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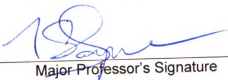
ESSAYS ON APPLIED PRODUCTION ANALYSIS IN
AGRICULTURE

presented by

ZHIYING XU

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Ph.D. degree in Agricultural Economics


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ESSAYS ON APPLIED PRODUCTION ANALYSIS IN AGRICULTURE

By

Zhiying Xu

A DISSERTATION

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ABSTRACT

ESSAYS ON APPLIED PRODUCTION ANALYSIS IN AGRICULTURE

By

Zhiying Xu

This dissertation extends prior research under two important themes in agricultural production study: technology adoption and crop production analysis. New perspectives are incorporated into this dissertation under each research theme; in particular, it underscores the relevance of agricultural input marketing system in analyzing farmers' input use in the context of developing countries, and the relevance of agronomic principles to crop production analysis. New framework and methods developed in this study are used to analyze fertilizer adoption and maize production in Zambia.

Many governments in developing countries distribute fertilizer at subsidized prices to stimulate small farmers' agricultural productivity and food security. Prior studies investigating the farmer and community characteristics associated with fertilizer use largely fail to account for the effects of government input distribution programs on farmers' fertilizer purchase decisions. Using nationally representative rural household panel data in Zambia, we distinguish between commercial and subsidized fertilizer purchases and measure the "crowding in/out" effect of government input programs on commercial fertilizer sales using a double hurdle modeling framework. Results indicate that private sector fertilizer sales can decline substantially due to government programs. In areas where private sector is not already active, government program may possibly enhance commercial demand over the long run. Empirical studies explicitly modeling

farmers' fertilizer purchase behavior within a dual marketing framework can provide important insights for agricultural policy discussions in developing countries.

While raising small farmer fertilizer use and staple food productivity has been a major goal of Zambian government's agricultural policy, a recent survey of beneficiary farmers indicates that government program has very little impact in terms of increasing maize production and household incomes. In the second essay, we use nationwide panel survey data to estimate maize production function and determine profitability of fertilizer use under a range of small farm conditions in Zambia. Based on agronomic principles of crop growth process, we develop a crop production function that distinguishes different roles of inputs and examine the effects of various farm inputs, government programs, and household socioeconomic characteristics on maize yield. Our analysis suggests that fertilizer use is largely unprofitable under most smallholder conditions due to low yield response rates and unfavorable price conditions. Programs to achieve the yield and profitability potentials of fertilizer use will require efforts to ensure more timely delivery of fertilizer, reduce input and output marketing costs and provide sensible extension services to small farmers.

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I dedicate this work to my parents and to the memory of my grandparents.

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INTRODUCTION

This dissertation consists of two essays. The first essay deals with agricultural input use and the second essay deals with farm crop production, both in the context of developing countries. Empirical analyses are based on rural household survey data from Zambia.

In sub-Saharan Africa, farm productivity growth is widely recognized as a precondition for broad based economic development. Achieving this productivity growth is likely to involve, among many other things, much greater use of fertilizer by African farmers. To this end, a number of approaches have been attempted over the past three decades, including state subsidized distribution programs, targeted input credit programs, free starter packs, interlinked credit-input-crop marketing arrangements, and “liberalization” whereby private traders are encouraged to develop commercial input marketing networks. In recent years, many African countries have re-instated fertilizer subsidy programs to operate alongside commercial fertilizer distribution systems. Despite these efforts, fertilizer use in sub-Saharan Africa has been consistently low and currently stands at 9 kilograms per cropped hectare, by far the lowest of any region of the world.

The first essay is broadly motivated by an urgent need for research into understanding the challenges of raising farmers’ fertilizer use and how best to meet these challenges in sub-Saharan Africa. A double hurdle modeling framework is used to analyze households’ fertilizer acquisition within the context of a dual input marketing system. The theoretical model is applied to small-scale maize farmers in Zambia using nationally representative household panel data. Zambian government agricultural policy

has focused on subsidized fertilizer distribution programs to increase farm productivity and nurture the development of private sector in fertilizer distribution. Empirical studies taking explicit account of dual input marketing system in modeling farmer input use can provide important insights for agricultural policy discussions in developing countries.

This article goes beyond prior studies in three ways. First, it provides a framework for estimating the degree of crowding in/out of private sector sales resulting from government input subsidy programs, an important policy issue that has largely lacked empirical foundation to date. Second, by explicitly distinguishing between commercial and subsidized input purchases, the framework more accurately identifies household and community characteristics affecting effective input demand as distinct from those associated with acquisition of subsidized input. Third, it addresses some of the problems affecting prior studies associated with controlling for unobserved household heterogeneity. Relevant variables are almost always missing, such as between-household variation in land quality, farmer skill, and risk attitude, which are hard to obtain or difficult to measure. Unobserved household heterogeneity is controlled for in this essay through panel data estimation method.

A recent assessment of the implementation and effectiveness of the government fertilizer support programme (FSP) based on a survey of randomly selected 116 beneficiary farmers in Zambia indicates that FSP has very little impact in terms of increasing maize production and enhancing household incomes and livelihoods. Several factors were identified as responsible for reducing the effectiveness of the Programme: Delays in input supply, inadequate supply of farm inputs, poor crop marketing arrangements, high input prices and low output prices, and poor transport facilities,

among others. This highlights the need for an in-depth study of maize yield response to fertilizer use, timeliness of fertilizer application and other crop management practices, and profitability of fertilizer use under current small farm conditions to inform policy process aimed at achieving sustainable increase in maize productivity and smallholder incomes. These issues are addressed in the second essay.

While recognizing the importance of providing extension services to small farmers, extension messages and fertilizer distribution programs in Zambia have been based on one nationally recommended application rate, which largely ignores heterogeneity in small farm conditions and differing market conditions. As fertilizer remains an expensive input in many countries in sub-Saharan Africa, extension messages and government programs promoting fertilizer use should emphasize technically viable and economically efficient use of fertilizer, taking account of agroecological conditions, complementary farming practices and cost-effectiveness of fertilizer application.

In recent years with greater availability of large farm survey data in developing countries, there has been a rapid increase in the number of studies that used survey data to estimate crop production functions at the farm level. The extent to which a mathematical form of production function can approximate the actual input-output relationships in field production depends crucially on the knowledge of these relationships. Prior studies largely ignore agronomic principles of crop growth process and treat all inputs symmetrically in production function specification. In addition, simultaneity problem that often exists in empirical crop production analysis has not received enough attention. The second essay deals with these issues with an application to smallholder maize production in Zambia. By incorporating agronomic principles into

the specification of production function and by using panel data technique to address simultaneity problem, we expect to obtain more precise estimates of the maize production function and derive valid policy implications.

ESSAY 1:
DO INPUT SUBSIDY PROGRAMS “CROWD IN” OR “CROWD OUT”
COMMERCIAL MARKET DEVELOPMENT? MODELING FERTILIZER USE
DECISIONS IN A TWO-CHANNEL MARKETING SYSTEM

1.1 Introduction

Fertilizer use in sub-Saharan Africa currently stands at 9 kilograms (kgs) per cropped hectare – by far the lowest of any region of the world. There is widespread consensus that African farmers will need to make much greater use of fertilizer to generate the growth in farm productivity needed to reduce poverty. However, there is considerable debate about exactly how to achieve sustainable increases in fertilizer use in sub-Saharan Africa.¹ Over the past 30 years, a number of different approaches have been attempted, including state subsidized distribution programs, targeted input credit programs, free starter packs, interlinked credit-input-crop marketing outgrower arrangements, and “liberalization,” whereby private traders are encouraged to develop commercial input marketing networks in rural areas. A review of the literature reveals mixed evidence and much debate about the appropriate roles of government and the private sector in sustainably raising small farmers’ use of fertilizer (for reviews, see Morris et al., 2007; Crawford et al., 2006; Dorward et al., 2004; Gladwin et al., 2002; Minot, 2002).

In recent years, many African countries have re-instated fertilizer subsidy programs to operate alongside commercial fertilizer distribution systems. The rising role

¹ For example, the Fertilizer Summit in Abuja (2006) and its resulting “Abuja Declaration” (2006), endorsed by the African Union and its African member states, signaled the intention to scale-up the use of fertilizer subsidies as a means to address rural poverty. Meanwhile, the recent World Bank fertilizer report (Morris et al., 2007) strongly questions the contribution that fertilizer subsidies can make to sustained poverty reduction in sub-Saharan Africa.

of state fertilizer subsidy programs reflects disillusionment in some quarters with the private sector's ability to stimulate small farmers' use of fertilizer to levels deemed essential for achieving rapid agricultural productivity growth and poverty reduction. Dorward et al. (2004) contend that state-led input and output marketing policies featured prominently in the "green revolution" successes achieved in Asia in the 1970s and 1980s and that similar programs will be needed in Africa. Moreover, some fertilizer subsidy programs have been designed in such a way as to "crowd-in" private sector investment by awarding contracts to firms for the distribution of subsidized fertilizer, which may reduce the fixed costs of investing in commercial supply channels, and possibly raise the effective demand for fertilizer among farmers who had not previously used it.

On the other hand, there are concerns that sustainable increases in fertilizer use are blocked by a "catch-22" situation in which government fertilizer distribution programs undermine the demand for commercially distributed fertilizer, which may "crowd out" private investment in input marketing, and then justify the rationale for continued government programs (Jayne et al., 2003; Pletcher, 2000). In this way, subsidy programs designed to correct for temporary market failure or achieve other social and developmental objectives may actually impede national policy objectives to achieve sustainable growth in commercial fertilizer use.

There is a vast literature on fertilizer marketing in Africa using household survey data, including many applied econometric studies attempting to understand the factors affecting small farmers' fertilizer use decisions.² However, to our knowledge none of these analyses have explicitly taken into account the parallel state and commercial

² For reviews, see Morris et al., (2007), Kelly (2006), and Minot (2002). Specific country studies include Abdoulaye and Sanders (2005), Chirwa (2005), Croppenstedt et al. (2003), Isham (2002), Kaliba et al. (2000), Minot et al. (2000), Adugna (1997), Nkonya et al. (1997), and Green and Ng'ong'ola (1993).

channels that characterize the input marketing situation in many African countries. As a result, the applied literature to date is largely unable to inform important policy questions about how the state and commercial input distribution systems interact to affect overall fertilizer use, and specifically whether the state input distribution programs crowd-in or crowd-out private sector input sales.

This study develops a double hurdle modeling framework for analyzing households' fertilizer purchases within the context of a dual input marketing system. We then apply the theoretical model to small-scale maize farmers in Zambia using nationally representative household panel data. Zambia, in southern Africa, provides an interesting case to examine the interactions between government and private input distribution channels and the measurement of "crowding in/out" of commercial fertilizer market development. Zambian government agricultural policy has for the past several decades focused on subsidized fertilizer distribution programs to increase farm productivity and nurture the development of the private sector in fertilizer distribution.

This study has several innovations compared to prior studies. First, the study provides a framework for estimating the degree of crowding in/out of private sector input sales resulting from government input subsidy programs, an important policy issue that has largely lacked an empirical foundation to date. Second, by explicitly distinguishing between commercial and subsidized fertilizer purchases, the framework more accurately identifies household and community characteristics associated with effective input demand as distinct from those associated with acquisition of subsidized input. Household characteristics affecting fertilizer acquisition from the two channels may be very different; merging them together into one input demand function would be a source of

model mis-specification. Government programs often attempt to target poor households, while commercial fertilizer sales, being a function of effective demand, may be accounted for mainly by relatively wealthy and educated farmers. Third, this study addresses some of the problems affecting prior studies associated with controlling for unobserved household heterogeneity. Relevant variables are almost always missing, such as between-household variation in land quality, farmer skill, and risk attitudes, which are hard to obtain or difficult to measure. Unobserved household heterogeneity is controlled for through the use of panel data estimation method in this study.

The remainder of the paper is organized as follows. First, we briefly describe the structure and behavior of fertilizer markets and the government fertilizer program in Zambia. Section 3 presents a framework for measuring the crowding in/out effect of government input programs on commercial fertilizer sales using a double hurdle modeling approach that explicitly takes into account the effects of government subsidy programs on households' commercial fertilizer acquisition. Estimation techniques to control for unobserved heterogeneity are also presented in this section. We then describe the data and variable construction in Section 4, followed by the main findings in Section 5. Section 6 summarizes the main points of the study and considers possible implications for public policy.

1.2 Zambia's Fertilizer Marketing System

Promoting small farmers' access to fertilizer has been a longstanding policy concern in many African countries. For most of its history, fertilizer distribution in Zambia was controlled by government. The financial burden and inefficiencies of the

public input subsidy programs prompted the legalization of private fertilizer trade in the early 1990s. However, almost continuously during the “liberalization” period, various types of government credit and/or input subsidy programs have operated alongside the emerging private distribution system. Starting in 1993, the government designated private agents to distribute fertilizer on loan to “resource poor” farmers, and then to recover the loans after harvest through purchasing maize from the loan recipients. In each year since 1993, the loan recovery rate was never higher than 43 percent and was typically below 30 percent (Govereh et al., 2002).

Starting in 2002, the government eliminated the fertilizer credit program and initiated its Fertilizer Support Programme (FSP), which continues to this day. In both the fertilizer loan program and the FSP, the scale, regions of delivery, and selection of beneficiary farmers are determined by national and local government bodies and are therefore exogenous from the standpoint of individual farmers. The Ministry of Agriculture tender board invites private firms to submit tenders for procuring fertilizer from international sources and deliver them to district depots (there are roughly 70 districts).³ Next, government selects local input distributors to deliver fertilizer from the district depots to satellite depots and cooperative warehouses for subsequent release to approved individual farmers at approximately 50% of the full retail cost. Hence, if the government is distributing fertilizer in a particular area, a farmer who might otherwise choose to purchase fertilizer at full price from a private dealer may perceive an advantage in trying to acquire fertilizer from the government program instead. Despite these

³ Over the past several years, two firms have consistently been awarded these regional tenders. Government generally pays these firms a flat commission for the distribution of fertilizer to the district depots in each region. Some studies have concluded that the consistent awarding of tenders to two large and prominent firms has caused other commercial firms to withdraw from fertilizer distribution in Zambia and has led to a more concentrated and oligopolistic market at wholesale level (Govereh et al., 2006).

government's efforts over the last 15 years, overall fertilizer consumption has expanded slowly and only 20% of smallholder farmers used fertilizer in the 2002/2003 crop season.

An explicit objective of the government subsidy program is to nurture the development of private fertilizer channels (GRZ, 2002). By contracting private firms to distribute fertilizer on behalf of government, the Fertilizer Support Programme is intended to reduce the fixed costs that private firms would otherwise face in developing supply channels to remote rural areas, thereby "crowding-in" private investment. The program is also intended to expand farmers' effective demand for fertilizer over time. Indeed, between 1999 and 2005, the volume of fertilizer distributed under government programs has been roughly constant at 40,000 to 50,000 tonnes of maize, but private sector fertilizer sales appear to have grown moderately (Table 1.1). Yet it is also possible that the government's distribution of large quantities of subsidized fertilizer, especially if targeted to relatively wealthy farmers, could adversely affect investment in the fertilizer market by private firms as well. There has been little evidence-based research to date to help policy makers understand the extent to which their fertilizer promotion program affects sales by the private sector and hence the long-term development of input markets in a liberalized policy environment.

1.3 Modeling Framework

1.3.1 Crowding in/out Effect

The "crowding in/out" effect of government input subsidy programs can be defined as the change in private sector sales caused by an increase in the amount of input distributed under the government program: $\frac{\Delta PRIV}{\Delta GOV}$, where ΔGOV refers to change in the

amount of input distributed by government, and $\Delta PRIV$ refers to change in private sector sales. The effect of government input subsidy program on total input consumption is expressed as

$$(1) \quad \frac{\Delta TOTAL}{\Delta GOV} = \frac{\Delta(GOV + PRIV)}{\Delta GOV} = 1 + \frac{\Delta PRIV}{\Delta GOV}$$

where $\Delta TOTAL$ refers to the change in total input consumption.

We divide the possible outcome of $\frac{\Delta TOTAL}{\Delta GOV}$ into three categories based on the sign of $\frac{\Delta PRIV}{\Delta GOV}$:

- (i) If $\frac{\Delta PRIV}{\Delta GOV} > 0$, then $\frac{\Delta TOTAL}{\Delta GOV} > 1$
- (ii) If $\frac{\Delta PRIV}{\Delta GOV} = 0$, then $\frac{\Delta TOTAL}{\Delta GOV} = 1$
- (iii) If $\frac{\Delta PRIV}{\Delta GOV} < 0$, then $\frac{\Delta TOTAL}{\Delta GOV} < 1$

If (i) is found to exist, this means that government distribution is contributing positively to private sector sales, such that each additional unit of input distributed by the government generates a more-than-one unit increase in total input consumption.

Condition (ii) implies that government programs have no effect on the volume of input sold by private traders, i.e., the crowding in/out effect is zero. However, if condition (iii) is found to exist, this means that each additional unit of input distributed by government depresses or displaces sales by private traders and hence total input consumption rises by less than one unit. Conditions (i) and (iii) are the mathematical representations of the “crowding in” and “crowding out” effect.

1.3.2 Measuring “Crowding in/out” Using a Double Hurdle Model

Using the conceptual framework of double hurdle model used in the literature on consumption of a variety of products (see e.g., Lin and Milon, 1993; Jones, 1989; Haines, 1988; Cragg, 1971), a household’s decision to participate in the fertilizer market and the conditional decision to purchase a certain amount of fertilizer ($q > 0$) can be written as

$$p = P(z_1)$$
$$q = Q(z_2)$$

where p refers to the probability of market participation, q is the amount purchased, z_1 and z_2 are vectors of variables (they can be the same or different) that influence these decisions by functions $P(\cdot)$ and $Q(\cdot)$. The double hurdle model is a bivariate generalization of the Tobit model and it allows the decisions about whether to purchase and how much to purchase to be determined by different processes.

In the literature, factors typically entering input demand functions in developing country studies can be divided into three major categories: household socio-economic and demographic characteristics, input and output prices and indicators of market access conditions, and agro-ecological attributes. In this study, we distinguish between input acquisition from two channels – commercial and government, and examine the effects of these variables on household fertilizer acquisition from each channel using the double hurdle model framework. In addition to these variables, for the analysis of household commercial channel fertilizer purchase we argue that it is important to explicitly model the effects of government subsidy programs on farmers’ purchase of commercial fertilizer, in areas where such programs exist. We construct a community-level variable

describing the government fertilizer program in a double hurdle model of commercial fertilizer purchase. Consider a double hurdle model with the following structure⁴:

$$(2) \quad d_{it}^* = \gamma x_{it} + \alpha G_t + \theta G_t w_{it} + e_{it}$$

$$d_{it} = \begin{cases} 1 & \text{if } d_{it}^* > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$y_{it}^* = \lambda k_{it} + \beta G_t + \varphi G_t w_{it} + u_{it}$$

$$y_{it} = \begin{cases} y_{it}^* & \text{if } y_{it}^* > 0 \text{ and } d_{it}=1 \\ 0 & \text{otherwise} \end{cases}$$

$$i=1,\dots,N; t=1,\dots,T$$

where the subscript it refers to the i th household during period t , d_{it} is the discrete fertilizer market participation decision, d_{it}^* denotes the latent (unobservable) variable of d_{it} , y_{it} refers to the amount of commercial purchase, y_{it}^* is the latent variable of y_{it} , x_{it} and k_{it} are vectors of explanatory variables assumed to be exogenous (x_{it} and k_{it} may contain the same or different variables), G_t is the community-level government program variable during period t , e_{it} and u_{it} are random errors that are normally distributed, and $\gamma, \alpha, \theta, \lambda, \beta, \varphi$ are parameters to be estimated. If we assume that the impact of G_t depends on particular household characteristics such as wealth, w_{it} (which are also included in x_{it} and k_{it}), then it would be appropriate to include interaction terms

⁴ Government channel double hurdle model in this study can be written with a similar structure in equation (2) without the G_t terms, and thus it is omitted.

such as $G_t w_{it}$ in (2).⁵ The specific forms for the distributions of discrete d_{it} and

truncated-at-zero y_{it} can be expressed in terms of the normal distribution as follows:

$$P(d_{it} = 1 | x_{it}, G_t, G_t w_{it}) = \Phi((\gamma x_{it} + \alpha G_t + \theta G_t w_{it}) / \sigma_e)$$

$$f(y_{it} | k_{it}, G_t, G_t w_{it}, \text{and } d_{it} = 1) = \frac{\phi((y_{it} - \lambda k_{it} - \beta G_t - \varphi G_t w_{it}) / \sigma_u)}{\sigma_u \Phi((\lambda k_{it} + \beta G_t + \varphi G_t w_{it}) / \sigma_u)}, y_{it} \geq 0$$

where P refers to the probability, f refers to the density function, “|” denotes conditional on, ϕ and Φ are the probability density and cumulative distribution functions for the normal distribution, σ_e is the standard deviation of the normal distribution of e_{it} , and σ_u is the standard deviation of the normal distribution of u_{it} .

Both the quantity of fertilizer distributed under government programs and the number of farm households in a community may affect an individual household's decision to purchase fertilizer at full price from a private trader. Other things equal, the more subsidized fertilizer to be distributed in a particular community, the greater the likelihood that farmers will receive it and therefore not need to purchase their fertilizer at commercial prices from private retailers. The greater the number of farm households in the community, the less likely it is that any individual farmer will be able to acquire a given quantity of subsidized fertilizer to be distributed in that community. Based on these considerations, we model the government program variable, G_t , as the ratio of the quantity of fertilizer distributed during period t by government in a region r where the i th household is located, GOV_{rt} , to the number of farm households in that region, N_{rt} ,

⁵ A priori, we might expect that poor households are less likely to buy commercial fertilizer, hence the magnitude of crowding out would be lower than among wealthier households.

$$(3) \quad G_t = \frac{GOV_{rt}}{N_{rt}}$$

This modeling framework explicitly takes into account the effects of government fertilizer programs on commercial fertilizer acquisition and thus reduces potential bias in parameter estimates of x_{it} and k_{it} associated with omitted variable problems. We are particularly interested in the research question of the extent to which government fertilizer programs affect, either positively or negatively, commercial fertilizer sales when other factors are held constant, i.e., the magnitude of $\frac{\Delta PRIV}{\Delta GOV}$ in equation (1).

First, based on the model estimates we test the hypothesis H_0 that government program has no effect on fertilizer acquisition from private sector, that is, $H_0 : \alpha, \theta, \beta, \varphi = 0$. Specifically, α and β describe the effects⁶ of government program G_t on households' commercial fertilizer acquisition and the amount of acquisition, and θ and φ describe the effects of government program interacting with household wealth w_{it} on fertilizer acquisition and the amount of acquisition respectively. If H_0 can not be rejected, it is considered there is no evidence of either crowding in or out, and thus condition (ii) for equation (1) is supported. If H_0 is rejected, it suggests that government program affects commercial fertilizer acquisition. Particularly, if estimates of α and/or β are statistically significant whereas estimates of θ and φ are not, it suggests

⁶ It should be noted that under the nonlinear model assumptions, regression parameters α, θ, β , and φ are not equal to the partial effects; nevertheless, the directions of regression parameters are the same as the corresponding partial effects and the magnitude of partial effects are proportional to regression parameters. See Green (2003) and Wooldridge (2002) for detailed discussion of partial effects and regression parameters in nonlinear models.

that government program affects households' commercial fertilizer acquisition, but the effect does not vary by household wealth.

There is evidence of crowding out if coefficient estimates of α , θ , β , and φ are statistically significant and negative. To quantify the crowding out effect of government program on commercial fertilizer sales in a region r during period t , $\left(\frac{\Delta PRIV}{\Delta GOV}\right)_{rt}$, we use estimates of partial effects, $\tilde{\alpha}$, $\tilde{\theta}$, $\tilde{\beta}$, and $\tilde{\varphi}$, as well as information on the number of farm households (N_{rt}), the number of households acquiring commercial fertilizer (n_{rt}), the average amount acquired by a household among market participants ($\bar{q}_{rt}$), and the average wealth level of households that acquire commercial fertilizer ($\bar{w}_{rt}$). The magnitude of $\left(\frac{\Delta PRIV}{\Delta GOV}\right)_{rt}$ is expressed as

$$(4) \quad \left(\frac{\Delta PRIV}{\Delta GOV}\right)_{rt} = \frac{(\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}\bar{q}_{rt}}{N_{rt}} + \frac{(1 + \tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}(\tilde{\beta} + \tilde{\varphi}\bar{w}_{rt})}{N_{rt}}$$

The volume of commercial fertilizer sales is affected by the government program through changes in two sources: one is decline in the number of households acquiring commercial fertilizer, and the other is decline in the amount acquired by those who participate in the market. The right hand side of equation (4) which is comprised of two parts shows the degree of change from each source respectively. The first part gives estimate of the change in commercial sales due to some households no longer buying from private traders. $\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt}$ can be interpreted as the change in the percentage of households purchasing commercial fertilizer from traders when the government program variable G_t increases by one unit. Thus, multiplying $\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt}$ by the number of

original market participant n_{rt} , gives the estimate of the change in the number of households purchasing commercial fertilizer, and further multiplying $(\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}$ by the average purchase volume $\bar{q}_{rt}$ describes the change in the quantity of commercial sales. The change, $(\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}\bar{q}_{rt}$, is associated with a one-unit increase in the quantity of G_t . Because government program variable G_t is modeled as $\frac{GOV_{rt}}{N_{rt}}$ in equation (3), one-unit increase in G_t is N_{rt} unit increase in the amount of government distribution in region r ($\Delta GOV_{rt} = N_{rt}\Delta G_t = N_{rt}$). The value $(\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}\bar{q}_{rt}$ is thus divided by the number of households N_{rt} to obtain the marginal effect of increasing government fertilizer distribution in region r .

The second term of equation (4) is the estimate of the change in commercial sales due to some households altering the quantity of fertilizer that they purchase in response to changes in government fertilizer distribution. $(1 + \tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}$ is the estimate of the number of households that purchase from commercial retailers, and multiplying it by the decline in the amount of fertilizer purchased by a market participant, $\tilde{\beta} + \tilde{\varphi}\bar{w}_{rt}$, gives the estimate of the change in the amount of commercial fertilizer sales. For the same reason discussed in the first part of the equation, we divide $(1 + \tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}(\tilde{\beta} + \tilde{\varphi}\bar{w}_{rt})$ by N_{rt} to derive the marginal effect. Adding the two parts together gives the total decline in private sector sales from a one-unit increase in government fertilizer distribution in a

region r during period t . Consequently the ratio of change in total fertilizer consumption over change in government distribution, $\left(\frac{\Delta TOTAL}{\Delta GOV}\right)_{rt}$, is

$$(5) \quad \left(\frac{\Delta TOTAL}{\Delta GOV}\right)_{rt} = 1 + \left(\frac{\Delta PRIV}{\Delta GOV}\right)_{rt} \\ = 1 + \frac{(\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}\bar{q}_{rt}}{N_{rt}} + \frac{(1 + \tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}(\tilde{\beta} + \tilde{\varphi}\bar{w}_{rt})}{N_{rt}}$$

We further conduct simulation analysis and explore the magnitude of change in aggregate commercial fertilizer sales during period t , $(\Delta PRIV)_t$, when government distributes additional amount of fertilizer in areas where private sector operates. Using expression in equation (4) we write $(\Delta PRIV)_t$ as

$$(6) \quad (\Delta PRIV)_t = \sum_{r=1}^k \left(\frac{\Delta PRIV}{\Delta GOV}\right)_{rt} (\Delta GOV)_{rt} \\ = \sum_{r=1}^k \left(\frac{(\tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}\bar{q}_{rt}}{N_{rt}} + \frac{(1 + \tilde{\alpha} + \tilde{\theta}\bar{w}_{rt})n_{rt}(\tilde{\beta} + \tilde{\varphi}\bar{w}_{rt})}{N_{rt}} \right) (\Delta GOV)_{rt}$$

where k is the number of regions chosen by the government programs. Equation (6) suggests that the magnitude of change in commercial fertilizer sales depends on the selection of regions as well as the selection of farm households by the government programs, and the extent to which government programs increase fertilizer distribution in these regions.

If the coefficient estimates of α , θ , β , and φ are statistically significant and positive, then condition (i) is satisfied and it suggests that government fertilizer programs crowd in private investment in input marketing. We measure this effect with a similar approach discussed above. If not all coefficient estimates are statistically significant,

corresponding calculation is simplified by setting insignificant estimates at zero in respective equations. We also apply above method to quantify crowding in/out effect when parameter estimates have different signs.

1.4 Estimation

Controlling for relevant household characteristics in input demand functions is a challenge due to unobserved household heterogeneity. Unobserved household effects can be controlled for through the use of panel data in this research. We estimate the double hurdle models using the correlated unobserved effects model (Chamberlain, 1984; Mundlak, 1978), both with the pooled estimator and the random effects estimator. Unobserved heterogeneity is explicitly taken into account in the Mundlak–Chamberlain (hereafter M-C) approaches. Due to the incidental parameters problem⁷, we do not estimate a “fixed effects” double hurdle model which treats the unobserved effects c_i as additional parameters to estimate.

The M-C approach allows for correlation between unobserved heterogeneity c_i and explanatory variables X_i by assuming a conditional normal distribution of c_i :

$c_i | X_i \sim \text{Normal}(\tau + \bar{X}_i \xi, \sigma_a^2)$ ⁸, where X_i is the vector of explanatory variables across all time periods for household i , $\bar{X}_i$ is the average of X_{it} , $t=1, \dots, T$, τ and ξ are

⁷ Incidental parameters problem (Newman and Scott, 1948) arise with maximum likelihood estimation of panel data models that treat unobserved effects as additional parameters to estimate, leading to inconsistent estimators when N is large and T is small and fixed (Wooldridge, 2002).

⁸ An alternative is to have X_i in place of $\bar{X}_i$ in the linear expectation of the conditional distribution $c_i | X_i$ (Chamberlain, 1984); we use $\bar{X}_i$ (Mundlak, 1978) to conserve on parameters. The estimator of regression coefficients on time-variant variables when having $\bar{X}_i$ is the same as the fixed effects estimator (also called within estimator) in linear models.

constants, and σ_a^2 is the constant variance of a_i in the equation $c_i = \tau + \bar{X}_i\xi + a_i$, where a_i has a normal distribution, $a_i | X_i \sim \text{Normal}(0, \sigma_a^2)$. In practice, τ is absorbed into the intercept term and additional variables $\bar{X}_i$, which include the time averages of all explanatory variables except time-invariant variables, are added to the model. Using a Wald test, we reject the hypothesis of zero correlation ($\xi=0$) between unobserved heterogeneity and explanatory variables, thus indicating that the M-C approach is superior to the standard pooled model and the random effects model which assumes that the unobserved heterogeneity c_i is independent of the explanatory variables X_i . The double hurdle model with the correlated unobserved effects characterized above is estimated using both the pooled estimator with standard errors robust to serial correlation and the random effects estimator. The M-C approach with pooled estimator does not impose the assumption of conditional independence between dependent variables across time t (Wooldridge, 2002). Although it does not consistently estimate parameters and partial effects, we may still obtain approximate average partial effects⁹. The random effects estimator of the M-C's device is the conditional maximum likelihood estimator and fully efficient under the assumption of independence between dependent variables across time conditional on the explanatory variables and unobserved heterogeneity c_i .

1.5 Data and Variable Construction

⁹ Average partial effects are the partial effects averaged across the whole distribution of c_i . See Wooldridge (2002) for detailed discussion.

1.5.1 Data

Household data used in the current study are from three surveys, the 1999/2000 Post Harvest Survey (PHS), the linked First Supplemental Survey to the 1999/2000 PHS, and the Second Supplemental Survey to the 1999/2000 PHS. These surveys, conducted by the Central Statistical Office of the Government of Zambia, provide a two-year panel dataset of 5,342 small and medium-scale farm households for the 1999/2000 and the 2002/2003 seasons. The PHS is a nationally representative survey using a stratified three-stage sampling design. Census Supervisory Areas (CSAs) were first selected within each district; one Standard Enumeration Area (SEA) was then sampled from each selected CSA; at the last stage a sample of households were selected from a listing of households within each sample SEA. The SEA is the most disaggregated geographic unit in the data. An SEA in Zambia typically includes 2-4 villages of several thousand people.

These surveys cover detailed information on agricultural production as well as household demographic and socioeconomic attributes. After excluding households in two urban districts, and after dropping 451 other households due to missing information, our sample reduced to 4,206 households in 70 districts. Because maize is the main staple crop in the country and is the intended crop for fertilizer under the government subsidy programs, we also confined the sample to households growing maize in both years of analysis. The data set contains a panel of 3,189 maize-producing households with detailed records of agricultural activities over the two seasons 1999/2000 and 2002/2003.

1.5.2 Explanatory Variables

Household socio-economic and demographic characteristics: Household characteristics included in x_{it} and k_{it} are the value of household assets, landholding size¹⁰, the age, gender, and education of the household head, the number of resident adult males, females, and children in the household, binary variables for recent adult mortality, whether a civil servant member is resident in the household, and whether the household head or the spouse is related to the village headman. Holding other factors constant, asset value, landholding size, education level of household head, and number of adults are expected to positively influence commercial fertilizer purchase. The *ceteris paribus* effects of other variables are unclear due to lack of straightforward theory and inconclusive findings in the literature.

Market price and access conditions: Fertilizer-maize price ratio¹¹ is expected to have a negative effect on farmers' decision to use fertilizer. Community-level (SEA) average prices for fertilizer and maize are used to derive price ratio because some households did not purchase fertilizer or sell maize. Distance from a district town is used as a proxy for transportation cost and access to markets. The distance variable is expected to be inversely related to the probability and amount of fertilizer use.

Agro-ecological attributes: Incentives for purchasing commercial fertilizer are expected to be higher for certain soil types and agro-zones because of better maize yield response to fertilizer. Different yield response across soil types and agro-zones affects

¹⁰ Since household income is likely to be endogenous, there are advantages in empirical investigation to use asset value and cropland size as proxies for wealth, which are accumulated over time and hence arguably exogenous.

¹¹ Price ratio is used instead of separate prices of fertilizer and maize because of high collinearity between these prices and the average price terms in the M-C models.

profitability of fertilizer use and thus we expect fertilizer demand to differ accordingly. These agro-ecological attributes are SEA-level variables.

The Government program variable is defined as in (3), the amount of fertilizer distributed under the government program in an SEA divided by the number of maize-producing households in that SEA. We also examine the significance of the interaction terms between government fertilizer program and household asset value and landholding size. The definitions for dependent and explanatory variables used in this study are presented in Table 1.2.

1.6 Findings

As a prelude to econometric estimation, we first provide some descriptive statistics to provide basic features of the data. Table 1.3 shows the percentages of households that acquired basal fertilizer and the average amount acquired among households that obtained fertilizer from government fertilizer program and private sector respectively. About 14 percent of the nationally-representative sample received subsidized fertilizer from the government in the 2002/03 season, up from 9.7 percent in 1999/00. Just over 15 percent of households purchased fertilizer from private retailers in 2002/03, up from 13.6 percent in 1999/00. Those acquiring fertilizer from government and those purchasing from retailers used similar amounts, around 120 kgs per household. The government program appears to have targeted relatively wealthy farmers, who might have otherwise purchased fertilizer from local retailers if they were not beneficiaries of the government program. On average, households receiving government subsidized fertilizer and households acquiring fertilizer from the private channel both have higher

incomes and asset levels, larger landholding sizes, and are closer to district towns than households not acquiring any fertilizer. Wald-test results find significant differences in all of these attributes when comparing fertilizer users (regardless of source) with non-users. This provides some *a priori* grounds for suspecting that government fertilizer distribution may to some extent displace commercial retailer fertilizer sales.

Figures 1.1 and 1.2 show the quantity of fertilizer acquired from private traders versus from the government program at the community level for each survey period respectively. These graphs show that in some cases, government programs distributed fertilizer in communities where farmers purchased very little from commercial retailers, but in other cases, the government distributed fertilizer in areas where private retailers were actively selling fertilizer. Among the 356 communities in the nationwide sample, the number of communities where both private retailers and the government programs operated is 100 in the 1999/2000 season and 139 in the 2002/2003 season. During 1999/2000 (2002/2003), there are 35 (78) communities in which households only received fertilizer from the government and no household purchased fertilizer from private retailers, and in 73 (56) communities households only purchased fertilizer from private retailers.

1.6.1 Estimation Results

Table 1.4 and Table 1.5 present estimates of the double hurdle model for households' fertilizer acquisition from the government program and from the private sector, respectively. The M-C approach with both pooled estimator and random effects estimator were used to estimate these models. Likelihood ratio test result from each

model rejects the hypothesis that there are no random effects, thus the random effects M-C model is favored over the pooled M-C model.

Results in Table 1.4 show that households with larger landholdings are more likely to be targeted by government programs and are allocated more fertilizer. The negative effect of the squared landholding size in the consumption equation suggests that the increase in government fertilizer allocation gets smaller as farm size rises.

Households located in agrozone IIA and III (which include the prime maize growing areas of Zambia) increase the probability of being targeted by the government program. Government programs tend to target households closer to the district towns and the chance of being selected as a beneficiary is higher in 2002/03 than in 1999/00. The probability of receiving subsidized program fertilizer as well as the amount of fertilizer received increase with the educational attainment of the household head and with the number of children.

Table 1.5 presents estimation results of the double hurdle model for households' fertilizer acquisition from private sector.¹² Households purchasing fertilizer tended to have larger landholdings. Amount of fertilizer purchase was also positively related to farm size at a decreasing rate. The coefficients on the agrozone and soil variables indicate that households having relatively favorable agroecological conditions are more likely to acquire fertilizer, but after the decision to purchase fertilizer, these conditions appear not to significantly affect the amount purchased per household, *ceteris paribus*. In addition, households located farther from district towns are less likely to purchase fertilizer, which was also found in the model of fertilizer acquisition from the government program. The

¹² Our sample includes communities where at least one household purchased fertilizer from private retailers for at least one period.

fertilizer-maize price ratio is negatively related to the amount of fertilizer purchased, as expected. The number of children and female adults in the household is positively associated with the amount procured, but has no significant effect on the probability of purchasing commercial fertilizer. Above findings suggest that the determinants of fertilizer acquisition are likely to be different from those affecting how much to acquire. We tested the double-hurdle model against the Tobit model for both the M-C pooled and random effects models using likelihood ratio tests and rejected the hypothesis that the Tobit model and double hurdle model are statistically equivalent. Therefore, a standard Tobit model, which assumes that the processes which characterize the discrete choice and the continuous choice are identical, would be inappropriate in analyzing households' fertilizer acquisition behavior in our sample.

Focusing now on the main issue of this study, the model estimates from the M-C pooled and random effects estimators both rejected the hypothesis that government fertilizer programs in the community have zero effect on households' fertilizer acquisition from private sector. We further rejected the hypothesis that unobserved heterogeneity c_i is uncorrelated with explanatory variables, implying that in the traditional pooled and random effects models, the inability to control for unobserved effects which are correlated with explanatory variables may lead to biased estimates. Therefore, the M-C models are favored over the traditional pooled or random effects models. In addition, the random effects M-C model is favored over the pooled M-C model based on the likelihood ratio test result. Random effects M-C model estimates show that the government fertilizer program variable G is negatively associated with the probability of acquiring fertilizer from private sector, and the interaction terms $G*ASSET$

and $G*CLAND$ have negative effects on the quantity of commercial purchase. We interacted the government fertilizer program variable and the year dummy and found no significant effects. Above empirical evidence suggests that government fertilizer programs may be crowding out rather than crowding in private fertilizer sales.

1.6.2 Magnitude of the Crowding out Effect

The effect of government fertilizer distribution on total fertilizer consumption by small-scale maize farm households, $\left(\frac{\Delta TOTAL}{\Delta GOV}\right)_{rt}$, is evaluated by equation (5) using partial effect estimates of $\tilde{\alpha} = -0.0009$, $\tilde{\beta}=0$, $\tilde{\theta}=\begin{pmatrix} 0 \\ 0 \end{pmatrix}$, $\tilde{\varphi}=\begin{pmatrix} -0.03 \\ -0.05 \end{pmatrix}$, number of households (N_{rt}), number of households acquiring fertilizer from private sector (n_{rt}), average acquisition amount ($\bar{q}_{rt}$), and the average asset level and cropland holding size of households that acquired commercial fertilizer ($\bar{w}_{rt}$). Table 1.6 presents estimates of $\left(\frac{\Delta TOTAL}{\Delta GOV}\right)_{rt}$.

The mean effect for each period is around 0.9, suggesting that a one-ton increase in the quantity of government program fertilizer distributed in a community results in a 100-kg decline in the amount of fertilizer purchased from private traders, and hence an overall 900-kg increase in total fertilizer use. The minimum and maximum values in Table 1.6 indicate that the extent of displacement varies greatly across areas. Among the communities with the largest crowding out effects, a one-ton increase in the quantity of subsidized government fertilizer causes half of one-ton decline in the amount of fertilizer sold by the private sector. Anecdotal information from some commercial fertilizer

distributors indicate that they often wait to see where government fertilizer subsidy programs are occurring and then ship their fertilizer to other areas where they will not compete against the subsidized fertilizer. Table 1.7 shows the crowding out effects by the percentage of households purchasing fertilizer in an area in which both government and private channels were operating.

We further derive aggregate change in private sector sales, $(\Delta PRIV)_t$, based on equation (6). Table 1.8 presents the estimates when government program increases fertilizer distribution by one ton in communities where both government and private fertilizer channels were operating. As noted earlier, both the government program and the private sector operated in 100 SEAs during 1999/2000 and 139 SEAs during 2002/2003, out of a total 356 SEAs.

Table 1.8 indicates that if government increases fertilizer distribution by one ton in each SEA where private traders were already operating, such that the total amount of government program fertilizer distributed to farmers increases by 100 and 139 tons, then private sector sales in these areas will be reduced by around 8 and 10.56 ton for the two periods respectively. Table 1.8 also presents the magnitude of crowding out in the ten communities with the largest crowding out effects. The prospect of competing with subsidized government fertilizer causes some private fertilizer traders to avoid stocking fertilizer in that year, in anticipation of limited demand while the government program operates. Unfortunately however, the cut-backs in private fertilizer distribution provides the impression that the private sector is not adequately meeting effective demand for fertilizer and is not a reliable supplier.

1.7 Conclusions

Parallel input marketing channels, featuring government and private distribution channels are very common in developing countries. Some government fertilizer subsidy programs are designed to nurture the development of commercial input marketing systems. Yet there are concerns that such government programs may depress the commercial demand for fertilizer and thus have unintended long-term consequences for the development of sustainable input marketing systems to serve small farmers. There is a dearth of empirical analysis to inform such policy debates. Most studies analyzing farmer input use decisions do not consider the effects of government input subsidy programs on farm demand for inputs. This study constructs household fertilizer use models distinguishing between the two input channels and investigates the effects of household socioeconomic and demographic characteristics, market access conditions, agro-ecological attributes, and government fertilizer programs on household fertilizer acquisition using nationwide household survey data in Zambia. We develop an approach for quantifying the degree of crowding in/out of private sector fertilizer sales and overall change in consumption due to government programs, which sold fertilizer to selected beneficiaries in selected farming areas at 50% of the full cost.

For each channel the set of factors influencing whether to acquire (or receive) fertilizer is found to be different from those that affect how much to acquire (or receive), indicating the importance of a double hurdle approach in modeling household fertilizer acquisition. Households' landholding size and proximity to district towns are correlated with fertilizer acquisition from both channels. The correlation between these variables and the commercial purchase of fertilizer is not surprising. However, the rationale for

many government input distribution programs is to meet the input needs of farmers in remote areas where the private sector is perceived to be unwilling to operate. The finding that proximity to towns and indicators of household wealth are positively correlated with farmers' receipt of subsidized government fertilizer suggests that the treasury costs of these programs are being captured disproportionately by relatively wealthy farmers in relatively accessible areas. Households targeted by government programs were more likely to have purchased fertilizer from private traders if they had not had access to subsidized government program fertilizer. These findings provide evidence of contemporaneous crowding out effects. Over the entire country, an additional ton of fertilizer distributed under the government program increased total fertilizer use by roughly 700 kgs.

There may also be dynamic crowding in/out effects over time, yet our 2-year panel study is only able to investigate contemporaneous effects. Future study can investigate the potential lagged crowding in/out effects of government programs in a given community on private sales in subsequent years by adding lagged terms of government program variables in the panel data double hurdle model.

The findings in this study imply that government fertilizer distribution programs may be more effective if they target areas where the private sector is not already active, other things equal, and where a lack of knowledge and extension problems may provide opportunities for subsidized distribution to facilitate learning so as to expand the commercial demand for fertilizer over time. This may require appropriate management extension messages to small farmers, and complementary investments in more fertilizer-responsive seeds, physical infrastructure, and transport logistics, so that fertilizer use can

be made to be more profitable for farmers. These investments, coupled with targeted promotional fertilizer use in areas where the private sector is not already active, would promote the objectives of sustainable intensification of smallholder agriculture in sub-Saharan Africa. On the other hand, as the findings of this study indicate, poorly targeted fertilizer subsidy programs may be a costly way of crowding out the development of commercial distribution systems without contributing much to sustainable intensification.

Table 1.1: Quantities of fertilizer procured by smallholder farmers, by type of supplier, 1995/1996 – 2005/2006

	% of small farms using fertilizer on maize		Metric tons distributed	
	From government programs	From private traders	Government programs	Commercial sales*
	(a)	(b)	(c)	(d)
1995/96	18.5%	n.a.	61,141	69,000
1996/97	13.2%	n.a.	65,577	108,000
1997/98	3.0%	12.3%	15,000	81,900
1998/99	6.0%	12.9%	43,028	65,912
1999/00	8.4%	8.4%	24,825	118,925
2000/01	3.5%	14.2%	23,975	81,307
2001/02	6.7%	17.4%	29,580	58,141
2002/03	13.9%	15.3%	54,120	74,485
2003/04	n.a.	n.a.	76,927	111,850
2004/05	n.a.	n.a.	54,094	129,295
2005/06	n.a.	n.a.	57,130	148,486

Notes: * Commercial sales include purchases by smallholders and large-scale farmers, based on government stated quantities distributed under government programs and private sector imports. Sources: column (a) and (b) from Post-Harvest Surveys, Central Statistical Office (2002/03 is the last year for which data is available); columns (c) and (d) from Agricultural Statistical Bulletins (various years) and Ministry of Agriculture and Cooperatives files.

Table 1.2: Definitions for variables

Variables	Definition
Dependent variables	
<i>BASAL_G</i>	1 if household acquired basal dressing fertilizer ^a from government channel; 0 otherwise
<i>BASAL_P</i>	1 if household acquired basal dressing fertilizer from private channel; 0 otherwise
<i>QBASAL_G</i>	Quantity of basal dressing fertilizer from government channel by the household (kilogram)
<i>QBASAL_P</i>	Quantity of basal dressing fertilizer from private channel by the household (kilogram)
Explanatory variables	
<i>Household socio-economic and demographic characteristics</i>	
<i>ASSET</i>	Asset value including farm equipment, transportation equipment, and livestock value (million Kwacha)
<i>CLAND</i>	Area of cropland owned by the household (hectare)
<i>AGE</i>	Age of household head (years)
<i>FEMALEHH</i>	1 if household head is a female; 0 otherwise
<i>EDUC</i>	Education of household head (years)
<i>N_MALE</i>	Number of male adults who live in the household
<i>N_FEMALE</i>	Number of female adults who live in the household
<i>N_CHILD</i>	Number of children aged less than 15 who live in the household
<i>HHDEATH</i>	1 if household head deceased within last 3 years of survey season; 0 otherwise
<i>SPDEATH</i>	1 if household head's spouse deceased within last 3 years of survey season; 0 otherwise
<i>ODEATH</i>	1 if any other adult deceased within last 3 years of survey season; 0 otherwise
<i>CSERVANT</i>	1 if household has civil servant member; 0 otherwise
<i>RELATED_HH</i>	1 if household head was related to village headman when he/she procured land; 0 otherwise
<i>RELATED_SP</i>	1 if household head's spouse was related to village headman when he/she procured land; 0 otherwise
<i>Market price and access conditions</i>	
<i>PRICERATIO</i>	SEA-level basal fertilizer – maize price ratio
<i>DISTTOWN</i>	Distance to the nearest district town from center of SEA (kilometer)
<i>Government fertilizer program</i>	
<i>G</i>	Ratio of quantity of government basal fertilizer distribution to number of maize farm households in SEA (kilogram/household)
<i>G*ASSET</i>	Interaction term between <i>G</i> and <i>ASSET</i>
<i>G*CLAND</i>	Interaction term between <i>G</i> and <i>CLAND</i>
<i>Agro-ecological attributes</i>	
<i>ZONEIIA</i>	1 if SEA belongs to agro-zone IIA; 0 otherwise
<i>ZONEIIB</i>	1 if SEA belongs to agro-zone IIB; 0 otherwise
<i>ZONEIII</i>	1 if SEA belongs to agro-zone III; 0 otherwise
<i>AF</i>	1 if soil type is acrisols or ferrasols; 0 otherwise
<i>AL</i>	1 if soil type is alisols or lixisols; 0 otherwise
<i>HG</i>	1 if soil type is histosols or gleysols; 0 otherwise
<i>FV</i>	1 if soil type is fluvisols or vertisols ; 0 otherwise

Table 1.2 (cont'd)

<i>LR</i>	1 if soil type is leptosols or regosols; 0 otherwise
<i>Aggregate time effect</i>	
<i>YEAR2002</i>	1 if survey season is 2002/2003; 0 otherwise

Notes: ^a Farmers typically use two types of fertilizer on maize: basal dressing (compound D) and top dressing (urea) at planting and weeding stage, respectively. Model estimates for top dressing are very similar to those for basal dressing as households either did not acquire any of them or acquired them at roughly a fixed ratio, 1:1, whether from private or government channel. Hence we only report model estimates for basal dressing fertilizer in this study.

Table 1.3: Fertilizer use patterns by source of procurement and by household wealth status, 2002/2003

	Households receiving fertilizer from government program	Households purchasing fertilizer from commercial retailers	Households not using fertilizer
Share of total household sample	13.9%	15.3%	79.1%
Fertilizer acquired per household (kgs)	122	120	0
Total household income (000 kwacha)	804	774	266
Asset value (000 kwacha per capita)	425	342	173
Landholding size (ha per capita)	0.23	0.20	0.15
Distance to district town (kms)	29.8	28.4	35.2

Source: Second Supplemental Survey, Central Statistical Office, 2004.

Table 1.4: Partial effect estimates of double hurdle model for fertilizer acquisition from government program

Variables	Probability of acquisition		Quantity acquired	
	(i) Pooled M-C	(ii) Random Effects M-C	(i) Pooled M-C	(ii) Random Effects M-C
<i>ASSET</i>	-0.0027 (0.0027)	-0.0026 (0.0028)	0.75 (2.35)	-0.74* (0.42)
<i>CLAND</i>	0.0266*** (0.0039)	0.0243*** (0.0031)	14.14*** (5.38)	5.19*** (0.36)
<i>CLAND</i> ²	-0.0009*** (0.0003)	-0.0008*** (0.0002)	-0.53* (0.29)	-0.14*** (0.02)
<i>AGE</i>	0.001 (0.0006)	0.0009 (0.0006)	1.18 (0.79)	0.09 (0.11)
<i>FEMALEHH</i>	0.0159 (0.0337)	0.0142 (0.0368)	-8.04 (33.91)	1.98 (8.13)
<i>EDUC</i>	0.0055** (0.0026)	0.0052** (0.0025)	2.38 (1.92)	1.00*** (0.39)
<i>N_MALE</i>	0.0046 (0.0067)	0.0043 (0.0063)	-3.56 (5.65)	2.07*** (0.78)
<i>N_FEMALE</i>	0.0084 (0.0072)	0.0077 (0.0068)	0.12 (5.85)	0.28 (0.90)
<i>N_CHILD</i>	0.0074*** (0.0025)	0.0068*** (0.0024)	-0.02 (2.38)	0.94*** (0.35)
<i>HHDEATH</i>	0.0062 (0.0421)	0.0047 (0.0452)	68.13 (52.63)	5.81 (8.72)
<i>SPDEATH</i>	0.028 (0.0438)	0.0273 (0.0463)	5.18 (26.40)	5.07 (4.73)
<i>ODEATH</i>	0.0016 (0.0185)	0.0021 (0.0178)	-21.23 (20.37)	-1.37 (2.34)
<i>CSERVANT</i>	0.0638 (0.0559)	0.0627 (0.0604)	30.47 (24.08)	4.47 (4.09)
<i>RELATED_HH</i>	-0.0107 (0.0094)	-0.0104 (0.0082)	-1.84 (9.29)	-1.97 (1.51)
<i>RELATED_SP</i>	0.0009 (0.0157)	0.0005 (0.0147)	9.61 (12.33)	2.30 (1.85)
<i>PRICERATIO</i>	-0.0057 (0.0388)	-0.0067 (0.0344)	53.87 (43.90)	-0.38 (5.92)
<i>DISTTOWN</i>	-0.0011*** (0.0002)	-0.0011*** (0.0002)	-0.38 (0.25)	-0.06* (0.03)
<i>ZONEIIA</i>	0.0472*** (0.0177)	0.0423** (0.0167)	98.69** (44.94)	7.86 (4.98)
<i>ZONEIIB</i>	-0.0068 (0.0237)	-0.0059 (0.0227)	-27.84 (39.53)	3.79 (10.11)
<i>ZONEIII</i>	0.0581** (0.0227)	0.0535** (0.0224)	92.33** (44.02)	7.93 (5.09)
<i>AF</i>	0.0443*** (0.0131)	0.0399*** (0.0126)	1.30 (12.13)	-0.49 (1.68)
<i>AL</i>	0.0252 (0.0178)	0.0233 (0.0168)	12.37 (15.13)	-0.04 (2.05)
<i>HG</i>	-0.0244 (0.0257)	-0.0207 (0.0249)	-42.51 (35.32)	-7.52 (9.67)
<i>FV</i>	-0.0032 (0.0217)	-0.0031 (0.02)	-31.75 (22.22)	-8.80** (3.78)
<i>LR</i>	0.0750*** (0.0183)	0.0718*** (0.0187)	-7.49 (13.34)	1.99 (1.88)

Table 1.4 (cont'd)

<i>YEAR2002</i>	0.057*** (0.0217)	0.0528*** (0.0198)	-50.85* (26.36)	1.41 (3.29)
<i>ASSET</i>	0.007** (0.0032)	0.0065** (0.0031)	2.35 (2.29)	3.14*** (0.43)
<i>AGE</i>	-0.0003 (0.0007)	-0.0003 (0.0007)	-0.91 (0.87)	-0.16 (0.13)
<i>FEMALEHH</i>	-0.0188 (0.034)	-0.0159 (0.0362)	-46.97 (46.05)	-0.74 (8.84)
<i>EDUC</i>	0.0022 (0.0029)	0.0019 (0.0027)	-1.15 (2.20)	-0.45 (0.45)
<i>N_MALE</i>	0.0098 (0.0082)	0.009 (0.0076)	0.96 (5.61)	0.28 (0.88)
<i>N_FEMALE</i>	-0.0047 (0.0091)	-0.0041 (0.0083)	9.86 (6.99)	1.12 (1.15)
<i>N_CHILD</i>	-0.0063* (0.0036)	-0.0059* (0.0034)	4.37 (4.13)	-0.80* (0.47)
<i>HHDEATH</i>	0.0498 (0.06)	0.0483 (0.0623)	-70.66 (57.94)	-2.41 (10.21)
<i>SPDEATH</i>	-0.0224 (0.0619)	-0.0234 (0.0575)	-10.05 (67.29)	0.14 (8.03)
<i>ODEATH</i>	-0.0046 (0.0278)	-0.0062 (0.0254)	-7.48 (30.35)	-0.95 (3.35)
<i>CSERVANT</i>	0.0304 (0.0521)	0.0262 (0.0502)	-25.96 (31.10)	10.16* (5.36)
<i>PRICERATIO</i>	-0.0401 (0.0533)	-0.0365 (0.0478)	-86.45 (62.79)	-8.72 (8.12)

Notes: Numbers in parentheses are standard errors. Asterisks(, ,) significant at 10%, 5%, and 1%, respectively.

Table 1.5: Partial effect estimates of double hurdle model for fertilizer acquisition from private sector

Variables	Probability of purchase		Quantity purchased	
	(i) Pooled M-C	(ii) Random Effects M-C	(i) Pooled M-C	(ii) Random Effects M-C
<i>ASSET</i>	0.0029 (0.0029)	0.0027 (0.0028)	1.26 (0.82)	0.48 (0.39)
<i>CLAND</i>	0.025*** (0.0052)	0.0209*** (0.0042)	22.80** (10.05)	6.27*** (0.80)
<i>CLAND</i> ²	-0.0011*** (0.0004)	-0.0009*** (0.0003)	-0.88* (0.46)	-0.10** (0.04)
<i>AGE</i>	-0.0009 (0.0007)	-0.0007 (0.0006)	-0.23 (0.48)	0.005 (0.17)
<i>FEMALEHH</i>	-0.0114 (0.0358)	-0.0114 (0.0272)	29.93 (28.71)	0.45 (13.01)
<i>EDUC</i>	-0.0033 (0.0028)	-0.0029 (0.0022)	1.01 (1.63)	0.02 (0.66)
<i>N_MALE</i>	0.0124* (0.0073)	0.0095 (0.0059)	7.35 (5.39)	0.69 (1.48)
<i>N_FEMALE</i>	0.0038 (0.0083)	0.0027 (0.0061)	0.56 (4.10)	3.32** (1.53)
<i>N_CHILD</i>	-0.0028 (0.0028)	-0.0022 (0.00022)	5.99** (2.55)	1.91*** (0.38)
<i>HHDEATH</i>	0.0474 (0.0627)	0.0435 (0.0567)	-113.89* (62.96)	-3.31 (14.37)
<i>SPDEATH</i>	-0.0279 (0.0309)	-0.0245 (0.0235)	-31.13 (27.59)	-6.40 (9.50)
<i>ODEATH</i>	-0.0309* (0.0160)	-0.0245* (0.0126)	10.37 (14.10)	1.55 (4.84)
<i>CSERVANT</i>	-0.0383 (0.0380)	-0.0267 (0.0246)	-10.36 (22.37)	-9.19 (7.59)
<i>RELATED_HH</i>	-0.0317*** (0.0105)	-0.0262*** (0.0083)	4.72 (10.94)	-3.22 (2.04)
<i>RELATED_SP</i>	-0.0142 (0.0170)	-0.0111 (0.014)	-5.72 (7.77)	-0.81 (3.61)
<i>PRICERATIO</i>	0.0181 (0.0371)	0.0134 (0.03)	-14.05 (23.13)	-14.22* (7.47)
<i>DISTTOWN</i>	-0.0015*** (0.0003)	-0.0013*** (0.0002)	-0.09 (0.14)	-0.06 (0.05)
<i>G</i>	-0.0011*** (0.0003)	-0.0009*** (0.0002)	-0.03 (0.11)	-0.04 (0.05)
<i>G*ASSET</i>	0.0001 (0.0001)	0.0001 (0.0001)	0.00 (0.01)	-0.03*** (0.005)
<i>G*CLAND</i>	-0.0001 (0.0001)	-0.0001 (0.0001)	0.00 (0.02)	-0.05*** (0.01)
<i>ZONEIIA</i>	0.1418*** (0.0254)	0.1178*** (0.0214)	20.51 (23.93)	12.77 (12.43)
<i>ZONEIIB</i>	-0.0501* (0.0304)	-0.0327 (0.0225)	-30.24 (54.96)	8.62 (21.50)
<i>ZONEIII</i>	0.1672*** (0.0383)	0.1614*** (0.0394)	10.60 (25.19)	13.05 (12.60)
<i>AF</i>	0.0485*** (0.0151)	0.0428*** (0.0135)	2.03 (9.60)	-0.26 (2.71)
<i>AL</i>	0.0356* (0.0203)	0.0325* (0.0189)	2.52 (9.53)	2.00 (3.13)

Table 1.5 (cont'd)

<i>HG</i>	-0.0147 (0.0369)	-0.0133 (0.0258)	16.66 (15.21)	-6.68 (9.44)
<i>FV</i>	0.0004 (0.0262)	0.0022 (0.0212)	8.39 (14.70)	-10.96* (5.77)
<i>LR</i>	0.0441** (0.0202)	0.0406** (0.0186)	-6.02 (11.15)	0.56 (3.27)
<i>YEAR2002</i>	0.0035 (0.0211)	0.0033 (0.0168)	18.29 (14.26)	8.56** (4.15)
<i>ASSET</i>	0.0087** (0.0038)	0.0063* (0.0035)	2.52* (1.42)	3.92*** (0.49)
<i>AGE</i>	0.0008 (0.0008)	0.0006 (0.0007)	0.17 (0.52)	-0.05 (0.18)
<i>FEMALEHH</i>	0.0015 (0.0399)	0.0024 (0.0324)	-43.87 (37.51)	2.72 (13.83)
<i>EDUC</i>	0.0146*** (0.0032)	0.0122*** (0.0026)	-0.44 (2.11)	1.04 (0.64)
<i>N_MALE</i>	-0.0187** (0.0094)	-0.0142* (0.0075)	-9.37 (7.19)	-2.92* (1.61)
<i>N_FEMALE</i>	0.0004 (0.0105)	0.0008 (0.008)	3.72 (6.13)	-4.31** (1.77)
<i>N_CHILD</i>	0.0036 (0.0042)	0.0029 (0.0033)	-6.02 (4.19)	-1.67** (0.67)
<i>HHDEATH</i>	-0.0862 (0.0799)	-0.0668 (0.0614)	68.66 (47.26)	-8.98 (20.42)
<i>SPDEATH</i>	0.1082* (0.0605)	0.0914* (0.053)	8.48 (35.09)	9.70 (10.89)
<i>ODEATH</i>	0.0377 (0.0312)	0.031 (0.0251)	-15.64 (22.73)	-4.65 (7.40)
<i>CSERVANT</i>	0.1105* (0.0574)	0.0877* (0.0463)	39.00 (29.66)	17.25* (9.92)
<i>PRICERATIO</i>	0.0678 (0.0542)	0.0604 (0.0449)	-39.56 (49.14)	17.45 (11.63)
<i>G</i>	0.0024*** (0.0004)	0.002*** (0.0003)	0.32 (0.20)	0.04 (0.06)
<i>G*ASSET</i>	-0.0001 (0.0001)	-0.0001 (0.0001)	-0.04* (0.02)	0.01 (0.01)
<i>G*CLAND</i>	0.0000 (0.0001)	-0.0001 (0.0001)	0.00 (0.03)	0.09*** (0.01)

Notes: Numbers in parentheses are standard errors. Asterisks(*, **, ***) significant at 10%, 5%, and 1%, respectively.

Table 1.6: Effects of government fertilizer program on total fertilizer consumption

Period	Maximum	Median	Minimum	Mean
1999/2000	0.99	0.936	0.758	0.92
2002/2003	0.99	0.946	0.52	0.924

Table 1.7: Effects of government program on total fertilizer consumption by areas based on percentage of households purchasing commercial fertilizer

Percentage of households purchasing commercial fertilizer in an area in which both government and private channels were operating	1999/2000		2002/2003	
	Number of Areas	Average $\left(\frac{\Delta TOTAL}{\Delta GOV} \right)_{rt}$	Number of Areas	Average $\left(\frac{\Delta TOTAL}{\Delta GOV} \right)_{rt}$
(0, 10%]	16	0.976	21	0.981
(10, 25%]	32	0.944	53	0.951
(25%, 50%]	35	0.911	44	0.917
(50%, 100%]	17	0.842	21	0.814

Table 1.8: Total changes in private sector sales

Period	Change in Government Distribution in Each Area (ΔGOV) _{rt}	Number of Areas (<i>k</i>)	Total Change in Government Distribution (ΔGOV) _t	Total Change in Private Sector Sales ($\Delta PRIV$) _t
	(a)	(b)	(c) = (a)×(b)	Using Equation (6)
1999/2000	1 ton	100	100 ton	-8 ton
	1 ton	10	10 ton	-2.06 ton
2002/2003	1 ton	139	139 ton	-10.56 ton
	1 ton	10	10 ton	-2.7 ton

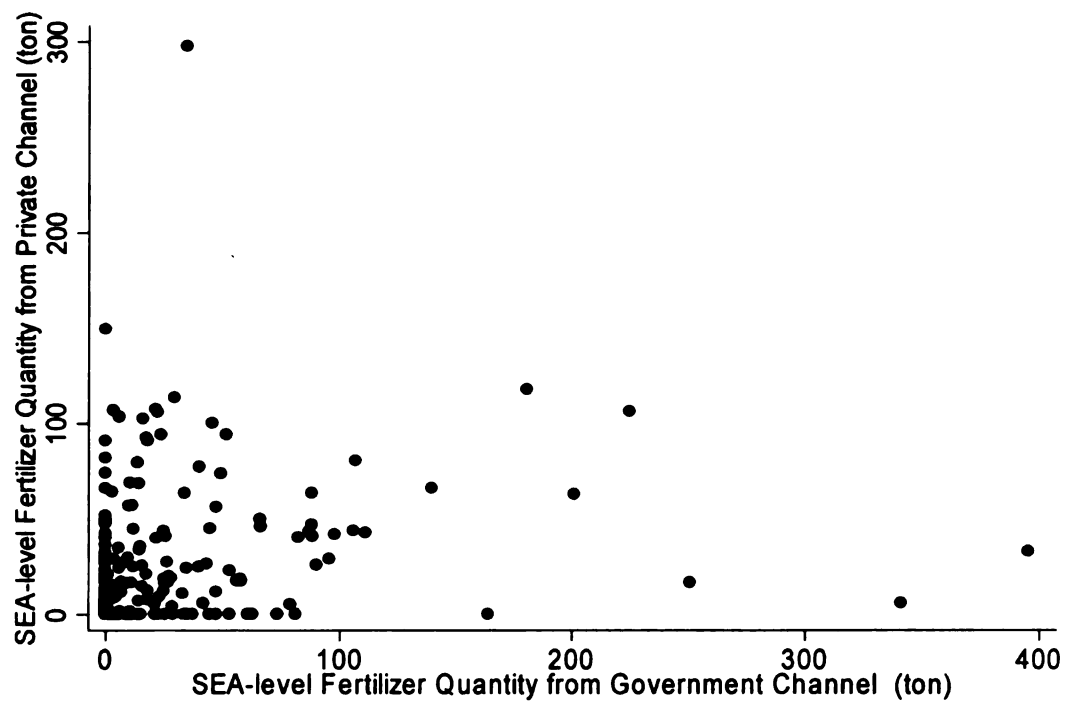


Figure 1.1: Community-level (SEA) quantity of fertilizer acquired from private sector versus from government program, 1999/2000

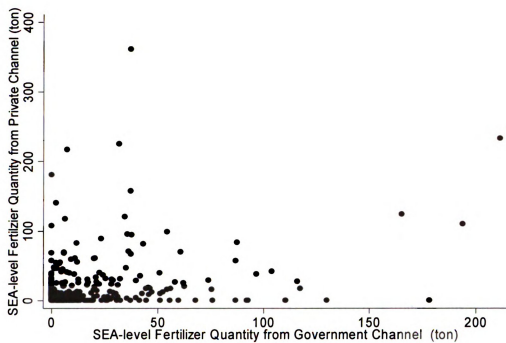


Figure 1.2: Community-level (SEA) quantity of fertilizer acquired from private sector versus from government program, 2002/2003

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ESSAY 2: AN ASYMMETRIC CROP PRODUCTION MODEL AND THE APPLICATION TO MAIZE PRODUCTION IN ZAMBIA

2.1 Introduction

The majority of agricultural production in Zambia remains rainfed and based on small-scale, subsistence family farming systems. Smallholder farmers that own less than 5 hectares of land, about 900,000 of them, comprise the vast majority of farmers in Zambia. Zambian government agricultural policy has for the past several decades focused on fertilizer subsidies and targeted credit programs to stimulate small farmers' agricultural productivity, enhance food security and ultimately reduce poverty. Improving maize productivity has been a major goal of the government policy. Over 70% of the small-scale farmers grow maize as the major staple crop and they are responsible for 65% of the maize production in the entire country. Agricultural marketing among smallholders is dominated by maize sales (Govere et al., 2003).

In 2002, the Zambian Government launched programs and policies under the framework of the Poverty Reduction Strategy Paper (PRSP) which in the agricultural sector included Fertilizer Support Programme (FSP), out-grower schemes, land and infrastructure development, technology development, agriculture extension, and maize marketing in support of small-scale farmers (PRSP, 2002/2004; World Bank, 2002a; 2002b). Despite government's efforts over the past several decades, overall fertilizer consumption has expanded slowly and maize yields remain at the level of 0.7 to 2.5 tons per hectare falling far behind Latin America and south/southeast Asia. A recent assessment of the implementation and effectiveness of the FSP based on a survey of randomly selected 116 beneficiary farmers indicates that FSP has very little impact in

terms of increasing maize production and enhancing household incomes and livelihoods (CSPR, 2005). Several factors were identified as responsible for reducing the effectiveness of the Programme: Delays in input supply, inadequate supply of farm inputs, poor crop marketing arrangements, high input prices and low output prices, and poor transport facilities, among others. This highlights the need for an in-depth study of maize yield response to fertilizer use, timeliness of fertilizer application and other crop management practices, and profitability of fertilizer use under current small farm conditions to inform policy process aimed at achieving sustainable increase in maize productivity and smallholder incomes.

While recognizing the importance of providing extension services to small farmers, extension messages and fertilizer distribution programs in Zambia have been based on one nationally recommended application rate of 200 kilograms of basal fertilizer (compound D) and 200 kilograms of top dressing fertilizer (urea) per hectare of maize. This one-size-fits-all recommendation largely ignores heterogeneity in small farm conditions and differing market conditions. As fertilizer remains an expensive input in many countries in sub-Saharan Africa, extension messages and government programs promoting fertilizer use should emphasize technically viable and economically efficient use of fertilizer, taking account of agroecological conditions, complementary farming practices and cost-effectiveness of fertilizer application.

In this article we examine maize yield response to a range of farm inputs, determine profitability of fertilizer use by small-scale farmers, and identify the potential to increase maize productivity and profitability of fertilizer use through public policy tools. Empirical analyses are based on nationally representative panel household survey

data for 1999/00 and 2002/03 agricultural seasons in Zambia. Use of panel data sets allows controlling for unobserved household/farm heterogeneity and thereby overcomes the limitation of cross-sectional studies that may bias the results. In addition, use of a nationally representative large sample enables generalization from the results to make broader inferences.

Modeling and estimation of crop response functions has been of interest in agricultural economics for decades. In crop response research many different functional forms have been used including quadratic, Cobb-Douglas, transcendental logarithmic (translog), Mitscherlich-Spillman, resistance, generalized power, and others (Dillon and Anderson, 1990). In particular, flexible functional forms, such as quadratic (Lau, 1974) and translog (Christensen, Jorgenson and Lau, 1971, 1973), that can achieve second-order approximations¹ to arbitrary functions have been widely used. A large number of studies treated farm inputs symmetrically in the response function specifications. Symmetric treatment of inputs basically ignores agronomic principles, where different inputs are considered to contribute to crop growth through distinct processes. Failure to take account of the underlying production process in modeling production functions may lead to misspecification and inaccurate inferences (Guan et al., 2006).

In terms of econometric estimation, translog or quadratic production functions contain parameters that increase quickly (or explosively) as the number of variables increase, due to the large number of the square terms and interaction terms. Practitioners

¹ According to Lau (1974), there are two types of second-order approximations: differential approximation (Diewert, 1971) and numerical approximation (Christensen, Jorgenson and Lau, 1973). Under the first definition, a function $H(y)$ is a second-order approximation to another function $G(y)$ at y_0 if the first and second derivatives of the two functions are equal at y_0 ; under the second definition, a function $H(y)$ is a second-order approximation of $G(y)$ if $H(y)=G(y)$ at y_0 and, if in a prescribed neighborhood of y_0 , the deviations of the approximation from the true function are constrained to be relatively small.

in production analysis generally face a dilemma: to avoid omitted variable bias, it is necessary to include all relevant input information available. However, the explosive increase in the number of parameters often quickly reduces the degrees of freedom and poses a practical problem for econometric estimation. Consequently, many researchers choose to limit the number of variables used in the model specification. To this end, practitioners commonly adopt either of three strategies: 1) Start from a broader set of variables and do the stepwise regressions, dropping the insignificant terms each step; 2) Drop the variables that are considered to be the least important in the production process; and 3) Aggregate inputs such as fertilizer, seed, etc. into a general category “variable inputs”. Similarly, “capital” may include many things, such as machinery, equipment, livestock, and building. It should be noted that all these strategies have problems. The stepwise regression usually ends up with incomplete models as linear, cross and quadratic terms may be dropped without theoretical justification. The resulting specification is usually arbitrary and incomplete as far as second-order approximation is concerned. The stepwise regression is not widely seen in the literature. Dropping an entire set of terms associated with specific variables is more frequently seen, which is either based on properly justified arguments or simply ad hoc choice. Although the resulting model specification serves as a proper second-order approximation as such, the ad hoc choice of variables could lead to misspecification. Aggregating inputs into a general category is a more justifiable practice for theoretical and practical considerations. But the aggregation would generally results in loss of valuable information and in some cases may lead to aggregation bias (Griliches, 1957).

To summarize, concerns arise from the classic modeling mentality of second-order approximation. Instead of looking into the underlying production process, specifications based on second-order approximation, such as translog and quadratic, lack theoretical underpinnings and are mainly employed for mathematical convenience. Pursuing flexibility, these models claim to be able to approximate any unknown process and are virtually “universal”. Though widely used in the agricultural economics literature, traditional flexible functional forms per se have little to do with agriculture or economics. Translog function does not allow concavity (Antle and Aitah, 1983), a basic principle in economics. Lack of theoretical appeal and absence of relevant agricultural element make it difficult, if not impossible, to make insightful inroads into empirical intricacies of most agricultural complexes.

Some recent studies on crop response to pesticide and fertilizer have recognized particular biophysical processes and integrated agronomic information into theoretical framework and choice of functional forms (Lichtenberg and Zilberman, 1986; Babcock et al., 1992; Paris, 1992; Chambers and Lichtenberg, 1994; Chambers and Lichtenberg, 1996; Carpentier and Weaver, 1997; Saha et al., 1997; Berck et al., 2000; Oude Lansink and Carpentier, 2001; Holloway and Paris, 2002; Guan et al., 2005). Guan et al. (2006) proposed categorization of inputs into growth inputs and facilitating inputs based on agronomic principles. The complete production function consists of a crop-growth model and a scaling function incorporating asymmetric treatment of growth inputs and facilitating inputs. In their empirical crop-growth model, a translog function was specified for modeling crop response to growth inputs. Translog specification has limitations since it does not allow for concavity and zero input level. In our study, we

adopt the theoretical framework developed by Guan et al. and use a quadratic function for modeling crop response to growth inputs. Quadratic function does not have the limitations of translog function, so it is a more general treatment. These recent crop response studies are either based on experimental data which only included water, pesticide or nutrients as inputs, or based on farm level data but have a restricted set of variables in the model. We use household-level survey data and extend the scope of facilitating inputs used in Guan et al.'s study to include crop management practices, household socioeconomic conditions, and government policies and programs that presumably can affect actual farm yield. By controlling for a wide range of variables and use of panel data techniques we expect to obtain more accurate estimates of crop yield response to fertilizer.

The remainder of this article is organized as follows. We first provide the modeling framework for crop response analysis. In the third section, we present data and potential econometric issues. Empirical model is presented in the fourth section, followed by estimation results. We conclude the article in the last section with closing remarks.

2.2 Modeling Framework

We adopt the conceptual framework recently developed by Guan et al. (2006) for modeling crop production function. Agricultural inputs are dichotomized into growth inputs and facilitating inputs based on agronomic perspectives on crop production levels and different factors influencing these levels². Growth inputs are defined as those that are

² In agronomic literature, three distinct yield levels were proposed: potential, attainable, and actual yield. These yield levels are determined by different growth conditions which depend on three groups of factors: growth defining, growth limiting, and growth reducing factors. Growth defining factors such as weather and species characteristics determine the potential yield, assuming there are no growth limiting and

directly involved in biological process of crop growth and thus essential for crop growth, such as seed, nutrients, and water. Attainable yield is determined by the level of growth inputs in a given biophysical environment, assuming no yield-reducing factors for maximum yield such as weeds, diseases, pests, and imperfect labor and machinery operation. These factors cause actual farm yield lower than the attainable yield.

Facilitating inputs are defined as those that are not directly involved in the basic biological process, but can help create or alter growth conditions under which growth inputs take effect. Guan et al. included labor, capital, and pesticides in this category. In this study, we do not restrict the scope of facilitating inputs to crop management practices alone; instead, yield gap between actual yield and attainable yield is hypothesized to be also related to household socioeconomic characteristics and government policies and programs. Through controlling for these factors that are likely to be correlated with farm household's input use decision, we expect to obtain more accurate estimates of the crop production function, especially crop response to fertilizer that is of particular interest in our study.

A general conceptual crop production function is written as:

$$(1) \quad y = G(x) \cdot S(z)$$

where y is crop yield, x is a vector of growth inputs, and z is a vector of facilitating inputs.

Growth inputs x and facilitating inputs z affect crop output through different mechanisms

indicated by crop growth function $G(\cdot)$ and scaling function $S(\cdot)$. Crop-growth function

$G(\cdot)$ determines the attainable yield level given the biophysical environment. The scaling

reducing factors. Attainable yield is lower than the potential yield due to growth limiting factors such as water and nutrients. Yield gap between actual yield and attainable yield is caused by the growth reducing factors such as weeds, pests, and diseases. In practice, potential yield is typically not achieved due to growth limiting and growth reducing factors; also, it may not be economically viable to attempt to achieve potential yield (Rabbinge, 1993; Van Ittersum and Rabbinge, 1997; Van de Ven et al., 2003).

function $S(\cdot)$ is defined in the interval $[0, 1]$. When $S(\cdot)$ reaches 1, i.e., when growth conditions are optimal for a given level of growth inputs x , crop output y attains its maximum value $G(x)$. Actual yield is lower than the attainable yield and scaled down by the factor $S(\cdot)$ under non-optimal growth conditions.

This modeling framework incorporates agronomic perspectives on crop production levels and explicitly addresses distinct roles of different factors in crop growth process. In field crop production, yield differences among farmers in the same area are frequently observed because of different levels of growth inputs and facilitating inputs. In empirical studies using farm data, we can estimate the crop production function with explicit functional form specifications for $G(\cdot)$ and $S(\cdot)$.

2.3 Data and Econometric Issues

2.3.1 Data

Household-level data used in this study are from three surveys, the 1999/2000 Post Harvest Survey (PHS), the linked First Supplemental Survey to the 1999/2000 PHS, and the Second Supplemental Survey to the 1999/2000 PHS conducted by the Central Statistical Office in Zambia. A panel dataset for two agricultural seasons 1999/2000 and 2002/2003 is available from these surveys. PHS is a nationally representative survey using a stratified three-stage sampling design. Census Supervisory Areas (CSA) were first selected within each district, next one Standard Enumeration Area (SEA) was sampled from each selected CSA, and at the last stage a sample of households were randomly selected from a listing of households within each sample SEA. The SEA is the most disaggregated geographic unit in the data, which typically includes 2-4 villages of

several thousand people. Agro-ecological zone and soil type information is available at the SEA level. The primary maize growing areas include Zone IIA (medium rainfall areas) and Zone III (high rainfall areas) with dominant soil type Acrisols or Ferrolsols (hereafter AF). In this study, crop production functions are estimated for four regions that have distinct biophysical environments: Zone IIA soil type AF, Zone IIA soil type non-AF, Zone III soil type AF, and Zone III soil type non-AF.

The output specified in this study is maize yield in kilogram (kg) per hectare. Growth inputs address fertilizer, seed, and rainfall. We include nitrogen application rate (the most important nutrient in maize growth) in kg per hectare³, and the percentage of basal fertilizer among total fertilizer applied in order to examine the effect of this variable on maize yield⁴. Seed is specified as a dummy variable indicating whether hybrid seed was used. Rainfall is annual district-level rainfall in millimeters. Facilitating inputs examine the effects of a range of variables including mechanical or animal draught power usage, maize area, timeliness of fertilizer application, fertilizer acquisition from government program, extension service, characteristics of household head (age, gender, and education), number of adults, and adult mortality. A year dummy is also included in the model. Table 2.1 presents variable definition.

2.3.2 Econometric Issues

Simultaneity

³ It is calculated based on the amount of basal fertilizer (compound D) and top dressing fertilizer (Urea) used per hectare and the nutrient components in these fertilizers. 100kg of Compound D contains 10kg nitrogen (N), 20kg phosphorous (P), and 10kg potassium (K); 100kg Urea contains 46kg N.

⁴ Farmers adopting fertilizer typically used basal and top dressing at 1:1 ratio.

In previous empirical studies of crop production function using nonexperimental farm data, simultaneity problem has not received enough attention. Farm inputs such as fertilizer and seed are unlikely to be random because farmers can control input use. Deaton (1997) pointed out that farm input use is unlikely to be independent of land quality, thus inputs are at least partly determined by crop yield. As a result, the usual estimates of the production function using cross-sectional farm data are likely to suffer from simultaneity bias. Simultaneity in this context can be considered as an omitted variable problem where land quality is missing. Land quality and farmer skill are unobserved heterogeneity, and it is precisely the correlation between unobserved heterogeneity and observed explanatory variables that is the source of difficulty in cross-sectional study of crop production function ((Deaton, 1997). Use of panel data makes it possible to get closer to the ideal experimental situation than a single cross section since it allows comparison of the same observation unit under different circumstances and use of that unit as their own control. Panel data techniques are employed in this study to control for unobserved heterogeneity and obtain consistent estimates of model parameters.

In addition, explanatory variables indicating presence or absence of government programs are unlikely to be random if these programs are not assigned randomly to the treatment (for example, household). In a randomized experiment, a dummy variable indicating the presence of government program will be uncorrelated with the error term and the usual cross-sectional estimates will be consistent. However, government programs are often not implemented as randomized experiments; on the contrary, they are often targeted to certain population. The econometric problem of evaluating the impact of government programs is similar to that encountered in estimating the effects of

farm inputs. It is the correlation between unobserved heterogeneity and the presence of government program that causes simultaneity bias and invalidates cross-sectional evaluation, and again panel data can be used to address this concern (Deaton, 1997). In this study, government program variables such as provision of extension service and subsidized fertilizer are unlikely to be random. There is empirical evidence that households targeted by the government's fertilizer program tend to be wealthy farmers in accessible areas (Xu et al., 2007). In the case of purposeful allocation, cross-sectional analysis can overestimate the program's true impact if unobserved heterogeneity is not controlled for in the model.

Attrition

Attrition is a common problem in panel survey data. Some households interviewed in the first round of survey are lost from the second round, leading to a reduction in the number of households in the panel. Reasons for sample attrition in developing countries may include household migration, dissolution due to head death, household split-off, or refusal⁵ (Deaton, 1997). Investigation of sample attrition is necessary because nonrandom attrition can cause the panel sample unrepresentative of the population of interest and potentially bias the empirical result.

Potential attrition bias can be tested using the methods suggested in the literature (Beckett et al., 1988; Fitzgerald et al., 1998a; Maluccio, 2004). First, a baseline sample of the households in the first survey is divided into two groups: those that remain (non-attritors) and those that are lost in the second survey (attritors). Sample averages of

⁵ Refusal rates are relatively low in developing countries, which may be related to low opportunity cost of time or cultural attitudes (Maluccio, 2004).

variables are then compared between the two groups to examine whether they are significantly different by attrition status. While univariate comparison can provide useful information about relevant attributes of attritors and non-attritors, it is not a formal test for potential attrition bias. In other words, if the underlying crop production functions for the two groups are the same, we can still obtain unbiased estimates of the population model using the subsample of non-attritors. A formal test can be conducted by using the full sample in the first period and estimating a crop production function which incorporates an attrition indicator and interaction terms between the indicator and other explanatory variables. Joint significance test of the attrition indicator terms will determine whether the model is statistically different between the two groups. If they are jointly insignificant, the hypothesis of homogeneous production function cannot be rejected, therefore inferences about the population crop production function based on the subsample of non-attritors will be valid. If they are jointly significant, attrition bias may be present and it can be corrected for using the inverse probability weighting method (Woodridge, 2002; Fitzgerald et al., 1998a, b).

2.4 Empirical Model

Under the general framework (1), we specify functional forms for the crop-growth function $G(\cdot)$ and the scaling function $S(\cdot)$ in our empirical application of maize production in Zambia. Instead of the translog function used in the literature (Guan et al., 2006), we propose to use the quadratic function for $G(\cdot)$ because it permits concavity and zero input. Concave yield response curves are consistent with most observable biological

relationships since excessive amount of fertilizer or rainfall can adversely affect crop growth. A quadratic model for the crop-growth function $G(\cdot)$ is specified as:

$$(2) \quad G_{it} = \alpha_1 N_{it} + \alpha_2 BSLPCT_{it} + \alpha_3 RAIN_{it} + \alpha_4 HYBD_{it} + \alpha_{11} N_{it}^2 + \alpha_{12} N_{it} \times BSLPCT_{it} + \alpha_{13} N_{it} \times RAIN_{it} + \alpha_{14} N_{it} \times HYBD_{it} + \alpha_{22} BSLPCT_{it}^2 + \alpha_{23} BSLPCT_{it} \times RAIN_{it} + \alpha_{24} BSLPCT_{it} \times HYBD_{it} + \alpha_{33} RAIN_{it}^2 + \alpha_{34} RAIN_{it} \times HYBD_{it}$$

where N , $BSLPCT$, $RAIN$, $HYBD$ are growth inputs defined in Table 2.1, and $\alpha_1 - \alpha_{34}$ are parameters to be estimated.

In specifying the scaling function $S(\cdot)$, we extend the scope of the facilitating inputs used in the literature to include crop management practices, government programs, and household socio-economic characteristics. We use the exponential form that does not impose monotonicity on the input-output relationship (Guan et al. 2006):

$$(3) \quad S_{it} = \exp[-(\beta_0 + \beta_1 ONTM_{it} + \beta_2 DRTPW_{it} + \beta_3 MZAR + \beta_4 EXTNSN_{it} + \beta_5 GVCHNL_{it} + \beta_6 ADULT_{it} + \beta_7 AGE + \beta_8 EDUC + \beta_9 FEMHD + \beta_{10} MRTLT_{it} + \beta_{11} YEAR_t)^2]$$

where $ONTM$, $DRTPW$, $MZAR$, $EXTNSN$, $GVCHNL$, $ADULT$, AGE , $EDUC$, $FEMHD$, $MRTLT$, and $YEAR$ are facilitating inputs defined in Table 2.1, and $\beta_0 - \beta_{11}$ are parameters to be estimated.

With the two functions specified above, maize production function is now written as:

$$(4) \quad YIELD_{it} = (\alpha_1 N_{it} + \alpha_2 BSLPCT_{it} + \alpha_3 RAIN_{it} + \alpha_4 HYBD_{it} + \alpha_{11} N_{it}^2 + \alpha_{12} N_{it} \times BSLPCT_{it} + \alpha_{13} N_{it} \times RAIN_{it} + \alpha_{14} N_{it} \times HYBD_{it} + \alpha_{22} BSLPCT_{it}^2 + \alpha_{23} BSLPCT_{it} \times RAIN_{it} + \alpha_{24} BSLPCT_{it} \times HYBD_{it} + \alpha_{33} RAIN_{it}^2 + \alpha_{34} RAIN_{it} \times HYBD_{it}) \exp[-(\beta_0 + \beta_1 ONTM_{it} + \beta_2 DRTPW_{it} + \beta_3 MZAR + \beta_4 EXTNSN_{it} + \beta_5 GVCHNL_{it} + \beta_6 ADULT_{it} + \beta_7 AGE + \beta_8 EDUC + \beta_9 FEMHD + \beta_{10} MRTLT_{it} + \beta_{11} YEAR_t)^2] + f_i + u_{it}$$

where $YIELD$ is maize yield in kilogram per hectare, f_i is unobserved household heterogeneity, and u_{it} is random error assumed to be i.i.d. $N(0, \sigma^2)$. We use the approach developed by Mundlak (1978) and Chamberlain (1984) (hereafter M-C approach) to control for unobserved heterogeneity f_i , which is assumed to have the form:

$$(5) \quad f_i = \tau + \bar{X}_i\gamma + a_i$$

where $\bar{X}_i$ is a vector of the averages of inputs $\bar{X}_{it}$ across time periods, τ is constant, γ is a parameter vector, and a_i is distributed as i.i.d. $N(0, \sigma_a^2)$ and independent of u_{it} .

Parameters $\alpha_1 - \alpha_{34}$, $\beta_0 - \beta_{11}$, τ , γ , σ^2 , and σ_a^2 are estimated using maximum likelihood estimation method (MLE). Under regularity conditions, MLE is asymptotically unbiased and efficient.

We can determine whether unobserved heterogeneity is correlated with $\bar{X}_i$ by the joint significance test of γ . If the hypothesis $H_0: \gamma=0$ is rejected, there is evidence of unobserved heterogeneity which is correlated with $\bar{X}_i$, thus parameter estimates of the crop production function will be inconsistent if the function is estimated ignoring the unobserved heterogeneity f_i .

Taking the expectation of $YIELD_{it}$ in equation (4) conditional on X_i and taking partial derivative with respect to N_{it} , we get

$$(6) \quad \partial[E(YIELD_{it} | X_i)] / \partial N_{it} = (\alpha_1 + 2\alpha_{11}N_{it} + \alpha_{12}BSLPCT_{it} + \alpha_{13}RAIN_{it} + \alpha_{14}HYBD_{it}) \exp[-(\beta_0 + \beta_1ONTM_{it} + \beta_2DRTPW_{it} + \beta_3MZAR + \beta_4EXTNSN_{it} + \beta_5GVCHNL_{it} + \beta_6ADULT_{it} + \beta_7AGE + \beta_8EDUC + \beta_9FEMHD + \beta_{10}MRTLTL_{it} + \beta_{11}YEAR_t)^2]$$

which is the partial effect of N_{it} on the expected $YIELD_{it}$. It is also the marginal productivity of N_{it} , i.e., the change in expected $YIELD_{it}$ as a result of adding an additional unit of N_{it} , ceteris paribus. As reflected by the formula in (6), marginal productivity of nitrogen is allowed to depend on the nitrogen level as well as the levels of all the other explanatory variables. Partial effects of other continuous variables can be derived similarly by taking the partial derivative of equation (6) with respect to the variable. Partial effect of a dummy variable is derived as the difference between the expected yields when the dummy variable changes from 0 to 1.

2.5 Empirical Results

2.5.1 Attrition

The sample of households in the first round of survey is divided into two subsamples: attritors and non-attritors. Table 2.2 shows estimates of the variable means and differences in the means between the two groups in 1999/2000. For example, for region Zone IIA soil type AF, results from equality of means tests indicate that households that were re-interviewed in the second round of survey on average had larger maize area, higher basal fertilizer percentage, more adults per hectare, and were located in regions with less rainfall. A higher percentage of non-attriting households used animal or mechanical draught power in land preparation and were headed by a male. The averages of other variables are not significantly different between the two subsamples.

Univariate comparison provides information on the unconditional means of variables. Whether these differences in means will cause attrition bias, i.e., whether the underlying crop production function will differ by attrition status is unknown from the

univariate analysis. To examine potential attrition bias, a formal test described in Section 3.2.2 was performed. Using the sample for the first period, crop production function in (4) was expanded to include an attrition indicator and the interaction terms between the indicator and explanatory variables. The function was then estimated for each agroecological region. The attrition indicator terms are jointly insignificant in all models, suggesting estimation of the crop production function based on the non-attriting sample is unlikely to have attrition bias problem in our study.

2.5.2 Production Function Estimation Results

Parameter estimates of the crop production function are presented in Table 2.3. Joint significance test of the average terms reject the hypothesis $H_0 : \gamma=0$ in (5), suggesting unobserved heterogeneity is correlated with the averages $\bar{X}_i$. Estimates of partial effects are presented in Table 2.4. Different estimates of the production function for the four distinct regions indicate that estimation of a single crop production function for the entire country without distinguishing different biophysical environments can lead to spurious estimates.

Results in Table 2.4 show that except household head characteristics including age, gender, and education level (*AGE*, *EDUC*, and *FEMHD*), the effects of other explanatory variables on maize yield are statistically significant for at least one of the four regions. The directions of partial effects are generally consistent with our expectations. Specifically, for Zone IIA soil type AF, nitrogen, timely availability of fertilizer, use of animal or mechanical draught power, and fertilizer acquisition from government channel (*N*, *ONTM*, *DRTPW*, and *GVCHNL*) has a positive effect on yield,

whereas rainfall, extension service, and recent adult mortality (*RAIN*, *EXTNSN*, and *MRTL*) has a negative effect on yield. The positive coefficient on fertilizer acquisition from government channel implies that household acquiring fertilizer from the government program have a higher average yield than those purchasing fertilizer from the commercial retailers, possibly because these farmers have adopted better crop management practices or reported maize production level higher than their actual harvest in order to demonstrate the program is effective on their farms. Negative effect of rainfall at its 50th percentile indicates that the amount of rainfall during the two seasons may have been excessive⁶. Extension service has a negative effect, suggesting recommendations offered by extension service were rather counterproductive. Results for the other three regions show that for Zone IIA soil type non-AF, nitrogen, percentage of basal fertilizer, adoption of hybrid seed, use of draught power, and number of adults per hectare has a yield increasing effect, whereas rainfall, maize area, and adult mortality has a yield decreasing effect. For Zone III soil type AF, yield is positively associated with nitrogen, adoption of hybrid seed, timely availability of fertilizer, use of draught power, fertilizer acquisition from government channel, and adult mortality. For Zone III soil type non-AF, nitrogen, timely availability of fertilizer, and extension service has a yield increasing effect, whereas rainfall, use of draught power, and fertilizer acquisition from government channel has a yield decreasing effect.

Marginal productivity of nitrogen (MPN) is of particular interest in our study. Table 2.4 shows that nitrogen has a positive and significant effect on maize yield for all the four regions. We further derived estimates of MPN at varying levels (25, 50, and 75 percentiles) of nitrogen and other explanatory variables that have significant interaction

⁶ Rainfall in both years was normal to above normal compared to 1995-2005 means.

effects with nitrogen for each region (Tables 2.5-2.8). As expected, marginal productivity of nitrogen declines as nitrogen increases implying a concave response curve for all regions. Timely availability of fertilizer has a significant and positive effect on marginal productivity of nitrogen in two areas, Zone IIA soil type AF and Zone III soil type non-AF. This demonstrates that fertilizer application in a timely manner can contribute substantially to the productivity gains achievable from fertilizer use. Marginal productivity of nitrogen is negatively associated with rainfall in Zone III soil type AF, indicating excessive amount of rainfall can cause a decrease in fertilizer efficiency. Results for some regions show that maize area is positively related to marginal productivity of nitrogen suggesting farmers with larger maize area may have adopted better cultural practices to make fertilizer more efficient, and higher marginal productivity of nitrogen for households with fewer adults per hectare of maize (thus more maize area per adult) could result from these households using better practices to improve fertilizer efficiency.

2.5.3 Profitability of Fertilizer Use

Based on the estimates of marginal productivity of nitrogen (MPN), marginal value-cost ratio (MVCR) of applying nitrogen was computed as

$$(7) \quad MVCR = \frac{MPN \times P_{maize}}{P_N}$$

where P_{maize} is the price of maize per kilogram and P_N is the price of nitrogen per kilogram⁷. The numerator indicates marginal value productivity (MVP) of nitrogen.

⁷ P_N was calculated using the basal and top dressing fertilizer prices and their nutrient component information. Let x denote the amount of each fertilizer required for 1kg of nitrogen given the 1:1

Technically, marginal value-cost ratio greater than one would imply fertilizer use by itself is profitable if no additional cost is incurred. This is not likely to be the case due to the transaction cost. For this reason as well as the risks associated with fertilizer use, experienced researchers have found that MVCR of 2 or greater is generally required to find farmers using fertilizer in any appreciable amounts (Crawford and Kelly, 2002). Our paper adopts this convention and considers marginal value-cost ratio of at least 2 as an indicator that fertilizer use is likely to be profitable.

Equation (7) indicates that MVCR is higher for higher MPN or higher output-input price ratio $\frac{P_{maize}}{P_N}$. Estimates of MVCR are presented in Tables 2.5-2.8. Results show that majority of cases have MVCRs less than two. For example, Table 2.5 shows that for Zone IIA soil type AF, only one case out of 18 cases has MVCR above 2 during the first period and 7 cases have MVCRs above 2 during the second period. At the given levels of marginal productivity of nitrogen, fertilizer use appears to be profitable at its full market cost for a minority of smallholder farmers. On the other hand, a large proportion of government fertilizer recipients (approximately 15% in our sample) may find fertilizer use profitable since they were able to acquire fertilizer at roughly half of the retail price and this would effectively double the MVCR values.

The last column in Tables 2.5-2.8 shows the level of nitrogen (N^*) at which MVCR is equal to 2 for each case. Nitrogen applied at a level lower than N^* has a higher marginal productivity and thereby a higher marginal value-cost ratio for profitable use of

application ratio of two types of fertilizers, based on the nutrient component information we have $10\%x + 46\%x = 1$. Solving for x yields $x = 1.79\text{kg}$, that is, 1kg of nitrogen costs approximately 1.79kg of basal and top dressing, therefore the formula for calculating P_N is $1.79 \times (\text{basal price per kg} + \text{top dressing price per kg})$.

fertilizer. The recommended nitrogen application rate by Zambia extension message (116kg of nitrogen per hectare of maize from 200kg of basal fertilizer and 200kg of top dressing) is higher than the N^* in these tables, suggesting fertilizer applied at the recommended level is unlikely to be economically viable under current market prices and most smallholder conditions.

2.6 Conclusions

Using two-year panel household survey data from Zambia, this study estimates maize production function adopting the conceptual framework recently developed in the literature. This framework incorporates agronomic perspectives on the underlying process of crop growth and thereby addressing the problem of identical treatment of inputs in the traditional quadratic and translog models. Unobserved household heterogeneity is controlled for using the Mundlak-Chamberlain's approach.

Empirical results indicate that maize yield is positively associated with fertilizer and timely availability of fertilizer, while inappropriate extension message and excess amount of rainfall can have yield decreasing effect. Estimates of marginal value-cost ratio of nitrogen for a range of small farm conditions are generally low due to the low yield response rates to nitrogen and unfavorable price conditions. Only for beneficiaries of government fertilizer program that purchased input at a much lower price does fertilizer use appear to be clearly profitable. These findings suggest that small farmers may lack incentive to purchase commercial fertilizer even for those having the capacity and resources to do so, which may explain why only a small proportion of small farmers (15%) acquire fertilizer commercially in Zambia. Strategies to make fertilizer use more

profitable for small farmers will require efforts to raise yield response rates and reduce input and output marketing costs. Our study finds empirical evidence that farmers' ability to acquire fertilizer on time has a strong positive effect on maize yield as well as maize yield response to fertilizer. 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 a certain area of operation before deciding to sell fertilizer (Govere et al., 2003). These dynamics give rise to the late acquisition of fertilizer through both public and private channels. Fertilizer use in an appreciable amount is unlikely to be profitable until efforts are made to ensure more timely delivery of fertilizer. Moreover, the extension service may consider revising their recommended fertilizer application rates both by region and by smallholder characteristics taking into consideration whether fertilizer is available on time and whether they acquired fertilizer through government program or commercial retailers at full cost. All of these factors are shown to influence the profitability of fertilizer use in Zambia.

Table 2.1: Variable definition

Variable	Description
<i>YIELD</i>	Maize yield (kg/hectare)
<i>N</i>	Nitrogen application (kg/hectare)
<i>BSLPCT</i>	Percent of basal fertilizer over total fertilizer application
<i>RAIN</i>	Rainfall (mm)
<i>HYBD</i>	1=used hybrid seed
<i>ONTM</i>	1=basal fertilizer available on time
<i>DRTPW</i>	1=used animal or mechanical draught power in land preparation
<i>MZAR</i>	Maize planting area (hectare)
<i>EXTNSN</i>	1=received extension service
<i>GVCHN</i>	1=acquired fertilizer from government channel
<i>ADULT</i>	Number of adults (above age 14) per hectare of maize
<i>AGE</i>	Age of household head
<i>EDUC</i>	Years of schooling of household head
<i>FEMHD</i>	1=female household head
<i>MRTLTL</i>	1=adult mortality within past three years
<i>YEAR</i>	1=2002 season

Table 2.2: Means between attritors and non-attritors, 1999/00

	Zone IIA AF			Zone IIA non-AF			Zone III AF			Zone III non-AF		
	Attritors	Non-Attritors		Attritors	Non-Attritors		Attritors	Non-Attritors		Attritors	Non-Attritors	
<i>YIELD</i>	1701.32	1797.04		1860.93	1958.69		1507.24	1591.6		1418.15	1490.44	
<i>N</i>	15.22	20.32		24.42	23.02		19.94*	30.13		15.13	15.07	
<i>BSLPCT</i>	13.02*	18.96		2022	17.26		12.93*	19.5		7.25	9.15	
<i>RAIN</i>	856.69*	836.43		849.43	854.47		982.92*	942.88		916.01*	996.36	
<i>HYBD</i>	0.116	0.168		0.275	0.219		0.087*	0.139		0.04*	0.098	
<i>ONTM</i>	0.181	0.238		0.259	0.238		0.152*	0.252		0.075	0.109	
<i>DRTPW</i>	0.35*	0.475		0.389	0.416		0.033*	0.066		0.08*	0.03	
<i>MZAR</i>	0.96*	1.2		1.13	1.23		0.64*	0.87		0.5*	0.81	
<i>EXTNSN</i>	0.23	0.291		0.171*	0.242		0.143*	0.216		0.175	0.151	
<i>GVCHNL</i>	0.094	0.129		0.176	0.148		0.071*	0.117		0.04	0.077	
<i>ADULT</i>	2.53*	2.94		2.87*	3.1		2.62*	2.88		2.61*	2.89	
<i>AGE</i>	41.3	43.69		42.44	43.56		41.23	42.13		40.99*	43.92	
<i>EDUC</i>	5.04	4.61		6.3*	5.46		6.57	6.54		5.37*	6.23	
<i>FEMHD</i>	0.303*	0.197		0.245	0.197		0.203	0.18		0.125	0.153	
<i>MRTLT</i>	0.091	0.079		0.119	0.111		0.107	0.09		0.07	0.1	
Sample	164	707		335	1169		400	491		204	293	

Note: Asterisks indicate significantly different from non-attritors at 5% or higher level.

Table 2.3: Coefficient estimates of empirical crop production function

Parameter	Zone IIA AF	Zone IIA non-AF	Zone III AF	Zone III non-AF
$\alpha_1 (N)$	42.519** (0.000)	17.472* (0.030)	22.692** (0.005)	44.464** (0.000)
$\alpha_2 (BSLPCT)$	-10.891 (0.516)	2.515 (0.832)	-30.607* (0.034)	4.736 (0.859)
$\alpha_3 (RAIN)$	-2.449** (0.001)	-6.819** (0.000)	-2.944** (0.000)	-3.83** (0.000)
$\alpha_4 (HYBD)$	-972.07** (0.000)	-241.97** (0.000)	447.99** (0.000)	433.64** (0.000)
$\alpha_{11} (N^2)$	-0.112** (0.000)	-0.039* (0.020)	-0.009 (0.508)	-0.117** (0.000)
$\alpha_{12} (N \times BSLPCT)$	-0.043 (0.725)	0.108 (0.157)	0.109 (0.226)	0.199 (0.182)
$\alpha_{13} (N \times RAIN)$	-0.008 (0.320)	-0.006 (0.395)	-0.012* (0.021)	-0.021* (0.011)
$\alpha_{14} (N \times HYBD)$	0.129 (0.969)	-0.445 (0.863)	1.225 (0.719)	12.229** (0.003)
$\alpha_{22} (BSLPCT^2)$	0.38** (0.004)	0.18* (0.029)	0.209* (0.031)	0.319* (0.024)
$\alpha_{23} (BSLPCT \times RAIN)$	-0.013 (0.391)	-0.016 (0.102)	0.002 (0.883)	-0.023 (0.197)
$\alpha_{24} (BSLPCT \times HYBD)$	-7.1 (0.248)	0.439 (0.907)	3.468 (0.510)	-36.291** (0.000)
$\alpha_{33} (RAIN^2)$	0.001 (0.098)	0.004** (0.000)	0.002** (0.000)	0.002** (0.002)
$\alpha_{34} (RAIN \times HYBD)$	1.897** (0.000)	0.667** (0.000)	-0.439** (0.008)	0.809* (0.020)
β_0	-0.72** (0.003)	-0.796** (0.000)	-0.199 (0.509)	0.933** (0.002)
$\beta_1 (ONTM)$	0.456 (0.102)	-0.065 (0.153)	-0.134 (0.594)	-1.136** (0.002)
$\beta_2 (DRTPW)$	-0.109 (0.281)	-0.013 (0.604)	0.075 (0.750)	0.006 (0.980)
$\beta_3 (MZAR)$	0.336** (0.000)	0.099** (0.000)	0.205** (0.008)	-0.405** (0.001)
$\beta_4 (EXTNSN)$	-0.109 (0.297)	-0.042 (0.069)	0.349 (0.300)	0.113 (0.371)
$\beta_5 (GVCHNL)$	1.611** (0.000)	-0.083* (0.043)	-0.533 (0.603)	-0.271 (0.370)
$\beta_6 (ADULT)$	-0.226** (0.000)	-0.017** (0.002)	-0.068* (0.039)	0.011 (0.728)
$\beta_7 (AGE)$	0.001 (0.901)	-0.001 (0.313)	-0.006 (0.274)	0.004 (0.481)
$\beta_8 (EDUC)$	-0.013 (0.492)	-0.008 (0.204)	-0.014 (0.495)	0.014 (0.478)
$\beta_9 (FEMHD)$	0.063 (0.615)	0.017 (0.538)	-0.230 (0.477)	-0.274 (0.107)
$\beta_{10} (MRTLTL)$	-0.242 (0.154)	-0.007 (0.826)	-0.054 (0.771)	-0.06 (0.729)
$\beta_{11} (YEAR)$	0.218 (0.058)	0.222** (0.000)	1.130 (0.141)	-0.131 (0.383)
γ_0	-93.672** (0.000)	2666.69** (0.000)	2820.19** (0.000)	3217.24** (0.000)

Table 2.3 (cont'd)

$\gamma_1(\overline{N})$	3.365 [*] (0.039)	2.789 [*] (0.021)	0.081 (0.954)	-1.147 (0.623)
$\gamma_2(\overline{BSLPCT})$	-7.946 ^{**} (0.001)	-4.833 [*] (0.018)	-1.268 (0.700)	-1.717 (0.721)
$\gamma_3(\overline{RAIN})$	2.096 ^{**} (0.000)	0.614 ^{**} (0.007)	-0.64 ^{**} (0.004)	-1.064 ^{**} (0.000)
$\gamma_4(\overline{HYBD})$	-4.091 ^{**} (0.000)	129.38 ^{**} (0.000)	81.402 ^{**} (0.000)	-336.44 ^{**} (0.000)
$\gamma_5(\overline{ONTM})$	264.94 ^{**} (0.000)	-23.331 ^{**} (0.000)	285.58 ^{**} (0.000)	410.96 ^{**} (0.000)
$\gamma_6(\overline{DRTPW})$	255.17 ^{**} (0.000)	301.98 ^{**} (0.000)	317.94 ^{**} (0.000)	-104.71 ^{**} (0.000)
$\gamma_7(\overline{MZAR})$	110.03 ^{**} (0.000)	110.94 ^{**} (0.000)	-37.838 ^{**} (0.000)	-3.845 ^{**} (0.009)
$\gamma_8(\overline{EXTNSN})$	-69.176 ^{**} (0.000)	-90.781 ^{**} (0.000)	57.426 ^{**} (0.000)	195.66 ^{**} (0.000)
$\gamma_9(\overline{GVCHNL})$	189.00 ^{**} (0.000)	-29.547 ^{**} (0.000)	215.16 ^{**} (0.000)	-131.22 ^{**} (0.000)
$\gamma_{10}(\overline{ADULT})$	5.515 (0.725)	-15.1 (0.256)	-7.797 (0.520)	0.965 (0.942)
$\gamma_{11}(\overline{AGE})$	-2.803 (0.335)	-2.773 (0.372)	-2.747 (0.330)	-2.766 (0.589)
$\gamma_{12}(\overline{EDUC})$	-0.056 (0.996)	-0.049 (0.997)	-0.052 (0.997)	-0.063 (0.997)
$\gamma_{13}(\overline{FEMHD})$	-0.161 (0.635)	-0.159 (0.703)	-0.160 (0.540)	-0.163 (0.880)
$\gamma_{14}(\overline{MRTLTL})$	-300.59 ^{**} (0.000)	-339.76 ^{**} (0.000)	290.09 ^{**} (0.000)	23.761 ^{**} (0.000)
σ^2	848000 ^{**} (0.000)	920037 ^{**} (0.000)	800724 ^{**} (0.000)	720296 ^{**} (0.000)
σ_a^2	220000 ^{**} (0.000)	163700 ^{**} (0.000)	119000 ^{**} (0.000)	116000 ^{**} (0.000)
Number of observations	1414	2338	982	586

Note: Numbers in parentheses are p-values. * and ** indicate estimate is significantly different from zero at 5% and 1% significance level, respectively.

Table 2.4: Estimates of partial effects

Variable	Zone IIA AF		Zone IIA non-AF		Zone III AF		Zone III non-AF	
	1999/00	2002/03	1999/00	2002/03	1999/00	2002/03	1999/00	2002/03
<i>N</i>	7.80 [*] (0.002)	11.70 [*] (0.000)	6.75 [*] (0.000)	9.34 [*] (0.000)	8.45 [*] (0.000)	10.67 [*] (0.007)	5.73 [*] (0.014)	7.19 [*] (0.007)
<i>BSLPCT</i>	4.61 (0.068)	6.92 (0.062)	5.46 [*] (0.026)	7.55 [*] (0.026)	0.18 (0.971)	0.23 (0.971)	11.11 (0.077)	13.95 (0.051)
<i>RAIN</i>	-0.51 [*] (0.007)	-0.76 [*] (0.002)	-0.62 [*] (0.000)	-0.86 [*] (0.000)	0.34 (0.077)	0.43 (0.094)	-0.62 [*] (0.049)	-0.78 [*] (0.019)
<i>HYBD</i>	121.38 (0.090)	184.25 (0.084)	303.24 [*] (0.000)	369.83 [*] (0.000)	237.72 [*] (0.004)	278.69 [*] (0.013)	-165.26 (0.160)	-121.42 (0.390)
<i>ONTM</i>	201.06 [*] (0.000)	201.96 [*] (0.000)	110.17 (0.233)	116.43 (0.239)	339.48 [*] (0.000)	244.4 [*] (0.005)	405.36 [*] (0.009)	407.10 [*] (0.000)
<i>DRTPW</i>	267.49 [*] (0.000)	270.34 [*] (0.000)	328.08 [*] (0.000)	328.71 [*] (0.000)	287.41 [*] (0.002)	345.4 [*] (0.000)	-104.66 [*] (0.000)	-104.65 [*] (0.000)
<i>MZAR</i>	-40.54 (0.308)	-48.17 (0.292)	-205.11 [*] (0.000)	-208.90 [*] (0.000)	-86.7 [*] (0.028)	73.74 (0.192)	-3.23 (0.971)	-3.49 (0.971)
<i>EXTNSN</i>	-56.90 [*] (0.001)	-54.06 [*] (0.008)	-4.17 (0.927)	-0.98 (0.984)	-65.96 (0.286)	191.13 [*] (0.009)	196.51 [*] (0.000)	196.60 [*] (0.000)
<i>GVCHNL</i>	122.54 (0.065)	183.28 [*] (0.000)	139.65 (0.082)	148.89 (0.083)	408.91 [*] (0.000)	126.16 (0.510)	-133.53 [*] (0.035)	-133.56 [*] (0.037)
<i>ADULT</i>	27.33 (0.280)	32.47 (0.276)	35.76 [*] (0.001)	36.42 [*] (0.001)	29.24 (0.132)	-24.87 (0.343)	0.09 (0.970)	0.10 (0.970)
<i>AGE</i>	-0.06 (0.904)	-0.08 (0.904)	2.76 (0.295)	2.81 (0.298)	2.59 (0.307)	-2.2 (0.359)	0.03 (0.971)	0.04 (0.971)
<i>EDUC</i>	1.53 (0.522)	1.81 (0.517)	16.5 (0.192)	16.8 (0.197)	6.51 (0.448)	-5.53 (0.518)	0.11 (0.971)	0.12 (0.971)
<i>FEMHD</i>	-8.03 (0.661)	-9.30 (0.657)	-35.91 (0.539)	-36.29 (0.535)	88.69 (0.198)	-62.66 (0.326)	-2.51 (0.969)	-2.54 (0.969)
<i>MRTLTL</i>	-275.65 [*] (0.000)	-268.64 [*] (0.000)	-325.51 [*] (0.000)	-325.21 [*] (0.000)	305.47 [*] (0.000)	277.39 [*] (0.000)	23.27 (0.079)	23.23 (0.099)

Note: Numbers in parentheses are p-values. ^{*} indicates the estimate is significantly different from zero at 5% or higher level. Partial effects are evaluated at *HBRD*, *ONTM*, *DRTPW*, *EXTNSN*, *GVCHNL*, *FEMHD*, *MRTLTL* equal to zero, and *N*=(45.90, 49.19, 82.28, 74.67), *BSLPCT*=(50, 50, 50, 50), *RAIN*=(892.6, 892.6, 1086.3, 1087.9), *MZAR*=(1.215, 1.215, 0.75, 0.81), *ADULT*=(3, 3, 4, 4), *AGE*=(44, 44, 44, 46), *EDUC*=(6, 7, 7, 7), the 50 percentiles of households with *N*>0 for each agroecological region.

Table 2.5: Estimates of marginal productivity of nitrogen and marginal value-cost ratio, Zone IIA, AF

Cas	N			ONTM			MZAR			ADULT			MPN		MVCR		N* (MVCR=2)
	25% (28)	50% (45.90)	75% (69.31)	0	1	25% (0.81)	50% (1.215)	75% (2.02)	25% (2)	50% (3)	75% (4)	1999	2002	1999	2002	1999	2002
1	x			x			x			x		9.15	13.73	1.10	1.80	n.a.	14.85
2	x				x		x			x		19.24	23.68	2.32	3.11	44.72	71.31
3	x			x		x				x		6.76	10.77	0.82	1.42	n.a.	n.a.
4	x			x				x		x		14.94	19.94	1.80	2.62	14.65	56.69
5	x			x			x		x			13.93	18.95	1.68	2.49	4.93	51.88
6	x			x			x				x	5.42	8.98	0.65	1.18	n.a.	n.a.
7		x		x			x			x		7.80	11.70	0.94	1.54		
8		x			x		x			x		16.40	20.18	1.98	2.65		
9		x		x		x				x		5.76	9.18	0.70	1.21		
10		x		x				x		x		12.73	16.99	1.54	2.23		
11		x		x			x		x			11.88	16.16	1.43	2.12		
12		x		x			x				x	4.62	7.65	0.56	1.01		
13			x	x			x			x		6.03	9.05	0.73	1.19		
14			x		x		x			x		12.68	15.61	1.53	2.05		
15			x	x		x				x		4.46	7.10	0.54	0.93		
16			x	x				x		x		9.85	13.15	1.19	1.73		
17			x	x			x		x			9.19	12.50	1.11	1.64		
18			x	x			x				x	3.57	5.92	0.43	0.78		

Note: Other variables are held at *HBRD*, *DRTPW*, *EXTNSN*, *GVCHNL*, *FEMHD*, *MRTLT* equal to zero, and *BSLPCT*=50, *RAIN*=892.6, *AGE*=44, *EDUC*=6, which are the 50 percentile values from the sample of households that used fertilizer; n.a. denotes value is less than zero.

Table 2.6: Estimates of marginal productivity of nitrogen and marginal value-cost ratio, Zone IIA, Non-AF

Case	N			MZAR			ADULT			MPN		MVCR		N* (MVCR=2)	
	25% (27.72)	50% (49.19)	75% (82.5)	25% (0.81)	50% (1.215)	75% (2.5)	25% (2)	50% (3)	75% (4.94)	1999	2002	1999	2002	1999	2002
1	x				x			x		7.58	10.48	0.94	1.36	n.a.	n.a.
2	x			x				x		7.07	9.96	0.87	1.29	n.a.	n.a.
3	x					x		x		9.23	12.07	1.14	1.57	n.a.	n.a.
4	x				x		x			7.80	10.70	0.96	1.39	n.a.	n.a.
5	x				x				x	7.15	10.04	0.88	1.30	n.a.	n.a.
6		x			x			x		6.75	9.34	0.83	1.21		
7		x		x				x		6.30	8.87	0.78	1.15		
8		x				x		x		8.23	10.75	1.02	1.40		
9		x			x		x			6.95	9.54	0.86	1.24		
10		x			x				x	6.38	8.95	0.79	1.16		
11			x		x			x		5.47	7.57	0.68	0.98		
12			x	x				x		5.11	7.19	0.63	0.93		
13			x			x		x		6.67	8.72	0.82	1.13		
14			x		x		x			5.63	7.73	0.70	1.00		
15			x		x				x	5.17	7.25	0.64	0.94		

Note: Other variables are held at *HBRD*, *ONTM*, *DRTPW*, *EXTNSN*, *GVCHNL*, *FEMHD*, *MRTLT* equal to zero, and *BSLPCT*=50, *RAIN*=892.6, *AGE*=44, *EDUC*=7, which are the 50 percentile values from the sample of households that used fertilizer; n.a. denotes value is less than zero.

Table 2.7: Estimates of marginal productivity of nitrogen and marginal value-cost ratio, Zone III, AF

Case	N				RAIN			MPN			MVCN			N*
	25% (44.8)	50% (82.28)	75% (112)	75% (960.3)	50% (1086.3)	75% (1200.4)		1999	2002	1999	2002	1999	2002	(MVCN=2)
1	x				x			8.93	11.27	1.14	1.23	n.a.	n.a.	
2	x			x				9.91	12.51	1.26	1.36	n.a.	n.a.	
3	x					x		8.04	10.15	1.03	1.11	n.a.	n.a.	
4		x			x			8.45	10.67	1.08	1.16			
5		x		x				9.43	11.90	1.20	1.30			
6		x				x		7.56	9.55	0.97	1.04			
7			x		x			8.07	10.19	1.03	1.11			
8			x	x				9.05	11.43	1.16	1.24			
9			x			x		7.19	9.07	0.92	0.99			

Note: Other variables are held at *HBRD*, *ONTM*, *DRTPW*, *EXTNSN*, *GVCHNL*, *FEMHD*, *MRTLT* equal to zero, and *BSLPCT*=50, *MZAR*=0.75, *ADULT*=4, *AGE*=44, *EDUC*=7, which are the 50 percentile values from the sample of households that used fertilizer; n.a. denotes value is less than zero.

Table 2.8: Estimates of marginal productivity of nitrogen and marginal value-cost ratio, Zone III, Non-AF

Case	N			ONTM	MZAR			MPN		MVCR		N*	
	25% (44)	50% (74.67)	75% (112)		25% (0.405)	50% (0.81)	75% (1.50)	1999	2002	1999	2002	1999	2002
1	x			x		x		8.71	10.94	1.12	1.20	n.a.	n.a.
2	x			x		x		20.17	18.83	2.60	2.06	64.79	46.53
3	x			x		x		6.23	8.17	0.80	0.89	n.a.	n.a.
4	x			x			x	13.60	15.88	1.76	1.74	31.54	30.36
5		x		x		x		5.73	7.19	0.74	0.79		
6		x		x		x		13.27	12.38	1.71	1.35		
7		x		x		x		4.10	5.38	0.53	0.59		
8		x		x			x	8.95	10.45	1.15	1.14		
9			x	x		x		2.10	2.64	0.27	0.29		
10			x	x		x		4.86	4.54	0.63	0.5		
11			x	x		x		1.50	1.97	0.19	0.22		
12			x	x			x	3.28	3.83	0.42	0.42		

Note: Other variables are held at *HBRD*, *DRTWP*, *EXTNSN*, *GVCHNL*, *FEMHD*, *MRTL* equal to zero, and *BSLPCT*=50, *RAIN*=1087.9, *ADULT*=4, *AGE*=46, *EDUC*=7, which are the 50 percentile values from the sample of households that used fertilizer; n.a. denotes value is less than zero.

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