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Using Portfolio Theory to Enhance Wheat Yield Stability in Low-Income Nations: An Application in the Yaqui Valley of Northwestern Mexico

L. Lanier Nalley and Andrew P. Barkley

This study applies portfolio theory to wheat varietal selection decisions in order to find risk-minimizing outcomes while holding historical yields constant. Potential correlation across wheat cultivar yields increases the complexity of cultivar selection decisions, with gains in one attribute (yield potential) often associated with losses in another (yield stability). Using location-specific empirical data, portfolio theory can provide producers in low-income countries a tool for developing a recommended portfolio of varieties given a desired risk-aversion level. Based on data from Mexico's Yaqui Valley, results suggest that sowing a portfolio of wheat varieties could have lowered yield variance by 22% to 33% in Northwest Mexico.

Key Words: optimal variety selection, portfolio analysis, wheat

Introduction

Wheat producers often plant more than one cultivar each year in an attempt to diversify yield risk (Barkley and Porter, 1996). However, producers in both high- and low-income countries typically select combinations based on cultivar descriptions, intuition, and average yields, potentially ignoring one of the most important pieces of information: the relationship between varieties. Extension agencies worldwide offer programs that allow producers to select specific cultivars and receive recommendations on optimum seeding rates, seedbed preparation, seeding date range, and drill width. Yet there is a critical gap in these recommendations, perhaps the most important recommendation of all—which varieties to plant for optimal diversification.

The selection of wheat varieties through portfolio theory offers producers in low-income countries the potential to increase yield or decrease yield variability. Producers in low-income countries often value yield stability as much as yield potential. These producers frequently have a choice of several wheat varieties to sow and must evaluate the tradeoff between yield mean and variance. Relationships between cultivar attributes (e.g., yield potential, pest or disease resistance, and drought tolerance) increase the complexity of cultivar selection decisions, with gains in one attribute (yield potential) potentially associated with losses in another (yield stability). Using location-specific empirical data, portfolio theory can provide producers in low-income nations a tool that is able to recommend a bundle of varieties to meet specific objectives, either maximizing yield given variance or minimizing variance given yield.

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This paper applies the existing literature on portfolio theory to wheat varietal selection for the Yaqui Valley in Northwest Mexico, where wheat is the most commonly planted crop during the winter growing season. Varietal diversification may be an immediately plausible management strategy for this area. Two scenarios are evaluated. The first holds constant actual historical yield and develops a portfolio of Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) wheat varieties to minimize the variance around that yield. The second scenario holds historical yield variance constant and develops a portfolio of wheat varieties to maximize yield around the given variance. Resistance to Karnal bunt, a major disease problem in the Yaqui Valley, is also addressed and incorporated into the portfolio analysis. Karnal bunt has influenced varietal selection in the Yaqui Valley for over 20 years, resulting in a shift from bread to durum wheat varieties. We take the rather broad global extension recommendation of "diversifying wheat varieties to minimize risk" a step further by developing specific variety portfolios. While the Yaqui Valley is an example of a high-yielding production zone, this method could also be implemented by subsistence producers. For producers in low-income countries, varietal diversification could lead to a reduction in yield variance and thus contribute to the well-being of wheat producers.

Literature Review

Decreasing yield variability in low-income countries may be beneficial to both producers and consumers because it typically reduces price instability within markets. Gollin (2007) highlights three ways for improving wheat yield stability. The first is breeding for improved disease or pest resistance in modern varieties. As increased acreage is planted with these modern varieties, ceteris paribus, yield stability should increase. The second method for improving yield stability is by replacing traditional varieties with higher-yielding modern varieties, which may have lower relative yield variability. The third is by diffusing multiple varieties that differ in their susceptibilities to disease and resistance to pests; although individual modern varieties may be no more resistant than traditional varieties, in the aggregate, the portfolio of varieties will display lower overall yield variability than any single cultivar.[1]

Critics of modern varieties (MVs) have suggested that yields of MVs, although higher, vary more from season to season than traditional wheat varieties in low-income countries, thereby exposing consumers and producers to greater risks.[2] If modern varieties possess the potential for higher yields and higher yield variability than traditional or older varieties, then a combination of the two could be beneficial. By implementing portfolio theory for varietal selection, the yield potential in a portfolio of diverse individual varieties will be more than the yield potential inherent in sowing any single one of the individual varieties. Similarly, when selecting varieties using portfolio theory, the yield variance in a portfolio of diverse individual varieties will be less than the yield variance inherent in sowing any single one of the individual varieties. As an example, consider a portfolio containing two wheat varieties: one that yields well only with ample rainfall and one that is drought tolerant and yields better with sparse rainfall. A portfolio containing both varieties has the potential to pay off relative to

[1] Research-based methods other than genetic improvement may lower variability, including increased use of fertilizer and pesticides, or irrigation. These are important contributions to variance reduction, but outside the scope of our study. The data in this study are homogeneous in their growing environments, which would mitigate the effects of inputs.

[2] While some claim MVs have higher yields but greater volatility, the empirical record does not necessarily support this assertion (Gollin, 2007; Larson et al., 2004).

individual varieties if the variety yields are inversely correlated with rainfall (and the covariance between variety yields is negative or positive, but sufficiently small). Adding one risky cultivar to another can reduce the overall risk of crop failure due to a climatic (abiotic) or disease/pest (biotic) anomaly.

Decreased yield variance through portfolio implementation can lead to greater food security and a lessened dependence on imported grain, the relative price of which is subject to exchange rate fluctuations. Larson et al. (2004) show that the yield variance instability for wheat in India decreased from the pre-Green Revolution period to the post-Green Revolution period. The widespread adoption of Green Revolution varieties appears to be one of the main factors responsible for greater yield stability and the resulting increase in food security on the subcontinent. The driving factors behind the adoption of Green Revolution varieties are consistent with Gollin's three factors for lowering yield variability: (*a*) producers desired varieties that were disease or pest resistant, (*b*) producers desired varieties with lower *relative* yield variability, and (*c*) producers desired a diffusion of multiple varieties.

Timmer (1998) states that food security is a function of many short-run dimensions, including food price stability. Yield stability (or variance reduction) benefits food producers because it reduces the risks they incur. This risk reduction leads producers to increase investments in new technologies designed to increase overall productivity. Timmer also finds that consumers benefit from stable food prices because they do not face the risk of sudden and sometimes sharp reductions in real income. This benefit accrues disproportionately to the poor since they spend a larger portion of their budget on food. Thus, the benefits to consumers from price stabilization have a significant equity dimension which can play an important role in poverty alleviation.

Several studies (e.g., Detlefsen and Jensen, 2004; Jensen, 2001) use stochastic dominance as an aid for varietal selection. While stochastic dominance can indicate which single cultivar should be planted, it ignores the covariance between varieties. In some cases, the utility defined over all attributes (yield, yield stability, Karnal bunt resistance, etc.) may be increased through portfolio selection.[3] Detlefsen and Jensen use stochastic dominance to select a winter wheat cultivar to sow in Denmark based on the greatest net revenue and taking into consideration cost differentials for disease treatment and yield.

Portfolio theory was initially developed by Markowitz (1959) and Tobin (1958), with extensions by Lintner (1965) and Sharpe (1970) focusing on financial investments. A portfolio is defined as a combination of items: securities, assets, or other objects of interest. Portfolio theory is used to derive efficient outcomes through identification of a set of actions or choices that minimize variance for a given level of expected returns or maximize expected returns for a given level of variance. Decision makers (producers) can then use the efficient outcomes to find expected utility-maximizing solutions to a broad class of problems in investment, finance, and resource allocation (Robison and Brake, 1979). In other words, portfolio theory can be used to minimize yield around a given variance and can be implemented in a multitude of settings, including our application of selecting wheat varieties in low-income countries.

The analog of financial portfolio analysis can be applied to agricultural production and provide producers a tool for implementing cultivar seed purchase and planting decisions. Choosing wheat varieties allows producers to allocate money across investment opportunities (various varieties) with varying relative risks and yields. Since different varieties of wheat

[3] There may be a relationship between the application of stochastic dominance and portfolio theory, i.e., varieties found to be dominated by stochastic dominance criteria might lie inside the efficient mean-variance frontier.

respond differently to environmental conditions, risks associated with wheat varieties may in some way be correlated. Risks associated with certain wheat varieties will be positively related to other varieties, and some may be negatively correlated with other cultivar yields. Because of this correlation, there are potential benefits from planting multiple varieties to spread the risk associated with the aforementioned environmental conditions.

There is a large body of literature on expected utility theory, the dominant paradigm in decision making under risk, and its relationship to portfolio theory. Rothschild and Stiglitz (1970) demonstrated that greater variance differed from higher risk levels. Meyer (1979) derived conditions under which maximization of utility on a mean-variance frontier is equivalent to maximizing expected utility. Russell and Seo (1980) showed how stochastic dominance methods can be used to determine the expected utility efficient set and establish when mean-variance efficiency is a useful approximation. Bawa et al. (1985) extended Meyer's work using exact linear programming algorithms and found that the dominated set determined by Meyer is too large.

Levy (1992) provided an excellent summary of stochastic dominance and expected utility. Granger (2002) summarized what was known about risk at the time of publication; he noted that diversification can help in reducing risk, but the riskiness of one portfolio cannot be assessed without knowing the risks of other portfolios. Levy and Levy (2004) showed that while prospect theory results differ from mean-variance analysis, when diversification between assets occurs, the efficient sets of prospect theory and mean-variance analysis nearly coincide. More recently, Nyikal and Kosura (2005) used quadratic programming (QP) to solve for the efficient mean-variance frontier to better understand farming decisions in Kenyan agriculture. Redmond and Cubbage (1988) applied the capital asset pricing model (CAPM) to timber asset investments in the United States. Figge (2004) summarized the literature on how portfolio theory has been applied to biodiversity, and Sanchirico, Smith, and Lipton (2005) applied portfolio theory to develop optimal management of fisheries. While portfolio analysis is not a new concept to agriculture, its application to cultivar selection is.

Analyzing Kansas wheat producer cultivar selection decisions from 1974 to 1993, Barkley and Porter (1996) found that cultivar choice was statistically related to production characteristics (such as disease resistance) and end-use qualities. They concluded, "... wheat producers in Kansas take into account end-use quality in varietal selection decisions, but economic considerations lead many producers to plant higher-yielding varieties, some of which are characterized by low milling and baking qualities" (p. 209). Barkley and Porter also found that yield stability was a significant determinant of cultivar selection decisions. Their results indicated producers often planted the highest yielding varieties, which may be characterized by greater yield variance. Other studies have been conducted in low-income countries where cultivar attributes affect adoption rates (Dixon et al., 2006; Adesina and Zinnah, 2003; Smale et al., 2001; Dalton, 2004; Edmeades et al., 2008; Doss et al., 2003). Although structural variations exist due to the location differences of the studies, education through extension appears to play a significant role in the adoption of specific varieties.

Nalley et al. (2009) implemented portfolio theory to select varieties of rice in the Arkansas Delta. By using portfolio theory, they concluded rice producers could have increased profits by up to 20%, holding the expected variance of yields constant. Nalley et al. suggested that the benefit of using portfolio theory to choose varieties is the relationship between varieties themselves, summarized by the covariances across all varieties at a given location.

Methods

The current model uses a framework similar to that of Markowitz (1959), who developed portfolio theory as a systematic method of minimizing risk for given levels of expenditure for different financial investments. An efficient portfolio of wheat varieties can be elicited with the estimates of expected yield and variance of yields for each cultivar, combined with all of the pairwise covariances across all wheat varieties. The efficient mean-variance frontier for a portfolio of wheat varieties is then derived by solving a sequence of quadratic programming problems. Based on a producer's risk-aversion preferences, a specific point on the efficiency frontier can be identified as the optimal portfolio of wheat varieties.

We assume a producer's objective is to plant the optimal mix of wheat varieties, and the producer has X total acres dedicated solely to wheat production.[4] Therefore, the decision variable is x_i, the percentage of total acres planted to cultivar i, where $i = 1, \ldots, n$, and $\Sigma_i x_i = X$. Quadratic programming is used to solve for the efficiency frontier of mean-variance (M-V) combinations. This frontier is defined as the maximum yield mean for a given (or target) level of variance or, conversely, the minimum variation for a given (or target) mean yield using a portfolio of wheat varieties. If the mean yield of cultivar i is equivalent to y_i, then the total is the weighted average yield, equal to $\Sigma_i x_i y_i$.

The total farm cultivar yield variance (V) is defined in equation (1):

$$(1) \qquad V = \sum_j \sum_k x_j x_k \sigma_{jk} ,$$

where x_j is the percentage of total acres planted to cultivar j, σ_{jk} is the covariance of cultivar yields between the jth and kth wheat varieties, and σ_{jk} is the variance when $j = k$. The inclusion of covariances among wheat varieties is required for efficient diversification as a means of hedging against risk (Markowitz, 1959; Heady, 1952).

Hazell and Norton (1986) explained the intuition of equation (1) as follows: The total farm variance for all wheat varieties planted (V) is an aggregate of the variability of individual varieties and covariance relationships between the varieties. They note, "… combinations of varieties that have negative covariate yields will result in a more stable aggregate yield for the entire farm than specialized strategies of planting single varieties" (p. 81), and "… a cultivar that is risky in terms of its own yield variance may still be attractive if its returns are negatively covariate with yields of other varieties planted" (p. 81).

The mean-variance efficiency frontier is calculated by minimizing total farm variance (V) for each possible level of mean yields (y_i), as given in equation (2):

$$(2) \qquad \text{Min } V = \sum_j \sum_k x_j x_k \sigma_{jk} ,$$

subject to:

$$(3) \qquad \sum_j x_i y_j = \lambda$$

and

$$(4) \qquad x_j \geq 0 \; \forall \, j.$$

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[4] All land is assumed to be of the same quality.

The sum of the mean cultivar yields in equation (3) equals λ, defined as the target yield level, which is varied over the feasible range to obtain a sequence of solutions of increasing farm-level mean yield and variance, until the maximum possible mean yield is obtained. Equation (2) is quadratic in x_j; we therefore use the Excel Solver program to solve this non-linear equation.

Mexico's Yaqui Valley has experienced a high prevalence of Karnal bunt, a disease which marginally affects yield but has detrimental effects on quality. If the disease is prevalent, the infected wheat must be sold as animal fodder and cannot be used in human consumption due to its offensive fishy odor; this results in lost producer revenue. Since each variety has a resistance rating to Karnal bunt, a new constraint was introduced to ensure the portfolio only included those varieties with at least "moderate resistance" to Karnal bunt.[5] In this sense, the portfolio can more accurately account for the biotic differences between varieties while attempting to minimize the existence of Karnal bunt.

Data

Data were collected from the principal CIMMYT test plot in the Yaqui Valley of Mexico between 1990 and 2002. The experiment station, near Ciudad Obregón, has soil that is a coarse, sandy clay, mixed montmorillonitic typic calciorthid, low in organic matter (< 0.8%), and slightly alkaline (pH 7.7–8.2). Both nitrogen and phosphorous were regularly applied as fertilizer. The potassium in the soils was considered to be typically adequate for wheat. A total of 33 cultivars bred by CIMMYT were analyzed, with release years ranging from 1962 to 2001, including the cultivar Siete Cerros, which was the most popular semidwarf wheat of the Green Revolution. The plots were seeded with 300 viable seeds per m^{-2}. Although the test period for this data set is 1990–2002, the data include several cultivars released prior to 1990. The rotation in the experiment test plots was wheat in the winter and fallow in summer, which has also been the most common farmer rotation in the Yaqui Valley because of irrigation water shortages. All observations were obtained under irrigation management practices held constant throughout the time period; i.e., fertilizer, fungicide, pesticide, harvesting, and other management practices were held as constant as possible over time. Some cultivars were only tested for three or four years before being discarded because of poor performance. Bread (*Triticum aestivum*) and durum (*Triticum durum*) wheat were planted during the test period.

Although a gap between experimental and actual yields exists, Brennan (1984) wrote, "the only reliable sources of relative yields are cultivar trials" (p. 182). While yields are higher on the Yaqui Valley test plot than on producers' fields, the relative yield and yield variance differential should be equivalent. Table 1 shows the actual on-farm wheat varietal distribution for the Yaqui Valley from 1995–2001. Table 2 reports the varietal summary statistics from the Yaqui Valley test plot used in the study. The Karnal bunt susceptibility ratings of each variety were collected and are provided in table 2.[6]

The data set is times-series in nature, i.e., data from multiple years were obtained from the same experiment station. Variance-covariance matrices were calculated using a Just-Pope regression technique that accounts for multiplicative heteroskedasticity across varieties. A

[5] The ratings as provided by INIFAP-CIRNO (2010) are (1) resistant, (2) moderately resistant, (3) moderately susceptible, and (4) susceptible.

[6] While Karnal bunt scores were collected for most varieties, some varieties did not have a score because they were no longer planted in the Valley. These varieties were given a score of "susceptible" to obtain the most conservative estimates.

Table 1. Actual Wheat Varietal Distribution in the Yaqui Valley, 1995–2001

Variety	Release Year	94–95	95–96	96–97	97–98	98–99	99–00	00–01
Bread Wheat:								
Ciano†	1979	—	—	—	—	—	—	0.4
Opata†	1985	0.7	0.4	—	—	—	—	—
Cucurpe	1986	2.1	0.1	—	0.1	—	—	—
Oasis†	1986	1.9	0.7	—	—	—	—	—
Papago	1986	0.5	0.2	—	—	—	—	—
Bacanora†	1988	0.0	0.1	—	—	—	—	0.2
Rayon	1989	16.6	8.4	17.1	10.5	8.9	16.7	14.1
Tepoca	1986	13.7	6.7	4.0	3.5	—	—	—
Baviacora†	1988	0.1	—	—	—	—	—	—
Arivechi	1992	1.5	1.0	6.4	4.8	3.2	—	—
Durum Wheat:								
Altar†	1984	46.9	75.1	66.5	77.9	83.3	68.7	65.9
Achonchi†	1989	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	—	0.0	0.1	0.0	0.0	0.0	0.0	0.1

† Denotes CIMMYT lines.

regression, and subsequent variance-covariance matrix, was estimated for each year to hold climatic, agronomic, and other production conditions constant.[7]

Results

From the actual annual varietal distribution selected by producers (table 1), the model estimates annual variance and yield per acre. Since annual empirical data exist by cultivar for the Yaqui Valley, the model can calculate the "actual" variance and yield per acre annually and use these estimates as a baseline. From these data, two iterations of the model were run. First, holding the actual annual variance constant, the variance-covariance matrix is used to identify the portfolio that maximizes yield per acre. Second, by holding actual annual yield constant and using the variance-covariance matrix, the model can minimize yield variance per acre through the use of portfolio theory.

Minimizing Variance Given a Specific Yield Level

Many producers in low-income countries are risk averse and would prefer a target yield level (e.g., breakeven), minimizing the variance around that yield rather than choosing varieties having the highest average yield potential. Portfolio analysis allows for this possibility by holding yield constant and minimizing variance through the selection of different varieties.

[7] The variance-covariance matrices are available from the authors upon request.

Table 2. Yaqui Valley Test Plot Varietal Summary, 1995–2001

Variety	Release Year	Average Yield (kg/ha)	Standard Deviation (kg/ha)	Minimum Yield (kg/ha)	Maximum Yield (kg/ha)	Karnal Bunt Susceptibility Rating	No. of Observ.
Pitic	1962	7,146	785	5,804	8,552	—	22
7 Cerros	1966	7,740	841	5,989	9,569	Mod. Resistant	76
Chapala	1967	5,153	1,599	2,593	7,136	Susceptible †	16
Jori	1969	6,044	1,179	3,695	7,552	Susceptible †	16
Yecora	1970	7,949	1,018	5,763	9,311	Mod. Resistant	22
Cocorit	1971	8,056	705	6,585	9,627	Susceptible †	70
Mexicali	1975	8,519	1,039	6,221	10,940	Mod. Susceptible	73
Yoreme	1975	7,934	260	8,230	8,773	Susceptible †	4
Nacozari	1976	8,239	878	6,305	10,108	Susceptible	76
Caborca	1979	8,092	854	6,070	9,333	Susceptible †	23
Ciano	1979	8,166	982	6,487	9,905	Mod. Susceptible	22
Yavaroa	1979	8,880	842	7,406	11,028	Mod. Resistant	73
Seri 81	1981	8,047	1,028	6,767	9,717	Susceptible	6
Seri 82	1982	8,446	912	6,695	10,582	Susceptible	76
Alamos	1983	8,381	793	7,104	9,716	Resistant	17
Eronga	1983	8,785	978	6,978	11,098	Resistant	73
Altar	1984	8,930	790	6,945	10,610	Resistant	73
Opata	1985	8,057	656	7,502	9,478	Susceptible	8
Jilotecpec	1986	8,965	585	7,995	10,200	Mod. Resistant	27
Oasis	1986	8,501	982	5,982	10,404	Susceptible	68
Tarasca	1987	7,425	370	7,463	8,249	Susceptible †	4
Bacanora	1988	6,995	448	6,476	7,425	Susceptible	4
Super Kauz	1988	8,853	761	7,305	10,089	Susceptible †	75
Achonchi	1989	8,822	815	7,079	11,082	Resistant	73
Baviacora	1992	8,982	947	7,055	10,728	Susceptible	73
Borlaug	1995	8,501	1,000	6,244	10,049	Susceptible †	45
Tarachi	2000	8,157	467	6,712	8,138	Mod. Susceptible	9
Atil C	2001	9,082	917	7,611	9,380	Resistant	9

† Karnal bunt scores could not be obtained for these varieties. They were therefore assigned a "susceptible" rating to estimate the most conservative portfolio results.

By holding constant the estimated yields acquired from actual on-farm planting data in the Yaqui Valley, the model allows for selection of varieties that will maintain the year-specific yield while permitting the choice of a bundle of varieties to minimize yield variance. Table 3 reports the reductions in variance associated with using portfolio analysis to select varieties. Results show that yield variation can be reduced up to 33%, holding year-specific yield constant. The largest estimated decrease in variance occurred in 2001, at 33%. This is likely because the Yaqui Valley had the least number of wheat cultivars sown that year, and thus the greatest potential for diversification. The lowest single varietal variance is Yoreme, at 67,600 kg/ha^2 (table 2), which yielded an average of 8,439 kg/ha in the CIMMYT test plots from 1990–2002. The portfolio analysis provides more information than stochastic dominance through estimation of the efficiency frontier.

Maximizing Yield Given a Specific Variance

The frontier shows that with the same level of variance (67,600 kg/ha^2), yields could be increased to 9,021 kg/ha (6.4%) in 2001 by planting a portfolio of 58.6%, 39.3%, and 2.1% of Baviacora, Atil C, and Jilotecpec, respectively. The model can also estimate the maximum yield a producer could obtain holding the yield variance to its historical average. Table 4 shows the yield premiums associated with the portfolio varietal distribution for each year, holding the actual annual estimated variance constant.[8,9] Yield increases ranged from a low of 67.3 kg/ha in 2000 to a high of 95.1 kg/ha in 1995. While these increases are relatively small compared to advances in genetic breeding and increased application of inputs, any gains in output without increasing risk are vital to lifting people out of poverty. When producers select varieties, gains in one attribute (yield potential) are often associated with losses in another (yield stability). In low-income countries, this tradeoff can mean the difference between being food-secure or food aid-dependent. The above example illustrates how portfolio theory allows producers to select a bundle of varieties whereby there are gains in one attribute (yield potential) *without* an associated loss in another (yield stability).

Karnal Bunt

Given the high prevalence of Karnal bunt in the Yaqui Valley, a constraint was added to the model to ensure the portfolio consisted only of those varieties classified as either "resistant" or "moderately resistant" to Karnal bunt. Varieties rated as "moderately susceptible" or "susceptible" were excluded from this portfolio. Thus, a portfolio was built with varieties that reduced the probability of infection.

Table 3 reports the reductions in variance associated with using portfolio theory application to select varieties that are resistant or moderately resistant to Karnal bunt. Results show that yield variation can be reduced up to 25.87% compared to actual planting patterns holding year-specific yield constant. Table 4 shows the yield discounts associated with all acreage being sown to resistant and moderately resistant varieties compared to the unrestricted portfolio. The yield discount ranges from a low of 54 kg/ha in 2000 to a high of 179 kg/ha in 1998 and 1999. When constrained to the Karnal bunt-resistant portfolio, producers experience a marginal decrease in yield in order to limit potentially high revenue losses associated with Karnal bunt infection.

Global Extrapolation of Economic Benefits

CIMMYT breeds for 12 specific global "mega-environments," which are based on spatial climatic and agronomic conditions. Mega-environment 1, which includes the Yaqui Valley, is the largest mega-environment and accounts for 18.2% of the world's wheat production.[10]

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[8] It should be noted that some farmers prefer to plant bread wheat over durum or vice versa. This and the following calculations assume farmers are indifferent between wheat species.

[9] It is often recommended that farmers plant particular varieties for specific field conditions. That is, some varieties are susceptible to rust (a disease) and thus should be planted to an area with a low history of rust occurrence. Our analysis assumes all fields within a county are homogeneous.

[10] Mega-environment 1 and the Yaqui Valley are classified by CIMMYT as an "optimally irrigated, low rainfall area." Climate conditions during the growing season range from temperate to 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).

Table 3. Reduction in Yield Variation by Implementing Portfolio Theory, Holding Yield Constant at Annually Observed Levels

Year	Actual Variance (kg/ha)^2	Actual Yield (kg/ha)	Portfolio Yield (kg/ha)	Unrestricted Variance (kg/ha)^2	Karnal Bunt Resistant[a] Variance (kg/ha)^2	Unrestricted Variance Reduction (%)	Karnal Bunt Restriction Variance Reduction (%)
1995	34,575	8,882	8,882	27,029	28,478	21.83	17.63
1996	39,136	8,910	8,910	27,296	29,861	30.02	23.70
1997	39,769	8,921	8,921	27,790	30,853	30.12	22.41
1998	41,159	8,926	8,926	28,079	31,330	31.77	23.87
1999	41,363	8,926	8,926	28,086	31,413	32.01	24.05
2000	41,889	8,928	8,928	28,183	31,605	32.71	24.55
2001	41,807	8,922	8,922	27,850	30,988	33.38	25.87

[a] Constrains 100% of sown acreage to be either Karnal bunt resistant or moderately resistant varieties.

Table 4. Increase in Yield by Implementing Portfolio Theory, Holding Yield Variance Constant at Annually Observed Levels

	Constant		Portfolio Yield With and Without Karnal Bunt Restrictions			
Year	Actual Variance (kg/ha)^2	Actual Yield (kg/ha)	Unrestricted Yield (kg/ha)	Karnal Bunt Resistant Yield (kg/ha)	Unrestricted: Actual (kg/ha)	Unrestricted: KB Resistant (kg/ha)
1995	34,575	8,882	8,977	8,802	95.05	175.38
1996	39,136	8,910	8,990	8,814	79.18	175.96
1997	39,769	8,921	8,991	8,814	69.95	177.31
1998	41,159	8,926	8,993	8,814	68.18	179.47
1999	41,363	8,926	8,993	8,814	67.91	179.47
2000	41,889	8,928	8,994	8,941	67.29	53.52
2001	41,807	8,922	8,995	8,919	72.81	76.10

Since the CIMMYT cultivars used in this study were bred specifically for mega-environment 1, if the Yaqui Valley estimated yield benefits could be extrapolated to all mega-environment 1 acreage, estimates of a more global economic benefit from portfolio theory could be obtained. We acknowledge this is a somewhat heroic assumption. But accepting this assumption, first note that the historical acreage planted to CIMMYT varieties in mega-environment 1 ranged from 7.9 to 9.1 million acres from 1995–2001. Using historical global wheat prices to illustrate more potential global economic benefits from implementing portfolio theory to yield mix selection, estimates (in 2007 constant $US) of these possible gains are reported in table 5. The estimated benefit gains range from a low of $31.7 million in 2000 to a high of $72.5 million in 1996. Historically, 65%–77% of all CIMMYT seed samples have been sent to low-income countries, implying that a large share of any such benefits would go to low-income consumers and producers. Table 5 also gives estimated per acre economic gains, which range from a low of $3.63 in 2000 to a high of $8.91 in 1996.

Table 5. Potential Gains from Using Portfolio Theory in Maximizing Yield per Acre: No Karnal Bunt Acreage Restrictions

Year	Gain by Using Portfolio [a] (kg/ha)	Gain by Using Portfolio (bu/ac)	Acres in Mega-Environ. 1 Planted to CIMMYT Lines	Price of Wheat per Bushel (2007 $US)	Additional Bushels (Mega-Environ. 1)	Additional Gain from Portfolio (2007 $US)	Additional Gain/Acre from Portfolio (2007 $US)
2001	72.81	1.08	8,600,000	4.11	9,310,871	38,271,072	4.45
2000	67.29	1.00	8,730,000	3.63	8,735,054	31,665,541	3.63
1999	67.91	1.01	9,080,000	4.09	9,168,966	37,530,585	4.13
1998	68.18	1.01	8,800,000	5.01	8,918,936	44,653,302	5.07
1997	69.95	1.04	8,510,000	6.57	8,851,525	58,136,183	6.83
1996	79.18	1.18	8,140,000	7.57	9,583,865	72,526,437	8.91
1995	95.05	1.41	7,980,000	5.03	11,278,616	56,725,052	7.11

[a] Estimates obtained from table 4.

The Efficient Mean-Variance Frontier

While the above analysis holds variance constant and maximizes yield, what if the farmer was willing to take on slightly more risk for a higher yield or reduce risk to increase yield stability? This tradeoff is identified on the efficiency frontier, which defines the optimal portfolios derived from the quadratic programming model. The efficiency frontier between yield mean and variance, illustrated in figure 1, demonstrates how cultivar yield risk could be reduced by planting a portfolio of varieties. Portfolios located on the efficiency frontier are characterized by: (*a*) higher yields, (*b*) lower yield variance, or (*c*) both. Because producers could either maintain yield and lower variance or maintain variance and increase yield, any mix not located on the frontier is inefficient.

By combining experimental yields with varietal acreage planted data, the yield from the actual planted varietal distribution by famers in the Yaqui Valley in 2001 was calculated at 8,922 kg/ha, with a variance of 41,807 $(kg/ha)^2$. In comparison, if the entire Valley was planted with the popular cultivar "Achonchi," the estimated yield per acre would be slightly less at 8,822 kg/ha and the variance would be higher at 42,461 $(kg/ha)^2$. Figure 1 shows a portfolio of varieties (57% Baviacora, 17% Atil C, 16% Jilotecpec, and 10% Altar) that both increases yield from the 2001 actual planting varietal distribution by 69 kg/ha and lowers the variance by 1,106 $(kg/ha)^2$, a 6% reduction in variance. Holding the actual variance constant in 2001 by implementing portfolio theory, wheat farmers in the Yaqui Valley could have produced an additional 72.81 kg/ha. This translates to a revenue increase of $4.45 (2007 $US) per acre.[11] The same exercise was conducted for the Karnal bunt restriction and is also illustrated in figure 1. While these revenue numbers may appear small for high-income country producers and most in the Yaqui Valley, the majority of low-income producers are either subsistence farmers or sell only a small portion of their crop. Therefore, even a small increase in production while holding variability constant is attractive to millions of poverty-stricken farmers worldwide.

[11] An additional yield of 72.81 kg/ha is equivalent to 1.0826 bu./acre. The 2001 global wheat price per bushel is $4.11 in 2007 $US.

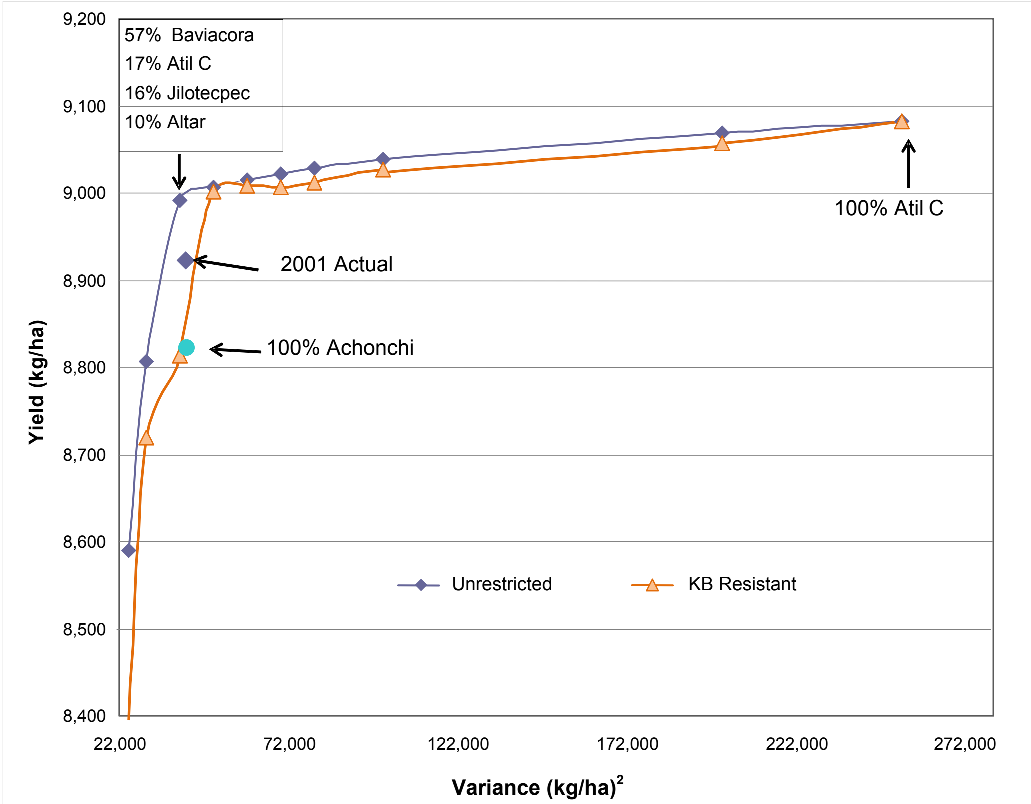

Figure 1. The efficient mean-variance frontier, the Karnal-bunt resistant mean-variance frontier, and the actual 2001 varietal distribution for the Yaqui Valley, Mexico

Conclusion

Portfolios take advantage of differences in how wheat varieties respond under different growing conditions. Since climate, pests, disease, and other environmental factors are not known prior to planting, cultivar diversification can result in positive economic benefits to low-income wheat producers. Specifically, there may be large potential gains from combining varieties that are characterized by inverse yield responses to growing conditions such as drought, pest infestation, or the presence of a specific disease such as Karnal bunt. When constrained to the Karnal bunt-resistant portfolio, producers experience a marginal decrease in yield in order to limit potentially large revenue losses associated with a Karnal bunt infection.

Traditionally, when farmers decide to seed multiple varieties, they choose combinations based on varietal descriptions, intuition, and average yields, ignoring information on variances and covariances. This study has created varietal combinations through the use of portfolio analysis, which incorporates the variance-covariance matrix. Several issues were analyzed, minimizing the yield variance while maintaining the actual yield observed and maximizing yield while holding yield variance constant at the cultivars' respective observed rates.

Using CIMMYT test plot data from 1990–2002 for 33 wheat cultivars, the model estimates indicate that by employing portfolio theory, annual yield variance could have been decreased between 21% and 33%, while holding yields constant at their annual levels. By using portfolio theory, model estimates suggest yield increases ranged from 1%–2% per acre, holding yield variance constant at annual levels. Extrapolating the average increase in yield for total wheat acreage in mega-environment 1 sown to CIMMYT wheat cultivars and yearly global wheat price results in an increase in revenue between $32 and $73 million (2007 $US) to low-income producers globally.

One of the major contributions of portfolio theory to poverty alleviation is the potential for decreased yield variability in low-income countries, which is beneficial to both producers and consumers in that it typically results in price stability within markets. The other contribution is the enhancement of yield potential without additional risk. Using CIMMYT's own projections, by 2020, low-income nations will need 40% more wheat than they consume today. Although some of this increased demand could be satisfied by an increase in imports, a large percentage must be generated through increased yields domestically. While portfolio theory alone will not increase supply by the amount required to meet the rising demand in low-income countries, it can be used in conjunction with new germplasm to increase yield while mitigating yield instability.

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References

Adesina, A., and M. Zinnah. "Technology Characteristics, Farmers' Perceptions, and Adoption Decisions: A Tobit Model Application in Sierra Leone." *Agr. Econ.* 9(2003):297–311.

Barkley, A. P., and L. L. Porter. "The Determinants of Wheat Variety Selection in Kansas, 1974–1993." *Amer. J. Agr. Econ.* 78(February 1996):202–211.

Bawa, V. S., J. N. Bodurtha, Jr., M. R. Rao, and H. L. Suri. "On Determination of Stochastic Dominance Optimal Sets." *J. Finance* 40,2(June 1985):417–431.

Brennan, J. P. "Measuring the Contribution of New Varieties to Increasing Wheat Yields." *Rev. Mkting. and Agr. Econ.* 52(1984):175–195.

Dalton, T. "A Household Hedonic Model of Rice Traits: Economic Values from Farmers in West Africa." *Agr. Econ.* 31, 2/3(December 2004):149–159.

Detlefsen, N., and A. Jensen. "A Stochastic Model for Crop Variety Selection." *Agr. Systems* 81(2004):55–72.

Dixon, J., L. Nalley, P. Kosina, P. Aquino, R. la Rovere, and J. Hellin. "Adoption and Economic Impact of Improved Wheat Varieties in the Developing World." *J. Agr. Sci.* [Centenary Review] 144(2006):489–502.

Doss, C. R., W. Mwangi, H. Verkuijl, and H. De Groote. "Adoption of Maize and Wheat Technologies in Eastern Africa: A Synthesis of the Findings of 22 Case Studies." CIMMYT Economics Work. Pap. No. 03-06. Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), Mexico, D.F., 2003.

Edmeades,S., D. Phaneuf, M. Smale, and M. Renkow. "Modelling the Crop Variety Demand of Semi-Subsistence Households: Bananas in Uganda." *Agr. Econ.* 59(2008):329–349.

Figge, F. "Bio-folio: Applying Portfolio Theory to Biodiversity." *Biodiversity and Conservation* 13(2004): 822–849.

Gollin, D. "Impacts of International Research on Intertemporal Yield Stability in Wheat and Maize: An Economic Assessment." Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), Mexico, D.F., 2007.

Granger, C. W. J. "Some Comments on Risk." *J. Appl. Econometrics* 17,5 [Special Issue: *Modelling and Forecasting Financial Volatility*] (September/October 2002):447–456.

Hazell, P. B. R., and R. D. Norton. *Mathematical Programming for Economic Analysis in Agriculture*. New York: MacMillan Publishing Co., 1986.

Heady, E. *Economics of Agricultural Production and Resource Use*. Englewood Cliffs, NJ: Prentice-Hall, 1952.

Instituto Nacional de Investigaciones Forestales y Agropecuarias (INIFAP). Personal communications with Dr. Guillermo Fuentes Dávila, INIFAP-CIRNO, Campo Experimental Valle del Yaqui, January 2010.

Jensen, A. "Building a Web-Based Information System for Variety Selection in Field Crops: Objectives and Results." *Computers and Electronics in Agr.* 32(2001):195–211.

Larson, D., E. Jones, R. Pannu, and R. Sheokand. "Instability in Indian Agriculture: A Challenge to the Green Revolution Technology." *Food Policy* 29(2004):257–273.

Levy, H. "Stochastic Dominance and Expected Utility: Survey and Analysis." *Mgmt. Sci.* 38,4(April 1992): 555–593.

Levy, H., and M. Levy. "Prospect Theory and Mean-Variance Analysis." *Rev. Finan. Stud.* 17,4(Winter 2004):1015–1041.

Lintner, J. "Security Prices, Risk, and Maximum Gains from Diversification." *J. Finance* 21(1965):587–615.

Markowitz, H. *Portfolio Selection: Efficient Diversification of Investments*. New York: John Wiley and Sons, 1959.

Meyer, J. "Mean-Variance Efficient Sets and Expected Utility." *J. Finance* 34,5(December 1979):1221–1229.

Nalley, L., A. Barkley, B. Watkins, and J. Hignight. "Enhancing Farm Profitability Through Portfolio Analysis: The Case of Spatial Rice Variety Selection." *J. Agr. and Appl. Econ.* 41,3(2009):641–652.

Nyikal, R. A., and W. O. Kosura. "Risk Preference and Optimal Enterprise Combinations in Kahuro Division of Muranga District, Kenya." *Agr. Econ.* 32(2005):131–140.

Redmond, C. H., and F. W. Cubbage. "Portfolio Risk and Returns from Timber Asset Investments." *Land Econ.* 64(November 1988):325–337.

Robison, L. J., and J. R. Brake. "Application of Portfolio Theory to Farmer and Lender Behavior." *Amer. J. Agr. Econ.* 61(February 1979):158–164.

Rothschild, M., and J. E. Stiglitz. "Increasing Risk I: A Definition." *J. Econ. Theory* 2(1970):225–243.

Russell, W. R., and T. K. Seo. "Efficient Portfolios by Stochastic Dominance." *S. Econ. J.* 46,3(January 1980):877–882.

Sanchirico, J. N., M. D. Smith, and D. W. Lipton. "Ecosystem Portfolios: A Finance-Based Approach to Ecosystem Management." Paper presented at the AERE Workshop: "Natural Resources at Risk," Jackson, WY, June 2005.

Sharpe, W. *Portfolio Theory and Capital Markets*. New York: McGraw-Hill, 1970.

Smale, M., B. Mauricio, A. Gomez, and, J. Alfonso. "Maize Diversity, Variety Attributes, and Farmers' Choices in Southeastern Guanajuato, Mexico." *Econ. Develop. and Cultural Change* 50,1(October 2001): 201–225.

Timmer, P. "The Macroeconomics of Food and Agriculture." In *International Agricultural Development*, eds., C. Eicher and J. Staatz. Baltimore, MD: Johns Hopkins University Press, 1998.

Tobin, J. "Liquidity Preference as Behavior Towards Risk." *Rev. Econ. Stud.* 25(1958):65–86.

van Ginkel, M., R. Trethwoan, K. Ammar, J. Wang, and M. Lillemo. *Guide to Bread Wheat Breeding at CIMMYT.* Wheat Special Report No. 5 (revised ed.). Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), Mexico, D.F., 2002.