THE GENETIC AND ECONOMIC IMPACT OF THE CIMMYT WHEAT BREEDING PROGRAM: A POLICY ANALYSIS OF PUBLIC WHEAT BREEDING

by

LAWTON LANIER NALLEY

B.S., The Ohio State University, 2002
M.S., Mississippi State University, 2004

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agricultural Economics
College of Agriculture

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Abstract

Previous studies show 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 genetic gains is slowing. Some reports claim that the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) breeding program "reached a plateau" in the 1980s. Such a breeding plateau would have global ramifications, since it is often poor consumers who benefit the most from yield enhancement of staple crops including wheat. CIMMYT estimates that by 2020, the developing world will need 40% more wheat than it consumes today. Because of the lack of involvement by private breeders in most low-income countries, CIMMYT, whose germplasm is used extensively in the developing world, will need to ensure that modern varieties that they release are increasing in yield to meet the rising wheat demand in the developing world.

CIMMYT, a non-profit organization, distributes improved germplasm to national agricultural research systems (NARS) for worldwide utilization. CIMMYT has consistently invested a large 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.

Wheat lines released by CIMMYT during 1962-2002 were analyzed to estimate genetic yield increases associated with the CIMMYT breeding program using test plot data from the Yaqui Valley in Mexico from 1990-2002. Using several econometric techniques including a Just-Pope production function to account for multiplicative heteroscedasticity across the different varieties, results indicate that through the release of modern varieties CIMMYT has contributed 53.77 kg/ha to yield annually in Mexico's Yaqui Valley during 1962-2002. Estimates of the gains attributed to CIMMYT's breeding program on a global scale equal 481.47 million (2002) USD annually from 1990-2002. CIMMYT's average total wheat breeding cost in from 1990-2002 was roughly 13.95 million USD making the average cost-benefit ratio approximately 1:34.

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CHAPTER 1 - Introduction

General Problem

Previous 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 indicates that the potential for genetic gains is slowing. Traxler et al. (1995) reported that the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) breeding program “reached a plateau” (p. 6) in the 1980s.[1] Such a breeding plateau would have global ramifications, since it is often poor consumers who benefit the most from yield enhancement of staple crops including wheat. Byerlee and Moya (1993) showed that over one half of the benefits of wheat research has been captured by poor consumers and farmers in South Asia, which has the world’s largest concentration of poverty. Motivation for this research is provided by the historical average yield of CIMMYT-released varieties and their initial increase, and gradual reduction in yield growth between 1990 and 2002 (figure 1-1) which, *ceteris paribus*, raises concern about the future direction of wheat breeding at CIMMYT.

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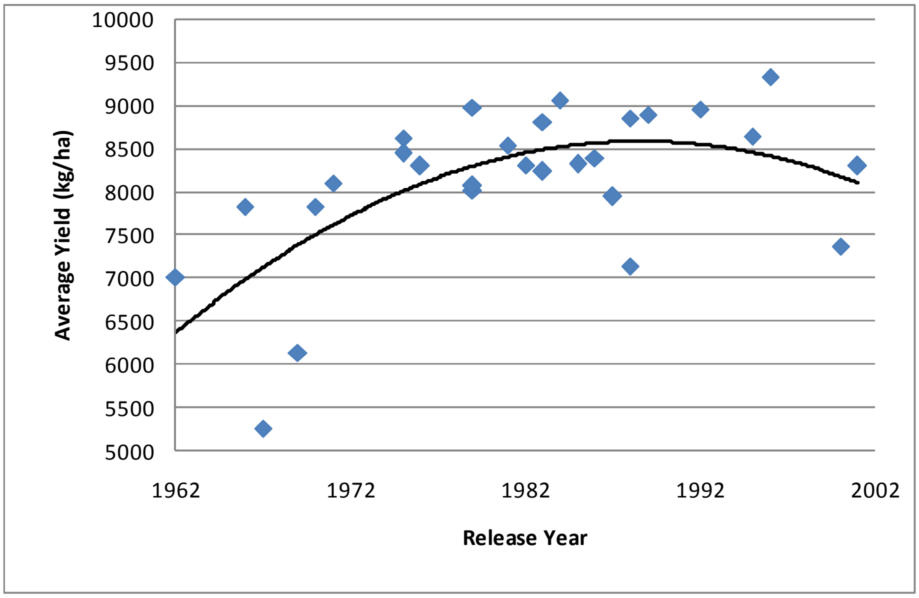
[1] The Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) is a nonprofit maize and wheat breeding research center based in El Batan, Mexico. CIMMYT was created to establish international networks to improve wheat and maize varieties in low-income countries.

Figure 1-1. Average CIMMYT Wheat Variety Yields and Trend: 1990-2002.



CIMMYT has invested a large amount of public funds in wheat breeding research each year for several decades. Estimates of the impact of the wheat breeding program on increasing wheat yield provides information to scientists, administrators, and policy makers regarding the efficiency 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 allows for the completion of a cost-benefit analysis of the wheat breeding program, and for the evaluation and assessment of the impact of the program on alleviating poverty in low-income nations that have adopted the wheat varieties.

Background

CIMMYT, a non-profit organization, distributes improved germplasm to national agricultural research systems (NARS) for worldwide utilization. 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. 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 approximately 80% of the total spring wheat area in developing countries (Lantican et al. 2005).[2] Private wheat breeders have little incentive to breed for most low-income countries. CIMMYT fills this gap, and as a result approximately 62% of the total wheat area in low-income countries is planted to CIMMYT-related varieties (Heisey et al. 2002).

CIMMYT has its principal wheat experiment station in northwest Mexico, located in the Yaqui Valley an area of approximately 235,000 hectares. The Yaqui valley is typical of approximately 40% of all developing nation wheat areas, making it an ideal location for testing new lines to be released worldwide (Pingali and Rajaram 1999).[3] Approximately 36 million hectares worldwide share the growing characteristics of the Yaqui Valley spread primarily through Asia and Africa between 35°S and 35°N latitude. Several studies (Fischer and Wall 1976; Waddington et al. 1986; Ortiz-Monasterio et al. 1997; and Sayre et al. 1997) found that through breeding programs annual rates of genetic gain in wheat yields in Northwest Mexico ranged from 0.05 to 1.7%. Gains in wheat yield can be attributed to two factors, genetic and agronomic. Agronomic management gains are attributed to improvements in fertilizer,

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[2] 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.

[3] The Yaqui Valley is classified by CIMMYT as an "optimally irrigated, low rainfall area" (van Ginkel et al. 2002). The climate 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), according to van Ginkel et al. 2002.

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.

While annual yield enhancement in wheat is not of the magnitude it is in maize, investment in the wheat breeding program is still of vital importance. The first generation of improved wheat varieties focuses on maximizing yield gain, while the second generation, known as maintenance breeding, not only attempts to maintain these initial higher yields as the existing lines face evolving attacks from disease and insects. Maintaining disease resistance alone can potentially contribute more than the gains received from genetic gains. A CIMMYT study (Byerlee and Moya 1993) concluded that the most important contribution of wheat breeding in the last 20 years was to develop newer (second generation) lines that were resistant to the evolving races of rust. So, while the annual attributed genetic gains to wheat breeding are marginal, the potential losses associated without the breeding program due to evolving disease could be immense. When evaluating a breeding program, the annual improvements in genetic gains are a good benchmark of productivity, but the story is incomplete without considering the impact of maintenance breeding. One needs to analyze the losses in yield that would have occurred had the second generation lines, which are resistant to disease, not replaced the older susceptible lines. In the case of the irrigated land studies, Byerlee and Moya (1993) have shown losses due to the lack of maintenance breeding to rust alone could range from 5 to 20%.

Historically, breeders have focused on increasing yield. Stability, which in this study refers to reducing variability in yields across years, as a breeding objective is gaining in importance. 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. Two empirical studies of Hazell 1989, and Traxler et al. 1995 countered this argument by finding that younger modern varieties actually have reduced variability of wheat yields in low-income countries. Gollin (2006) concluded that the decline in wheat variability is not attributed to more optimal growing conditions or increased use of inputs, but rather to the diffusion of modern varieties through successful breeding programs. The reduction in yield variability in modern varieties is pertinent to the breeders at CIMMYT, since CIMMYT germplasm is extensively planted.

Objectives

While several location-specific studies (eg. 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 agronomic gains attributed to wheat breeding, few have controlled for both planting techniques and specific weather variables and none has quantified the genetic improvements of public breeding in the Yaqui Valley during 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 is pivotal for yield, and thus yield variation estimation (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 Triticale) is grown in distinct parts of the world, and thus the yield for each is estimated separately. Furthermore, unlike past studies that analyze CIMMYT test plot data (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.

The goals of this research are; first to isolate the increases in wheat yield of CIMMYT-released lines attributed to genetic improvements. Test plot data from Mexico's Yaqui Valley are used to quantify yield increases and potential yield growth decreases over time.[4] Second, to analyze if modern lines released by CIMMYT have changed yield variability during the 1990-2002 period. Answering these two questions is important to CIMMYT because, using CIMMYT's own projections, by 2020 the developing world will need 40% more wheat than it consumes today. Because of the lack of involvement by private breeders in most low income-countries, CIMMYT, whose germplasm is used extensively by breeding programs in the developing world, will need to ensure that modern varieties they release are increasing in yield to meet the rising wheat demand in the developing world.

This study explores the trends in wheat breeding at CIMMYT in terms of both yield and yield variability and examining their causes to address the growing food security issues in the developing world. Along with quantifying the yield and yield variance evolution at CIMMYT, the last goal of this study is to conduct a cost-benefit analysis of the CIMMYT wheat breeding program. Estimating the CIMMYT cost-benefit ratio is important for deriving future policy decisions. Since many international donors rely on economic rates of return as a litmus test for possible donations, these results are important to CIMMYT, whose funding is based on international donations.

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[4] CIMMYT does not release or name varieties; that is the responsibility of cooperating national breeding programs. In what follows, a CIMMYT variety will refer to a line bred by CIMMYT that was released by a government as a variety.

The following chapters will first review previous research conducted on wheat breeding, and various estimation techniques for measuring yield and variance in variety trials. Following this, the dissertation will first outline the theoretical and then the empirical econometric models used to analyze the objectives laid out above. Specific estimates will be given and analyzed as to CIMMYT's ability to increase yield and reduce variance in modern varieties (MVs). This information will then be presented and evaluated such that recommendations for policy and future funding decisions can be made. A cost-benefit analysis will be conducted for the 1990-2002 period so that international donors can see what the typical return on investment was during that period. Lastly, conclusions will be drawn from the 1990-2002 period and recommendations will be made about the future of wheat breeding at CIMMYT.

CHAPTER 2 - Literature Review

The following are references to literature that employ a range of methods to quantify the agronomic gains from various wheat breeding organizations. Some address specific climatic conditions, while others focus on the effects of varying amounts of nitrogen, but all attempt to quantify breeding advancements.

Quantifying Genetic Gains Attributed to Wheat Breeding

Waddington et al. (1986) measured the genetic gain in 14 bread wheat lines released in Northwest Mexico for the period 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 nitrogen fertilizer applied at the same rates across years. During both growing seasons, the wheat grew through nets to prevent lodging. Also, 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 the variables, harvest index, phytomass, spikes, and yield, measured on each genotype. The average annual rate of gain in yield was estimated by regressing the mean annual grain yield 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 approximately 1.1% annually based on the two growing seasons analyzed. The authors attribute 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 region of Mexico. The eight tested lines were planted under irrigation, and were evaluated over six years (1989-1990 through 1994-1995). Daily radiation and mean temperature were recorded so that the photothermal quotient (solar radiation divided by the mean temperature minus 4.5^{o} C) could be calculated. Using the photothermal quotient to explain wheat yield is common in the agronomy literature due to the correlation between solar radiation and temperature with the flowering and grain filling period of wheat. The authors used the year that each respective line was released to measure the genetic progress. Using analysis of variance and regression analysis (an Eberhart and Russell (1966) regression) the authors found the rate of genetic progress to be approximately 0.88% per year. Interestingly, they found the photothermal quotient to be significant only when they dropped the 1992 planting season. The authors' conclusion was that the more recent lines yielded more because they produced more kernels under less solar radiation and higher temperatures preceding anthesis (the period when the wheat flower is fully open and functional). That is, they found that the younger lines were higher yielding through genetic breeding because they preformed well in sub-optimal conditions while still maintaining satisfactory yields when supra-optimal conditions prevailed.

Ortiz-Monasterio et al. (1997) studied 10 lines released by CIMMYT that were released in the Yaqui Valley of Mexico between 1950 and 1985. The authors' 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 study was to respond to the growing notion that CIMMYT's bread wheat germplasm performed poorly under low nitrogen levels. To address this issue, four replicates each year for each variety with varying amounts of nitrogen applied were analyzed. Both pesticide and fungicide were used in optimal manners. No weather data were 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%, depending 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 and utilization efficiency under different levels of nitrogen application. Importantly, the authors found that the CIMMYT-released material yielded at minimum a 1.0% annual gain in yield that can be attributed to genetic improvements.

Implementation of the Just -Pope Production Function to Elicit Genetic Gains

Traxler et al. (1995) analyzed 10 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) recognized that farmers and plant breeders evaluate lines based on several criteria, including yield and yield stability. Since CIMMYT focuses on 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. Data came from trials conducted by CIMMYT in the Yaqui Valley of Mexico. The authors used three growing seasons (1987-1989) with three treatments of each variety annually. The treatments allowed for varying amounts of nitrogen. No measure of weather variability was used in the analysis. Unlike other studies which used only an analysis of variance, Traxler et al. (1995) estimated a Just-Pope production function (Just and Pope, 1979). This is unique because it simultaneously allows one to test the hypotheses that the evolution of varietal technology has increased yield over time and decreased yield variance. Like the previous studies, release year was used as a proxy to calculate genetic gains, but the authors also included a release year squared term, which allows for curvature of the yield function. Estimating the Just-Pope production function, the authors found that yields increased steadily for release years between 1950-1980, but reached a plateau in the 1980s. The authors argue that the plateau findings are not robust. They did find that the variance of output peaked around 1970 but decreased after that. Overall, they concluded that progress is being made in producing "better" varieties, which indicates that modern varieties have improved either yield stability, increased yield, or both.

Photothermal Quotient (PTQ)

While the previous articles deal with the technique for measuring the genetic gains attributed to breeding, Fischer (1985) devised a ratio that has been widely accepted by agronomists as crucial for accurately measuring gains in yield. This ratio was based on multiple years of field tests at the CIANO test plots in the Yaqui Valley of Mexico, all under optimal irrigation, weed, and disease control. Fischer analyzed semi-dwarf varieties to see how the number of wheat kernels (which can be 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 square meter was highly dependent on both the amount of solar radiation received and mean growing temperature for the thirty days around anthesis. According to Fischer the relationship was simple; it was linear and positive for solar radiation and linear and negative for temperature. For the combined variation Fisher used solar radiation divided by the mean temperature minus 4.5.[5] This ratio is referred to

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[5] Since 4.5° C is the base temperature for wheat growth, it was subtracted from the mean temperature.

as the Photothermal Quotient (PTQ). The theory is that the period just before and after anthesis is a sensitive period in wheat production, and both radiation and temperature have an effect on kernels per square meter and thus yield. Fischer states 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 the number of kernels per square meter (which can be viewed as expected yield) for wheat crop models.

The next chapter will describe the Just-Pope theoretical model in detail and how it can be used to analyze both the yield and the yield variance simultaneously.

CHAPTER 3 - Conceptual Framework

This chapter will present the Just-Pope production function and its simultaneous estimation of output and variance. Second, this section will present alternative ways to estimate genetic gains in wheat breeding. Lastly, this section will address the issue of multiplicative heteroscedasticity and the issues it presents when attempting to quantify genetic gains associated with wheat yields.

The Just-Pope Production Function

A Just-Pope (1979) production function was selected for its ability to offer 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. The production function is as follows:

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

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 on the production function depends on some or all of the explanatory variables, it can thus be viewed as a multiplicative heteroscedasticity model, which is estimated using a three-stage procedure. If variance is an exponential function of K explanatory variables, the general model with heteroscedastic errors can be written as:

$$Y_i = X_i^{'}\beta + e_i, \quad i = 1,\ 2, \ldots, N \tag{2}$$

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

where $X_i^{'} = (x_{1i}, x_{2i}, ..., x_{ki})$ is a row vector of observations on the K independent variables. The vector $\alpha = (\alpha_1, \alpha_2, ..., \alpha_k)$ 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

$$\ln \sigma_i^2 = X_{\mathrm{i}}^{'}\alpha, \tag{4}$$

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:

$$\ln e_i^{*2} = X_i^{'}\alpha^* + u_i, \tag{5}$$

where e_i^* is the predicted values of e_i and where the error term is defined as:

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

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. The predicted values from equation (5) are then used as weights when re-estimating equation (2). The results from the re-estimation of equation (2) with the weights from equation (5), provide the effects of the independent variables on yield.

Genotype-By-Environment Interaction (GEI) Models

A popular starting point in the agronomy literature for genotype-by-environment interaction (GEI) analysis for a complete set of yield trials is the mixed ANOVA model, due to its relative computational simplicity (Kang and Gauch, 1999). A mixed ANOVA is typically implemented because of the nature of the data set. A mixed model is a model that has both fixed and random effects. A fixed ANOVA model is improperly specified when data are incomplete or unbalanced, while a mixed ANOVA model is indifferent to the nature of the data set. The differences of the mixed ANOVA and all other models in this chapter are summarized in table 3-1.

Shukla's Stability Variance Model

A second genotype-by-environment model, Shukla's stability variance model, was estimated because it treats the variance for each variety as a measure of stability. The Shukla model is often used to analyze variety trial data sets (Kang and Gauch 1999, and Piepho 1995), thus making it an ideal fit for this study. Shukla's stability variance model can be estimated as the following:

$$Y_{ik} = \mu + g_i + r_k + e_{ik} \tag{7}$$

where Y_{ik} $(i = 1,...,I; k = 1,...,K)$ represents the yield of the i^{th} variety of the k^{th} replicate. The general mean is represented by μ, g_i is the i^{th} variety main effect, r_k is the k^{th} block effect for replicate k, and e_{ik} is an experimental error corresponding with Y_{ik}. The random effects r_k and e_{ik}

are assumed to be independently distributed with zero mean and variances σ_r^2 (stablility variance), and σ_e^2 (Shukla 1972).

Fixed Effects Models

Another method for quantifying genetic gains in wheat is a fixed effects model. In many cases the measurement of genetic gains is estimated from several varieties of wheat (cross-sectional data) over time (time-series data) resulting in the use of panel data (pooling of time series and cross sectional observations). The fixed effects model accounts for the effect of each of the varieties. That is, it should not be assumed that one variety should behave identical to all others. The fixed effects model accounts for this "individuality" of each variety by letting the intercept for each variety vary but still assuming that the slope coefficients are constant across varieties. Essentially, the fixed effects model can be viewed as an intercept shifter for each variety. A general form of a fixed effects regression can be written as such

$$Y_{it} = \alpha_{1i} + \beta_N X_{Nit} + \beta_{N+1} X_{(N+1)it} + \dots\dots\dots\beta_{N+N} X_{(N+N)it} + \varepsilon_{it}. \tag{8}$$

Unlike in a common ordinary least squares (OLS) regression, there is a subscript *i* on the intercept term (α) which suggests that the intercept for the $(N+N)$ number of wheat varieties may be different. The intercept term is not time variant, in that the fixed effects model assumes that the slope coefficients of the regressors do not vary across individuals over time.

In a fixed effects model, the differential intercept dummy technique is used. If there are $(N+N)$ number of wheat varieties then would use only $(N+N)-1$ dummy variables in a fixed effects model (as to avoid the dummy variable trap with the inclusion of an intercept). In this fashion (α_1) represents the intercept of the omitted variety and $\alpha_2 \ldots \alpha_{(N+N)-1}$, the differential intercept coefficients, tell by how much the intercepts of the included varieties differ from the intercept of the omitted variety. Essentially, the omitted variety becomes the comparison variety to which all other varieties are evaluated against.

A Lagrange Multiplier (LM) test can then be estimated to determine if the vector of fixed effect estimates contributed to the overall model. A statistically significant LM value indicated that fixed effects should be included in the regression model.

Multiplicative Heteroscedasticity Correction

Since there is an *a priori* expectation that the variances across different varieties of wheat differ due to explicit differences in certain breeding agendas (heat stress resistance, quality improvements, etc.) a multiplicative heteroskedastic correction is made. 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) defines multiplicative heteroscedasticity as

$$\sigma_{vi} = \sigma \exp(Z_i \;\; \gamma), \tag{9}$$

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

$$\sigma_{vi} = \exp(Z_i \;\; \gamma_{\mathrm{i}}). \tag{10}$$

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 correction for multiplicative heteroscedastic correction is important for this data set because of the variations in both the species and breeding goals across CIMMYT wheat varieties. That is, since CIMMYT varieties are intended to be sown worldwide and are specifically bred for different climatic and agronomic conditions, the error terms across varieties may be heteroscedastic in nature. By accounting for this multiplicative heteroscedastic error term, comparisons across varieties are more statistically appropriate.

Table 3-1. Summary of Theoretical Models Used In Quantifying Wheat Yield Genetic Gains.

	OLS	White's	Multiplicative heteroscedasticity	Just-Pope	Shulka's	Fixed effects ANOVA
Attribute						
Fixed Effects	YES/NO[a]	YES/NO	YES	YES/NO	YES	YES
Calculate Variance Simultaneously	NO	NO	NO	YES	NO	NO
Mixed Model	NO	NO	NO	NO	YES	YES
Account for heteroscedasticity	NO	YES	NO	YES	YES	YES
Account for multiplicative heteroscedasticity	NO	NO	YES	YES	YES	NO

[a] A YES/NO indicates that the respective model may or may not fulfill an attribute depending on how the model is specified

While this chapter laid out the various theoretical models (Just-Pope, Shukla, Multiplicative Heteroscedasticity, and fixed effects) to be used in achieving the goals set forth in chapter 1 the next chapter will describe in detail the various empirical models to be used in quantifying the impact of the CIMMYT wheat breeding program. The next chapter will also describe the data used in the estimation and its collection techniques.

CHAPTER 4 - Methods

Estimation techniques from the previous chapter (see table 3-1) were conducted, all of which attempted to correct for an unbalanced panel data set.[6] Each of the estimation techniques accounted for the presence of multiplicative heteroscedasticity, which is embedded in the error terms of each tested wheat variety. The Just-Pope production function was used so that the mean yield and yield variance could be estimated simultaneously. Estimation of a fixed effects model accounted for the possibility of different yields across each variety. Lastly, an agronomic model, Shulka's stability variance model (1972), which assigns a separate variance for every variety and can be regarded as a measure of variety stability, was estimated. This chapter describes the data and the estimation of the theoretical models from the previous chapter used to derive results of the objectives laid out in chapter 1.

All of the models discussed in this chapter, see table 3-1) will deal with the unbalanced nature of this data set. Like most variety trial tests, those varieties that have been recently released have fewer observations than older varieties. Thus, this data set is unbalanced in that each respective variety will have a different number of observations.

Data

Varieties and Species

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 4-1), Brennan

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[6] The subsequent data set is classified as "unbalanced" due to the difference in number of varieties across trial years.

(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 genetic lines bred by CIMMYT 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. The test period for this data set is 1990-2002, but includes lines released prior to 1990. Rotation in the experiment test plots was wheat in the winter and fallow in summer which because of irrigation water shortages, has also been the most common farmer rotation in the Yaqui Valley. All of the observations were under irrigation management practices held constant throughout the time period.[8] Three species of wheat were planted during the test period; durum (*Triticum durum*), bread (*Triticum aestivum*), and triticale, which is 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 in 2002 (Lantican et al. 2005).

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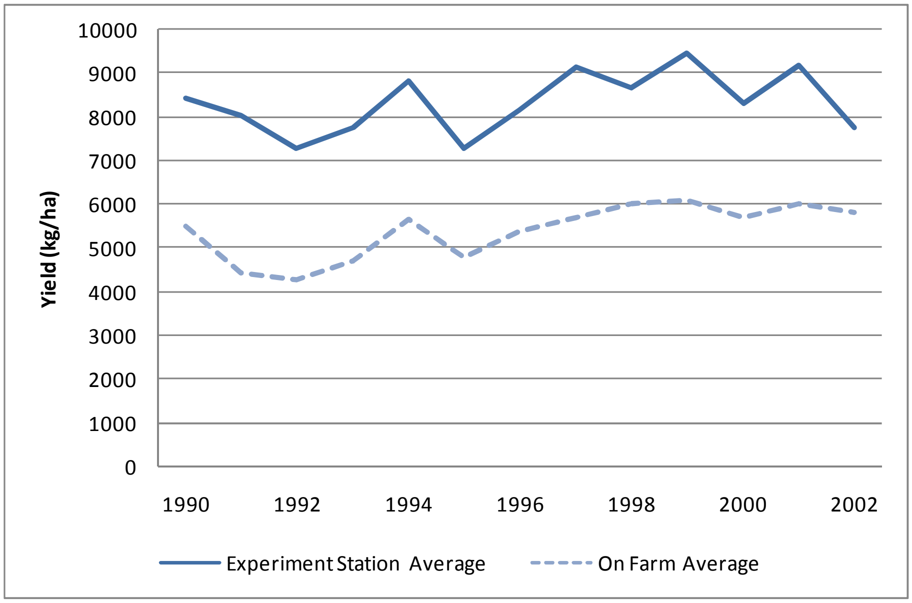
[7] Relative yield comparisons of varieties, according to Brennan (1984), are only reliable on test plots. That is, yield comparisons across varieties should be conducted when growing conditions, fertilizer usage, irrigation, fungicide, etc. is constant across varieties. A test plot with multiple varieties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

[8] Fertilizer, fungicide, pesticide, harvesting, and other management practices were kept as constant as possible throughout the time period, 1990-2002, according to CIMMYT agronomists interviewed.

Figure 4-1. Average Yaqui Valley Yield Differential Between Experiment Station and On-Farm Yields, 1990-2002.



Sources: CIMMYT data from Obregon experiment station in the Yaqui Valley of Mexico and CIMMYT Yaqui Valley Survey (1990-2002).

Planting Methods

Four distinct planting methods were used during the test period. The first method was the traditional melgas practice in Mexico's Yaqui Valley and using fungicide. Under the melgas practice, the land is simply seeded with wheat, 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 into the soil, 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 does, however, provide improved input use efficiencies and reduced production costs (Sayre et al. 2005). The second planting method used in the study was beds without fungicide. The third planting practice 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.[9]

Weather Data

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 degrees Celsius for each day. Fischer (1985) found that both solar radiation and temperature are important in determining the number of kernels per square meter. 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 results in increased photosynthesis, which is thought to be 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 over temperature, known as the photothermal quotient (PTQ), maximized yield when the PTQ was highest between 20 days before and 10 days after anthesis. Uniquely, the data set includes

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[9] Nets are used in test plots to lessen lodging as to extract the maximum possible yield from each variety. However, they are not used by farmers in the Yaqui valley due to their high cost.

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

Just- Pope Production Function and Variables

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). *RLYR* 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, the coefficient on *RLYR* represent the increases in yield due to genetic gains attributable to the CIMMYT wheat breeding program.

Release year is not a time trend variable, but is modeled similar to the way that Arrow's (1962) growth model denoted embodied technology (Traxler et al. 1995). Arrow (1962) assigned "serial numbers" of ordinal magnitude to the embodied technology in capital. In this model the variable *RLYR*, represents the embodied technology for a given year of release by the CIMMYT breeding program. Therefore, the coefficient on *RLYR* possesses both a cardinal and ordinal significance in defining the spacing as well as the sequencing of releases (Traxler et al. 1995). A *RLYR squared* term allows the model to capture curvature within the breeding program. Moreover, curvature provides breeders, administrators, and policy makers the ability to see not only if yield is increasing, but whether it is increasing at an increasing or decreasing rate.

Mean and variance of yield were also modeled as a function of their growing conditions; melgas with fungicide (*MelgasPlus*), beds with fungicide (*BedsPlus*), beds without fungicide (*BedsMinus*), and melgas with fungicide and nets (*Nets*). *MelgasPlus* was chosen as the default because it is the traditional planting method in the Yaqui Valley.

The average temperature (*MeanTemp*) and solar radiation (*Solar*) 20 days before and 10 days after anthesis for each plant, which are the components of the photothermal quotient (PTQ), also were used as explanatory variables. From the established literature on PTQs, an increase in the average temperature 20 days before and 10 days after anthesis is expected to decrease yield, while an increase in the average solar radiation over the same time period is expected to increase yield, *ceteris paribus*. The restrictive variable PTQ ratio was disaggregated into its ratio components (*Solar* and *MeanTemp*) to test for different effects for each variable.[10]

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 binary variables with *Bread* used as the default. A heat stress (*Stress*) variable was used to indicate the number of days in the growing season (January – April) when the temperature was at or exceeded 36° C (96.8 ° F).[11] This heat stress variable is included because in the maturation months of March and April, if the temperature is too hot the wheat kernel can scorch negatively impacting yield. Lastly, the interaction variable (*HeatTemp*) was created by multiplying (*Stress*) by the average temperature during the same growing season (January – April). This was included

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[10] A Likelihood Ratio Test was preformed on the restricted (PTQ ratio) and the unrestricted (separate variables for *Solar* and *MeanTemp*) models. The test result of 44.47, significant at the 1% level, indicated that the PTQ ratio should be disaggregated into separate components.

[11] The temperature 36° C was selected because it is two standard deviations above the mean, those days that are in the top 5% hottest days in the data set. This assumption was found to be robust when the results from 37° C and 35° C produced similar estimates. Conversely, 34° C and 33° C were found to provide lower levels of statistical significance.

to capture the potential of a growing season where temperature is well below average, implying that heat stress may adversely effect yield more under said conditions than a growing season with an average temperature well above average. The interaction between *RLYR*, which is a proxy for varietal technology, and the weather attributes was included because *a priori* it can be assumed that the various types of varietal improvements, and thus lines, may have been targeted towards certain weather conditions (drought tolerance, heat stress, etc.).[12] The interaction between certain weather characteristics and *RLYR* can be seen as 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 (11) and (12) and are referred to as model I.

$$\begin{aligned} Y_i = {} & \beta_0 + \beta_1 RLYR + \beta_2 Temp + \beta_3 Solar + \beta_4 Stress + \beta_5 HeatTemp + \beta_6 RLYR^2 + \beta_7 RLYRSolar + \\ & \beta_8 RLYRMeanTemp + \beta_9 RLYRHeatStress + \delta_1 BedsPlus + \delta_2 BedsMinus + \delta_3 Nets + \\ & \delta_4 Durum + \delta_5 Triticale + \varepsilon_i, \end{aligned} \tag{11}$$

and

$$\begin{aligned} \ln(e_i)^2 = {} & \Phi_0 + \Phi_1 RLYR + \Phi_2 Temp + \Phi_3 Solar + \Phi_4 Stress + \Phi_5 HeatTemp + \Phi_6 RLYR^2 + \Phi_7 RLYRSolar + \\ & \Phi_8 RLYRMeanTemp + \Phi_9 RLYRHeatStress + \gamma_1 BedsPlus + \gamma_2 BedsMinus + \gamma_3 Nets + \\ & \gamma_4 Durum + \gamma_5 Triticale + \varepsilon_i. \end{aligned} \tag{12}$$

Equation (11) is estimated first. Then, taking the natural log of its squared error terms as the dependent variable, equation (12) is then estimated to analyze yield variability. The coefficients and their respective signs in equation (12) can be seen as the effect of each independent variable on yield variability. This is an important aspect of this study because it not only allows for the measurement of yield variability and its relative increase/decrease but also isolates the factors that are correlated with the increases/decreases in yield variability. Using the

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

predicted values from (12) as weights and reestimating (11) using GLS it is possible to obtain the weighted least squares results. By reestimating equation (11) with the predicted values of (12) as weights, the subsequent coefficients can be viewed as the effect of each independent variable on yield (Just and Pope, 1979).[13]

Fixed Effects

A fixed effects model is then estimated similar to equation (11) but variables for each of the 33 varieties are included.[14] Variety 33 (Yoreme) is omitted as the base variety. The dummy 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 were perfectly collinear. The fixed effects model allows comparisons to be made between average historical yields for each variety with predicted yields holding all else constant, and can be seen as an intercept shifter. Since the RLYR variable could not be included in the various fixed effects models they were mainly implemented to estimate average yield for each variety by each respective model and to compare them to the average observed yield on the Yaqui Valley test plot from 1990-2002.

Shukla's Stability Variance Model

Shukla's (1972) stability variance is represented in equation (13)

$$Y_{ik} = \mu + \Theta_i + treatment_k + e_{ik}, \qquad (13)$$

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[13] The original estimates from equation 11, prior to weighting (the OLS estimates), can also be viewed as the effect of each independent variable on yield, but they do not account for the presence of multiplicative heteroscedasticity.

[14] A Hausman test was conducted which indicated that fixed effects model was more appropriate than a random effects model given this data set.

where Θ_i is a vector of qualitative variables for each of the 33 varieties. *Treatment* represents the respective treatment number of the variety within a given year, and where μ represents the general mean. Yoreme was again used as the base variety. Given the structure of this data set, the "environment" component of the genotype-by-environment is actually the replication of the same variety within the same year but under different planting conditions (Kang and Gauch, 1999). This allows comparisons to be made across both different varieties and across different planting methods (beds with fungicide, beds without fungicide, etc.) as well.

This chapter laid out the data collection methods and the specific empirical models to be used in achieve the goals set forth in chapter 1. The next chapter will present and discuss in depth the results from the empirical models described in this chapter.

CHAPTER 5 - Results

Table 5-1 reports the summary statistics and tables 5-2 through 5-5 present the results from the respective models. Table 5-2 reports the results from the Just-Pope model, both the effects on yield and on variance, the OLS and White's correction for heteroscedasticity results. The coefficients in table 5-3 account for the *RLYR* interaction terms that are included in the models in Table 5-2. By using the estimated *RLYR* interaction coefficients (*RLYR*MeanTemp, RLYR*Solar*, etc.) from table 5-2 and taking the first derivative with respect to *RLYR*, then holding all other variables at their respective means, partial derivatives of function with respect to release year can be calculated. The test statistics in table 5-3 were estimated using a bootstrapping procedure in SciLab. The variance-covariance matrix from the Just-Pope regression and the estimated coefficients were used in the bootstrapping procedure to account for the correlation between the independent variables. Table 5-4 represents the results of the various fixed effects models (ANOVA, Shukla, Just and Pope, and the multiplicative heteroscedastic) with each variety representing the fixed effect. Table 5-5 is a comparison of the various fixed effects models and their estimated yield for each variety compared to the average historical test plot yield for each respective variety.

Table 5-1. Summary Statistics for CIMMYT Wheat Yield Determinants.

	Mean	Standard Deviation	Minimum	Maximum
Independent Variable:				
Yield (kg/ha)	8430.35	1101.29	2593.00	11098.00
Dependent Variables:				
Solar (MJ/m^2/day)	5081.73	579.69	3686.52	6138.23
MeanTemp (^{o}C)	17.08	0.93	15.02	19.38
RLYR	1981.19	8.80	1962.00	2001.00
HeatStress	2.54	2.19	0.00	7.00
HeatTemp	47.04	40.73	0.00	128.18
Qualitative (0-1) Variables:				
Bread	0.51	0.50	0.00	1.00
Durum	0.36	0.48	0.00	1.00
Triticale	0.13	0.34	0.00	1.00
MelgasPlus[a]	0.51	0.50	0.00	1.00
BedsMinus[b]	0.22	0.41	0.00	1.00
BedsPlus[c]	0.19	0.39	0.00	1.00
Nets[d]	0.08	0.27	0.00	1.00

Number of observations equals 1133.

[a] MeglasPlus refers to the planting method of planting on flat ground with fungicide.

[b] BedsMinus refers to the planting method of planting on raised beds without fungicide.

[c] BedsPlus refers to the planting method of planting on raised beds with fungicide.

[d] Nets refers to the planting method of planting on flat ground with fungicide with the use of nets to lessen lodging.

Table 5-2. CIMMYT Wheat Yield Regression Results.

	MODEL I[a]			
	OLS	Whites	Just-Pope	
Variable	Yield	Yield	Yield	Variance
Constant	-4596486.251	-4596486.251	-4622962.109	1206.176
	[-3.552]***	[-3.883]***	[-3.504]***	[0.374]
Solar	56.781	56.781	57.038	-0.057
	[4.790]***	[4.303]***	[4.791]***	[-1.945]*
MeanTemp	-9867.077	-9867.077	-10133.675	-11.579
	[-1.462]	[-1.393]	[-1.501]	[-0.693]
RLYR	4531.445	4531.445	4559.834	-0.945
	[3.412]***	[3.791]***	[3.395]***	[-0.288]
HeatStress	7078.206	7078.206	7202.867	-2.633
	[2.574]***	[2.931]***	[2.577]**	[-0.384]
Durum	164.095	164.095	154.167	-0.085
	[2.752]***	[2.693]***	[2.569]***	[-0.581]
Triticale	5.471	5.471	1.653	-0.079
	[0.067]	[0.075]	[0.02]	[-0.394]
BedMinus	-244.713	-244.713	-243.698	0.159
	[-3.212]***	[-3.455]***	[-3.185]***	[0.846]
BedPlus	138.386	138.386	135.572	0.061
	[1.693]**	[1.802]**	[1.646]*	[0.298]
Nets	359.542	359.542	363.149	-0.322
	[3.096]***	[4.065]***	[3.050]***	[-1.21]
HeatTemp	54.354	54.354	53.367	0.074
	[3.426]***	[4.006]***	[2.357]***	[1.349]
RLYR^2	-1.112	-1.112	-1.12	0.0001
	[-3.284]***	[-3.675]***	[-3.269]***	[0.207]
RLYR*Solar	-0.029	-0.029	-0.028	0.00002
	[-4.786]***	[-4.286]***	[-4.769]***	[1.938]*
RLYR*MeanTemp	4.832	4.832	4.966	0.005
	[1.47]	[1.353]	[1.456]	[0.690]
RLYR*HeatStress	-4.160	-4.160	-4.214	0.0005
	[-3.105]***	[-3.682]***	[-3.095]***	[0.173]
Adj. R^2	0.39	0.39	0.39	0.019
Akaike Information Criteria	16.357	16.357	16.371	4.353
F-test	53.85*	53.85*	53.59*	2.63*

Number of observations equal 1133.

Brackets [ ] denote t-statistic.

[a] Partial impacts of interaction terms reported in table 5-3.

*** Denotes Statistical Significance at the 1% level.

** Denotes Statistical Significance at the 5% level.

* Denotes Statistical Significance at the 10% level.

Table 5-3. Partial Derivatives of Interaction Terms.

	OLS	Whites	Just-Pope	
	Yield	Yield	Yield	Variance
RLYR	58.395	58.395	53.771	-0.36
	[11.33]**	[11.63]**	[11.49]**	[-0.07]
Solar	-0.258	-0.258	1.5646	-0.017
	[-3.48]**	[-3.96]**	[3.69]**	[-1.42]
MeanTemp	-293.281	-293.281	-295.073	-1.673
	[-9.49]**	[-8.84]**	[-9.33]**	[-0.82]
HeatStress	-1611.788	-1611.788	-1145.877	7.272
	[-1.91]*	[-2.84]**	[-8.40]**	[1.44]

** Denotes statistical significance at the 1% level.

* Denotes statistical significance at the 10% level.

Brackets [ ] denote t-statistic.

Test statistics were calculated by a bootstrapping procedure in SciLab.

using the variance-covariance matrix and coefficients from the Just-Pope production function from table 5-2.

Table 5-4. CIMMYT Wheat Yield Determinants, Fixed Effects Models.

	OLS	Multiplicative Heteroscedasticity Correction	Just-Pope		Shukla	Fixed Effects ANOVA
Variable	Yield	Yield	Yield	Variance		
Constant	12227.090	11699.010	12209.746	14.080	10332.000	10198.000
	[18.539]***	[20.466]***	[17.913]***	[7.841]***	[3.92]***	[6.75]***
Solar	0.203	0.190	0.207	-0.208	0.215	0.236
	[3.666]***	[3.672]***	[3.700]***	[-1.379]	[1.88]*	[1.89]*
MeanTemp	-288.171	-296.102	-288.578	-0.143	-181.320	-172.160
	[-10.035]***	[-10.693]***	[-10.007]***	[-1.831]***	[-2.23]**	[-2.00]**
HeatStress	-654.141	-739.243	-623.790	-3.000	620.530	250.660
	[-1.751]*	[-2.107]***	[-1.650]*	[-2.950]***	[0.35]	[0.14]
BedMinus	-437.521	-381.434	-444.712	0.196	-615.750	-616.840
	[-6.318]***	[-6.006]***	[-6.361]***	[1.043]	[-11.37]***	[-11.35]***
BedPlus	-46.827	-12.199	-56.858	0.159	-204.440	-205.550
	[-0.632]	[-0.180]	[-0.759]	[0.792]	[-3.50]***	[-3.52]***
Nets	162.777	179.060	158.471	-0.283	-142.840	-139.270
	[1.566]	[1.942]*	[1.478]	[-1.002]	[-1.72]**	[-1.69]*
HeatTemp	26.279	30.911	24.734	0.155	-40.314	-19.730
	[1.312]	[1.699]*	[1.222]	[2.854]***	[-0.43]	[-0.22]
Adj R^2	0.531	--	0.537	0.050	--	--
Akaike Info. Crt.	16.119	--	16.142	4.306	17.242	17.250
BIC	--	--	--	--	17.263	17.252
Chi-Squared	--	91.358	--	--	--	--
F-test	38.76*	--	39.65*	2.75*	--	--

Individual variety fixed effect results reported in Appendix D.

Number of observations equals 1133.

Brackets [ ] denote t-stat.

*** Denotes Statistical Significance at the 1% level.

** Denotes Statistical Significance at the 5% level.

* Denotes Statistical Significance at the 10% level.

Table 5-5. Estimated CIMMYT Wheat Yield by Variety in kg/ha.

Variety	Release year	Average yield*	Multiplicative Heteroscedasticity	Just-Pope	Shukla	Fixed effects ANOVA	Coefficient of variation**
PITIC	1962	7013	6392	7104	7180	7193	1.04
7 Cerros	1966	7832	7113	7831	7823	7787	0.88
Chapala[a]	1967	5253	4495	5191	5186	5200	1.31
Jori[a]	1969	6134	5318	6017	6088	6091	1.09
Yecora	1970	7821	7140	7855	7972	7996	0.82
Cocorit	1971	8090	7305	8034	8040	8103	0.79
Mexicali	1975	8623	7865	8595	8500	8566	0.70
Nazozari	1976	8293	7565	8288	8262	8286	0.72
Caborca	1979	8020	7196	7908	8092	8139	0.72
Ciano	1979	8069	7424	8136	8190	8213	0.70
Yavaros	1979	8975	8223	8950	8882	8927	0.64
Seri 81	1981	8541	7667	8416	8057	8094	0.66
Seri 82	1982	8311	7674	8389	8441	8493	0.66
Alamos	1983	8233	7591	8302	8457	8428	0.66
Eronga	1983	8803	8068	8789	8792	8832	0.62
Altar	1984	9050	8297	9020	8939	8977	0.60
Opata	1985	8313	7511	8199	8088	8104	0.65
Jilotecpec	1986	9322	8371	9095	8879	9012	0.58
Oasis	1986	8386	7674	8403	8510	8548	0.63
Tarasca	1987	7939	6659	7355	7324	7472	0.71
Bacanora	1988	7134	6499	7187	7142	7042	0.72
Super Kauz	1988	8851	8134	8859	8851	8900	0.59
Achonchi	1989	8889	8149	8870	8829	8869	0.58
Baviacora	1992	8954	8319	9040	8982	9030	0.56
Borlaug	1995	8639	7850	8573	8498	8548	0.58
Tarachi	2000	7366	7472	8178	8148	8204	0.59
Atil C	2001	8296	8352	9071	8939	9129	0.53

* Actual Yaqui Valley test plot average yield from 1990-2002.

**Calculated from the fixed effect Just-Pope results in table 5-4.

[a] Two varieties, Chapala and Jori had average yields that were well below the rest. The varieties Chapala and Jori are durum wheats and were not recognized/bred for high yields but improvements in grain quality (Sayre 2007).

Table 5-1 indicates that 51% of the observations in the data set were bread wheat, 36% durum, and 13% triticale. Approximately half (51%) of the observations were planted on melgas with fungicide, 22% on beds without fungicide, 19% on beds with fungicide, and 8% on beds with fungicide with nets. Approximately 39% of the variation in wheat yields was explained by the non-fixed effects regressions (table 5-2). Inclusion of the fixed effects increased the explanatory power to 53% for the period (table 5-4). The multiplicative heteroskedastic regression (table 5-4) is highly statistically significant, as indicated by the Chi-Square test for the model equal to 91. Each of the included variables will be discussed below.

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. When using the Just-Pope results from Model I (table 5-2) and calculating the partial derivative with respect to release year, it was found that on average the CIMMYT breeding program added approximately 53.77 kg/ha annually (table 5-3) in the Yaqui Valley which was found to be statistically significant at the 1% level.[15] This result indicates that there was an expected annual increase of 53.77 kg/ha for CIMMYT bred wheat varieties annually over the time period 1962-2002. Given the average yield of 8430.35 kg/ha, the average yield increase due to the breeding program is equal to a 0.64% yield increase per year (53.77/8430.35). During the 1962-2002 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.

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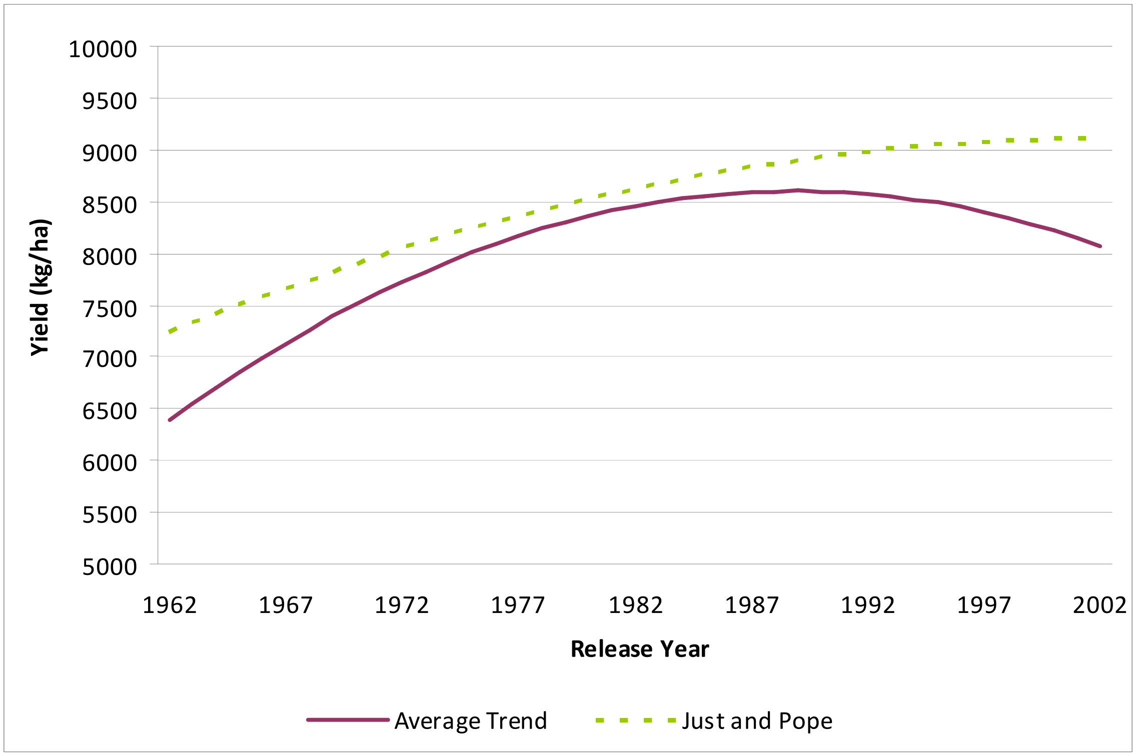
[15] By definition the inclusion of the squared term ($RLYR^2$) means that 53.77 kg/ha is not a constant but rather the average increase in annual yield over time period.

Unlike the Traxler, et al. (1995) study, the Just-Pope production function (table 5-2) does not indicate a yield plateau within the data set. The coefficient $RLYR^2$ is negative and statistically significant at the 1% level for each regression. Figure 5-1 shows how yield has increased over time comparing the Just and Pope estimated results with a simple quadratic trend of the observed average yields. Figure 5-1 illustrates how average historical yield does not tell the complete story if weather is not properly accounted for. That is, when you simply look at the trend of the average yields of CIMMYT released varieties over time it appears that yield has plateaued and subsequently decreased since the mid-eighties. Conversely, when accounting for weather, species, and planting conditions, yield still is increasing, but at a decreasing rate. Moreover, the fact that yields are increasing at a decreasing rate is not surprising given the large initial increases during the Green Revolution.

Figure 5-1. Just-Pope Predicted Yields and the Trend of the Average Observed Yields: 1990-2002.



Note: The average trend in this chart is equivalent to the trend line in figure 1-1.

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 argue that certain varietal improvements target certain climatic conditions (drought tolerance, heat stress, etc.).[16] When analyzing the *RLYR*Solar* variable, which is the year a variety *i* was released multiplied by the average amount of daily solar radiation received 20 days before and 10 days after anthesis, all three

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[16] 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 may have been bred for drought or heat resistance. For this reason the model includes the release year – climatic interaction terms.

regressions give statistically significant estimates at the 1% level, but the coefficients are different across the regressions (table 5-3). The OLS (and by definition the White) regressions yield coefficients that are negative and statistically significant at the 1% level. Initially, these results seem counterintuitive, in that newer varieties are thought to perform better in optimal conditions (more solar radiation or lower temperature) than older varieties. However, in their study, Sayre et al. (1997) concluded that the younger varieties yielded better because they performed better in sub-optimal (low radiation and high temperature) conditions while still maintaining satisfactory yields when super-optimal conditions prevailed. So, one explanation for the *RLYR*Solar* coefficient being negative is that CIMMYT is now breeding for sub-optimal conditions (low solar radiation) while attempting to maintain yields under optimal conditions.[17] Conversely, the Just-Pope results produce a coefficient that is positive and statistically significant at the 1% level (table 5-3), which indicates that newer varieties are being bred for optimal rather than suboptimal conditions.

In the Just-Pope results (table 5-3) the *RLYR*MeanTemp* variable, which is the year that a variety *i* was released multiplied by the average daily temperature 20 days before and 10 days after anthesis, was negative and statistically significant at the 1% level. The Just-Pope results show that for a marginal increase in the average daily temperature 20 days before and 10 days after anthesis that on average yield decreased by 295.07 kg/ha. From the Just-Pope regression (table 5-3), *RLYR*HeatStress,* which is the year a variety *i* was released multiplied by the number of days over 36° C in growing season *j*, was found to be statistically significant at the 1%

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[17] This data set includes a number of suboptimal years: 1992 and 1994 experienced low amounts of solar radiation, 1993 and 1996 saw high growing season temperatures, and 2002 experienced 7 consecutive days with temperatures over 36° C.

and indicates that for each subsequent year in the breeding program with the same number of days over 36^{o} C in the growing season that yield will decrease by 1145.88 kg/ha.

Climatic Variables

Photothermal Quotient Components

The effect of the mean temperature (*MeanTemp*) variable, which was the average temperature 20 days before and 10 days after anthesis, was found to negatively impact yield, and was statistically significant at the 1% level for the Just-Pope in model I when the partial impacts were calculated (table 5-3). These results indicate that for every degree Celsius increase in average temperature for the period between 20 days before and 10 days after anthesis yield decreased on average by 295.07 kg/ha. This result confirms Fischer's (1985) result that high temperature had a negative impact on yield. The other component of Fischer's PTQ was daily exposure to solar radiation. *Solar* was found to have a statistically significant positive coefficient at the 1% level of significance for the Just-Pope production function in model I when the partial impacts were calculated. The Just-Pope (model I) results indicate that on average that for every $MJ/m^2/day$ increase yield would increase by 1.565 kg/ha (table 5-3). This result reaffirms Fischer's (1985) hypothesis that high radiation during the period 20 days before and 10 days after anthesis results in increased photosynthesis, which is advantageous for yield.

Heat Issues

The *HeatStress* variable, which was the number of days during the growing season (December through May) which the temperature reached over 36^{o} C, on yield was found to be negative and statistically significant at least at the 10% level all the regressions in model 1 (table 5-3). The Just-Pope (model I) result was significant at the 1% level, and indicates that for each additional day in the growing season above 36^o C yield would decrease by an average of 1145.88 kg/ha (table 5-3). During the maturation months of March and April, if the temperature is too hot the wheat kernel can scorch thus having a negative impact on yield. This was evident in 2002 when the experiment station at Yaqui Valley experienced high temperatures towards the end of March and early April, during the peak period of grain fill for wheat sown in December 2001, and subsequently was a poor yielding season.

The results for the *HeatTemp* variable, which was created by multiplying (*Stress*) by the average temperature during the same growing season (January – April), was positive and statistically significant at the 1% level for all regressions in model 1 (table 5-2). The only fixed effects model where *HeatTemp* was statistically significant was the multiplicative heteroskedastic model. The interpretation of the *HeatTemp* variable is more nebulous than the aforementioned *HeatStress* variable in that it is an interaction of two separate climatic factors. It can be viewed as such; because the coefficient is positive, then in growing seasons with above average temperatures a sudden increase in temperature (above 36^o C) will not adversely effect yield as much as during a growing season with below average temperature that experiences the same number of heat stress days. This variable was included to capture the effect of a growing season where temperature is well below/above average, implying that heat stress will adversely effect yield more under said conditions than a growing season with an average temperature. The Just-Pope (table 5-2) 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 subsequent increase in yield of 53.37 kg/ha (table 5-2). Conversely and possibly more intuitively, it also can be interpreted as, for every degree Celsius cooler the growing season is, holding the number of days of heat above 36^o C constant, yield is expected to decrease by 53.37 kg/ha.

Planting Techniques

Comparing various planting techniques to the traditional Mexican system of planting wheat on flat seedbeds (melgas) model I (table 5-2) and the fixed effects regressions (table 5-4) have different results. The variable *BedsMinus* (planting on beds without the use of fungicide) was statistically less, at the 1% confidence level, compared to the default of *MelgasPlus* (melgas with the use of fungicide). The magnitude of the difference however is nearly twice the size for the fixed effect regressions (table 5-4) compared to the regressions form model 1 (table 5-2). The Just-Pope (model I) estimates indicate that if a farmer switched from using the traditional melgas with the use of fungicide to bed planting without fungicide, there would be an associated loss of 243.70 kg/ha in yield (table 5-2). The *BedsPlus* variable (plating on beds with fungicide) was positive across the various regressions in model I (table 5-2) and statistically significant at the 10% level, but only statistically significant in two (Shukla and ANOVA) fixed effects models (table 5-4). The Just-Pope (model I) indicates 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 (2005) result that bed planting typically does not result in immediate, large yield increases for irrigated wheat. The use of melgas production practice with fungicide and nets to lessen lodging (*Nets*) was positive and statistically significant at the 1% level for model I. The Just-Pope (model I) results indicate that by switching from planting on melgas with fungicide to planting on melgas with fungicide and the use of nets results in a yield increase of 363.14 kg/ha (a 4.3% increase), *ceteris paribus* (table 5-2).[18] 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 yield comparisons between flat bed planting (melgas) with and without nets ranged from 0% for varieties with no lodging to roughly 10% for lodging-prone varieties.

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 any of the regressions in Model I (table 5-2). 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 was, positive and statistically significant at the 1% level compared to bread wheat. The Just-Pope (model I) indicates that durum wheat yields 154.16 kg/ha (table 5-2) more than bread wheat, *ceteris paribus*.

Fixed Effects Analysis

The results from the fixed effects models are presented in table 5-4 with the predicted yields for each variety found in table 5-5. The *RLYR*, *RLYR*^{2}, and subsequently the *RLYR*-climatic variables were not included in the fixed effects models because in all years except for two in the study only one variety was released resulting in near perfect collinearity. Therefore, the various fixed effects models were implemented to estimate average yield by variety, and to

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

compare the variety yields to the average observed yield on the Yaqui Valley test plot from 1990-2002 (table 5-5).[19]

Output Variance Response

Model I (table5-3) suggests that release year (*RLYR*) did not have a statistically significant effect on the variance of output. This result leads to the conclusion that *ceteris paribus*, an older variety would have the same variance of yield as that of a newer variety. Solar radiation (*Solar*) was found to have a negative statistically significant impact at the 10% level. Model I (Just-Pope, table 5-3) results indicate that for marginal unit of $MJ/m^2/day$ that yield variance would decrease on average by 0.02 $(kg/ha)^2$. The R^2 for the model is low at 0.019 but the F-test for the variance component of Just-Pope (model I) is statistically significant at the 1% level (table 5-2).[20]

A coefficient of variation (CV), the standard deviation of yield over the mean yield for the same time period, for each genetic line was calculated as a measure of yield variability. Table 5-5 presents the calculated CV from the Just-Pope production function results from table 5-4 for each respective line (the CV is plotted in figure 5-2).

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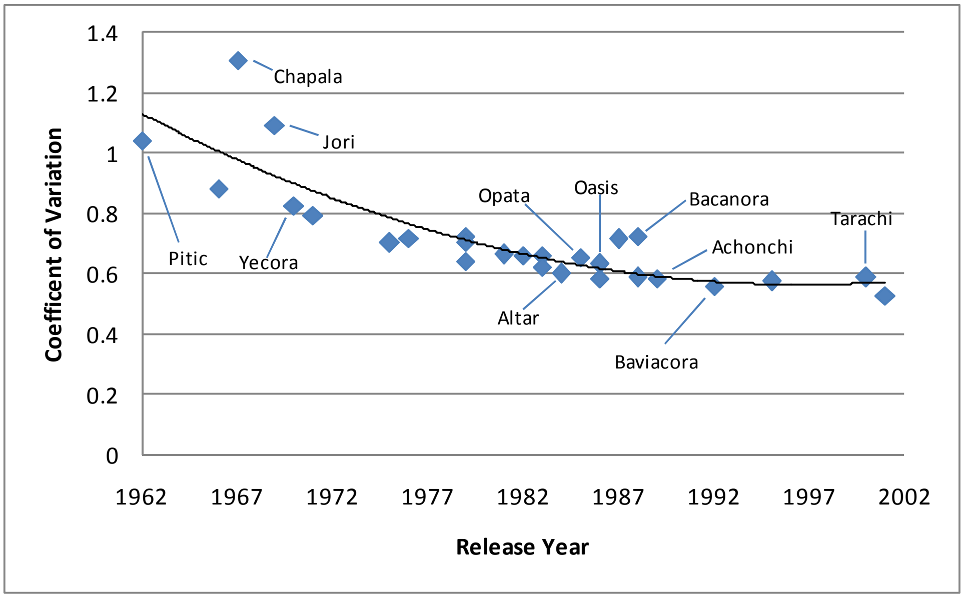
[19] Two other genotype-by-environment models were also estimated, the Finlay-Wilkinson (1963) and the Eberhart-Russell (1966) models. These two models did not converge, which according to Piepho (1999), is not uncommon when a data set has a combination of a large number of varieties and multiple replications within a year.

[20] Due to the nature of Just-Pope production function, the reported coefficients are effects on the proportional variance rather than the variance alone. The reason for this is that in equation 12 the natural log of the error terms are used as the dependent variable, resulting in a measure of proportional variance. In figure 5-2 and table 5-5 the antilog of the proportional variance was taken resulting in the variance.

Figure 5-2. Coefficient of Variation for CIMMYT Wheat Varieties: 1990-2002.



The combination of the fact that between 1990-2002 that CIMMYT lines have experienced an increase in annual yield and not seen an increase in variance seems to question if modern lines really increased yield at the expense of increased variance. The time period since the Green Revolution has typically been characterized by slower yield growth, and the regressions above indicate that yield is increasing at a decreasing rate, accompanied by a constant in yield variability over the same time period. Since the 1950s, evidence suggests that wheat yields have become more stable as mean yields have increased (Smale et al., 2002).

Cost-Benefit Analysis

An approximate cost-benefit ratio can be calculated using the results from table 5-3 and global and Yaqui valley historic wheat production data. The average historical Yaqui Valley farm gate wheat price (216.01 MT) from 1990-2002 was used, along with the average hectares (86,730 ha) planted to CIMMYT varieties in the valley over the same time period (CIMMYT, 2007). Detailed production data were obtained from the Yaqui Valley making it possible to isolate the percentage of area planted to CIMMYT-released varieties and. It was assumed that the percentage of area planted to CIMMYT varieties was proportional to the percentage of yield produced in the Valley.

Associated wheat breeding costs were lagged ten years to respective benefits because of a lag that exists with investment in wheat breeding and a line being released to the public. Interviewed CIMMYT breeders proclaim that on average there is a five-year breeding and testing period at CIMMYT followed by a three-to-four year testing period at experiment stations within Mexico, such as the Yaqui Valley station (Ammar, 2006). The last step is a two-year seed production stage before its release. From initial breeding to release is estimated at approximately ten years. Using the ten year lag, Lantican et al. (2005) calculated CIMMYT's average total wheat breeding cost from 1980 through 1992 at roughly 13.95 million 2002 USD, enabling a cost-benefit ratio to be estimated.

CIMMYT breeds for 12 specific "mega-environments" throughout the world, but does not disaggregate their breeding budget between environments.[21] Mega-environment 1, of which the Yaqui Valley is a part of, is the largest mega-environment accounting for 18.2% of the world's wheat production. The CIMMYT varieties used in this study were bred for mega-environment 1. While 18.2% of the world wheat production takes place in mega-environment 1, approximately 40% of the spring wheat lines and 19% of the durum lines CIMMYT releases in developing countries are targeted specifically for mega-environment 1 (Heisey et al., 2002).

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[21] Mega-environment 1 is classified as low latitude (35°N- 35°S), irrigated land, temperate climate, with the major constraints being rust and lodging. It consists of 35% of the wheat production in South and East Africa, 33% in West Asia and North Africa, 28% in South and East Asia, and 7% in Latin America. It accounts for 42.9% of the worlds total durum wheat acres and 16.5% of its total bread wheat acres (Lantican et al., 2005).

Since CIMMYT does not break down breeding costs into specific mega-environments, the following calculations will attribute all breeding costs to mega-environment 1. Thus the cost-benefit ratios to follow will be conservative since the costs have been overstated.

Yaqui Valley

The results from table 5-3, which indicated that CIMMYT contributed approximately 53.77 kg/ha or 0.05377 MT/ha, during the 1962-2002 time period, or a 15.11 kg/ha average annual increase, from the 1990-2002 time period.[22] An important aspect when calculating the cost-benefit analysis for a time period is to take into account the cumulative effects of the breeding program over that entire period. That is, the benefits received in 1991 are those observed in 1991 plus those seen in 1990. So, the additional genetic benefits for 2002 would be the genetic gain from 2001 to 2002 plus the genetic gain from 1990 to 2001. Table 5-7 shows the cumulative benefits from 1990-2002 with the average being 0.13717 MT/ha or 137.17kg/ha. Thus the average annual cumulative gain from the CIMMYT breeding program from 1990-2002 is 137.17 kg/ha. Results show that for the period of 1990-2002, an approximate estimate of what CIMMYT contributed to the Yaqui Valley through its wheat breeding program was approximately $2.57 million (2002) USD annually (0.13717MT/ha*86730ha*$216.00MT) (table 5-6).

Since CIMMYT only provides global and not location-specific breeding costs, a proportion of total breeding costs must be calculated for the Yaqui Valley. Previous literature (Lantican et al. 2005) has estimated that there were approximately 22.3 million hectares planted to CIMMYT crosses globally in 2002, thus 0.38% (86,730/22,300,000) of the total hectares

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[22] Since there was an inclusion of the squared term (*RLYR*^{2}) in the model it implies that the mean 53.77 kg/ha is not a constant but rather the average increase in annual yield over time period 1962-2002. When that average is calculated for the 1990-2002 period (table 5-7) the result is an average annual increase of 15.11 kg/ha.

planted to CIMMYT crosses are located in the Yaqui Valley. Thus, the cost-benefit ratio for the Yaqui Valley when taking their share of the global breeding cost (10.01 million 2002 USD) into account is approximately of 1:48 $\left(\left[\dfrac{\$2,569,698}{(0.0038)*\$13,950,000}\right]=48.48\right)$ (table 5-6)

Cross Rule

The average world wheat price from 1990-2002, of $157.40 (2002) USD, was used to evaluate global surplus measures (FAOSTAT 2007).[23] Using the total land planted to CIMMYT crosses, 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, there were approximately 22.3 million hectares planted to CIMMYT lines in 2002. If the same average cumulative yield advancements estimated for the Yaqui Valley (0.13717 MT/ha) were applied on a global scale, CIMMYT would account for an additional 481.47 ($157.40* 0.13717* 22,300,000) million 2002 USD in additional value for a 1:34 cost-benefit ratio.[24]

Parent Rule

Using the same calculations but different classification of CIMMYT germplasm, CIMMYT accounted for an additional 537.60 million (2002) USD in value using the CIMMYT parent rule classification (table 5-6). In the case of the parent rule however the benefits must be halved because only half of the germplasm is from CIMMYT, resulting in an additional 268.80

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[23] Specific country prices, while available, proved to be unusable 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. This is an obvious limitation to the subsequent calculations.

[24] This was calculated at the mean of the Release Year (*RLYR*) coefficient (1981.19). As noted above, the release year coefficient is diminishing thus, *ceteris paribus*, the cost-benefit ratio will be diminishing as well.

million (2002) USD in grain value in "direct" benefits.[25] When calculating the benefits for the parent rule the same 13.95 million dollar cost is associated but the sum of the benefits of the cross rule (481.47) and the parent rule (268.80) is taken to obtain the "actual" benefit of 750.27 million (2002 USD). That is because CIMMYT does not have explicit costs associated with "parents" but rather their costs are associated with the initial "cross" of germplasm. The costs of the parent rule are incurred from the non-CIMMYT breeder who uses the CIMMYT parent. So, assuming the same cost of (13.95 million) and summing the benefits for the cross and parent rule (750.27) the cost- benefit ratio for the parent rule is approximately for a 1:53 (750.27/13.95) cost-benefit ratio (table 5-6). So, even though the costs remain the same for the parent and cross rule and the later accrues larger benefits, by definition the benefits from the parent rule include the cross rules benefits, thus its cost-benefit ratio is larger.

Ancestor Rule

Applying the CIMMYT ancestor rule to the 14.9 million global acres planted to CIMMYT ancestors results in CIMMYT accounting for an additional 321.67 million (2002) USD in grain output. However, since by definition a CIMMYT ancestor is simply a CIMMYT line somewhere in the pedigree of the wheat, applying the full benefits would be an inflation of the true effect. Thus it is assumed that on average that a CIMMYT ancestor is composed of 20% CIMMYT germplasm for a 64.33 million dollar in "direct" benefits (table 5-6). Like the parent rule there are no direct costs accrued by CIMMYT associated with the ancestor rule, and like the parent rule the "actual" benefits of the ancestor rule are the summation of its own benefits plus

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[25] This assumes that both parents are not CIMMYT varieties.

the benefits of the cross and the parent rules.[26] The benefits are summed because by definition a CIMMYT ancestor at one point of its genetic life had to be a CIMMYT cross, and more than likely a CIMMYT parent as well, before it could move down the genetic line and be classified as an ancestor. With that being said, "actual" total benefits for CIMMYT ancestors is 814.60 (481.47+ 268.80+ 64.33) million 2002 USD for a 1:58 (814.60/13.95) cost-benefit ratio.

While table 5-6 calculated an average cost-benefit analysis for the time period 1990-2002 using the RLYR coefficient calculated at its mean (1981.19) figure 5-4 shows the evolution of the cost-benefit analysis over the 1990-2002 period using actual annual data. Since the $RLYR^2$ variable from table 5-2 is negative it is a given that the CIMMYT wheat breeding program is diminishing in its yield increases. Table 5-7 uses annual acres planted to CIMMYT crosses, parents, and ancestors; the average wheat price in metric tons (154.70, 2002 USD), and the kg/ha gain attributed to the CIMMYT program for the respective year, and the cumulative gain for each respective year, from 1990-2002 to calculate a year specific cost-benefit analysis calculated on table 5-8. Annual total benefits on table 5-8 are calculated by summing the benefits from CIMMYT crosses (cumulative gain in Ton/ha * # of hectares planted to crosses *average price of a metric ton of wheat from 1990-2002 in 2002 USD) on an annual basis plus 50% of the gain attributed to parents plus 20% of the gain attributed to ancestors.[27] The costs and benefits are then discounted at a rate of 10% to obtain the discounted costs and benefits (table 5-8). To obtain the cost-benefit analysis, total benefit is divided by total cost. Total cost for a given year is

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[26] Assuming the crosses made with the CIMMYT germplasm resulting in a CIMMYT ancestor is not undertaken by CIMMYT.

[27] Price was held at the average for the time period so that yearly wheat price variation would not affect the cost-benefit ratio from year to year.

lagged 10 years due to the average 10 year period between initial wheat cross and its eventual release by CIMMYT.

The cost-benefit results in figure 5-3 are driven by the cumulative Ton/ha gain attributed to the CIMMYT breeding program, the number of global hectares planted to CIMMYT varieties, and the discounted expenditure on wheat breeding for a given year (table 5-8). In general, the cost-benefit ratio has been increasing at a decreasing rate from 1990 to 2002. The “absolute” decrease in the cost-benefit ratio from 2001 to 2002 is a function of both a reduction in hectares planted for that given year, but mainly driven by the diminishing returns in the wheat breeding program. Table 5-7 shows how the annual genetic gain attributed to the CIMMYT breeding program has diminished from 0.0286 Ton/ha (28.6 kg/ha) to 0.0017 Ton/ha (1.7 kg/ha) from 1990-2002. Thus, the cumulative gains by definition have been increasing but at a decreasing rate from attributed to the deceleration of the annual genetic increase.

Table 5-6. Average Annual Global and Yaqui Valley Cost-Benefit Ratio for CIMMYT Varieties: 1990-2002.

Origin of Germplasm	Area (million ha) sown in 2002 to CIMMYT lines	Average cost 1980-1992 (million 2002 USD)	Benefits (million 2002 USD)	Cumulative benefits (million 2002 USD)	Cost-benefit ratio**
Global*					
CIMMYT Cross	22.3	13.95	481.47	481.47	1:34
CIMMYT Parent	24.9	13.95	268.80[a]	750.20	1:53[c]
CIMMYT Ancestor	14.9	13.95	64.33[b]	814.60	1:58[d]
Yaqui Valley***					
CIMMYT	0.09	0.0531	2.59	2.59	1:26[e]

*Using the global average wheat price ($157.40 2002 USD) from 1990-2002.

**Using the average CIMMYT wheat breeding expenditure for 1980-1992 (13.95 million 2002 USD).

***Using the Yaqui Valley average wheat price ($216.01 2002 USD) from 1990-2002.

[a] Benefits for CIMMYT parents are considered to only be 50%, because germplasm is only 50% CIMMYT.

[b] Benefits for CIMMYT ancestors are considered to only be 20%, estimating that germplasm is only 20% CIMMYT.

[c] Benefits associated to parent rule is the sum of parent and cross benefits.

[d] Benefits associated to ancestor rule is the sum of ancestor, parent and, cross benefits.

[e] Using the proportion of the Yaqui Valley's share of the global expenditure.

Table 5-7. Year Specific and Cumulative Genetic Gains Attributed to the CIMMYT Wheat Breeding Program and Global Acres Planted to Various Classifications of CIMMYT Wheat, 1990-2002.

Year	Genetic gain (Tons/ha)[a]	Cumulative genetic gain (Tons/ha)	Cross hectares planted (Millions ha)	Parent hectares planted (Millions ha)	Ancestor hectares planted (Millions ha)	Average wheat price (1990-2002) (2002 USD$/Ton)
1990	0.0286	0.0286	24.70	15.10	19.46	157.40
1991	0.0263	0.0549	24.12	16.59	19.08	157.40
1992	0.0241	0.0790	23.54	18.07	18.70	157.40
1993	0.0218	0.1008	22.96	19.56	18.32	157.40
1994	0.0196	0.1204	22.38	21.04	17.94	157.40
1995	0.0174	0.1377	21.80	22.53	17.56	157.40
1996	0.0151	0.1529	21.22	24.01	17.18	157.40
1997	0.0129	0.1657	21.80	25.50	16.80	157.40
1998	0.0106	0.1764	21.90	26.99	16.42	157.40
1999	0.0084	0.1848	22.00	28.47	16.04	157.40
2000	0.0061	0.1909	22.10	26.39	15.66	157.40
2001	0.0039	0.1948	22.20	27.87	15.28	157.40
2002	0.0017	0.1965	22.30	24.90	14.90	157.40

[a] Calculated from results in Table 5-2.

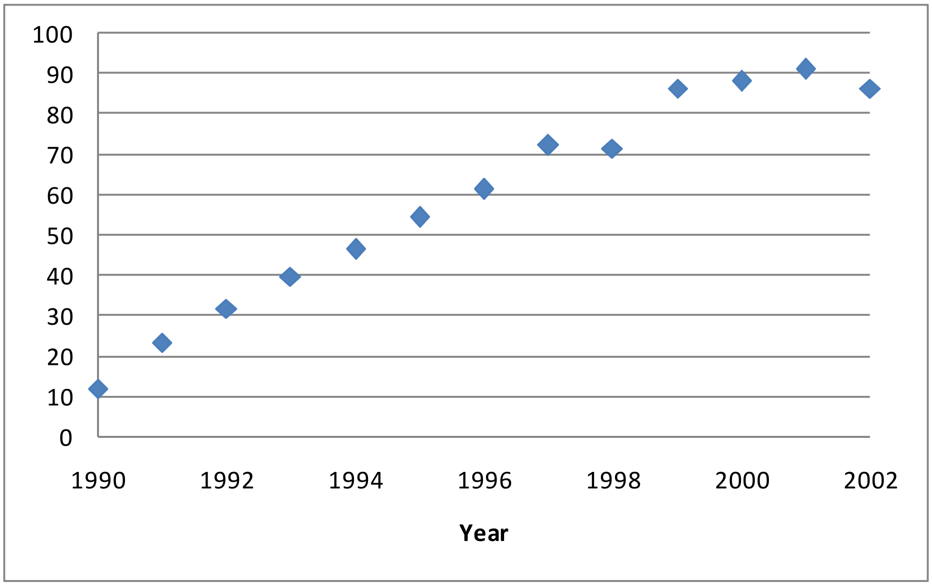
Table 5-8. Discounted Year Specific Cost-Benefit Analysis for the CIMMYT Wheat Breeding Program in 2002 USD Using Cumulative Genetic Gains Attributed to the CIMMYT Breeding Program, 1990-2002.

Year	Cross benefits (Million USD)	50% Parent benefits (Million USD)	20% Ancestor benefits (Million USD)	Total benefits (Million USD)	Discounted total benefits (Million USD)[a]	Costs (Million USD) 10 Year Lag[b]	Discounted costs (Million USD) 10 Year Lag	Cost-benefit ratio
1990	111.04	33.94	17.50	162.47	162.47	13.50	13.50	1:12
1991	208.35	71.63	32.96	312.95	284.50	13.40	12.18	1:23
1992	292.56	112.30	46.48	451.33	373.00	14.20	11.74	1:31
1993	364.26	155.14	58.13	577.53	433.91	14.50	10.89	1:39
1994	424.09	199.38	67.99	691.46	472.28	14.90	10.18	1:46
1995	472.65	244.22	76.14	793.02	492.40	14.60	9.07	1:54
1996	510.56	288.90	82.67	882.13	497.94	14.40	8.13	1:61
1997	568.69	332.60	87.65	988.94	507.48	13.70	7.03	1:72
1998	607.94	374.56	91.16	1,073.67	500.88	15.00	7.00	1:71
1999	639.78	413.99	93.29	1,147.05	486.46	13.30	5.64	1:86
2000	664.08	396.43	94.11	1,154.62	445.16	13.10	5.05	1:88
2001	680.74	427.32	93.71	1,201.78	421.21	13.20	4.63	1:91
2002	689.66	385.04	92.16	1,166.86	371.80	13.50	4.30	1:86

[a] Using a 10% discount rate

[b] 10 year lag associated with the average time between initial cross year and time until a line is released to the public

Figure 5-3. Annual Cost-Benefit Ratio for the CIMMYT Wheat Breeding Program, 1990-2002.



Many argue that the decline in genetic gain attributed to the CIMMYT wheat breeding program is attributed to the fact that funding in which they receive has decreased by over 110% from 1990-2002 resulting in fewer wheat scientists and less capital to work with. This argument may be true for maintaining a critical mass in the future, but seems to be mitigated if you lag costs by 10 years since the average breeding budget for 1980-1992 is nearly constant. That is, the reduction of genetic gains from 1990-2002 is not be a function of reduced funding for the same time period if there is a 10 year lag in observable benefits. Some agronomists argue that wheat breeding for optimal environments (access to irrigation, fertilizer, and pesticide), which varieties in this data set were, will only see marginal advancements in yield given today's technology.[28] Interviewed agronomists at CIMMYT claim that the future of breeding for developing countries lies in marginal environments (areas without irrigation and limited access to fertilizer). Although the kg/ha yield will not be as great in marginal environments the percent annual increase will be larger than in optimal environments. While overall yield may be less in these marginal areas, mostly located in Sub-Saharan Africa, and Latin America (who were largely left behind in the Green Revolution) they would certainly increase the diet and in some cases the revenue of many low-income countries.

Two important additional benefits to producers and consumers in low-income countries are not captured in this analysis. First; non-yield attributes in the form of grain quality, fodder and straw quantity and quality. Lantican et al. 2005 claim that these benefits can sometimes exceed the value of the actual yield benefits. Second, and as mentioned earlier is the notion of maintenance breeding. Maintenance breeding improves a line from diseases and pests while

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[28] Many of the same interviewed agronomist claim that if GMO technology was introduced to wheat that there would be large growth potential in optimal environments yet to be achieved.

attempting to maintain the original yield so that, so that potential yield losses are essentially foregone.

Other studies, Lantican et al. 2005, concluded the total value of additional wheat grain produced in developing countries that can be attributed to CIMMYT's breeding program range from a conservative 0.5 to 1.5 billion (2002) USD annually to a liberal estimate of 1.3 to 3.9 billion (2002) USD annually. The preceding cost-benefit results are lower than existing estimates of CIMMYT's breeding program, Lantican et al. (2005), found the cost-benefit ratio for CIMMYT's wheat breeding program ranges from 1:50 to 1:390. The discrepancy exists between the cost-benefit that Lantican et al. found and the cost-benefit calculated in this study because the annual genetic gains attributable to CIMMYT found by Lantican et al. were nearly four times larger in magnitude than was calculated in this study.

CHAPTER 6 - Summary and Conclusions

Summary

CIMMYT 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, which rely on CIMMYT for advancements in wheat breeding, must increase their per-hectare yield. Using test plot data from the Yaqui Valley from 1990-2002 with lines released by CIMMYT from 1962-2001 and estimating the Just-Pope production function, which accounts for heteroscedasticity across varieties, it was found through the release of modern varieties CIMMYT contributed on average approximately 53.77 kg/ha annually (a 0.64% increase) to wheat yield in the Yaqui Valley from 1962-2002. Genetic gains for CIMMYT were found to be increasing at a decreasing rate and for the 1990-2002 time period CIMMYT was found on average to add an additional 15.11kg/ha annually in yield. 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. Results from this analysis show otherwise in that the CIMMYT breeding program has kept yield variability constant 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 remained constant which is indicative of the post Green Revolution breeding era. That is, the post Green Revolution has been characterized by slower yield growth, yield increasing at a decreasing rate, accompanied by a leveling in yield variability over the same time period. These results are important to CIMMYT because the impact the wheat breeding program has on increasing wheat yields provides information to scientists, administrators, and policy makers regarding the efficacy and return to these investments.

Calculating an estimate of the cost-benefit ratio using historical prices and production in the Yaqui Valley using cumulative genetic gains for the period, it was found that CIMMYT has contributed on average approximately \$2.59 million (2002) USD annually from 1990-2002 to the Yaqui valley through its wheat breeding program. Assuming that the gains observed in the Yaqui valley are equivalent to CIMMYT's gains on a global scale, and using the average cumulative gain, on average an additional \$481.47 million annually (2002) USD in grain can be attributed to the CIMMYT breeding program using CIMMYT's cross rule definition from 1990-2002. CIMMYT's average total wheat breeding cost from 1990- 2002 was roughly \$13.95 million dollars (Lantican et al. 2005). Again using the CIMMYT cross rule definition and the average cumulative gains from 1990-2002, the average global cost-benefit ratio was approximately 1:34.

Conclusions

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 accumulating these small increases over several decades and extensive planting worldwide results in a large and significant enhancement of wheat yields. However, if CIMMYT's own estimation is true that the developing world will need 40% more wheat than they consume today by 2020 then those small increases will most likely not meet the projected increase in demand. While yield increases have been slowing, the stabilization in yield variation plays an important role in increasing food security for low-income countries. By stabilizing yield variability through the release of modern varieties, CIMMYT has reduced the exposure from yield, and thus income variability, for producers in low-income countries. These results imply that CIMMYT-released lines are simultaneously increasing in yield and stabilizing yield variance which is of utmost importance, given that CIMMYT is funded through and competing for limited public funds. Given the deceleration of wheat growth in optimal environments, CIMMYT may need to reallocate funds to breeding for marginal environments in the future. While overall yield may be less in these marginal areas the potential for % increase in yield is greater. These marginal environments mostly located in Sub-Saharan Africa and Latin America (who was largely left behind in the Green Revolution) would certainly benefit from an increase caloric intake and in some cases increased revenue from sales.

CHAPTER 7 - Bibliography

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Appendix A - Historical Yaqui Valley Wheat Production Data: 1990-2002.

The following table illustrates the historical production of wheat in Mexico's Yaqui Valley from 1990-2002 and the value of a metric ton of wheat received by farmers in the Yaqui Valley in both nominal Mexican Pesos and 2002 United States Dollars (USD).

Table A-1. Wheat Production in the Yaqui Valley, 1990-2002.

Year	Hectares Harvested	Yield (kg/ha)	Local Price (Pesos/Ton)*	Price in (2002 USD/Ton)
1990	143,060	5,508	484,000	245.22
1991	101,389	4,423	650,000	292.41
1992	119,968	4,269	700,000	293.15
1993	125,876	4,708	750,000	245.51
1994	130,511	5,659	630,000	218.60
1995	118,291	4,797	850	147.77
1996	75,729	5,358	1,750	267.60
1997	110,936	5,674	1,400	197.21
1998	103,586	5,996	1,400	180.48
1999	102,076	6,080	1,360	154.33
2000	173,997	5,705	1,515	171.98
2001	134,636	6,013	1,680	177.76
2002	171,186	5,786	1,660	175.99

*In December 1994 there was a large devaluation of the Mexican Peso.
Source: CIMMYT Yaqui Valley Survey

Appendix B - Historical Wheat Variety Selection by Farmers in Mexico’s Yaqui Valley: 1989-2001

The following table represents varietal selection by farmers in the Yaqui Valley from 1989-2001. It includes both CIMMYT and non-CIMMYT varieties. The table also illustrates the percentage of the total land planted to each wheat variety in a respective year.

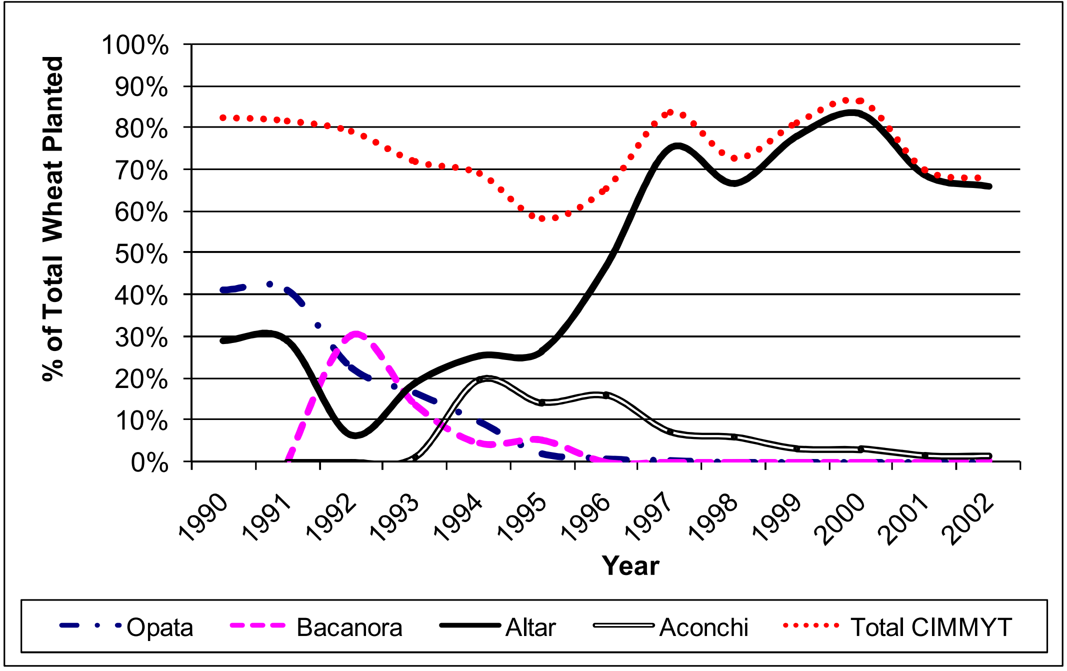
Table B-1. Historical Wheat Variety Selection and the Percent Planted to Respective Varieties by Farmers in the Yaqui Valley: 1989-2001.

Wheat Type	Variety	Release year	89-90	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01
Bread Wheats	Ciano*	1979	1.8	0.8										0.4
	Imuris	1979												
	Tesia	1979												
	Glennson	1981												
	Sonoita	1981	5.4	0.7	2.5									
	Tonichi	1981	5.8	0.5		0.1								
	Ures	1981	2.4											
	Seri*	1982												
	Opata*	1985	41.2	22.6	16.5	9.7	2.0	0.7	0.4					
	Cucurpe	1986	2.0	7.1	8.9	5.8	5.9	2.1	0.1		0.1			
	Oasis*	1986	7.5	18.9	21.1	9.6	10.0	1.9	0.7					
	Papago	1986	1.7	10.3	11.7	7.8	5.5	0.5	0.2					
	Bacanora*	1988		30.2	13.7	4.4	5.2	0.0	0.1					0.2
	Esmeralda	1988		0.2										
	Cumpas	1988		2.1	3.9	3.3	1.4							
	Rayon	1989			0.2	9.7	20.1	16.6	8.4	17.1	10.5	8.9	16.7	14.1
	Tepoca	1986			0.6	4.4	8.9	13.7	6.7	4.0	3.5			
	Baviacora*	1988					0.2	0.1						
	Arivechi	1992					0.1	1.5	1.0	6.4	4.8	3.2		

Wheat Type	Variety	Release year	89-90	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01
Durum Wheats	Mexicali*	1975												
	Yavaros*	1979	2.1	0.2	0.3									
	Altar*	1984	29.2	6.5	19.1	25.5	26.6	46.9	75.1	66.5	77.9	83.3	68.7	65.9
	Aconchi*	1989			1.3	19.7	14.2	15.9	7.3	6.0	3.3	3.0	1.4	1.3
	Rafi C-97	1997										0.9	7.5	14.0
	Nacori c-97	1997										0.7	5.7	4.0
	Other	--	0.9	0.0	0.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1

* Denotes CIMMYT lines

Figure B-1. Historical CIMMYT Varietal Usage on Farms as a Percentage of All Wheat Planted in Mexico's Yaqui Valley: 1990-2002.



Source: CIMMYT Yaqui Valley Survey.
Note: These lines to not encompass all CIMMYT lines planted in the Yaqui Valley but only those who had a significant percentage of the total.

Appendix C - Historical Yields of CIMMYT Released Varieties on the Yaqui Valley Experiment Station: 1990-2002

Table C-1. Historical Yield for CIMMYT Released Varieties on the Yaqui Valley Experiment Station, 1990-2002.

Vareity	Release Year	Average Yield (kg/ha)	Standard Deviation (kg/ha)	Min Yield (kg/ha)	Max Yield (kg/ha)
PITIC	1962	7013	785	5804	8552
7 CERROS	1966	7832	841	5989	9569
CHAPALA	1967	5253	1599	2593	7136
JORI	1969	6134	1179	3695	7552
YECORA	1970	7821	1018	5763	9311
COCORIT	1971	8090	705	6585	9627
MEXICALI	1975	8623	1039	6221	10940
YOREME	1975	8439	260	8230	8773
NACOZARI	1976	8293	878	6305	10108
CABORCA	1979	8020	854	6070	9333
CIANO	1979	8069	982	6487	9905
YAVAROA	1979	8975	842	7406	11028
SERI 81	1981	8541	1028	6767	9717
SERI 82	1982	8311	912	6695	10582
ALAMOS	1983	8233	793	7104	9716
ERONGA	1983	8803	978	6978	11098
ALTAR	1984	9050	790	6945	10610
OPATA	1985	8313	656	7502	9478
JILOTECPEC	1986	9322	585	7995	10200
OASIS	1986	8386	982	5982	10404
TARASCA	1987	7939	370	7463	8249
BACANORA	1988	7134	448	6476	7425
SUPER KAUZ	1988	8851	761	7305	10089
ACHONCHI	1989	8889	815	7079	11082
BAVIACORA	1992	8954	947	7055	10728
BORLAUG	1995	8639	1000	6244	10049
TARACHI	2000	7366	467	6712	8138
ATIL C	2001	8296	517	7611	9380

Appendix D - Regression Results for Individual CIMMYT Varieties from the Various Fixed Effects Models in Table 5-4.

The following table shows the results for each variety of wheat tested in the Yaqui Valley test plots from the fixed effects model in table 5-4. All of these results are relative to the default variety Yoreme and are in conjunction with the rest of the explanatory variables listed in table 5-4.

Table D-1. Individual Variety Fixed Effect Results from Table 5-4.

	OLS	Multiplicative Heteroscedasticity Correction	Just-Pope		Shukla	ANOVA
Variable	Yield	Yield	Yield	Variance		
7 Cerros	12.628	1.096	14.939529	1.569	-65.222	-193.200
	[0.032]	[0.007]	[0.035]	[1.473]	[-0.03]	[-0.36]
Achonchi	1051.078	1037.381	1053.605	0.970	1005.930	888.140
	[2.686]*	[7.196]*	[2.491]**	[0.911]	[0.44]	[1.66]***
Alamos	477.995	479.230	485.7133	2.118	634.060	447.680
	[1.131]	[1.777]***	[1.079]	[1.841]***	[0.27]	[0.80]
Altar	1200.515	1185.358	1203.6126	1.308	1115.680	996.410
	[3.069]*	[8.118]*	[2.849]*	[1.228]	[0.49]	[1.87]**
Atil C	1253.966	1240.123	1254.2379	2.399	1115.680	1148.210
	[2.713]*	[5.837]*	[2.552]**	[1.907]***	[0.49]	[1.62]***
Bacanora	-629.150	-613.060	-629.152	0.673	-681.050	-938.980
	[-1.162]	[-2.527]**	[-1.884]***	[0.456]	[-0.25]	[-1.29]*
Baviacora	1217.730	1206.484	1223.8136	2.125	1158.990	1048.910
	[3.098]*	[7.851]*	[2.888]*	[1.986]**	[0.51]	[1.93]***
Borlaug	750.088	738.146	756.83465	1.924	675.220	567.050
	[1.874]**	[4.276]*	[1.757]***	[1.766]***	[0.03]	[1.00]
Caborca	86.281	83.467	91.224248	2.116	269.390	157.990
	[0.21]	[0.394]	[0.208]	[1.891]**	[0.13]	[0.29]
Chapala	-2620.521	-2617.378	-2625.034	3.611	-2636.560	-2780.620
	[-6.163]*	[-7.063]*	[-5.853]*	[3.119]*	[-1.13]	[-4.93]*
Ciano	310.683	312.225	319.24844	1.364	366.900	232.440
	[0.751]	[1.491]	[0.719]	[1.211]	[0.16]	[0.42]
Cocorit	213.196	192.854	217.26527	1.260	217.430	122.820
	[0.545]	[1.34]	[0.514]	[1.182]	[0.01]	[0.23]
Eronga	969.131	955.767	972.46612	1.681	968.500	851.3
	[2.476]**	[5.971]*	[2.302]**	[1.577]	[0.42]	[1.59]
Jilotecpec	1271.066	1258.879	1278.3013	1.028	1055.750	1031.710
	[3.104]*	[7.171]	[2.901]*	[0.922]	[0.46]	[1.79]***
Jori	-1796.069	-1794.350	-1799.721	2.581	-1734.770	-1889.83
	[-4.23]*	[-6.065]*	[-3.994]*	[2.233]**	[-0.75]	[-3.36]*
Mexicali	774.117	752.692	778.07511	1.957	676.880	585.07
	[1.979]**	[4.5]*	[1.844]***	[1.838]**	[0.30]	[1.10]
Nazozari	466.369	452.580	471.01971	1.352	438.830	305.34
	[1.193]	[3.083]*	[1.116]	[1.27]	[0.19]	[0.57]
Oasis	576.760	561.720	586.0318	1.688	686.930	567.22
	[1.47]	[3.555]*	[1.384]	[1.58]	[0.30]	[1.05]
Opata	380.199	398.500	382.82115	1.426	265.420	123.06
	[0.814]	[1.818]***	[0.771]	[1.122]	[0.12]	[0.20]
PITIC	-722.849	-719.576	-712.1435	2.268	-642.700	-787.92
	[-1.746]**	[-3.489]*	[-1.611]***	[2.012]**	[-0.28]	[-1.42]
Seri 81	591.500	554.786	599.7884	1.715	233.670	113.3
	[1.204]	[1.561]	[1.16}	[1.283]	[0.10]	[0.16]
Seri 82	567.010	561.458	572.24704	1.979	617.900	512.38
	[1.445]	[3.631]*	[1.352]	[1.853]***	[0.27]	[0.96]
Super Kauz	1030.903	1021.699	1042.0443	1.761	1028.370	919.15
	[2.631]*	[7.037]*	[2.465]**	[1.651]***	[0.45]	[1.72]***
Tarachi	369.286	360.225	361.759	1.646	325.320	223.65
	[0.796]	[1.997]**	[0.726]	[1.303]	[0.14]	[0.31]
Tarasca	-459.771	-453.414	-461.143	0.988	-499.520	-508.3
	[-0.862]	[-2.275]**	[-0.813]	[-1.36]	[-0.21]	[-0.72]
Yavaros	1127.259	1110.996	1133.9777	1.391	1058.830	946.47
	[2.882]*	[7.526]*	[2.685]*	[-1.732]***	[0.46]	[1.77]***
Yecora	31.547	27.572	38.378475	2.123	148.800	15.812
	[0.076]	[0.127]	[0.087]	[1.884]***	[0.06]	[0.03]
Adj. R²	0.531	--	0.537	0.050		
Akaike Information Criteria	16.119	--	16.142	4.306	17241.600	17249.600
Chi-Squared	--	91.358	--	--		
F-test	38.760	--	39.650	2.750		

* Denotes Statistical Significance at the 1% level.

** Denotes Statistical Significance at the 5% level.

*** Denotes Statistical Significance at the 10% level.