The Impact of the CIMMYT Wheat Breeding Program on Wheat Yields in Mexico's Yaqui Valley, 1990-2002: Implications for the Future of Public Wheat Breeding

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Abstract

CIMMYT has invested a large and significant amount of public expenditures in wheat breeding research each year for several decades. Estimates of the impact of the wheat breeding program on wheat yield increases provides information to scientists, administrators, and policy makers regarding the efficacy and the rate of return to these investments, providing important information for future funding decisions. Using CIMMYT test plot data from the Yaqui Valley in Mexico from 1990-2002, regression results indicate that the release of modern CIMMYT varieties has contributed approximately 53.77 kg/ha to yield annually. The growing conditions of the experiment fields located in the Yaqui Valley approximate 40% of the developing world's wheat growing conditions. A rough estimate of the gains attributed to CIMMYT's wheat breeding program on a global scale is 304 million (2002) USD annually during the period 1990-2002. CIMMYT's total wheat breeding cost in 2002 was approximately 6 million dollars, making the benefit cost ratio approximately 50 to 1.

The Impact of the CIMMYT Wheat Breeding Program on Wheat Yields in Mexico's Yaqui Valley, 1990-2002: Implications for the Future of Public Wheat Breeding.

Recent studies (Sayre 1996, Bell et al. 1995, and Byerlee 1992) have shown that there has been a deceleration in world wheat yield growth, specifically in irrigated areas, which has led some to believe that the potential for future genetic gains is slowing. Traxler et al. (1995) reported that the CIMMYT breeding program "reached a plateau" in the 1980s.[1] This breeding plateau would have global ramifications, since it is often poor consumers who benefit the most from yield enhancement of staple crops such as wheat. Byerlee and Moya (1993) showed that over half of the benefits of wheat research have been captured by poor consumers and farmers in South Asia, which has the world's largest concentration of poverty. Figure 1 illustrates the motivation behind this research: the initial increase of average yield of CIMMYT-released varieties, and the yield reduction between 1990 and 2002, raising concern about the future funding of wheat breeding at CIMMYT.

CIMMYT has invested a large and significant amount of public expenditures in wheat breeding research each year for several decades. Estimates of the impact of the wheat breeding program on increasing wheat yields provides information to scientists, administrators, and policy makers regarding the efficacy and return to these investments. Quantitative estimates of yield improvements due to the wheat breeding program provide important information for future funding decisions. Estimates of yield improvement also allow for the completion of a cost-benefit analysis of the wheat breeding program, and for evaluation and assessment of the impact

[1]The Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) is a nonprofit maize and wheat breeding research center based in El Batan, Mexico. CIMMYT was created to establish international networks to improve wheat and maize varieties in low-income countries.

of the program on alleviating poverty in low-income nations that have adopted the wheat varieties.

The goals of this paper are twofold. First, to isolate and quantify the increases in wheat yield of CIMMYT-released wheat lines attributed to genetic improvements. Test plot data from Mexico's Yaqui Valley were used to quantify yield increases and potential yield decreases over time.[2] Second, to analyze yield variability of modern lines released by CIMMYT during the 1990-2002 period. Changes in mean yield and yield variability are of central importance to CIMMYT, since their projections indicate that by 2020, the developing world will need 40% more wheat than it consumes today. This is particularly true due to a lack of involvement by private breeders in most low-income countries. Wheat germplasm produced by CIMMYT is used extensively by breeding programs in the developing world. The motivation of this study is to determine the impact of the CIMMYT wheat breeding program on both (1) yield and (2) yield variability, to better assess CIMMYT's ability to address growing food security issues in the developing world.

CIMMYT, through the release of modern wheat varieties, has generated substantial increases in grain yields, improved grain quality, reduced yield variability, and reduced environmental degradation in low-income countries since the Green Revolution. CIMMYT, a non-profit organization, distributes improved germplasm to national agricultural research systems (NARS) for worldwide utilization. On average, 65–77% of these crossed samples were sent to developing countries. CIMMYT germplasm is present in roughly 24% of all wheat types using the cross rule, 38% using the cross or parent rule, 64% using the any ancestor rule, and

[2]CIMMYT does not release varieties, they give lines to various governmental breeding programs that can choose to release a line bred by CIMMYT as a variety. In what follows, a "CIMMYT variety" refers to a line breed by CIMMYT that was released by a government as a variety.

approximately 80% of the total spring wheat area (Lantican et al. 2005).[3] Private breeders have little incentive to breed for most low-income countries. CIMMYT fills this gap, as approximately 62% of the total wheat area in low-income countries is planted to CIMMYT-related varieties (Heisey et al. 2002).

The principal CIMMYT wheat experiment station in northwest Mexico, located in the Yaqui Valley, composed of approximately 235,000 hectares. The Yaqui valley is typical of approximately 40% of all wheat acres located in developing nations, making it an ideal location for testing new lines to be released worldwide (Pingali and Rajaram 1999).[4] Approximately 36 million hectares worldwide share the growing conditions of the Yaqui Valley spread primarily through Asia and Africa between 35^{o}S and 35^{o}N latitude. Several studies (Fischer and Wall 1976, Waddington et al. 1986, Ortiz-Monasterio et al. 1990, and Sayre et al. 1997) found that the annual rates of genetic gain in wheat yields attributed to genetic improvements in Northwest Mexico through breeding programs ranged from 0.05 to 1.7 percent. Gains can be attributed to two factors, genetic and agronomic. Agronomic gains are attributed to improvements in fertilizer, pesticides, fungicides or other factors that are not embodied in the seed. Genetic gains are associated with improved wheat breeding, or technology that is embodied within the seed.

Historically, breeders have focused on increasing yield. Yield stability is gaining in importance, particularly in low-income countries. Critics of modern varieties (MVs) have suggested that, in developing countries, yields of MVs vary more from season to season than

[3]The term, "CIMMYT cross" refers to a cross made at CIMMYT and the selections to obtain fixed lines that were either made at CIMMYT or by a non-CIMMYT breeding program. The term, "CIMMYT parent" refers to a cross made by a non-CIMMYT breeding program using one of the parents coming directly from CIMMYT. Lastly, the term, "CIMMYT ancestor" means that there is CIMMYT pedigree somewhere in the wheat, so a CIMMYT wheat is not used directly in the cross, but was used in developing one of the parents.

[4]The Yaqui Valley is classified by CIMMYT as an "optimally irrigated, low rainfall area" (van Ginkel et al. 2002). The climatic conditions during the growing season range from temperate to conditions of late heat stress. Other areas with similar growing conditions are the Gangetic Valley (India), the Indus Valley (Pakistan), the Nile Valley (Egypt), sections of Zimbabwe, Chengdu (China), Kano (Nigeria) and Medani (Sudan), (van Ginkel et al. 2002).

traditional varieties, thereby exposing consumers and producers to greater risks (Gollin 2006). Empirically, several studies (Hazel 1989, and Traxler et al. 1995) found that younger modern varieties have actually reduced instability of wheat yield in low income countries. Gollin (2006) stated that the decline in wheat variability is not attributed to growing conditions or inputs but rather to the diffusion of modern varieties. The first wave of improved CIMMYT wheat varieties focused on maximizing yield gain, while the second wave of improved varieties not only attempts to increase yield, but also maintain these initial higher yields as it faces evolving attacks from disease and insects (also called, "maintenance breeding"). The reduction in yield variability in modern varieties is pertinent to the breeders at CIMMYT, since their germplasm is extensively planted.

While several location-specific studies (Traxler et al. 1995) and some regional studies (Fischer and Wall 1976, Byerlee and Moya 1993, Sayre et al. 1997, and Heisey et al. 2002) have quantified the genetic gains solely attributed to wheat breeding, few have controlled for both planting techniques and specific weather variables, and none have quantified the genetic improvements of public breeding in the last decade. Lobell et al. (2005) concluded that increases in yield of Mexican wheat since the 1980s are mainly attributable to improved climatic conditions, not advancements in breeding.

This paper will use the Traxler et al. (1995) template for measuring yield and yield variation, but will use more detailed weather data, in the form of solar radiation and mean temperature, which the agronomy literature suggests are pivotal for yield determination (Lobell et al. 2005, Richards 2000, Hobbs et al. 1998, Ortiz-Monasterio, et al. 1994, and Fischer 1985). This paper also takes into consideration that each of the three wheat species (Durum, Bread, and Tritacale) are grown in distinct parts of the world, and thus the yield for each is disaggregated.

Furthermore, unlike past studies that analyze CIMMYT test plots (Waddington et al. 1986, Traxler et al. 1995, Bell et al. 1995, Sayre et al. 1997, and Ortiz-Monasterio et al. 1997) this study incorporates several planting techniques found in the developing world. Therefore, this study recognizes that many farmers in the developing world can not adopt permanent bed planting, mainly due to the lack of appropriate permanent bed seeders.

Literature Review

Waddington et al. (1986) tested the genetic gain in fourteen bread wheat lines released in Northwest Mexico from 1950-1982. The authors analyzed yields from two growing seasons 1982-1983 and 1983-1984 from the Agricultural Research Center for the Northwest (CIANO) experiment station in the Yaqui Valley of Mexico. Each season the wheat was under irrigation with both fertilizer and nitrogen applied at the same rates. During both growing seasons the wheat grew through nets to prevent lodging. A full weed, disease, insect and bird control program was employed both seasons. Weather differences in the growing seasons were noted by the authors, but not used in direct calculation of genetic gain. The authors used an analysis of variance on all of the variables, harvest index, phytomass, grains, spikes, and yield, measured on each genotype. The average annual rate of gain in yield was estimated by regressing the mean grain yield, each year, of each line, on the year of release for the respective line. The authors found that gains associated with genetic improvement in the Yaqui valley were roughly 1.1% annually. The authors attributed this increase in genetic yield to breeders proactively crossing lines that historically yielded well.

Sayre et al. (1997) attempted to measure genetic gain in CIMMYT lines from the CIANO experiment station. Eight lines were tested that had historically been planted in the Northwest part of Mexico. The eight tested lines were planted under irrigation, which is common in that

section of Mexico, in six growing seasons (1989-1990 to 1994-1995). Daily radiation and mean temperature was recorded so that a photothermal quotient, solar radiation divided by the mean temp minus 4.5^{o} C, could be calculated. The authors used the year that each respective line was released to measure the genetic progress. Using analysis of variance and a linear regression analysis, an Eberhart and Russell regression, the authors found the rate of genetic progress to be roughly 0.88% per year. Interestingly, they found the photothermal quotient to be significant only when they dropped the planting season 1992. The authors' conclusion was that the more recent lines were yielding more because they produced more kernels under less solar radiation and higher temperatures proceeding anthesis. That is, it was their opinion that the younger lines were yielding better through genetic breeding because they preformed well in sub-optimal conditions while still maintaining satisfactory yields when super-optimal conditions prevailed.

Ortiz-Monasterio et al. (1997) study ten lines released by CIMMYT that were released in the Yaqui Valley of Mexico from 1950 to 1985. The author's field study took place in Ciudad Obregon, in Sonora, Mexico. The field trials were conducted for three growing seasons, 1987 to 1989, with varying amounts of applied nitrogen for each replicate. The authors analyzed the changes in yield attributed to genetics and nitrogen use efficiency. The basis for this article was to respond to the growing notion that CIMMYT's bread wheat germplasm performed poorly under low nitrogen levels. To address this issue were four replicates each year for each variety with varying amounts of nitrogen applied. Both pesticide and fungicide were used in optimal manners. No weather data was used in their study. An analysis of variance was performed with year of release considered a continuous quantitative variable for calculating genetic gains. The authors found that genetic gains on an annual basis ranged from 1.0% to 1.9% based on the amount of nitrogen used. The authors concluded that the reason for the wide adoption of

CIMMYT's genetic material worldwide is the flexibility of nitrogen uptake efficiency and utilization efficiency under different levels of nitrogen application. Importantly, the authors found that the CIMMYT-released material resulted in a minimum of a 1.0% annual gain in yield that can be attributed to genetic improvements.

Traxler et al. (1995) analyzed ten wheat lines released in Mexico from 1950-1985. Their goal was to see if CIMMYT released lines had progressively increased yield, improved yield stability, or both over time. Unlike other studies, Traxler et al. (1995) recognize that farmers and plant breeders evaluate lines based on several criteria, mainly yield and yield stability. Since CIMMYT breeds for low income countries yield variability plays an important role in their breeding agenda, because it is often poor producers and consumers that bear the brunt of exposure to greater risk presented by yield variation. Traxler et al.'s data came from trials conducted by CIMMYT in the Yaqui Valley of Mexico. The authors used three growing seasons 1987-1989 with three replicates of each variety annually. The replicates allowed for varying amounts of nitrogen. No weather data was used in this study. Unlike other studies which only used an analysis of variance, Traxler et al. (1995) used a Just-Pope production function. This is unique because it simultaneously lets one test the hypotheses that the evolution of varietal technology has increased yield over time and decreased yield variance. Like in previous studies, release year was used as a proxy to measure genetic gains, but unlike the aforementioned studies this one included a release year squared term which allows for curvature. Estimating the Just-Pope production function, the authors found that yields increased steadily between 1950-1980, but reached a plateau in the 1980s. The authors stated that the plateau findings are not robust. They found that the variance of output peaked around 1970, but decreased in later years. Overall,

they concluded that progress is being made in producing "better" varieties; which indicates that modern varieties have improved either yield stability, overall yield, or both.

While all the aforementioned articles deal with the technique for measuring the genetic gains attributed to breeding, Fischer (1985) devised a ratio which has widely been accepted as crucial for accurately measuring gains in yield. Fischer used multiple years of field tests at the CIANO test plots in the Yaqui Valley of Mexico all under irrigation, weed and disease control. He analyzed semi-dwarf varieties to see how the number of kernels in wheat (which can be seen as an early proxy for yield) was influenced by temperature and solar radiation. Daily solar radiation and mean temperature were recorded for each growing season.

The author found that the number of wheat kernels per meter squared was highly dependent on both the amount of solar radiation received and mean growing temperature for the thirty days around anthesis. The relationship according to Fischer was simple, it was linear and positive for solar radiation and liner and negative for temperature. For the combined variation Fisher used solar radiation divided by the mean temperature – 4.5.[5] This ratio is referred to as the Photothermal Quotient (PTQ). The theory is that just before and after anthesis (the period when the wheat flower is fully open and functional) is a sensitive period in wheat production, and both radiation and temperature have an effect on kernels per square meter and thus yield. Fischer stated that high radiation results in increased photosynthesis, which is advantageous for yield. A high temperature has negative impacts on yield, as it shortens the duration of the spike growth period. Fischer concludes that the PTQ can be useful for estimating number of kernels per meter squared (which can be viewed as expected yield) for wheat crop models. This study will implement the Just-Pope production function following Traxler et al. (1995), but will also incorporate both detailed weather information of Sayer et al. (1997).

[5]Since 4.5^{o} C is the base temperature for wheat growth, it is subtracted from the mean temperature.

Methodology

Estimation will attempt to correct for the unbalanced nature of the CIMMYT data.[6] The estimation technique will account for the presence of multiplicative heteroscedasticity, which may exist across wheat varieties. Yield variances may differ across varieties, due to differences in breeding objectives (some varieties are bred for to resist heat stress, some for quality improvements etc.). Harvey's (1976) correction for multiplicative heteroscedasticity is implemented to correct for unbalanced variances across varieties. To incorporate variety-related heteroscedasticity into the model, some assumptions are made as to the nature of the heteroscedasticity. Greene (1990) referred to as multiplicative heteroscedasticity as

$$\sigma_{vi} = \sigma \exp(Z_i \ \gamma) \tag{8}$$

where Z_i is a vector of variables related to yield and γ is a vector of unknown parameters. If Z_i includes an intercept, the preceding expression can be simplified to

$$\sigma_{vi} = \exp(Z_i \ \gamma_i) \tag{9}$$

Multiplicative heteroscedasticity has some computational advantages because it automatically constrains $\sigma_{vi} > 0$. In addition, the functional form in (9) is easily constrained to yield the homoscedastic case, making a likelihood ratio test possible.

The Just-Pope Production Function

A Just-Pope (1979) production function was selected for its flexibility in describing stochastic technological processes. This estimation provides a straightforward way of testing the effects of increased yield on yield stability. The Just-Pope production function allows inputs to affect both the mean and variance of outputs. This production function specification includes two general functional forms – one which specifies the effects of inputs on the mean of output, and

[6]The data used here is "unbalanced" due to the difference in replications across trial years.

another which specifies the effects of inputs on the variance of outputs. The production function is specified as follows:

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

where Y_i is yield of the i^{th} variety , the $\mathbf{X}_i$ are explanatory variables, β and α are parameter vectors, and ε_i is a random variable with a mean of zero. The first component of the production function $f(\mathbf{X}_i, \beta)$ relates the explanatory variables to mean output. The function $g(\mathbf{X}_i, \alpha)\varepsilon_i$ relates the explanatory variables to the variance in output. Since the basis of the Just-Pope production function is that the error term of the production function is correlated with some or all of the explanatory variables, it can thus be viewed as a multiplicative heteroscedasticity model. The multiplicative heteroscedastic model is estimated using a three-stage estimation procedure. If variance is an exponential function of *K* explanatory variables, the general model with heteroscedastic errors can be written as

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

$$\mathrm{E}(e_i^2) = \sigma_i^2 = \exp[\mathrm{X_i}'\alpha] \quad (3)$$

where $X_i' = (x_{1i}, x_{2i}, \ldots, x_{ki})$ is a vector of observations on the *K* independent variables. The vector $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \ldots, \alpha_k)$ is of the dimension (K x 1) and represents the unknown coefficients. $\mathrm{E}(e_i) = 0$ and $\mathrm{E}(e_i e_s) = 0$ for $i \neq s$. Equation (3) can be rewritten as

$$\ln\sigma_i^2 = X_i'\alpha \quad (4)$$

where the σ_i^2 is unknown, but using the least squared residuals from equation (2) the marginal effects of the explanatory variables on the variance of production can be estimated. Such that,

$$\ln e_i^{*2} = X_i^{'}\alpha^{*} + u_i \qquad (5)$$

where the error term can be defined as

$$u_i = \ln\left(\frac{e_i^{*2}}{\sigma_i^2}\right) \qquad (6)$$

The predicted values from equation (5) are used as weights for generating generalized least squares (GLS) estimators for the mean output equation (2). That is, the estimates from equation (5) can be viewed as the effects of the independent variables on yield variability.

Fixed Effects

A second model of the unbalanced cross-section, time series data is estimated and reported for 1990-2002, following Johnston (p. 397), by including fixed effects (intercept shifters) for each of the varieties. A Lagrange Multiplier (LM) test for fixed effects across varieties is estimated to determine if the vector of fixed effect estimates contributed to the overall model. A high value and statistical significance of the LM statistic indicates that Fixed Effects are highly statistically significant, and should be included in the regression model (Greene).

Data

Data were collected from CIMMYT test plots in the Yaqui Valley of Mexico from 1990-2002. Although a gap between experimental and actual yields exists (Figure 2), Brennan (1984) wrote, "The only reliable sources of relative yields are variety trials" (p. 182).[7] Therefore, annual changes in relative yields are measured with performance test data. A total of 33 varieties were analyzed with release years ranging from 1962-2001, including the variety Siete Cerros, which was the most popular semidwarf wheat of the Green Revolution. All of the observations were

[7]Relative yield comparisons, according to Brennan (1984), are only reliable on test plots. Restated, yield comparisons across varieties should be done when growing conditions, fertilizer usage, irrigation, fungicide, etc. is constant among varieties. A test plot with multiple varieties allows for this ideal comparison.

under irrigation and had the "ideal" amounts of fertilizer application.[8] Three species of wheat were planted during the test period; durum (*Triticum durum*), bread (*Triticum aestivum*), and Triticale, a cross between wheat (*Triticum*) and rye (*Secale*). Approximately 93% and 6% of the total area sown in developing countries was sown to bread and durum wheat, respectively (Lantican et al. 2005).

Four distinct planting methods were implemented for the test period. First, using traditional practice (melgas) and using fungicide. Under the melgas practice, the land is simply covered completely with wheat plants, with the objective of enabling the wheat to compete for water, space, light, and nutrients. The melgas planting system is used on flat seedbeds and seed is either broadcast and then incorporated, or a small grain seeder can be used to distribute seed continuously in rows (Aquino 1998). During the 1970s, a technique of planting on narrow raised beds, with irrigation water confined to furrows between the beds was adopted in the Yaqui Valley. By 1991, nearly 65% of the valley's wheat was produced using beds, and by 2001 nearly 84% (Fischer et al. 2005). Bed planting typically does not result in immediate, large yield increases for irrigated wheat; it provides improved input use efficiencies and reduced production costs (Sayre et al. 2005). The second planting method was beds without fungicide. Third, was the use of beds plus the application of fungicide. Fourth, was the use of melgas with nets (for lodging protection) and the application of fungicide.

Daily weather data were collected for both temperature and solar radiation exposure. The average solar radiation exposure in mega joules per square meter per day ($MJ/m^2/day$) was recorded daily, along with the maximum and minimum temperature in Celsius for each day. Fischer (1985) found that both solar radiation and temperature can be paramount in determining

[8]Fertilizer applications were held constant throughout the time period under consideration, 1990-2002 according to interviewed CIMMYT agronomists.

the number of kernels per meter squared. The theory is that just before and after anthesis (the period when the wheat flower is fully open and functional) is a sensitive period in wheat production, and both radiation and temperature have an effect on kernels per square meter and thus yield. High radiation is expected to result in increased photosynthesis, which is advantageous for yield. A high temperature has negative impacts on yield, as it shortens the duration of the spike growth period. Temperature in the growing season is also important because higher temperatures close to the grain-filling period result in grain abortions and forced development of underweight grains (Hobbs et al. 1998). Several studies (Richards 2000, Dhillon and Ortiz-Monasterio 1993, and Abbate et al. 1995) concluded that the ratio of solar radiation to temperature, know as the photothermal quotient (PTQ), maximized yield when the PTQ was highest between twenty days before and ten days after anthesis. Uniquely, this data set includes the number of days to reach anthesis, which was measured and reported for each individual observation. The number of days to anthesis for each observation is necessary to calculate the PTQ for each variety.

Empirical Model

The mean and variance of yield were specified as a function of the release year (*RLYR*) of each variety, which can be interpreted as the "vintage" of the wheat breeding technology (Traxler et al. 1995). It captures the progression of wheat breeding technology across time, forming the main variable for measurement and analysis of the impact of the CIMMYT wheat breeding program on wheat yields in performance fields. That is, *RLYR* represents the increases in yield due to genetic gains attributable to the CIMMYT wheat breeding program. A $RLYR^2$ term allows the model to capture curvature within the breeding program. Mean and variance of yield were also modeled as a function of growing conditions; melgas with fungicide

(*MelgasPlus*), beds with fungicide (*BedsPlus*), beds without fungicide (*BedsMinus*), and melgas with fungicide and nets (*Nets*). *MelgasPlus* was selected as the default because it is the traditional planting method in the Yaqui Valley.

The average temperature (*MeanTemp*) and solar radiation (*Solar*) twenty days before and ten days after anthesis for each plant, which are the components of the PTQ, were also used as explanatory variables. From the established PTQ literature, an increase in the average temperature twenty days before and ten days after anthesis should decrease yield, while an increase in the average solar radiation over the same time period should increase yield, *ceteris paribus*. The PTQ ratio may be too restrictive and the ratio components (*Solar* and *MeanTemp*) were included as two separate variables. The ratio PTQ forces the estimated coefficients on the numerator and the denominator to be equal, but of opposite signs.

Yield mean and variance were also modeled as a function of the species of wheat; bread (*Bread*), durum (*Durum)* and triticale (*Triticale)*. The species were represented by qualitative variables with *Bread* used as the default. A heat stress (*HeatStress*) variable was used to indicate the number of days in the growing season (January – April) where the temperature reached over 36^{o} C (96.8^{o} F).[9] In the maturation months of March and April, if the temperature is too hot the wheat kernel can scorch and have a negative impact on yield. Lastly, the interaction variable of *HeatStress* and *MeanTemp* (*HeatTemp*) was included to capture the potential of a growing season where temperature (*MeanTemp*) is well below average, implying that *HeatStress* should adversely effect yield more under low average temperatures than a growing season with an average temperature well above average. The interaction between *RLYR* and the weather attributes was included because *a priori* it can be assumed that varietal improvements may have

[9]The temperature 36^{o} C was selected because it is two standard deviations above the mean. This would then indicate those days that are in the top 5% hottest days in the data set.

been targeted towards certain weather conditions (drought tolerance, heat stress, etc.).[10] The interaction between the weather characteristics *Solar*, *MeanTemp*, and *HeatStress* and *RLYR* are slope shifters. The estimated equations for yield (Y_i) in kg/ha and the log variance of yield $\left(e_i^2\right)$ are modeled as in equations (10) and (11) (Model I).

$$Y_i = \beta_0 + \beta_1 RLYR + \beta_2 Temp + \beta_3 Solar + \beta_4 Stress + \beta_5 HeatTemp + \beta_6 RLYR^2 + \beta_7 RLYRSolar + \quad (10)$$
$$\beta_8 RLYRMeanTemp + \beta_9 RLYRHeatStress + \delta_1 BedsPlus + \delta_2 BedsMinus + \delta_3 Nets +$$
$$\delta_4 Durum + \delta_5 Triticale + \varepsilon i$$

and

$$\ln(e_i)^2 = \beta_0 + \beta_1 RLYR + \beta_2 Temp + \beta_3 Solar + \beta_4 Stress + \beta_5 HeatTemp + \beta_6 RLYR^2 + \beta_7 RLYRSolar + \quad (11)$$
$$\beta_8 RLYRMeanTemp + \beta_9 RLYRHeatStress + \delta_1 BedsPlus + \delta_2 BedsMinus + \delta_3 Nets +$$
$$\delta_4 Durum + \delta_5 Triticale + \varepsilon_i$$

Estimating (10) and using the natural log of its squared error terms as the dependent variable, equation (11) is then estimated to analyze yield variability. The coefficients and their respective signs on equation (11) can be seen as the effect of each independent variable on yield variability. Using the predicted values from (11) as weights and re-estimating (10), it is possible to obtain the weighted least squares results from which hypothesis tests can be drawn, correcting for multiplicative heteroscedasticity.

A fixed effects model was also estimated, similar to equation (10), but with a vector of qualitative variables for each of the 33 variaties.[11] Variety 33 (Yoreme) is the omitted as the base variety. The qualitative variables representing the species of wheat (*Bread*, *Durum*, and *Triticale*) and *RLYR* along with interaction variables that included *RLYR* were omitted from the fixed effects model because they were embedded in each variety and thus perfectly collinear.

[10] An example of this would be if a specific breeding period focused on one attribute more than others, like heat stress due to the increased literature on global warming. Breeding for heat stress may have been a more pronounced goal of the breeding program in the last ten years, and thus would need to be accounted for.

[11] A Hausman test was conducted which showed that Fixed Effects model was more appropriate than the Random Effects given this data set.

The fixed effects model allows comparisons between average historical yields for each variety with predicted yields with all else held constant, and can be seen as an intercept shifter.

Econometric Results

The overall results of the estimated regressions provided some evidence that the results are robust. The large number of observations contributed to the robust nature of the estimates. The mean of variables included in the model is reported in table 1, and tables 2-4 present the regression results from the two Just-Pope regression models. Approximately 39 percent of the variation in wheat yields was explained by the yield regressions (table 2). Inclusion of the fixed effects increased the explanatory power to 53 percent for the period (table 2). Each of the included variables will be discussed below. All of the coefficients have the anticipated signs and the results tended to be robust across the two models.

Release Year

The coefficient on release year (*RLYR*) is the main variable of focus in this study, since it captures the "vintage" of each variety, or the technology that is embedded into each variety of wheat. Since there are several interaction terms of RLYR, in addition to the RLYR variable and the squared RLYR variable, the coefficients must be interpreted with care. The partial effect of RLYR is found by taking the first derivative of the estimated model, as found in table 3. The Just-Pope results from Model One reveal that the CIMMYT breeding program added roughly 53.771 kg/ha annually (table 3), statistically significant at the 1% level. Given the average yield of 8430.35, the yield increase due to the CIMYYT breeding program is equal to a 0.64 percent yield increase per year (53.77/8430.35). During the 1990-2002 period, the CIMMYT wheat breeding program contributed 645.25 kg/ha, or an additional 7.65% (645.25/8430.35) to wheat yields in the Yaqui Valley.

Unlike the Traxler, et al. study, the Just-Pope production function (table 2) does not indicate a yield plateau within the data set. The $RLYR^2$ is negative and statistically significant at the 1% level (Model One, table 2), indicating that yield will eventually decrease but not until the year 2035. Figure 3 shows how yield has evolved over time based on the Just-Pope estimated results, compared to the trend of the observed average yields. Figure 3 illustrates how misleading the analysis of average historical yield can be if weather is not held constant. The trend of average yields of CIMMYT-released varieties over time it looks as if yield has reached a plateau and subsequently decreased since the mid-eighties. Conversely, when holding weather, species, and planting conditions constant yield is increasing, albeit at a decreasing rate. The fact that yields are increasing at a decreasing rate should not come as a surprise, given the large initial increases during the Green Revolution. The discrepancy highlighted in figure 3 between the Just-Pope predicted yields and the trend of the average yields can be attributed to several things including holding the climatic conditions constant throughout the time period analyzed.

Climatic Variables

Photothermal Quotient Components

The effects of the mean temperature (*MeanTemp*) variable, which was the average temperature 20 days before and ten days after anthesis, on yield were found to be negative and statistically significant at least at the 10% percent level for the fixed effect Model Two, but not in Model One (table 2). This result is likely due to the inclusion of the *RLYR*MeanTemp* interaction variable. The fixed effect Just-Pope results would indicate that for every degree Celsius increase in average temperature twenty days before and ten days after anthesis that yield would decrease by 288.58 kg/ha (table 2). This result seems to confirm Fischer's (1985) proclamation that high temperature has negative impacts on yield, as increased temperature

shortens the duration of the spike growth period. The other component of Fischer's PTQ was daily exposure to solar radiation. *Solar* was found to have a positive coefficient and statistically significant at least at the 10% level for Models One and Two (table 2). The Just-Pope (model I) results indicate that for every MJ/m^2/day increase per day that yield would increase by 1.565 kg/ha (table 3). This result reaffirms Fischer's (1985) hypothesis that high radiation during the period twenty days before and ten days after anthesis results in increased photosynthesis, which is advantageous for yield.[12]

Heat Issues

The results of the *HeatStress* variable, which was the number of days in a given growing season which the temperature reached over 36^o C, on yield was found to be negative and statistically significant at least at the 5% level for Model I. *HeatStress* was found to be statistically significant at the 10% level in the fixed effect Model Two. The Model One results indicate that for each additional day in the growing season above 36^o C, yield would decrease by 1145.88 kg/ha. This *HeatStress* result is intuitive, since if during the maturation months of March and April the temperature is too hot, then the wheat kernel can scorch, reducing yield. This was evident in 2002 when the experiment station at Yaqui Valley experienced high temperatures towards the end of March and during early April, during the peak period of grain fill for wheat sown in December 2001 and subsequently had a poor yielding season.

The results for the *HeatTemp* variable was positive and statistically significant at the 1% level for Model One (table 2), but not statistically significant in Model Two. Since the coefficient is positive, then in growing seasons with above average temperatures, a sudden increase in temperature (above 36^o C) will not result in a decrease in yield as great as a growing

[12]The model was also run using the PTQ ratio. The model using *Solar* and *MeanTemp* as separate variables performed better in terms of adjusted R^2 and RMSE.

season with below average temperature that experiences the same number of heat stress days. The Just-Pope Model One results indicate that for every degree Celsius warmer the growing season is that an additional day of heat above 36^{o} C there will be an increase in yield by 53.37 kg/ha. Conversely and possibly more intuitively, it also can be interpreted as, for every degree Celsius colder the growing season holding the number of days of heat above 36^{o} C constant, you will see a decrease in yield by 53.37 kg/ha.

Release Year and Climatic Interactions

The interaction between *RLYR*, which is a proxy for varietal technology, and various weather attributes was included because one can assume that certain varietal improvements may have been targeted towards certain climatic conditions (drought tolerance, heat stress, etc.) at various times throughout CIMMYT's breeding history.[13] The *RLYR*Solar* variable was negative and statistically significant at the 1% level (table 2). Initially, this result seems counterintuitive in that newer varieties should perform better in optimal conditions (more solar lower temperature) than older varieties. However, Sayre et al. (1997) concluded that that the younger varieties yielded better because they preformed well in sub-optimal (low radiation and high temperature) conditions while still maintaining satisfactory yields when super-optimal conditions prevailed. Therefore, one explanation for the *RLYR*Solar* coefficient being negative is that CIMMYT is now breeding for sub-optimal conditions (low solar radiation) while attempting maintain yields under optimal conditions.

The *RLYR*MeanTemp* variable, the year a variety *i* was released multiplied by the average daily temperature 20 days before and 10 days after anthesis, is insignificant.

[13]Around 1999 the CIMMYT bread wheat program was split in two with one unit giving more attention to drought tolerance. Attention to drought and heat at CIMMYT goes back roughly 25 years, indicating that many varieties in this study were not bred for drought or heat resistance. Thus, the inclusion of the release year – climatic interaction terms.

*RLYR*HeatStress*, the year a variety *i* was released multiplied by the number of days over 36° C in growing season *j*, shows that for each subsequent year in the breeding program with the same number of days over 36° C in the growing season that yield will decrease by 4.214 kg/ha.

Planting Techniques

Planting techniques different from the traditional Mexican system of planting wheat on flat seedbeds (melgas) were significant determinants of yield. The variable *BedsMinus* (planting on beds without the use of fungicide) was found to yield statistically less, at the 1% confidence level, compared to the default of *MelgasPlus* (melgas with the use of fungicide). The Just-Pope Model One estimates indicates that if a farmer switched from using the traditional melgas with the use of fungicide to bed planting without fungicide that there would be an associated loss of 243.70 kg/ha in yield. The *BedsPlus* variable (plating on beds with fungicide) was marginally statistically insignificant (table 2), indicating that if a farmer switched from production using melgas with fungicide to implementing bed planting with fungicide *ceteris paribus* that there would be an expected yield increase of 135.57 kg/ha (a 1.6% increase). This reaffirms Sayre et al.'s (1995) proclamation that bed planting typically does not result in immediate, large yield increases for irrigated wheat. The use of *Nets* (melgas production practice with fungicide and nets to lessen lodging) was positive and statistically at the 1% level in Model One (table 2), indicating that by switching from planting on melgas with fungicide to planting on melgas with fungicide and the use of nets that one should anticipate a yield increase of 363.15 kg/ha (a 4.3% increase), *ceteris paribus*.[14] This 4.3% increase is consistent with the results that Tripathi et al. (2005) obtained during a test plot trial examining lodging behavior. The authors concluded that

[14]Nets are only used in the research plots and not in production in the Yaqui Valley. The reason they are employed at the test plot to be able to measure genetic yield potential of different genotypes in the absence of lodging.

yield comparisons between flat bed planting (melgas) with and without nets ranged from roughly 10% for lodging-prone varieties and 0% for varieties with no lodging.

Species Comparisons

Using bread wheat as the default, comparisons can be made with respect to both triticale and durum. The coefficient on *Triticale* was not statistically significant in Model One (table 2). That is, there is no statistical difference in yield between triticale and bread wheat. The species dummy variables were left out of the fixed effects models because each variety (the fixed effect) perfectly identified the species of wheat. The *Durum* variable is positive and statistically significant at the 1% level (Model One, table 2), showing that durum wheat yields 154.17 kg/ha more than bread wheat, *ceteris paribus*.

Fixed Effects Analysis

The results from the fixed effects Model Two are presented in table 2 with the predicted yields for each variety located on table 4. Since the *RLYR*, $RLYR^2$, and the *RLYR*-climatic interaction variables could not be included in the fixed effects models, the fixed effects model were mainly implemented to estimate average yield by variety and compare them to the average observed yield on the Yaqui Valley test plot from 1990-2002 (table 4).

Output Variance Response

Model One (table 2) shows that release year (*RLYR*) did not have a statically significant effect on the variance of output. This result would lead to the conclusion that *ceteris paribus*, an older variety would have the same variance of yield that a newer variety. Solar radiation (*Solar*) was found to have a negative and statistically significant impact. Model One results indicate that for marginal unit of MJ/m^2/day that yield variance has not increased or decreased over the perios 1990-2002. These results are intriguing because yield has increased, while variance of yield has

not increased. That is, the post Green Revolution has been characterized by slower yield growth, the regression results reported here indicate that yield is increasing at a decreasing rate, accompanied by no significant increase or decrease in yield variability over the same time period.

Benefit Cost Analysis

Following Alston et al. (1995) a surplus distribution model was implemented for a homogenous good (wheat), where supply is shifted due to research induced technical change. This model was implemented for both the Yaqui Valley and on a global scale. Historical Yaqui valley wheat prices were used from 1990-2002 along with production data from the same period. Detailed production data was obtained from the Yaqui Valley to isolate the percentage of area planted to CIMMYT released varieties. It was assumed that the percentage of area planted to CIMMYT varieties was equal to the percentage of yield produced in the Valley. A peso amount was then placed on the total amount of CIMMYT released wheat harvested in the Yaqui Valley using historic prices, and subsequently converted into U.S. dollars (USD). Results show that for the period of 1990-2002 a rough estimate of what CIMMYT contributed to the Yaqui Valley through its wheat breeding program was approximately $5.53 million (2002) USD per year.

On a global scale, an average world wheat price was used to evaluate global surplus measures.[15] Using the total land planted to CIMMYT varieties (cross, parent, and ancestor rule) there was roughly 62 million hectares planted to CIMMYT varieties in 2002. If the same yield advancements that were measured in the Yaqui Valley were applied on a global scale, a 304 million (2002) USD annual surplus would result from the CIMMYT wheat breeding program. CIMMYT's total wheat breeding cost in 2002 was roughly 6 million dollars (Lantian et al.

[15]Specific country prices, while available, proved to be unfeasible due to the fact that CIMMYT has a rough estimate of global hectares planted to CIMMYT varieties, however, they don't have a disaggregated country by country analysis.

2005). The benefit cost ratio would be roughly 50:1. This result is at the low end of what Lantican et al. (2005) found when they concluded that the benefit to cost ratio for CIMMYT's wheat breeding program ranges from 50:1 to 390:1. While these numbers seem high, it can be put into context with the extensive use of CIMMYT germplasm by public and private breeders world wide.

Results and Conclusions

CMIMMYT anticipates that by 2020, the developing world will need 40% more wheat than it consumes today, which must be provided using roughly the same amount of hectares currently under production. For this demand to be met low-income countries, must increase their per hectare yield. Using test plot data from the Yaqui valley from 1990-2002 and implementing the Just-Pope production function, which accounts for heteroscedasticity across varieties, it was found through the release of modern varieties CIMMYT contributes roughly 53.77 kg/ha annually to wheat yield in the Yaqui Valley. Critics of modern varieties (MVs) have suggested that, in developing countries, yields of MVs vary more from season to season than traditional varieties, thereby exposing consumers and producers to greater risks. Our results show that the CIMMYT breeding program has maintained or not contributed to yield variability since the release of the first semi-dwarf variety Pitic 62.

The results from this study indicate that CIMMYT's wheat breeding program has been increasing yield but at a decreasing rate. Over the same time period yield variance has not increased, indicative of the post Green Revolution breeding era. Both of these results are of central importance to CIMMYT estimates of the impact of the wheat breeding program on increasing wheat yields provides information to scientists, administrators, and policy makers regarding the efficacy and return to these investments.

Calculating a rough estimate of the benefit-cost analysis using historical prices and production in the Yaqui Valley, it was found that CIMMYT has contributed approximately $5.53 million (2002) USD annually from 1990-2002 to the Yaqui valley through its wheat breeding program. Given the average numbers of hectares planted to CIMMYT varieties in the Yaqui Valley over the same time period, CIMMYT's wheat breeding program contributed an additional $63.76 (2002) USD annually on a per hectare basis. Assuming that the gains that were observed in the Yaqui valley are equivalent to CIMMYT's gains on a global scale that would be a $304 million (2002) USD annual surplus resulting from the CIMMYT breeding program. CIMMYT's total wheat breeding cost in 2002 was roughly $6 million dollars (Lantican et al. 2005). The benefit-cost ratio is approximately 50 to 1.

All of these results are pertinent to global food security and poverty alleviation because CIMMYT is the leader in wheat breeding for low income countries. Yield increases were found to be increasing at a decreasing rate, but culminating these small increases over several decades and extensive planting worldwide results in a large and significant enhancement of wheat yields. While yield increases have been slowing, the reduction in yield variation can not be understated as an integral part of food security. By lowering or even stabilizing yield variability through the release of modern varieties CIMMYT has reduced the exposure from yield, and thus income variability, amongst and producers in low income countries.

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Figure 1. CIMMYT Wheat Variety Yields by Year of Release and Polynomial Trend, 1962-2002.

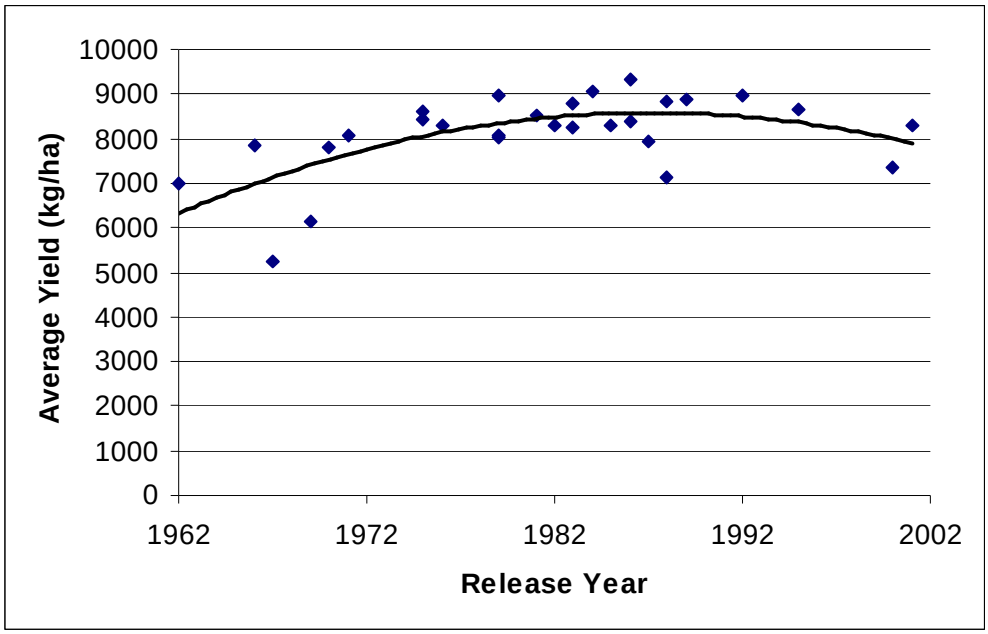


Figure 2. Average Yield Difference Between Wheat Yields at the Yaqui Valley Experiment Station and On Farm Yields in The Vaqui Valley, 1990-2002.

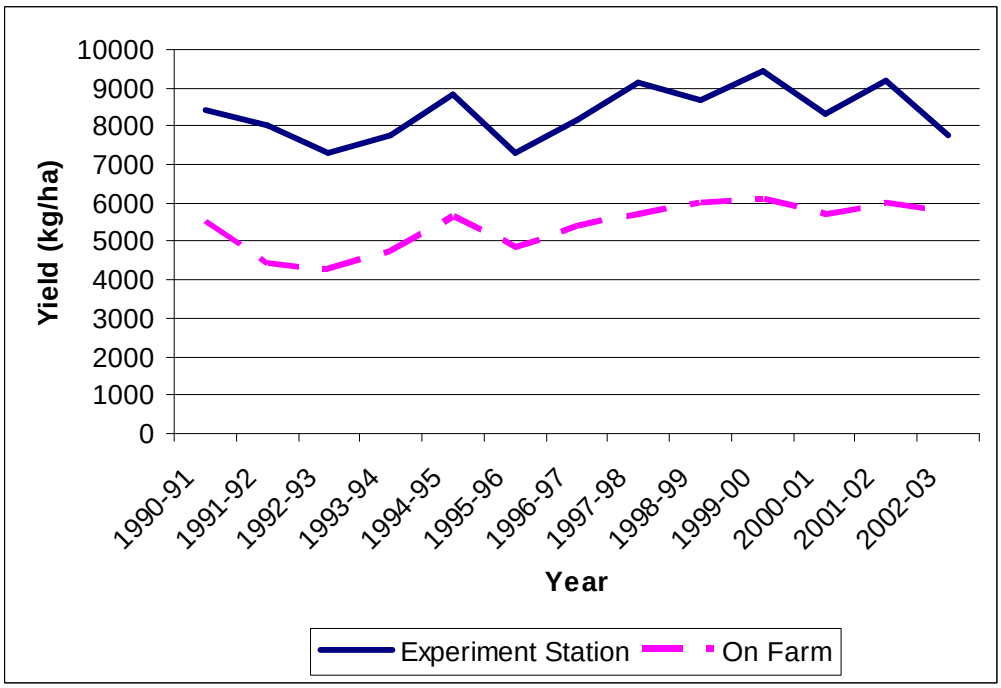
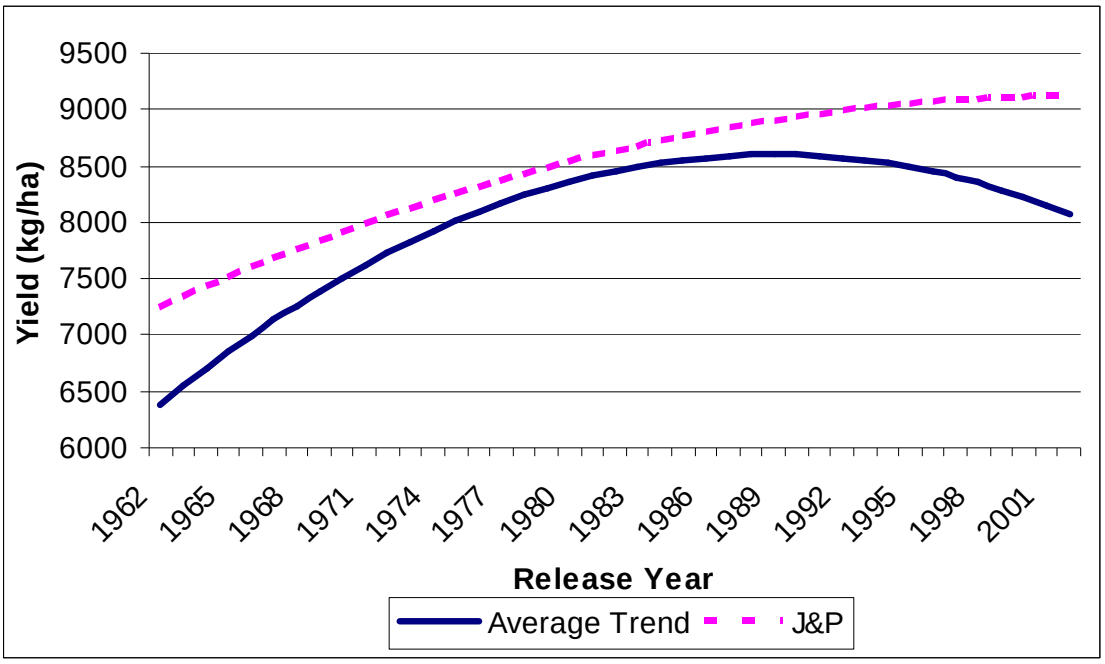


Figure 3. Difference in Just-Pope Predicted Yields Holding Weather Constant and the Trend of the Average Observed Yields by Year of Release, 1962-2002.



Note: the average polynomial trend in figure 3 is the same that appears in figure 1.

Table 1. Summary Statistics of Variables Used in CIMMYT Wheat Yield Regression Models.

Variable	Mean	Release Year
Solar	5081.732	--
MeanTemp	17.078	--
RLYR	1981.192	--
HeatStress	2.540	--
Durum	0.356	--
Tritiacale	0.131	--
BedMinus	0.220	--
BedPlus	0.188	--
Nets	0.079	--
HeatTemp	47.035	--
$RLYR^2$	3925200.7	--
RLYR*Solar	10069951.	--
RLYR*MeanTemp	33834.246	--
RLYR*HeatStress	5034.598	--
Varieties		
7 Cerros	0.067	1966
Achonchi	0.061	1989
Alamos	0.016	1983
Altar	0.063	1984
Atil C	0.008	2001
Bacanora	0.003	1988
Baviacora	0.066	1992
Borlaug	0.040	1995
Caborca	0.021	1979
Chapala	0.017	1967
Ciano	0.019	1979
Cocorit	0.060	1971
Eronga	0.065	1983
Jilotecpec	0.023	1996
Jori	0.015	1969
Mexicali	0.067	1975
Nazozari	0.065	1976
Oasis	0.060	1986
Opata	0.007	1985
Seri 81	0.005	1981
Seri 82	0.068	1982
Super Kauz	0.066	1988
Tarachi	0.007	2000
Tarasca	0.003	1987
Yavaros	0.063	1979
YYecora	0.021	1970
Yoreme	0.003	1975

Table 2. Just-Pope Regression Results for CIMMYT Wheat Yield Test Plots, 1990-2002.

	Model One: Release Year Variables				Model Two: Variety Fixed Effects			
	Yield		Variance		Yield		Variance	
Variable	Estimated Coefficient	t-test	Estimated Coefficient	t-test	Estimated Coefficient	t-test	Estimated Coefficient	t-test
Constant	-4.623 E6	[-3.504]***	1206.176	[0.374]	11497.602	[19.193]***	16.3477	[10.076]***
Solar	57.038	[4.791]***	-0.057	[-1.945]*	0.207	[3.700]***	-0.208	[-1.379]
MeanTemp	-1.013 E4	[-1.501]	-11.579	[-0.693]	-288.578	[-10.007]***	-0.143	[-1.831]*
RLYR	4559.834	[3.395]***	-0.945	[-0.288]	--	--	--	--
HeatStress	7202.867	[2.577]**	-2.633	[-0.384]	-623.790	[-1.650]*	-3.000	[-2.950]***
Durum	154.167	[2.569]***	-0.085	[-0.581]	--	--	--	--
Tritiacale	1.653	[0.020]	-0.079	[-0.394]	--	--	--	--
BedMinus	-243.698	[-3.185]***	0.159	[0.846]	-444.712	[-6.361]***	0.196	[1.043]
BedPlus	135.572	[1.646]	0.061	[0.298]	-56.858	[-0.759]	0.159	[0.792]
Nets	363.149	[3.050]***	-0.322	[-1.21]	158.471	[1.478]	-0.283	[-1.002]
HeatTemp	53.367	[2.357]***	0.074	[1.349]	24.734	[1.222]	0.155	[2.854]***
$RLYR^2$	-1.120	[-3.269]***	0.0001	[0.207]	--	--	--	--
RLYR*Solar	-0.028	[-4.769]***	0.00002	[1.938]*	--	--	--	--
RLYR*MeanTemp	4.966	[1.456]	0.005	[0.690]	--	--	--	--
RLYR*HeatStress	-4.214	[-3.095]***	0.0005	[0.173]	--	--	--	--
7 Cerros	--	--	--	--	727.083	[3.961]***	-0.698	[-1.384]
Achonchi	--	--	--	--	1765.748	[9.520]***	-1.297	[-2.560]***
Alamos	--	--	--	--	1197.856	[4.994]***	-0.150	[-0.227]
Altar	--	--	--	--	1915.756	[10.375]***	-0.960	[-1.895]*
Atil C	--	--	--	--	1966.381	[6.31]***	0.131	[0.156]
Bacanora	--	--	--	--	91.254	[0.213]	-1.595	[-1.421]
Baviacora	--	--	--	--	1935.957	[10.354]***	-0.142	[-0.277]
Borlaug	--	--	--	--	1468.978	[7.213]***	-0.344	[-0.616]
Caborca	--	--	--	--	803.367	[3.613]***	-0.152	[-2.48]
Chapala	--	--	--	--	-1912.89	[-8.098]***	1.343	[1.991]**
Ciano	--	--	--	--	1031.391	[4.537]***	-0.903	[-1.460]
Cocorit	--	--	--	--	929.408	[5.004]***	-1.008	[-1.979]**
Eronga	--	--	--	--	1684.609	[9.147]***	-0.586	[-1.158]
Jilotecpec	--	--	--	--	1990.444	[8.877]***	-1.239	[-2.043]**
Jori	--	--	--	--	-1087.577	[-4.508]***	0.313	[0.464]
Mexicali	--	--	--	--	1490.218	[8.116]***	-0.310	[-0.612]
Nazozari	--	--	--	--	1183.163	[6.449]***	-0.916	[-1.819]*
Oasis	--	--	--	--	1298.175	[6.965]***	-0.580	[-1.131]
Opata	--	--	--	--	1094.964	[3.449]***	-0.842	[-0.987]
Seri 81	--	--	--	--	1311.931	[3.730]***	-0.552	[-0.577]
Seri 82	--	--	--	--	1284.390	[6.956]***	-0.288	[-0.567]
Super Kauz	--	--	--	--	1754.187	[9.511]***	-0.507	[-0.999]
Tarachi	--	--	--	--	1073.902	[3.343]***	-0.622	[-0.737]
Tarasca	--	--	--	--	251.001	[0.588]	-1.280	[-1.36]
Yavaros	--	--	--	--	1846.121	[10.015]***	-0.876	[-1.732]*
Yecora	--	--	--	--	750.521	[3.346]***	-0.145	[-0.234]
Yoreme	--	--	--	--	712.143	[1.611]	-2.268	[-2.012]***
Adj R^2	0.390		0.019		0.537		0.050	
Akaike Info. Crt.	16.371		4.353		16.142		4.306	
F-test	53.590		2.630		39.650		-2.750	

* Denotes Statistical Significance at the 10% level
** Denotes Statistical Significance at the 5% level
*** Denotes Statistical Significance at the 1% level
Solar

Table 3. Partial Impacts of Release Year and Climate on CIMMYT Wheat Yield, 1990-2002.

Model One: Release Year Variables

Variable	Yield	Variance
RLYR	53.771	-0.36
Solar	1.565	-0.017
MeanTemp	-295.073	-1.673
HeatStress	-1145.877	7.272

Note: The partial impacts reported here are the first derivatives of the estimated model one in table 2 with respect to each of the reported variables.

Table 4. Wheat Variety Yield Estimates and Average Historical Test Plot Yield, 1990-2002.

Variety	Release Year	Just-Pope Yield Estimate	Average Yield[1]
7 Cerros	1966	7831	7832
Achonchi	1989	8870	8889
Alamos	1983	8302	8233
Altar	1984	9020	9050
Atil C	2001	9071	8296
Bacanora[2]	1988	7189	7134
Baviacora	1992	9040	8954
Borlaug	1995	8573	8639
Caborca	1979	7908	8020
Chapala[2]	1967	5191	5253
Ciano	1979	8136	8069
Cocorit	1971	8034	8090
Eronga	1983	8789	8803
Jilotecpec	1986	9095	9322
Jori[2]	1969	6017	6134
Mexicali	1975	8595	8623
Nazozari	1976	8288	8293
Oasis	1986	8403	8386
Opata	1985	8199	8313
Seri 81	1981	8416	8541
Seri 82	1982	8389	8311
Super Kauz	1988	8859	8851
Tarachi	2000	8178	7366
Tarasca	1987	7355	7939
Yavaros	1979	8950	8975
Yecora	1970	7855	7821

[1]Test plot average, 1990-2002.

[2]Three varieties, Chapala, Jori, and Bacanora, had average yields well below the rest. The varieties Chapala and Jori are durum varieties, not bred for high yields, but improvements in grain quality. Bacanora had poor leaf rust resistance and usually yielded poorly with no disease control.