreases in variability. The numbers are modest: at $\gamma = 5$ and using the preferred coefficient estimate for β, the estimated benefits of the reductions in yield variability for sample countries are comparable to a 0.338% increase in mean yield. In other words, the diffusion of modern varieties of wheat to countries in the sample had an impact of about one-third of a percent through reductions in yield variability, on top of the direct benefits on yield levels.

This seems like a small benefit, but note in the second panel that this corresponds to an annual value of almost 1 million tons of additional grain output across the region for which we have data. At the prevailing world wheat price of US \$145/t in 2000, this translates to annual benefits of US \$143.3 million.[13]

How sensitive are these estimates to the risk aversion parameter or the standard error of the coefficient estimate on yield reduction? The remaining cells in Table 11 suggest a likely range from about US \$10 million to about US \$300 million in annual benefits from MV

[12] Note that for maize, our regression results use ln MV values; similarly, our dependent variables are absolute deviations from trend yield. The conversions to the form specified here involve some approximation, but the loss of precision (for example in estimating "variance" from "absolute deviation from trend") does not seem to be a significant concern.

[13] We assume that the changes are small enough that we do not need to worry about general equilibrium impacts on the world wheat price level.

contributions to yield variance reductions. These are large impacts, and note that they already adjust for the variability-reducing effects of irrigation and other inputs, as well as for the direct yield-increasing impact of MVs.

Table 12 reports similar calculations for maize. Recall that the regression estimates of MV impacts on deviation from trend were somewhat less robust. This leads to a wider range of estimates for potential impact than for wheat. The coefficient

Table 11. Benefits of reducing wheat yield variability through use of modern varieties.

	Elasticity of yield variability reduction with respect to MV use.				
Risk aversion	-2 S.E. (-0.00004)	-1 S.E. (-0.00021)	Mean (-0.00038)	+1 S.E. (-0.00055)	+2 S.E. (-0.00072)
	Gain in production that is equivalent in utility terms to the actual reduction in yield variability.				
γ = 2 (low)	0.00025	0.00103	0.00133	0.00118	0.00060
γ = 5 (medium)	0.00064	0.00259	0.00338	0.00304	0.00163
γ = 10 (high)	0.00129	0.00528	0.00695	0.00637	0.00038
	Absolute annual gain in production (MT) that would be equivalent in utility terms to the actual reduction in yield variability.				
γ = 2 (low)	70,649	287,221	372,530	331,814	169,801
γ = 5 (medium)	178,634	730,204	955,220	864,492	466,399
γ = 10 (high)	363,974	1,500,909	1,990,094	1,845,506	1,072,448
	Absolute annual dollar benefit of reductions in yield variability.				
γ = 2 (low)	$ 10,597,350	$ 43,083,150	$ 55,879,500	$ 49,772,100	$ 25,470,150
γ = 5 (medium)	$ 26,795,100	$109,530,600	$143,283,000	$129,673,800	$ 69,959,850
γ = 10 (high)	$ 54,596,100	$225,136,350	$298,514,100	$276,825,900	$160,867,200

Table 12. Benefits of reducing maize yield variability through use of modern varieties.

	Elasticity of yield variability reduction with respect to natural log of MV use.				
Risk aversion	-2 S.E. (+0.0014)	-1 S.E. (-0.0019)	Mean (-0.0052)	+1 S.E. (-0.0085)	+2 S.E. (-0.0118)
	Gain in production that is equivalent in utility terms to the actual reduction in yield variability.				
γ = 2 (low)	-0.00065	0.00102	0.00316	0.00579	0.00892
γ = 5 (medium)	-0.00163	0.00255	0.00799	0.01446	0.02230
γ = 10 (high)	-0.00327	0.00509	0.01579	0.02893	0.04460
	Absolute annual gain in production (MT) that would be equivalent in utility terms to the actual reduction in yield variability.				
γ = 2 (low)	(145,066)	226,162	701,351	1,284,832	1,981,083
γ = 5 (medium)	(362,666)	565,406	1,753,378	3,212,080	4,952,708
γ = 10 (high)	(725,332)	1,130,812	3,506,755	6,424,161	9,905,416
	Absolute annual benefit (US$) of reductions in yield variability.				
γ = 2 (low)	(12,330,610)	19,223,770	59,614,835	109,210,720	168,392,055
γ = 5 (medium)	(30,826,610)	48,059,510	149,037,130	273,026,800	420,980,180
γ = 10 (high)	(61,653,220)	96,119,020	298,074,175	546,053,685	841,960,360

estimate for β used in the analysis: was β = -0.0052, with this coefficient applied to the natural logarithm of MV diffusion instead of the absolute level. Results are reported for this value of β, as well as for one and two standard errors above and below the point estimate. As for wheat, three different values of the risk aversion parameter were used.

At a moderate level of risk aversion, the point estimate for the coefficient suggests that MV impacts on yield variability were worth about three-quarters of a percent (0.799%) in terms of yield increase. Aggregating over the countries in the data, this corresponds to about 1.75 million tons of maize production; valued at the year 2000 price of US $85/t, this gives an estimated annual value of reductions in yield variability of approximately US $149 million.

Because the regression results for maize give higher standard errors, the range of possible results is much broader, however. At one standard error from the point estimate, the range of values goes from US $19 million to US $546 million, and at two standard errors distance, the possible range extends from -US $62 million to US $842 million, with the negative numbers corresponding to the possibility that MV diffusion could possibly have *increased* yield variability. In short, the range of the results for maize is too broad to give a statistically clear understanding of whether MV diffusion has had a positive or negative net effect in terms of yield variability.

8. Conclusions

It is difficult to generate any watertight account of declines in yield variability at the aggregate level that can be attributed to any specific research program. But the evidence is strong nonetheless that yield variability has declined with the diffusion of modern wheat varieties, and possibly also with maize. As reported by previous researchers, there has factually been a decline in the variability of national-level wheat yields and, to a lesser extent, maize yields. This decline has been associated with the diffusion of new crop varieties. From the data, the declines in variability have coincided spatially and temporally with the diffusion of modern varieties. The declines in variability are not attributable to changes in irrigation or any inputs that grow linearly or geometrically over time. Thus, there appears to be a real and (for wheat) statistically significant connection between MV diffusion and declining national-level yield variability. For maize, the results are slightly less clear, in the sense that the relationship between variability declines and MV diffusion is less significant statistically, when irrigation and time trends are controlled for.

Nevertheless, the benefits from MV-induced declines in yield variability are substantial. Although the "output equivalents" are small (0.3% of production in the case of wheat, 0.8% of production in the case of maize), the sheer scale of wheat and maize production in the developing world implies that the benefits are large in absolute terms. Assuming a moderate level of risk aversion and taking the central coefficient estimates for the magnitude of reductions in yield variability, the benefits are about US $143 million for wheat and about US $149 million for maize, on an annual and recurring basis.

Relative to the magnitude of worldwide expenditures on wheat and maize research for the developing world, these are very high returns in dollar terms. Although it is not possible to attribute these returns to any particular research theme or program, the kinds of research that are generating reductions in yield variability are research on disease and pest resistance, drought tolerance, crop management, and other similar themes. Such topics are perhaps less glamorous than research on increasing the yield frontier, but the results presented here suggest that they have high payoffs nonetheless.

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CIMMYT
International Maize and Wheat Improvement Center
Apartado Postal 6-641, 06600 Mexico, D.F., Mexico
www.cimmyt.org