MAIZE YIELD RESPONSE TO FERTILIZER AND PROFITABILITY OF FERTILIZER USE AMONG SMALL-SCALE MAIZE PRODUCERS IN ZAMBIA

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Introduction

Farm productivity growth is widely understood to be a precondition for broad based economic development in most of the developing world (Johnston and Mellor, 1961; Tiffen, 2003). Achieving this productivity growth is likely to involve, among many other things, substantially increased use of inorganic fertilizer. Currently, fertilizer use in Sub-Saharan Africa averages 9 kilograms per hectare, the lowest of any developing region by far (FAO, 2004). While African policy makers and international donors recognize the urgency of raising fertilizer use by small farmers, for achieving both poverty alleviation and agricultural growth objectives, there is little consensus on the most appropriate policy and programmatic course of action.

Maize is the staple food in Zambia and most small-scale farming households are engaged in maize production. Fertilizer is used predominantly on maize and agricultural marketing is dominated by maize sales among smallholders (Govereh et al., 2003). Improving maize productivity has been a major goal of the Zambian government. Currently, there is a dearth of empirical knowledge on the relationship between fertilizer use, yield response, and profitability, under a range of environmental, management, and market conditions. For these reasons, it is difficult to understand whether the reasons for low fertilizer use are related primarily to market failures that prevent farmers from using fertilizer despite being profitable for them to do so, or whether input/output price conditions and low response rates make fertilizer use unprofitable. Our study aims to redress this knowledge gap.

The objective of this paper is to estimate maize yield response to fertilizer under a range of small farm conditions, determine economic returns to fertilizer use for various soils, climates, management practices, and market conditions, and identify the potential to increase fertilizer use and profitability through public policy tools in Zambia. Nationwide household survey datasets containing detailed production information are used to estimate maize yield response. There are a few challenges to getting good estimates of the parameters of response functions using survey data, which have seldom been treated in previous analyses. These challenges are identified in following section. We then provide a theoretical framework for our analysis, a section describing the survey data and methods, followed by the main findings and conclusions.

Challenges

Data aggregation, measurement error problems, and omitted variables are the three main classes of problems in estimating fertilizer response using survey data. Data aggregation problems arise when some households farm more than one field but only the summed or averaged household-level information is available. Households with multiple fields may have used different seed types and fertilizer quantities on different fields and harvested different maize quantities from these fields, but field-level production information is not available. Measurement error commonly occurs when approximate estimates of soil types, soil pH, and climate (rainfall) are available but do not take account of micro-variability at the household level. Measurement error and data aggregation generally cause parameter estimators to be biased and inconsistent. Collinearity between nitrogen (N) and phosphorus (P_2O_5) poses additional problem in terms of separating out individual effects; most households tend to use N and P_2O_5 in the ratio recommended by the national extension service.

Phosphorus provides a special challenge under survey conditions because much of plant uptake in the current year is the result of previous phosphorus applications and inherent soil fertility. The fact that the stock of the phosphorus in the soil is not observed may create an omitted variable problem from an estimation perspective. For example, if a household's current phosphorus application is correlated with phosphorus application in previous years, cross-sectional regression estimates of yield response to phosphorus could be biased upward. The approach taken in dealing with these challenges was to use robust estimation techniques. In addition, supporting Monte Carlo simulation was done to provide insight into the direction and magnitude of bias.

Theoretical Framework

Crop yields can be seen as a function of input variables that are under the farmer's control and exogenous variables that are beyond the farmer's control. The yield response model that maps input and exogenous variables to output can be written as

$$y = f(x_i, Z),\ i=1,\ldots\ldots, n. \qquad (1)$$

where y is the stochastic crop yield, x_i is the ith input variable, and Z is a vector of exogenous variables that are beyond farmer's control.

The farmer's expected profit maximizing decision is

$$\underset{x_i}{Max}\ pE(y) - \sum_{i=1}^{n} w_i x_i \text{ subject to } x_i \geq 0 \qquad (2)$$

where p is the output price, w_i is the ith input price, and E is the expectation operator. If the yield response function is strictly concave which exhibits diminishing marginal product of input i, the first order condition for the optimal level of input i satisfies

$$p\frac{\partial E(y)}{\partial x_i} - w_i = 0 \quad (3)$$

Simplifying (3) gives

$$\frac{\partial E(y)}{\partial x_i} = \frac{w_i}{p} \quad (4)$$

Because the optimal input level is directly affected by this price ratio, a change in the ratio leads to the corresponding alteration in the optimal solution. In addition, optimal input levels are expected to vary across agroecological areas since yield response functions are not likely to be the same.

If the yield response function is linear in input *i*, it exhibits constant marginal product and the optimal decision is either not to apply at all or apply as much as possible depending on whether the slope of the yield function is less or greater than the price ratio w_i/p.

Above conventional input allocation rules are optimal for nitrogen but are generally not optimal for phosphorous which has substantial carryover (storage) in the soil. Yield is affected by the total amount of available phosphorous which is determined by the amount added at the current period and the stock of phosphorous carried over into the current period. Yield is a function of the total available amount. If yield response is nonlinear in phosphorous, the conventional allocation rules are sub-optimal because the marginal product of phosphorous is now affected by both current application and phosphorous stock in the soil instead of just current application.

Data and Methods

Maize production data from 1996/97 to 1999/2000 production seasons are obtained from the Central Statistical Office in Zambia. The source of the data is the Post Harvest Survey, a nationally representative annual survey covering roughly 7,500 rural households each year. We also collected soil type, soil pH, rainfall, and price data from the Central Statistical Office.

Fertilizer is dominantly applied in two of Zambia's agro-climatic zones that are relatively well suited to maize production: IIa and III. Soil and rainfall conditions in the other two zones (I and IIb) have low cropping potential under rainfed conditions especially with fertilizer and very few households in these zones used fertilizer.

Some farmers used only basal or top dressing fertilizer, but most farmers applied both and followed the extension service recommendation in terms of fixed ratios of N and P_2O_5, although at different levels. To address the collinearity problem, we isolated households applying the roughly fixed ratios of N and P_2O_5, and used a nitrogen index in the regression model to capture the synergistic effects of N and P_2O_5.

The effects of a range of variables are investigated including soil type, soil pH, rainfall, hybrid seed, timeliness of fertilizer application, use of mechanical or animal draft power, gender and age of household head, and farm size.

Estimates of the marginal products of N multiplied by the output/input price ratio define the value-cost ratio (VCR). VCRs are commonly used in the literature in developing countries, especially when costs of labor and other inputs are not available to compute more detailed estimates such as gross margins or returns to labor. Technically, VCRs greater than 1 would imply profitability of fertilizer as long as other inputs were not altered as a result of using fertilizer. This is not likely be the case, and for this reason as well as the risks associated with fertilizer use, experienced researchers have found that VCRs of two or more are generally required to find farmers using fertilizer in any appreciable amounts (Crawford and Kelly, 2002). This paper adopts this convention and considers a VCR above 2 as an indicator that fertilizer use is most likely to be profitable.

Results

The effects of some variables[1] on maize yield are inconclusive due to measurement error/insufficient variation in these variables. Coefficient estimate on gender of household head, for example, are not stable across specifications which is not surprising given that they are less than 15% of the total cases. For each combination of soil type and soil pH in the two zones, we estimated maize yield response to *N* index for each of the four groups when there are meaningful number of observations[2]: (i) *usepower*=0 and *fertontime*=0; (ii) *usepower*=1 and *fertontime*=0; (iii) *usepower*=0 and *fertontime*=1; and (iv) *usepower*=1 and *fertontime*=1, where *usepower* is an index variable which is equal to 1 if the household used mechanical or animal draft power, 0 otherwise; *fertontime* is an index variable which is equal to 1 if the household obtained basal fertilizer on time, 0 otherwise.

Plots of maize yield versus nitrogen index and the corresponding Lowess smoothing curves suggest a clear linear response up to the level of approximately 110kg/ha of *N* for each soil type. Spline model fits the data best compared to the quadratic and Mitschelich-Baule specifications based on the non-nested hypothesis tests. Estimate of the knot in the spline function is around 110kg/ha and most households

[1] These variables include gender and age of household head, use of hybrid seed, and farm size.
[2] Generally above 100.

applied *N* less than this level[3]. Table 1 reports the linear response estimates for *N*<110 by soil type using median regression.

Table 1: Regression Results

Soil Type	Soil pH	Group	Constant	*N*	Number of Observations
Acrisols	4.2	(i) *usepower*=0 *fertontime*=0	486** (214)	14.80*** (3.86)	139
		(ii) *usepower*=1 *fertontime*=0	578*** (204)	20.78*** (4.27)	103
		(iii) *usepower*=0 *fertontime*=1	583*** (142)	20.20*** (2.42)	479
		(iv) *usepower*=1 *fertontime*=1	701*** (104)	22.13*** (2.01)	424
Leptosols	5.1	*usepower*=0	878*** (227)	13.17*** (4.75)	124
		usepower=1	1029*** (196)	20.67*** (4.47)	208
Vertisols	4.5	pooled	947*** (213)	18.61*** (4.12)	137

Note: ***, **, ***** denote statistical significance at 10%, 5%, 1% levels respectively. *N*=nitrogen index in kg/ha. Numbers in parentheses indicate standard errors.

Zones IIa and III are pooled for these cases because Chow tests showed no evidence that regression parameters are significantly different between the two zones. The correlation coefficient between the two variables, *usepower* and *fertontime* was found nearly zero in each zone.

For acrisols, which is the dominant soil group where much of the maize is produced and fertilizer is applied, estimates of marginal products of *N* are lowest for Group (i) households (neither obtained fertilizer on time nor used animal or mechanical power) and highest for Group (iv) households (obtained fertilizer on time and used animal or mechanical power), which is consistent with our expectation. Group (ii) has a similar response rate as Group (iii), so little can be said with respect to which variable,

[3] Beyond this level, yield still increases as *N* increases but the slope of the linear regression line is less steep. The number of cases above this level is very small.

timeliness of fertilizer application or use of animal draft or mechanical power, has a larger impact on fertilizer efficiency. For leptosols, the number of cases for each Group (i), (ii) and (iii) is very small and yield response to *N* was not found significantly influenced by whether or not fertilizer was available on time possibly due to the noise of the data. Thus we obtained yield response functions for two groups stratified by use of draft power. As expected, the response rate is higher for those households that used power than did not use power. For vertisols, yield response to *N* was obtained for the pooled data because data are limited for further stratification. No clear patterns are found in terms of nitrogen response rates being systematically higher (or lower) for a particular combination of agro-climatic zone, soil type and pH.

We also obtained maize yield response to *N* for households that used only top dressing fertilizer. Except acrisols, no other soil group has meaningful number of cases. First, data were pooled due to small number of cases and yield response model was estimated for each of the two zones IIa and III respectively. The hypothesis that regression parameters are the same for acrisols across the two zones cannot be rejected by Chow tests. Thus we pooled data from the two zones and obtained marginal product estimate of *N*, 10.12kg per hectare, which is statistically significant at 1% level. This response rate is very low compared to the results in Table 1, which can be explained by the fact that most households that applied only top dressing acquired it at a low price from government fertilizer distribution program and their main source of income is off-farm income (for example, civil service employee).

Table 2 and Table 3 show the farm-level price ratios of median nitrogen index prices to median maize prices and the corresponding VCR for each group of households that are located at/near the provincial centers and in remote areas that are at least 200kms from the provincial center respectively. Provincial median maize real prices from 1992 to 2002 were allocated to the provincial centers. Maize prices for remote districts were estimated by adjusting for transport and handling costs from the corresponding provincial center to the district. Fertilizer prices were originally Lusaka commercial prices. We worked first with the US dollar Lusaka-based prices since the bulk of the fertilizer was imported, then added transport and handling cost to each province. This gave us the provincial center prices. For those districts far from the provincial center, another adjustment for transport and handling was made. Transport and handling costs typically increase prices by 13 to 24 percent above those at/near provincial centers. The price for nitrogen is obtained from urea (top dressing) and compound D (basal), i.e., it is a weighted price based on the amount of nitrogen available when equal proportions of urea and compound D are applied.

Table 2: Farm-level Price Ratios and VCRs at/near Provincial Centers

Province	District	Price Ratio	Soil Type	VCR					
				Group(i)	Group(ii)	Group(iii)	Group(iv)	*usepower* =0	*usepower* =1
Central	Chibombo	9.28	Acrisols	1.59	2.24	2.18	2.38		
			Vertisols						2.00 (pooled)
	K.M.	9.66	Acrisols	1.53	2.15	2.09	2.29		
Copperbelt	Kalulushi	10.77	Acrisols	1.37	1.93	1.88	2.06		
	Kitwe	9.56	Acrisols	1.55	2.17	2.11	2.32		
	Luansha	9.56	Acrisols	1.55	2.17	2.11	2.32		
	Masaiti	10.77	Acrisols	1.37	1.93	1.88	2.06		
	Mufulira	9.56	Acrisols	1.55	2.17	2.11	2.32		
Eastern	Chipata	13.31	Acrisols	1.11	1.56	1.52	1.66		
			Leptosols					0.99	1.55
	Katete	13.31	Acrisols	1.11	1.56	1.52	1.66		
			Leptosols					0.99	1.55
	Petauke	13.31	Acrisols	1.11	1.56	1.52	1.66		
			Leptosols					0.99	1.55
Luapula	Mansa	9.43	Acrisols	1.57	2.20	2.14	2.35		
	Milenge	12.04	Acrisols	1.23	1.73	1.68	1.84		
	Mwense	12.04	Acrisols	1.23	1.73	1.68	1.84		
	Samfya	9.43	Acrisols	1.57	2.20	2.14	2.35		

Lusaka	Chongwe	9.65	Acrisols	1.53	2.15	2.09	2.29		
	Kafue	9.65	Vertisols						1.93 (pooled)
Northern	Chinsali	11.04	Acrisols	1.34	1.88	1.83	2.01		
	Kasama	11.04	Acrisols	1.34	1.88	1.83	2.01		
	Mpika	11.04	Acrisols	1.34	1.88	1.83	2.01		
N.W.	Solwezi	10.04	Acrisols	1.47	2.07	2.01	2.20		
Southern	Choma	10.76	Acrisols	1.37	1.93	1.88	2.06		
			Leptosols					1.22	1.92
	Kalomo	11.24	Acrisols	1.32	1.85	1.80	1.97		
			Leptosols					1.17	1.84
	Monze	10.76	Acrisols	1.37	1.93	1.88	2.06		
			Leptosols					1.22	1.92
	Mazabuka	10.06	Vertisols						1.85 (pooled)

Note: K.M. denotes Kapiri Mposhi; N.W. denotes Northwestern.

Table 3: Farm-level Price Ratios and VCRs in Remote Areas

Province	District	Price Ratio	Soil Type	VCR Group(i)	VCR Group(ii)	VCR Group(iii)	VCR Group(iv)	*usepower* =0	*usepower* =1
Central	Mumbwa	11.99	Leptosols					1.10	1.72
			Vertisols						1.55 (pooled)
	Serenje	11.99	Acrisols	1.23	1.73	1.68	1.85		
Copperbelt	Lufwanyama	14.05	Acrisols	1.05	1.48	1.44	1.58		
	Mpongwe	11.77	Acrisols	1.26	1.77	1.72	1.88		
Eastern	Chadiza	18.21	Acrisols	0.81	1.14	1.11	1.22		
			Leptosols					0.72	1.13
	Lundazi	18.21	Acrisols	0.81	1.14	1.11	1.22		
			Leptosols					0.72	1.13
	Mambwe	18.21	Leptosols					0.72	1.13
Luapula	Chiengi	14.33	Acrisols	1.03	1.45	1.41	1.54		
	Kawambwa	14.33	Acrisols	1.03	1.45	1.41	1.54		
Northern	Isoka	13.04	Acrisols	1.13	1.59	1.55	1.70		
	Kaputa	17.36	Acrisols	0.85	1.20	1.16	1.27		
	Luwingu	14.32	Acrisols	1.03	1.45	1.41	1.55		
	Mbala	15.00	Acrisols	0.99	1.39	1.35	1.48		
	Mporokoso	14.32	Acrisols	1.03	1.45	1.41	1.55		
	Mpulungu	15.00	Acrisols	0.99	1.39	1.35	1.48		
	Mungwi	15.00	Acrisols	0.99	1.39	1.35	1.48		
	Nakonde	13.04	Acrisols	1.13	1.59	1.55	1.70		
N.W.	Kabompo	13.53	Acrisols	1.09	1.54	1.49	1.64		
	Mwinilunga	12.94	Acrisols	1.14	1.61	1.56	1.71		
Southern	Itezhi-tezhi	18.28	Leptosols					0.72	1.13
			Vertisols						1.02 (pooled)
	Namwala	17.53	Acrisols	0.84	1.19	1.15	1.26		
Western	Kaoma	12.44	Acrisols	1.19	1.67	1.62	1.78		

Note: N.W. denotes Northwestern.

There are two clear patterns from Tables 2 and 3: (1) for each district, VCR is the highest for Group (iv) and the lowest for Group (i); (2) for each group of households, VCR is lower in the remote districts than in their corresponding provincial centers.

Households belonging to Group (i), i.e., those that did not obtain fertilizer on time and did not use draft power, hardly benefited from fertilizer use, no matter whether they are located at the provincial centers or in remote areas. Fertilizer use was more likely to be profitable for Group (iv) households, who are at/near provincial centers, obtained fertilizer on time and used animal draft power or mechanical power for land preparation. Households in remote areas face adverse conditions because of the high fertilizer-maize price ratios which result in low VCRs and consequently fertilizer use is unlikely to be profitable unless the households obtained fertilizer on time, used animal draft or mechanical power, and are located in districts where the price ratios were favorable.

If a household had to apply for loans to purchase fertilizer and the interest rate was high, fertilizer use may not have been profitable. For example, Group (iv) households that are located in Mansa District and borrowed money to purchase fertilizer are not likely to have financially benefited from fertilizer use if the interest rate is 30% in which case the VCR becomes 1.80 instead of 2.35. The break-even interest rate for this case is 17.29% for VCR equal to 2. That is, if interest rates are higher than 17.29%, fertilizer use on maize for these groups of households is not likely to be profitable.

Conclusions

Post Harvest Survey data for the period 1996/1997 – 1999/2000 in Zambia were used to estimate maize yield responses to nitrogen index in Zones IIa and III with various soil types and pH levels. Statistical analyses of the estimation results suggest that the marginal product of nitrogen index is the highest for the group of households that obtained fertilizer on time and used animal draft or mechanical power for land preparation.

Results from the economic analyses of fertilization suggest the following key messages. First, households that obtained fertilizer on time and used animal draft power or mechanical power in land preparation are more likely to find fertilizer use profitable than other groups of households located in the same district. Subsidized fertilizer under government programs in Zambia has often been distributed late. These programs have also caused uncertainty for private traders, who first assess whether subsidized government fertilizer will be circulated in their area of operation before deciding to sell fertilizer (Govereh et al., 2003). These dynamics give rise to the late acquisition of fertilizer, which affected roughly 25% of the households using fertilizer in our sample. Second, farmers' proximity to the provincial centers has a significant impact on the profitability of fertilizer use. Greater distances and transport costs from provincial centers erode the profitability of fertilizer use. Applying fertilizer is likely to be more profitable near provincial centers where the price ratio of maize to fertilizer is the highest. Third, high interest rates reduce the profitability of fertilizer use. Consequently, despite achieving relatively high crop response rates to fertilizer use in some areas, small farmers may find fertilizer use unprofitable until efforts are made to reduce transportation costs and interest rates as well as to ensure more timely delivery of fertilizer.

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