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A STOCHASTIC PRODUCTION FUNCTION ANALYSIS OF MAIZE HYBRIDS AND YIELD VARIABILITY IN DROUGHT-PRONE AREAS OF KENYA

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Tegemeo Institute of Agricultural Policy and Development is a Policy Research Institute under Egerton University with a mandate to undertake empirical research and analysis on contemporary economic and agricultural policy issues in Kenya. The Institute is widely recognized as a centre of excellence in policy analysis on the topical agricultural issues of the day, and in its wide dissemination of findings to government and other key stakeholders with a view to influencing policy direction and the decision making process. Tegemeo's empirically based analytical work, and its objective stance in reporting and disseminating findings has over the past decade won the acceptance of government, the private sector, civil society, academia and others interested in the performance of Kenya's agricultural sector.

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Abstract

The importance of maize as a staple food and source of cash for smallholder farmers in drought-prone areas of Sub-Saharan Africa, and the threat of greater climatic variability, have led recently to considerable investment in maize breeding for water-use efficiency. Kenya is a target country for this research. Although trial data suggest that improved genetic materials in the research pipeline may increase mean yields and reduce yield variability, relatively little has been documented concerning the variability of maize yields on smallholder farms in Kenya. This research serves as a baseline by testing the effect of current maize hybrids on the mean, variance, and skewness of yields with a stochastic production function applied to survey data collected by Tegemeo Institute during the 2006-7 cropping season. We find that, relative to other maize types, hybrids enhance mean yields, although there is scant evidence of their effect on the variance of yields. Perhaps more importantly, hybrids reduce the exposure of smallholders to extremely low yields, pulling maize yields toward the mean. Additional research is required to confirm these findings using longitudinal data and rainfall data.

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1.0 Introduction

Most of the world's 160 million hectares of maize are rainfed, and an estimated 15 percent of global maize production is lost each year to drought (Edmeades, 2008). Drought stress, which occurs even in better-watered areas, is one of two physical factors that most limits maize productivity (soil quality is the second). Globally, the relative importance of water constraints appears to be highest in Sub-Saharan Africa (Cooper et al. 2008). Over a decade ago, before scientists recognized the potential impact of climate change, Heisey and Edmeades (1999) estimated that in Sub-Saharan Africa, roughly a quarter of the 18 million ha of maize then grown in the lowland and mid-altitude subtropics grew under frequent stress from drought.

A study of the economic costs of climate change in Kenya concluded that, on top of the substantial costs of existing climate variability in Kenya, the future additional costs of climate change could be equivalent to a loss of 2.6% of GDP each year by 2030 (SEI 2009). Variation in precipitation, which can result in yields that are 20 percent lower or higher on an annual basis (Isik, 2003), makes production risk in the drought-prone areas of Kenya a significant element of farmer decision-making process.

Most smallholder farmers in Kenya grow maize, and according to panel data collected since 1997 by Tegemeo Institute, most maize growers plant hybrids (Smale and Olwande, 2011). Historically and today, adoption rates have differed sharply across agro-ecological zones (Hassan 1998; De Groote et al., 2005; Smale and Olwande 2011). Smallholder farmers in Kenya, and particularly farm households that grow maize for food, have limited access to credit and no access to insurance. They have strong incentive to plant seed that reduces the variance of yields and limits their exposure to downside risk. Donors and the Government of Kenya are currently investing in the development of maize varieties that are tolerant to drought and water-use efficient. To our knowledge, whether hybrid seed reduces or exacerbates yield risk (variability and downside risk) for farmers in drought-prone areas of Kenya has not yet been tested in an economic model of farmer decision-making.

This analysis has two objectives. The first is to explore the effects of the maize hybrids currently grown by smallholder farmers in drought-prone areas of Kenya on the mean, variance and skewness of yields. We test these effects in the framework of a stochastic production model, including both full order and partial order moments. The second is to provide “baseline information” to gauge the future impacts of the adoption of water-efficient improved maize by the same population of farmers.

This study contributes to an old debate whether the yields of improved seed varieties are higher but also more variable than those of unimproved, farmers’ varieties, especially given the use of nitrogenous fertilizer (e.g. Anderson and Hazell 1989). It also has relevance for a continued debate concerning the efficiency of agricultural research investment to increase domestic maize productivity in high potential areas versus the equity implications of investing in areas with lower yield potential (e.g., Karanja, Renkow and Crawford, 2003). Karanja, Renkow and Crawford (2003) concluded that while technology adoption in high potential areas has a substantially greater, positive impacts on aggregate real incomes, it is likely to have inferior income distributional outcomes compared to technology adoption in marginal regions. A premise of plant breeding research for drought-prone environments is that improved seed can reduce yield risk for farmers and enhance the food security of smallholders in marginal areas. In Kenya, such a strategy may also reduce the maize import bill, with consequences for the national economy.

The methodological framework applied in this study is described next, including the stochastic production framework, specification, functional form and data source. Selected descriptive statistics and econometric findings are presented in Section 4. Conclusions are drawn in the final section.

2.0 Methods

2.1 The Stochastic Production Framework

Growing crops is inherently risky, because it depends on a series of weather events that occur after the seed has planted. The farmer can adapt to, or take measures to mitigate the impacts of these stochastic events, but cannot control them. In a seminal article, Just and Pope (JP, 1978) argued that an estimated production function should be flexible, allowing inputs to influence the deterministic and stochastic components of production separately so that the sign of the effect can differ in direction. They proposed a general functional form in which inputs can serve to both enhance yields and reduce (increase) variance.

Initially estimated in the form of a multiplicative heteroskedasticity model, the Just-Pope (1978) production function has been widely used by applied economists to analyze the effects of input use on both the yield and the variance of crop output. The heteroskedasticity of the error term can be viewed as valuable information to be explored and explained. A heteroskedastic error term implies that there is a factor (or set of factors) that can explain variation in the error component, and these may be the same inputs that affect the mean production function. Since these inputs are under the control of a producer, input choice can be used to manage production risk.

Examples of applications of this approach include Traxler et al. (1995), who analysed the impact of wheat genetic improvement on wheat yields using trial data, and Smale et al. (1998), who adapted Traxler's approach to analyze the effects of wheat variety diversity on district yields in the Punjab province of Pakistan. More recently, Shankar et al. (2007) applied the framework to explore the risk properties of Bt cotton. Di Falco, Chavas and Smale (2007 applied Antle's (1983) method and the Just-Pope production function to examine the effects of input use and wheat diversity on skewness as well as the mean and variance of yields in Ethiopia. Recently, in a further development of the 'method of moments,' Antle (2010) proposed methods to estimate asymmetric effects of inputs on potato yield distributions.

The stochastic production function (including three moments) we estimate is given by

$$y = f(\mathrm{H}, \mathbf{X}, \alpha) + g(\mathrm{H}, \mathbf{X}, \beta) + h(\mathrm{H}, \mathbf{X}, \delta) + \varepsilon_i. \quad (1)$$

H represents hybrid seed use, **X** is a vector of production inputs, α, β, and δ are vectors of parameters that will be estimated, and ε is a randomly distributed error term. The first term in equation 1 represents the mean model component of the stochastic production function, while the second and third terms represent the variance and skewness models, respectively.

During the Green Revolutions in rice and wheat in Asia, researchers often hypothesized that although improved varieties increased average yields, they also increased yield variance. A major paradigm for analyzing farmer decision-making was the portfolio theory of investment, in which investors choose combinations of assets to trade-off means and variance of returms (Just and Zilberman, 1983) In retrospect, evidence from applied research was inconclusive concerning this relationship. In some environments, and with some germplasm types or crops, improved varieties increased both means and variance; in others, the yields of improved varieties were not only higher but more stable. Findings also depending on the scale of analysis and crop (Hazell 1989).

Thus, our hypothesis concerning the effects of maize hybrids on yield variance is ambivalent. We consider that possibility that hybrid seed is risk-increasing, risk-neutral or risk-decreasing on farms in Kenya, by testing:

$$\frac{\partial\, Var(y)}{\partial X} > 0, 0, < 0 \quad . \qquad (2)$$

However, given that our geographical interest is targeting more arid regions, the interaction between agroecology and genetic content may affect the relative benefits and riskiness of improved varieties. Hence, as JP acknowledged, risk-averse farmers have an incentive to use risk-reducing inputs to manage their exposure to risk and its implicit cost. It is an empirical question what impact hybrid maize varieties have upon mean yields and production risk in more drought prone areas. We extend the study of production risk to explore the impact of varietal choice on the skewness of maize yields.

Traxler et al. (1995) specified an exponential form [exp (H, **X**, β)] for g (H, **X**, β), and [exp (H, **X**, δ)] for h (H, **X**, δ). In that specification, the variance was estimated by squaring the absolute value of the residual, where g = exp $|e_i|^2$. The skewness of the yield distribution was estimated by cubing the absolute value of the residual (h = exp $|e_i|^3$). Next, weighted least squares regression was employed to estimate $y = f(\mathrm{H}, \frac{1}{\bar{\sigma}_i}\mathbf{X}, \alpha) + \varepsilon_i$.

In this analysis, an ordinary least squares (OLS) regression is estimated for the mean model and tested for the null hypothesis of homoskedasticity. When the null hypothesis is rejected, weighted least squares (WLS) regression is estimated in place of the OLS regression for the model explaining mean yields. Estimation of the variance and skewness models is described next.

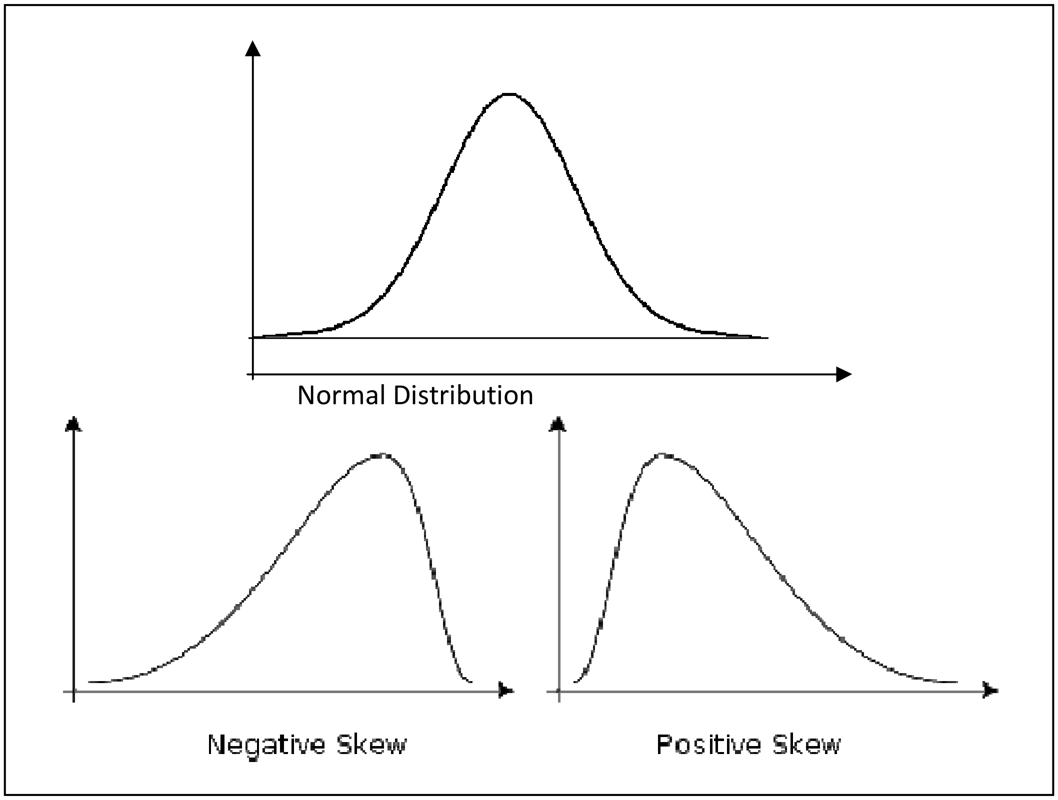
2.1.1 Full Order Moments

Full order moments refer to the full observed distribution of the estimated variance and skewness, whether negative or positive in value. To estimate the variance model in the stochastic production framework, the residual (ε) is retained from the initial OLS regression and used to calculate the dependent variable for the following regression:

$$\ln |u_i|^2 = g\,(\mathbf{H},\mathbf{X},\beta) + \varepsilon_i \tag{3}$$

Skewness in statistical theory refers to the asymmetry of probability distributions for random variables. **Error! Reference source not found.**1 displays the normal probability distribution, as well as examples of positive and negative skewness.

Figure 1: Skewness in probability distributions



In the normal probability distribution, all observations are centered around a mean. In a negatively skewed distribution, most of the distribution is concentrated on the right side of the distribution and the left tail is longer. In a positively skewed distribution, the distribution is concentrated on the left side of the distribution with a long right tail.

The skewness regression is analogous to the variance regression. The dependent variable is the natural logarithm of the cubed error term from the OLS regression:

$$\ln |u_i|^3 = h\,(\mathrm{H}, \mathbf{X}, \delta\,) + \varepsilon_i \tag{4}$$

2.1.2 Partial Order Moments

Antle (2010) argues the importance of analyzing partial order moments of skewness to identify which factors negatively and positively affect asymmetry in yield distributions. The partial order moments of skewness for positive and negative skewness are represented by equations 4 and 5, respectively.

$$\ln u_i^3 = h\,(\mathbf{H}, \mathbf{X}, \delta\,) + \varepsilon_i \quad \text{for } \varepsilon_i > 0 \tag{5}$$

$$\ln u_i^3 = h\,(\mathbf{H}, \mathbf{X}, \delta\,) + \varepsilon_i \quad \text{for } \varepsilon_i < 0 \tag{6}$$

To summarize the overall approach, first, the mean model was estimated using an OLS regression. When the null hypothesis of homoscedasticity was rejected, a WLS regression was carried out for the mean model approach. From the OLS model, the residual, u_i, was retained.

The residual was squared and cubed to create the dependent variables for the variance and skewness models. In addition to the full order moment skewness model, the partial order moment models were estimated to identify factors affecting positive and negative deviations. This allowed us to test whether input effects were asymmetric in the skewness model.

2.2 Functional Form

We considered four common functional forms to express input-yield relationships: linear, quadratic, Cobb Douglas, Generalized Leontief (r=2), and Generalized Leontief (r=3). The translog function was not included because interactions between zero values of independent variables prevented its estimation. Each form has implications for the marginal impact of inputs on productivity (the mean regression), and risk (the variance and skewness equations).

Table 1: Functional forms

Function	**Functional Form** (*i, j, k = 1, … , n*)
Linear	$y = \propto + \sum_i \beta_i X_i$
Quadratic	$y = \propto + \sum_i \beta_i X_i + \sum_i \sum_j \delta_{ij} X_i X_j$
Cobb-Douglas	$y = \propto \prod_i X_i^{\beta} i$
Generalized Leontief (r=2)	$y = \sum_i \sum_j \delta_{ij} X_i^{\frac{1}{2}} X_j^{\frac{1}{2}}$
Generalized Leontief (r=3)	$y = \sum_i \sum_j \delta_{ij} X_i^{\frac{1}{3}} X_j^{\frac{1}{3}}$

Source: Griffin et al. (1987)

2.3 Specification

Equation (7) represents the inputs and shift variables included in the mean regression model:

Yield = *f* (acres, seed quantity, hired labor, family labor, nitrogen, phosphate, season, seed type, agro-ecological zones, slope of land, credit assistance, land tenure, hybrid maize experience) (7)

Maize yield in tons per acre was regressed against plot size, seed quantity, hired labor, family labor, nitrogen use, phosphate use, and years of hybrid maize experience. Dummy variables were included for cropping season, hybrid seed use, agro-ecological zones, terraced land, credit, and tenure. Interaction terms were included for each pair of inputs and between the hybrid dummy and each input. For simplicity, the variance and skewness models did not include the interaction terms.

Table 1 shows the construction of explanatory variables. Both hired and family labor were aggregated across labor activities to create two labor variables. Compound and nitrogen fertilizers were converted to nitrogen and phosphate nutrient equivalents to account for varied compositions. Potassium was dropped from the analysis as most households use compound fertilizers that have zero percent of this element.

Table 2: Construction of explanatory variables

Variable	Description
Acres	Plot area in acres
Seed Quantity	Kgs of seed used per acre.
Hired Labor	The total amount of hired labor in days per acre, aggregated across production activities (e.g. first plowing, second plowing, harrowing, planting, first weeding, top-dressing, second weeding, field dusting, stoking and harvesting).
Family Labor	The total amount of family labor in hours per acre, aggregated for men, women, and children across production activities (e.g. first plowing, second plowing, harrowing, planting, first weeding, top-dressing, second weeding, field dusting, stoking and harvesting).
Nitrogen Use	The total amount of nitrogen in nutrient kgs per acre by each household.
Phosphate Use	The total amount of phosphate in nutrient kgs per acre.
Harvest Dummy	Value of one for the main season and zero for the short season.
Hybrid Dummy	The hybrid dummy takes a value of one for purchased F1 hybrid seed, a mixture of F1 hybrid and local seed, or a mixture of F1 hybrid and retained hybrid seed. The variable takes a value of zero for seed that was entirely retained hybrid, seed of improved open pollinated varieties, and local varieties.
AEZ2 Dummy	The data consists of three agro-ecological zones in Kenya: AEZ2 or the lowlands, AEZ3 or the lower midland 3-6, and AEZ4 or the lower midland 1-2. The AEZ2 dummy takes on a value of one for those households in AEZ2, and a value of zero for those households in AEZ3 and AEZ4.
AEZ4 Dummy	The data consists of three agro-ecological zones in Kenya: AEZ2 or the lowlands, AEZ3 or the lower midland 3-6, and AEZ4 or the lower midland 1-2. The AEZ4 dummy takes on a value of one for those households in AEZ4, and a value of zero for those households in AEZ2 and AEZ3.
Terraced Land Dummy	The terraced land dummy takes on a value of one for land characterized as steep-terraced and moderate-terraced, and a value of zero for land characterized as flat, steep, or moderate.
Credit Dummy	The credit dummy takes on a value of one if the household received cash credit, and zero otherwise.
Tenure Dummy	The tenure dummy takes on a value of one if the land is owned with or without a title deed or owned by parent/relative, and takes on a value of zero if the land is rented or owned by government /communal /cooperative.
Hybrid Maize Experience	The number of years the household has had experience growing hybrid maize, including the 2006-7 cropping seasons.

2.4 Data

The data used for this study was collected by Tegemeo Institute of Agricultural Policy and Development and Michigan State University during the 2006-7 cropping season from 1,397 households and 2,588 maize plots sampled across 24 districts. This analysis includes a subset of 459 households with 951 maize plots located in agro-ecological zones (AEZ) two (lowland), three (lower midland 3-6), and four (lower midland 1-2). Households located in high potential maize-growing areas have been excluded.

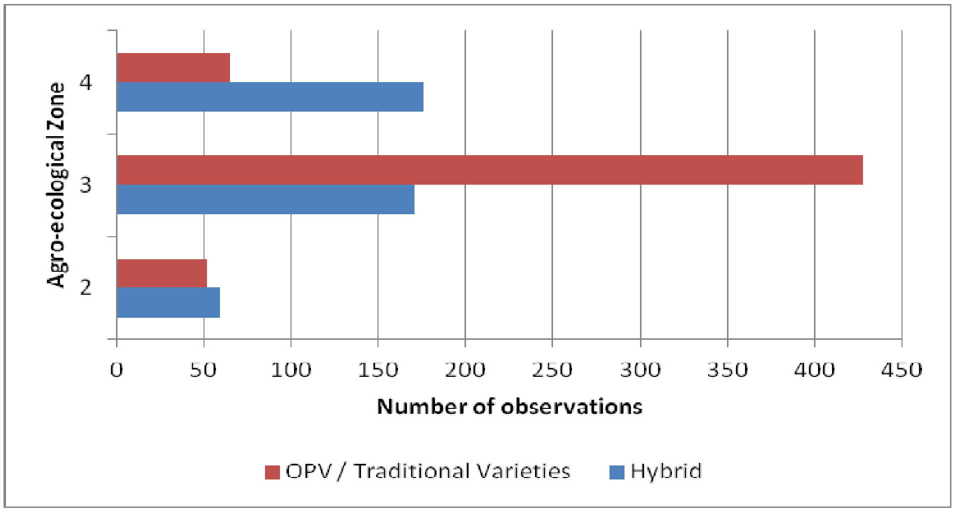
In addition to identifying drought prone areas, maize plots were classified according to seed type. The final sample included 406 hybrid plots and 545 non-hybrid plots. Thus, roughly 40 percent of plots in drought prone areas of Kenya were planted to hybrid maize during the 2006-7 cropping season.

3.0 Results

3.1 Frequency of Maize Plots by Seed Type

Figure 2 depicts seed type by agro-ecological zone. In AEZ4, the frequency of hybrid plots is over twice as high as that of non-hybrid plots. Frequencies are similar for the two seed types in AEZ2. However, in AEZ3, non-hybrid plots far outweigh hybrid plots.

Figure 2: Cross tabulation of seed variety by agro-ecological zone for maize plots



Source: Jones 2011, based on Tegemeo survey data collected in 2006-7.

Descriptive statistics of the independent and dependent variables are presented in Table 3, by AEZ.

Table 3: Descriptive statistics for maize plots, by AEZ, both seasons

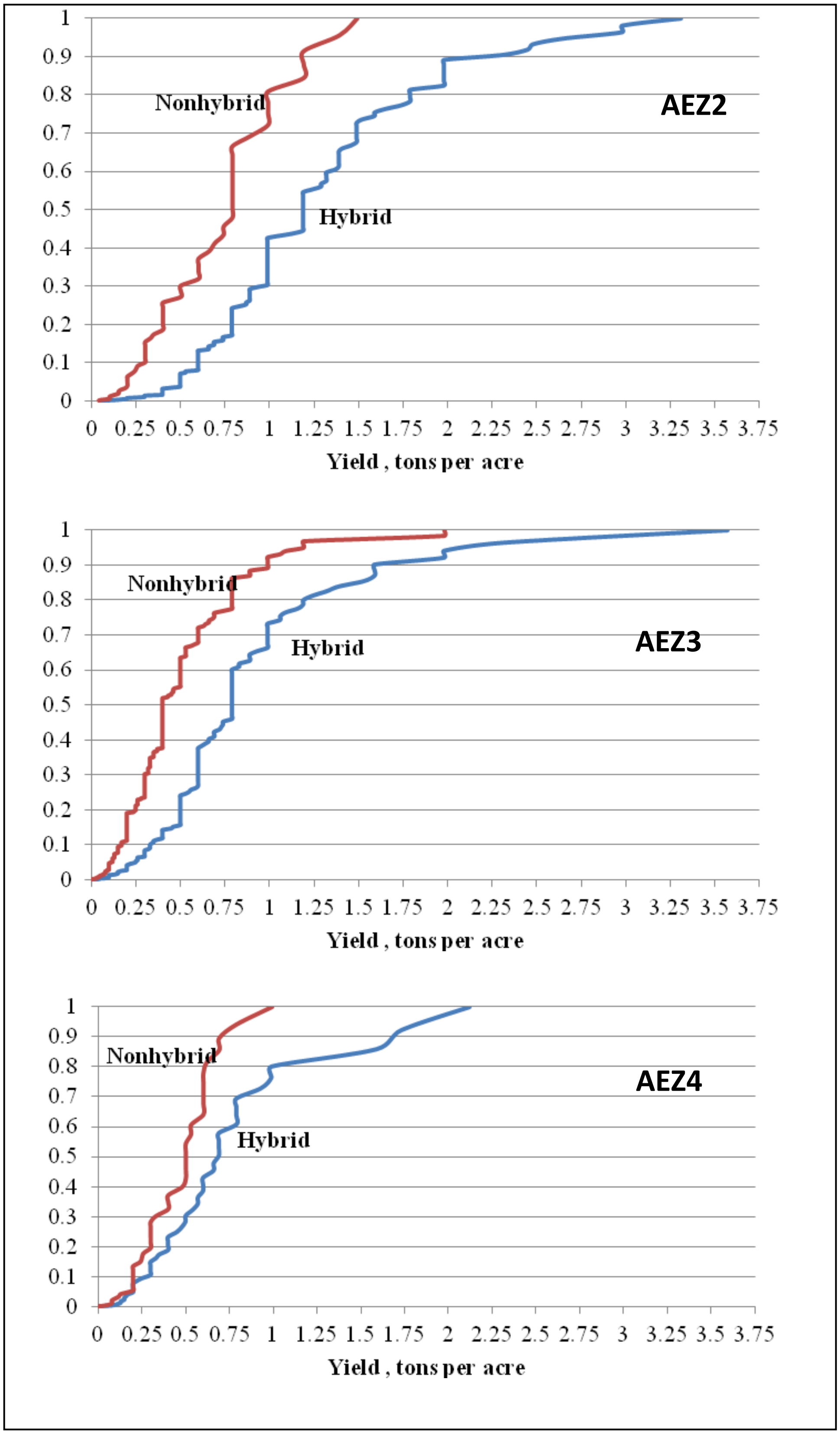
	AEZ 2		**AEZ 3**		**AEZ 4**	
Variable	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Yield (kgs/acre)	362.9	317.4	342.4	323.8	793.4	509.2
Acres	0.9	0.5	1.4	1.4	1.0	0.9
Seed Quantity (kgs/acre)	5.0	2.6	4.2	2.4	4.3	2.0
Hired Labor (days/acre)	7.3	11.5	2.8	6.4	0.7	3.4
Family Labor (hours/acre)	326.6	369.4	194.4	191.6	377.0	377.6
Nitrogen Nutrient Use (kgs/acre)	1.3	5.6	1.1	3.6	12.7	15.2
Phosphate Nutrient Use (kgs/acre)	2.0	9.8	1.4	3.7	13.1	14.0
Hybrid Dummy	0.5	0.5	0.3	0.5	0.7	0.4
Terraced Dummy	0.0	0.2	0.5	0.5	0.4	0.5
Credit Dummy	0.3	0.4	0.3	0.5	0.1	0.3
Tenure Dummy	0.7	0.5	0.4	0.5	0.4	0.5
Years Hybrid Maize Experience	13.5	10.7	5.6	7.7	16.6	13.5

Source: Jones 2011, based on Tegemeo survey data collected in 2006-7.

3.2 Cumulative Yield Distributions

Figure 3 displays the cumulative distribution of yields for hybrids versus non-hybrids in each AEZ studied. As expected given comparative yield potential and the differences in nutrients applied by maize type in each zone, hybrid maize yields dominate non-hybrids in a first-order stochastic dominance sense. In other words, the data suggest that regardless of attitudes toward risk, farmers would prefer to grow hybrids because the probability of obtaining lower yields is greater with non-hybrids than with hybrids at any yield level. This analysis does not however, imply that higher yields translate into higher net returns for farmers once the cost of seeds and other inputs are taken into consideration. In particular, the close proximity of the two yield distributions at the low yield outcomes suggests that the cumulative distribution of net returns may cross. We leave this issue for future study.

Figure 3: Observed cumulative frequency of yields for AEZ 2, 3, and 4



3.3 Mean Maize Yields

OLS estimates for mean output response are shown by functional form in Tables 4a and 4b. The Breusch-Pagan test statistic is distributed as chi-squared under the null hypothesis of homoscedasticity. The values of these tests were: 314.0 for the linear form ($P \leq 0.001$), 293.6 for the quadratic ($P \leq 0.001$), 223.8 for the Cobb-Douglas ($P \leq 0.001$), 322.8 for the generalized Leontief (r=2) ($P \leq 0.001$), and 337.3 for the generalized Leontief (r=3) ($P \leq 0.000$). As a result of heteroscedasticity, the least squares estimators are biased and inefficient. The estimates of the variances are also biased, which invalidates statistical tests of significance. White robust standard errors have been calculated and are included in Tables 4a and 4b to present robust OLS estimates for comparison.

Table 4a: Mean maize production function without interaction effects, by functional form (OLS)

	Linear			Quadratic			Cobb-Douglas			Generalized Leontief			Generalized Leontief (r=3)		
	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std. Error
INTERCEPT	0.1	***	4.4E-02	-0.1		0.1	0.8	*	0.4	-0.5	**	0.2	-1.2	**	0.5
Acres	-2.9E-02	***	9.9E-03	4.3E-02		3.8E-02	-0.3	***	0.1	0.3	***	0.1	0.8	***	0.3
Seed Quantity (tons/acre)	21.4	***	5.9	72.0	***	22.1	0.1	**	0.1	11.8	***	3.5	9.6	***	3.2
Hired Labor (days/ acre)	3.4E-04		2.0E-03	-9.3E-04		7.8E-03	-0.1		0.1	0.0		0.1	-3.6E-02		0.1
Family Labor (hours/acre)	1.8E-05		6.4E-05	2.2E-04		2.0E-04	-0.1	***	3.1E-02	0.0	*	0.0	0.1		0.1
Nitrogen Use (tons/acre)	8.3	**	4.1	11.3		12.4	0.2	***	4.8E-02	-2.3		3.7	-1.4		2.9
Phosphate Use (tons/acre)	7.3	**	3.6	-4.0		11.4	3.6E-02		4.6E-02	1.3		3.7	-4.4E-02		2.8
Harvest Dummy	0.2	***	2.1E-02	0.2	***	2.1E-02	0.7	***	0.1	0.2	***	2.1E-02	0.2	***	2.1E-02
Hybrid Dummy	0.2	***	3.0E-02	0.3	***	0.1	0.5	***	0.1	0.4	*	0.2	0.4		0.3
AEZ2 Dummy	-0.1	***	3.9E-02	-0.1	***	4.1E-02	-0.5	***	0.2	-0.1	**	4.0E-02	-0.1	**	3.9E-02
AEZ4 Dummy	0.1	***	4.5E-02	0.1	**	4.5E-02	0.3	***	0.1	0.1	***	4.4E-02	0.1	***	4.4E-02
Terraced Dummy	-0.1	***	2.8E-02	-0.1	***	2.9E-02	-0.3	***	0.1	-0.1	**	3.0E-02	-0.1	**	3.1E-02
Credit Dummy	-1.4E-03		2.5E-02	1.7E-02		2.5E-02	-0.2	**	0.1	0.0		2.4E-02	1.3E-02		2.4E-02
Tenure Dummy	0.1	**	2.4E-02	0.1	***	2.3E-02	0.1		0.1	0.1	***	2.3E-02	0.1	***	2.3E-02
Years Hybrid Maize Experience	2.4E-03	*	1.4E-03	2.6E-03	*	1.4E-03	8.7E-03	**	3.7E-03	2.8E-	**	1.4E-03	2.8E-03	**	1.4E-03

Model Performance

	Linear		Quadratic		Cobb-Douglas		Generalized Leontief		Generalized Leontief (r=3)	
N	951		951		951		951		951	
R^2	0.45		0.51		0.35		0.50		0.49	
Adjusted R^2	0.44		0.48		0.34		0.48		0.47	
F Statistic	39.35	***	21.18	***	41.8	***	20.61	***	20.56	***
Heteroskedasticity Test (chi^2)	313.98		293.59		223.79		322.80		337.26	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

Table 4b: Mean maize production model by functional form, interaction effects only (OLS)

	Quadratic			Generalized Leontief (r=2)			Generalized Leontief (r=3)		
	Coeff		**Std. Error**	**Coeff**		**Std. Error**	**Coeff**		**Std. Error**
INTERCEPT	-0.1		0.1	-0.5	**	0.2	-1.2	**	0.5
Acres*Seed Quantity	-4.0		11.4	0.0		0.0E+00	0.0		0.0
Acres*Hired Labor	0.2	***	2.1E-02	0.3	***	0.1	0.8	***	0.3
Acres*Family Labor	0.3	***	0.1	11.8	***	3.5	9.6	***	3.2
Acres*Nitrogen Use	-0.1	***	4.1E-02	3.2E-03		0.1	-3.6E-02		0.1
Acres*Phosphate Use	0.1	**	4.5E-02	1.6E-02	*	8.5E-03	0.1		0.1
Seed Quantity*Hired Labor	-0.1	***	2.9E-02	-2.3		3.7	-1.4		2.9
Seed Quantity*Family Labor	1.7E-02		2.5E-02	1.3		3.7	-4.4E-02		2.8
Seed Quantity*Nitrogen Use	0.1	***	2.3E-02	0.2	***	2.1E-02	0.2	***	2.1E-02
Seed Quantity*Phosphate Use	2.6E-03	*	1.4E-03	0.4	*	0.2	0.4		0.3
Hired Labor*Family Labor	2.1E-03		3.5E-03	-0.1	**	4.0E-02	-0.1	**	3.9E-02
Hired Labor*Nitrogen Use	-1625.2		1397.8	0.1	***	4.4E-02	0.1	***	4.4E-02
Hired Labor*Phosphate Use	4.6E-05		1.5E-04	-0.1	**	3.0E-02	-0.1	**	3.1E-02
Family Labor*Nitrogen Use	5.9E-08		8.7E-08	1.3E-02		2.4E-02	1.3E-02		2.4E-02
Family Labor*Phosphate Use	-129.5	*	67.5	0.1	***	2.3E-02	0.1	***	2.3E-02
Nitrogen Use*Phosphate Use	366.5	*	191.4	2.8E-03	**	1.4E-03	2.8E-03	**	1.4E-03
HybridDum*Acres	-17.1	***	4.6	-5.9	***	1.6	-5.3	***	1.6
HybridDum*Seed Quantity	-1.1E-03		4.7E-03	-5.8E-05		2.7E-02	2.8E-02		0.1
HybridDum*Hired Labor	-2.2E-04	**	9.8E-05	-9.7E-03	**	4.0E-03	-3.6E-02	*	2.1E-02
HybridDum*Family Labor	-3.2		4.0	-0.8		2.0	-1.0		1.5
HybridDum*Nitrogen Use	6.0	*	3.4	1.7		1.7	1.8		1.3
HybridDum*Phosphate Use	-0.5		0.7	-0.4		0.5	-0.3		0.5
Acres^2	0.0		0.0						
Seed Quantity^2	4.3E-02		3.8E-02						
Hired Labor^2	72.0	***	22.1						
Family Labor^2	-9.3E-04		7.8E-03						
Nitrogen Use^2	2.2E-04		2.0E-04						
Phosphate Use^2	11.3		12.4						

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

Despite inefficiencies caused by heteroskedasticity, OLS regressions are presented to illustrate the differences between the OLS and WLS regressions. Since the standard deviation of the error term is not constant over all values of the explanatory variables, the WLS regression helps correct for lack of equality in the error variances. In this case, different observations are not treated equally, and the WLS regression gives different weights proportional to $1/\hat{\sigma}_i$ to different observations. The following equation is used to derive the WLS regression results for this model:

$$y_i = f_1(\mathrm{H}, \frac{1}{\hat{\sigma}_i} \boldsymbol{X}, \alpha) + \varepsilon_i \qquad 8$$

Equation 8 takes the original OLS regression and uses the new proportional data to estimate the WLS regression. This regression is presented to show the effect that weighting a key variable, such as land size, has on the results. While the regression coefficients do not change much, the standard errors are different. The WLS regression corrects for heteroskedasticity and also leads to more efficient unbiased estimates. The regression estimates from the WLS regression are presented in **Error! Reference source not found.**5a and **Error! Reference source not found.** 5b.

Error! Reference source not found. 5a shows the results in which the model is weighted by the first variable, acres, giving those observations with smaller size greater weight. At least 9 of 14 variables are statistically significant at the one percent level. Comparing Table 5 with Table 4, the R^2 for each model increased after correction for heteroskedasticity and increased the number of significant variables.

Signs and significance differ for a number of inputs between the OLS and WLS models. For example, the coefficient of hired labor, which was insignificant in all forms in the OLS model, is negative and significant at the one percent level in the linear and Cobb-Douglas functional forms of the WLS model. By contrast, family labor is significant in the Cobb-Douglas and Generalized Leontief (r=2) forms of the OLS model. In the WLS model, this coefficient is significant at the one percent level across all functional forms, but its magnitude is small. Now, examining the terraced land dummy, the WLS results suggest that this input exerts a positive and significant effect on maize yields regardless of functional forms, but the coefficient of terracing has a negative sign in the OLS model.

Other aspects are similar between the OLS and WLS regressions. First, plot size is inversely related to productivity in both sets of regressions. Season is always significant in explaining yield differences. Farm location in AEZ4, where rainfall is higher, always influences yield positively. Interestingly, years of hybrid maize experience has no impact on yield in either set of regressions, consistent with Suri's (2011) hypothesis that learning is not related to hybrid use in Kenya at this late stage of adoption. Perhaps most importantly for this analysis, the effect of hybrid seed use is positive and significant across four models of mean production at the one percent level.

An F-test was conducted on all interaction effects in the WLS to test joint significance. The F statistic in the quadratic functional form is 26.96 and significant at the one percent level, while the F statistic for the Generalized Leontief forms is 32.53 and is also significant at the one percent level. As such, these interaction effects are important and contribute to explaining nonlinearities in the relationship between yields and inputs. Table 5b shows that the following interactions are significant in all three forms: Acres*Seed Quantity, Seed Quantity*Family Labor, Hired Labor*Family Labor, Nitrogen Use*Phosphate use, HybridDum*Acres, HybridDum*Seed Quantity, HybridDum*Hired Labor, and HybridDum*Family Labor. In terms of the squared variables, nitrogen use, which was negative, and phosphate use, which was positive, are the only squared terms that exhibit significance. These findings suggest diminishing returns to nitrogen nutrients, but increasing returns to phosphate.

Table 5a: Mean maize production model without interaction terms, by functional form (WLS)

	Linear			Quadratic			Cobb-Douglas			Generalized Leontief			Generalized Leontief		
	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.
INTERCEPT	2.9E-02		4.9E-	-0.2		0.1	0.6		0.5	-1.1	***	0.3	-2.4	***	0.6
Acres	-0.2	***	4.9E-	0.3	**	0.2	-0.3	***	0.1	0.9	***	0.3	1.9	***	0.5
Seed Quantity	49.6	***	5.0	49.5	*	29.8	0.3	***	0.1	14.6	***	3.4	12.9	***	3.1
Hired Labor (days/acre)	-6.4E-	***	1.4E-	-2.4E-		7.3E-	-0.1	***	3.4E-	-4.4E-		0.1	-0.1		0.2
Family Labor	-1.0E-	***	3.2E-	4.1E-04	***	1.5E-	-0.1	***	3.2E-	2.5E-02	***	8.3E-03	0.2	***	0.1
Nitrogen Use	19.0	***	2.8	51.6	***	20.4	0.4	***	0.1	8.3		6.0	7.8		5.1
Phosphate Use	-8.6	***	2.4	-36.0	***	13.7	-0.3	***	0.1	-9.2	*	5.0	-8.8	**	4.5
Harvest Dummy	0.2	***	3.0E-	0.2	***	2.8E-	0.6	***	0.1	0.2	***	2.8E-02	0.2	***	2.8E-02
Hybrid Dummy	0.3	***	3.1E-	0.3	***	0.1	0.5	***	0.1	0.5	**	0.2	0.4		0.3
AEZ2 Dummy	0.4	***	4.5E-	0.1		4.8E-	1.8E-		0.1	0.1	*	4.9E-02	0.1	**	4.9E-02
AEZ4 Dummy	0.2	***	3.6E-	0.1	***	3.5E-	0.2	*	0.1	0.1	***	3.5E-02	0.1	***	3.5E-02
Terraced Dummy	0.1	***	3.5E-	0.1	*	3.3E-	0.1		0.1	0.1	***	3.4E-02	0.1	***	3.3E-02
Credit Dummy	-0.1		3.8E-	-1.0E-		3.6E-	-0.2	**	0.1	8.1E-03		3.6E-02	1.4E-		3.6E-02
Tenure Dummy	0.1	**	3.0E-	3.6E-02		2.8E-	0.1		0.1	0.1	**	2.8E-02	0.1	*	2.8E-02
Years Hybrid Maize	8.5E-04		1.5E-	9.2E-04		1.4E-	1.2E-	***	3.5E-	1.4E-03		1.4E-03	7.3E-		1.4E-03
Model Performance															
N	951			951			951			951			951		
R2	0.51			0.60			0.34			0.63			0.63		
F Statistic	70.75	***		33.45	***		34.1	***		44.19	***		44.47	***	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

Table 5b: Mean maize production model, interaction effects only, by functional form (WLS)

	Quadratic			Generalized Leontief (r=2)			Generalized Leontief (r=3)		
	Coeff		Std. Error	Coeff		Std. Error	Coeff		Std. Error
INTERCEPT	-0.2		0.1	-1.1	***	0.3	-2.4	***	0.6
Acres*Seed Quantity	-49.2	***	18.0	-12.0	***	3.4	-9.6	***	2.7
Acres*Hired Labor	2.7E-03		9.7E-03	2.3E-02		0.1	-1.3E-02		0.1
Acres*Family Labor	3.1E-06		2.3E-04	2.8E-03		8.5E-03	-1.5E-02		3.8E-02
Acres*Nitrogen Use	-12.9		10.7	-8.9	**	4.0	-7.5	**	3.3
Acres*Phosphate Use	14.7		9.7	9.1	***	3.6	7.9	***	3.0
Seed Quantity*Hired Labor	-2.7E-02		0.4	-2.4E-04		0.4	0.1		0.5
Seed Quantity*Family Labor	-3.9E-02	***	1.1E-02	-0.3	***	0.1	-0.7	***	0.2
Seed Quantity*Nitrogen Use	-3782.7	***	1523.6	-33.3		42.8	-16.0		16.4
Seed Quantity*Phosphate Use	1151.5		1119.5	5.6		36.2	5.7		14.3
Hired Labor*Family Labor	7.4E-06	***	2.6E-06	1.8E-03	***	7.1E-04	9.7E-03	*	5.1E-03
Hired Labor*Nitrogen Use	-0.1		0.8	2.3E-02		0.6	-0.2		0.6
Hired Labor*Phosphate Use	0.3		0.8	0.3		0.6	0.5		0.5
Family Labor*Nitrogen Use	-1.8E-03		1.1E-02	0.1		0.1	0.2		0.2
Family Labor*Phosphate Use	-1.1E-02		8.1E-03	-0.1		0.1	-0.2		0.2
Nitrogen Use*Phosphate Use	-826.8	***	244.1	26.1	***	5.7	11.6	***	2.1
HybridDum*Acres	-0.3	***	0.1	-0.6	***	0.2	-0.7	***	0.2
HybridDum*Seed Quantity	70.7	***	11.3	8.6	***	1.8	5.2	***	1.1
HybridDum*Hired Labor	-8.0E-03	***	2.9E-03	-0.1	***	1.6E-02	-0.1	***	2.8E-02
HybridDum*Family Labor	-3.4E-04	***	7.7E-05	-1.9E-02	***	3.4E-03	-0.1	***	1.3E-02
HybridDum*Nitrogen Use	22.2	*	11.5	1.4		1.5	1.1		0.8
HybridDum*Phosphate Use	-5.6		6.8	-0.3		1.3	-0.5		0.7
Acres2	-3.2E-02		3.2E-02						
Seed Quantity2	109.9		1445.0						
Hired Labor2	-4.2E-05		1.2E-04						
Family Labor2	-1.4E-09		5.7E-08						
Nitrogen Use2	-232.7	***	93.8						
Phosphate Use2	1028.1	***	194.1						
Model Performance									
N	951			951			951		
R2	0.60			0.63			0.63		
F Statistic	33.45	***		44.19	***		44.47	***	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

3.4 Variance of Maize Yields

Results of variance regressions are shown in **Error! Reference source not found.** 6 by functional form. Comparing across functional forms, several variables are consistently significant. Production during the main season, the higher rainfall of AEZ4, and ownership of land within the household contribute to greater yield variance among plots. Variables that are less consistent among functional forms include plot size, which reduces variance in the linear model. Seed density per acre generally increases variance. As in the mean models, the effect of family labor is positive and small. Nitrogen and phosphate rates are considered to be either variance-reducing or variance-increasing, depending on the functional form. Notably, hybrid seed is a significant factor in the variance regression only in the linear and Cobb-Douglas forms, and with conflicting signs.

Table 6: OLS regression results for variance model

	Linear			Quadratic			Cobb-Douglas			Generalized Leontief (r=2)			Generalized Leontief (r=3)		
	Coeff		Std. Error	Coeff		Std. Error	Coeff		Std. Error	Coeff		Std. Error	Coeff		Std. Error
INTERCEPT	-5.3	***	0.3	-5.0	***	0.7	-4.5	***	0.9	-6.6	***	1.3	-7.5	***	2.7
Acres	-0.1	*	0.1	-0.5		0.3	2.5E-03		0.1	0.5		0.7	0.8		1.6
Seed Quantity (tons/acre)	60.0	**	29.9	83.7		122.5	-0.2	**	0.1	45.6	***	17.7	31.5	**	15.0
Hired Labor (days/acre)	9.6E-03		1.2E-02	-2.5E-02		4.7E-02	0.1		0.1	-0.4		0.3	-1.8	***	0.7
Family Labor (hours/acre)	2.2E-04		3.1E-04	9.7E-04		9.5E-04	0.1		0.1	0.1	**	4.5E-02	0.5	**	0.2
Nitrogen Use (tons/acre)	0.1		13.4	-126.0	**	60.3	-0.4	***	0.2	1.2		16.6	38.9	*	20.0
Phosphate Use (tons/acre)	17.5		13.5	112.1	***	43.9	0.2	*	0.1	-4.9		17.2	-47.9	***	19.0
Harvest Dummy	0.7	***	0.2	0.5	***	0.2	-0.7	***	0.2	0.6	***	0.1	0.7	***	0.2
Hybrid Dummy	0.5	***	0.2	0.7		0.5	-0.4	***	0.2	1.0		1.1	1.5		1.7
AEZ2 Dummy	0.2		0.3	0.4		0.3	1.3	***	0.2	0.4		0.3	0.4	*	0.3
AEZ4 Dummy	0.8	***	0.2	0.7	***	0.2	0.4	*	0.2	0.5	**	0.2	0.6	**	0.3
Terraced Dummy	2.4E-02		0.2	0.3		0.2	0.3	*	0.2	0.3	*	0.2	0.4	**	0.2
Credit Dummy	0.1		0.2	0.1		0.2	0.9	***	0.2	0.2		0.2	0.3		0.2
Tenure Dummy	0.4	***	0.1	0.3	**	0.2	0.1		0.1	0.3	**	0.1	0.3	*	0.1
Years Hybrid Maize Experience	5.6E-03		8.1E-03	4.8E-04		8.1E-03	-1.3E-02		8.4E-03	7.1E-03		7.7E-03	7.7E-03		7.9E-03
R^2	0.13			0.15			0.13			0.18			0.21		
F Statistic	9.87	***		7.37	***		10.4	***		7.47	***		6.95	***	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

3.5 Full Order Moment Skewness Model Results

Error! Reference source not found. 7 presents the OLS regression results associated with all functional forms for the skewness model with full order moments. As in the variance regressions, factors that are consistently significant across forms include harvest season, AEZ4, and tenure. Each of these factors reduces downside risk by shifting the probability mass (Figure 2) toward higher values. Considering the variables that are less consistent across models, both plot size and hybrid seed are statistically significant in two or fewer forms. Fertilizer and seeding density are skewness-increasing in several of the forms.

The full order moment of skewness regression does not distinguish between positive and negative residuals for each observation. By taking the absolute value of the residuals, deviations from the mean have been aggregated into one category of asymmetry. The next section relaxes that constraint.

3.6 Partial Order Moment Skewness Results

Table 7: Full order moment skewness of maize yields, by functional form (OLS)

	Linear			**Quadratic**			**Cobb-Douglas**			**Generalized Leontief**			**Generalized Leontief**		
	Coeff		**Std.**	**Coeff**		**Std.**	**Coeff**		**Std.**	**Coeff**		**Std.**	**Coeff**		**Std.**
INTERCEPT	-8.0	***	0.4	-7.5	***	1.0	-6.7	***	1.4	-9.9	***	2.0	-11.2	***	4.1
Acres	-0.2	*	0.1	-0.7		0.50	0.0		0.2	0.7		1.1	1.3		2.5
Seed Quantity (tons/acre)	90.0	**	44.9	125.6		183.7	-0.3	**	0.2	68.4	***	26.5	47.2	**	22.6
Hired Labor (days/acre)	1.4E-02		1.8E-	-3.8E-		0.1	0.1		0.1	-0.7		0.5	-2.8	***	1.1
Family Labor (hours/acre)	3.3E-04		4.7E-	1.5E-03		1.4E-	0.1		0.1	0.1	**	0.1	0.7	**	0.4
Nitrogen Use (tons/acre)	0.2		20.1	-189.0	**	90.4	-0.7	***	0.2	1.7		24.9	58.3	**	30.1
Phosphate Use (tons/acre)	26.3		20.2	168.2	***	65.8	0.4	*	0.2	-7.4		25.9	-71.9	***	28.6
Harvest Dummy	1.1	***	0.2	0.7	***	0.2	-1.0	***	0.2	0.9	***	0.2	1.0	***	0.2
Hybrid Dummy	0.7	***	0.3	1.1		0.7	-0.7	***	0.3	1.5		1.6	2.2		2.5

AEZ2 Dummy	0.3		0.4	0.6		0.5	1.9	***	0.4	0.5		0.4	0.7	*	0.4
AEZ4 Dummy	1.2	***	0.3	1.1	***	0.4	0.6	*	0.3	0.8	**	0.4	0.9	**	0.4
Terraced Dummy	0.0		0.2	0.4		0.3	0.5	*	0.3	0.4	*	0.3	0.5	**	0.3
Credit Dummy	0.1		0.3	0.1		0.3	1.3	***	0.2	0.3		0.3	0.4		0.3
Tenure Dummy	0.6	***	0.2	0.5	**	0.2	0.2		0.2	0.5	**	0.2	0.4	*	0.2
Years Hybrid Maize Experience	8.3E-03		1.2E-02	7.3E-04		1.2E-02	-1.9E-02		1.3E-02	1.1E-02		1.2E-02	1.2E-02		1.2E-02
N	951			951			951			951			951		
R2	0.13			0.15			0.13			0.18			0.21		
F Statistic	9.87	***		7.37	***		10.4	***		7.47	***		6.95	***	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

8 shows the results for partial order moments of positive skewness, while **Error! Reference source not found.** 9 shows the results for partial order moments of negative skewness, by functional form. Different independent variables are significant in each model. Production in the main season has a positive impact on skewness of maize yields, as does location in AEZ4 and ownership of land by the family. Few other inputs have significant effects across the models, although nitrogen and phosphate use appear in several of the functional forms.

Table 7: Full order moment skewness of maize yields, by functional form (OLS)

	Linear			Quadratic			Cobb-Douglas			Generalized Leontief			Generalized Leontief		
	Coeff		**Std.**	**Coeff**		**Std.**	**Coeff**		**Std.**	**Coeff**		**Std.**	**Coeff**		**Std.**
INTERCEPT	-8.0	***	0.4	-7.5	***	1.0	-6.7	***	1.4	-9.9	***	2.0	-11.2	***	4.1
Acres	-0.2	*	0.1	-0.7		0.50	0.0		0.2	0.7		1.1	1.3		2.5
Seed Quantity (tons/acre)	90.0	**	44.9	125.6		183.7	-0.3	**	0.2	68.4	***	26.5	47.2	**	22.6
Hired Labor (days/acre)	1.4E-02		1.8E-	-3.8E-		0.1	0.1		0.1	-0.7		0.5	-2.8	***	1.1
Family Labor (hours/acre)	3.3E-04		4.7E-	1.5E-03		1.4E-	0.1		0.1	0.1	**	0.1	0.7	**	0.4
Nitrogen Use (tons/acre)	0.2		20.1	-189.0	**	90.4	-0.7	***	0.2	1.7		24.9	58.3	**	30.1
Phosphate Use (tons/acre)	26.3		20.2	168.2	***	65.8	0.4	*	0.2	-7.4		25.9	-71.9	***	28.6
Harvest Dummy	1.1	***	0.2	0.7	***	0.2	-1.0	***	0.2	0.9	***	0.2	1.0	***	0.2
Hybrid Dummy	0.7	***	0.3	1.1		0.7	-0.7	***	0.3	1.5		1.6	2.2		2.5
AEZ2 Dummy	0.3		0.4	0.6		0.5	1.9	***	0.4	0.5		0.4	0.7	*	0.4
AEZ4 Dummy	1.2	***	0.3	1.1	***	0.4	0.6	*	0.3	0.8	**	0.4	0.9	**	0.4
Terraced Dummy	0.0		0.2	0.4		0.3	0.5	*	0.3	0.4	*	0.3	0.5	**	0.3
Credit Dummy	0.1		0.3	0.1		0.3	1.3	***	0.2	0.3		0.3	0.4		0.3
Tenure Dummy	0.6	***	0.2	0.5	**	0.2	0.2		0.2	0.5	**	0.2	0.4	*	0.2
Years Hybrid Maize Experience	8.3E-03		1.2E-02	7.3E-04		1.2E-02	-1.9E-02		1.3E-02	1.1E-02		1.2E-02	1.2E-02		1.2E-02
N	951			951			951			951			951		
R^2	0.13			0.15			0.13			0.18			0.21		
F Statistic	9.87	***		7.37	***		10.4	***		7.47	***		6.95	***	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

Table 8: Positive partial order moment skewness of maize yields, by functional form (OLS)

	Linear			Quadratic			Cobb-Douglas			Generalized Leontief			Generalized Leontief		
	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.
INTERCEPT	-8.1		0.7	-7.9	***	1.9	-6.1	***	1.7	-9.1	**	4.0	-9.3		8.4
Acres	0.1		0.2	-0.4		0.98	0.1		0.2	0.7		2.0	2.6		4.6
Seed Quantity	79.7		89.0	110.4		420.65	-0.2		0.2	60.8		56.7	29.5		48.9
Hired Labor (days/acre)	4.4E-02		3.2E-02	-1.5E-		0.12	0.1		0.1	-1.0		0.9	-4.0	*	2.1
Family Labor	1.2E-03		7.7E-04	3.4E-03		3.6E-03	5.0E-02		0.1	0.1		0.1	0.8		0.7
Nitrogen Use (kgs/acre)	27.4		39.4	-69.5		186.80	-0.5	*	0.3	4.6		52.7	79.3	**	35.5
Phosphate Use	10.0		36.3	170.6		150.62	0.2		0.3	8.7		49.7	-82.1	**	36.2
Harvest Dummy	0.8	*	0.4	0.5		0.45	-0.9	***	0.3	1.1	***	0.4	1.0	***	0.4
Hybrid Dummy	0.8		0.5	0.9		1.54	-0.5		0.3	-0.8		2.8	-3.4		4.0
AEZ2 Dummy	0.4		0.7	0.3		0.73	2.0	***	0.4	1.1		0.7	1.1		0.7
AEZ4 Dummy	1.3	**	0.6	1.1		0.71	0.8	**	0.4	1.3	**	0.6	1.4	**	0.6
Terraced Dummy	-0.1		0.5	1.9E-02		0.51	0.4		0.3	-1.7E-		0.5	0.2		0.5
Credit Dummy	-0.3		0.5	0.3		0.53	1.5	***	0.3	0.3		0.5	1.0	**	0.5
Tenure Dummy	0.8	**	0.4	0.4		0.44	0.1		0.3	0.5		0.4	-0.1		0.4
Years Hybrid Maize Experience	-2.6E-03		2.1E-02	2.4E-02		0.02	-3.0E-02	**	1.4E-02	8.4E-03		2.1E-02	3.5E-03		2.2E-02
Model Performance															
N	396			409			544			407			399		
R2	0.12			0.16			0.14			0.16			0.20		
F Statistic	3.59	***		1.72	***		6.0	***		1.97	***		2.63	***	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

Table 9: Negative partial order moment skewness of maize yields, by functional form (OLS)

	Linear			Quadratic			Cobb-Douglas			Generalized Leontief			Generalized Leontief		
	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.	Coeff		Std.
INTERCEPT	-8.0	***	0.5	-7.4	**	1.2	-7.1	**	2.6	-10.1	***	2.7	-9.7	*	5.9
Acres	-0.5	***	0.1	-0.9		0.6	-0.1		0.3	0.5		1.3	-0.7		3.2
Seed Quantity (tons/acre)	132.8	**	55.0	182.8		262.2	-0.5		0.3	64.4	*	35.3	43.3		32.7
Hired Labor (days/acre)	-9.5E-03		2.1E-02	-4.8E-02		0.1	0.2		0.3	-0.6		0.6	-2.5	*	1.5
Family Labor (hours/acre)	-3.9E-04		5.5E-04	4.9E-04		2.0E-03	0.2		0.2	0.1		0.1	0.2		0.6
Nitrogen Use (tons/acre)	-10.2		19.6	-295.8	*	162.4	-0.9	**	0.4	-56.7		43.1	17.3		47.9
Phosphate Use (tons/acre)	30.8		21.5	260.2	**	120.2	0.6		0.4	29.3		40.6	-39.4		44.4
Harvest Dummy	1.2	***	0.3	0.9	**	0.3	-1.4	**	0.4	0.8	***	0.3	1.0	**	0.3
Hybrid Dummy	0.9	***	0.3	1.3		1.0	-1.0	**	0.5	4.3	**	2.0	7.8	**	3.1
AEZ2 Dummy	0.2		0.5	0.7		0.6	2.1	**	0.8	0.2		0.5	0.2		0.5
AEZ4 Dummy	1.0	***	0.4	0.9	*	0.5	0.3		0.6	0.6		0.4	0.7		0.5
Terraced Dummy	0.1		0.3	0.5	*	0.3	0.5		0.4	0.9	***	0.3	0.7	**	0.3
Credit Dummy	0.5	*	0.3	2.7E-02		0.3	1.0	**	0.5	0.3		0.3	0.3		0.3
Tenure Dummy	0.6	**	0.3	0.6	**	0.3	0.3		0.4	0.6	**	0.3	0.8	**	0.3
Years Hybrid Maize Experience	1.6E-02		1.4E-02	-1.7E-02		0.0	-5.4E-03		2.0E-02	7.7E-03		1.4E-02	1.3E-02		1.5E-02
Model Performance															
N	555			542			407			544			552		
R^2	0.17			0.16			0.14			0.24			0.26		
F Statistic	7.86	***		2.79	**		4.5	**		4.58	***		5.31	**	

***,**,* indicates significance at the 1%, 5% and 10% levels respectively.

More of the inputs are statistically significant in the negative partial order moment regressions. Production in the main season is also significant in the negative partial order moments model across all models, suggesting that the effect of season on skewness can be either significantly positive or negative—exacerbating downside risk or working against it. The same is true for AEZ and the tenure variable. Nitrogen use appears to worsen downside risk, while credit offsets this effect. Terracing may also reduce risk exposure.

Hybrid seed does not have an impact on skewness in the positive partial order moment model, but is significant across all four functional forms and generally positive in the negative partial order moment model. This result is important: the data indicate that hybrid seed enables producers who experience yields below the mean to move closer to the mean.

To test the hypothesis of symmetric effects of inputs, a Chow test is used to test for equality of the parameters in equations 7 and 8. The Chow test is F distributed (14, 14) and the critical value is 2.4 at the 5 percent level. The results of the Chow test statistic are 1.25 in the linear form, 0.61 in the quadratic, 0.7 in the Cobb-Douglas, 0.7 in the generalized Leontief (r=2), and 0.9 in the generalized Leontief (r=3). These values indicate that we fail to reject the null hypothesis that coefficients are the same within both the positive and negative partial order moment results for skewness. This finding suggests that in this case, we do not lose information by using only the full order moment model.

4.0 Conclusions

This research contributes to an old debate about whether the yields of improved seed varieties are higher but also more variable, especially given the use of nitrogenous fertilizer. In today's Kenya, the debate is relevant for investment in water-efficient maize for drought-prone environments, especially under the threat of climate change and with an increasing maize import bill. The analysis presented here provides some baseline information about maize yields on smallholder farms in agro-ecologies of Kenya that are defined as drought-prone, based on the data collected by Tegemeo Institute from a representative sample during the main and short growing seasons of 2006-7.

The finding that maize hybrids yield more than non-hybrids is robust to all functional forms and statistical models. Maize yields are from 0.2 to 0.5 mt per acre higher in plots where farmers grew maize hybrids, controlling for other inputs. Results also suggest that hybrid seed increases the variance of maize yields, although this finding is sensitive to functional form and is not robust. Findings from the skewness models are of particular interest for policy. Hybrid seed positively affects skewness in the full order of moments, suggesting that it reduces the probability of very low crop yields (downside risk). When partial order moments are considered, hybrid seed has no effect on positive residuals, but has a significant positive effect on negative residuals. This means that hybrid seed effectively pulls farmers whose yields are lower than average closer to the mean.

These results are encouraging with respect to the potential impacts of increasing climate variability in Kenyan maize production given the current set of maize hybrids grown by farmers, even without the introduction of new, water-use efficient germplasm. An additional benefit of hybrid seeds is that they reduce the probability of extremely low yields. Hence, hybrid seed can be seen as a potential tool to mitigate catastrophic yield loss, as long as future conditions allow for some crop growth, and do not deviate drastically from what is prevailing today. Future research can shed more light on this hypothesis by examining the impacts of hybrid seed in terms of variability in net returns, and employing panel data methods with rainfall variables. Exploration of the impacts of hybrid seed use on the poverty and livelihoods of smallholder maize growers in drought-prone areas is also needed.

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