Modeling the Effects of Input Market Reforms on Fertilizer Demand and Maize Production: A Case Study of Kenya

Megan Sheahan[a*], Joshua Ariga[b], T.S. Jayne[c]

[a] consultant for Department of Agricultural, Food, and Resource Economics, Michigan State University;
[b] International Fertilizer Development Center;
[c] Department of Agricultural, Food, and Resource Economics, Michigan State University.

[*]Corresponding author: (email) megan.sheahan@gmail.com, (phone) +1-301-775-7749

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4-6, 2013.

Abstract: Kenya is one of the few countries in sub-Saharan Africa experiencing an impressive rise in fertilizer use on food crops grown by smallholder farmers since the liberalization of input markets starting in the early-1990s. The impacts of these reforms and associated private sector investments on national fertilizer use and food production have never been rigorously quantified, though doing so could shed new light on policy makers' options for raising food crop productivity in the region. This study estimates a double-hurdle model of fertilizer demand that controls for common forms of unobserved heterogeneity then simulates the effect of changes in fertilizer prices and distances from farm to the nearest fertilizer retailer associated with fertilizer market liberalization on the demand for fertilizer and the production of maize, the major staple crop in the country. The study concludes that over the period 1997-2010 the reduction in real fertilizer prices associated with input market liberalization is estimated to have raised maize yields by 15 to 100 kg/ha, depending on the province and year. Low average physical response rates of maize to fertilizer application in high fertilizer consuming areas of Kenya limits the degree to which increased fertilizer use via liberalization policies translates into food production improvements. These increases in maize yield specifically linked to changes in fertilizer prices accounted for between 1 and 11 percent of changes in maize production between survey years.

Acknowledgements: The authors wish to acknowledge the financial support of USAID/Kenya and the Bill and Melinda Gates Foundation for funding this study. We have also benefited from the insights and assistance of Roy Black, David Mather, Milu Muyanga, Jordan Chamberlain, John Olwande, Francis Karin, and colleagues at the Tegemeo Institute in Kenya.

1. INTRODUCTION

Raising agricultural productivity is a major challenge facing governments in developing countries. Farm productivity is especially low in sub-Saharan Africa (SSA), where fertilizer use lags far behind the rest of the world. Identifying strategies to raise fertilizer use in Africa in a cost-effective manner has been a persistent and increasingly topical policy priority. While most of the continent has struggled with raising fertilizer use in a sustainable manner, there may be several success stories from which to learn. If such cases can be identified, then it may be possible to isolate the specific factors leading to these successes and to consider their potential for replication elsewhere. Kenya may provide one such success story, as fertilizer use more than doubled between the early 1990s and 2010. Over this period, there has been a 34 percent increase in smallholder fertilizer use per hectare of cultivated maize and an 18 percent increase in maize yields. In the maize breadbasket areas, over 90 percent of smallholder farmers use fertilizer on maize with application rates comparable to areas of green revolution Asia.

Prior research has documented the role of input market liberalization of the 1990s in reducing domestic fertilizer distribution costs and encouraging massive new entry in rural fertilizer retailing in Kenya (Ariga and Jayne 2009, 2010). Alene et al. (2008) show how fixed and variable transactions costs (including distance) affect fertilizer demand using a Heckman model and joint estimation of output supply and input demand. Omamo and Mose (2001) explore the impact of liberalization on fertilizer trade in Kenya using data from a survey of fertilizer traders and dealers to describe factors related to fertilizer use. Freeman and Omiti (2003) use a Tobit model to look at fertilizer demand in a semi arid area of Kenya (Machakos) using data from the late-1990s and show that while there was an increase in the number of farmers using fertilizer due to increased village input retailing, use rates remain low due to high transaction costs that reduce the profitability of fertilizer for farmers. While many studies have looked at some facet of fertilizer demand or use in Kenya, there has been no rigorous evidence to date that has quantified the nationwide impacts of input market liberalization policies on commercial fertilizer use and maize productivity. Such a study would provide a more solid empirical foundation to guide other governments in the region in their efforts to promote small farm input use and staple crop productivity.

This study overcomes this knowledge gap by quantifying the effects of input market reforms in the early- to mid-1990s on the intensity of fertilizer use on maize and the associated impact on national maize production. Using five waves of household panel survey data covering a span of thirteen years (1997, 2000, 2004, 2007, and 2010) and drawing on preliminary findings using a sub-set of the data used in this analysis (Mather and Jayne 2011; Olwande, Sikei, Mathenge 2009; Ariga et al. 2008), we isolate the specific contributions to fertilizer use and maize yields resulting from (i) the more dense network of fertilizer retailers in rural areas, reducing the distance traveled by farmers to acquire fertilizer; and (ii) a reduction in fertilizer prices via the reduction in fertilizer marketing costs between the port of Mombasa and retail distribution points. Building on previous work on the response of maize to fertilizer application on farmers' fields (Sheahan, Black, Jayne 2013), we build a double-hurdle model of farmer demand for commercial fertilizer controlling for unobserved household heterogeneity then simulate the effects of changes in the distance traveled by farmers to the nearest fertilizer dealer and changes in farm-gate fertilizer prices associated with reductions in marketing costs on the quantity of fertilizer applied to maize fields by smallholders. To our knowledge, our use of fertilizer demand and maize response models provides the first empirical evidence linking specific input liberalization policy outcomes to changes in fertilizer demand and national maize production in Kenya.

2. FERTILIZER MARKET DEVELOPMENT IN KENYA

Prior to liberalization, fertilizer and maize markets were run by state or quasi-state agencies that set pan-territorial and pan-seasonal consumer and producer prices with tight control on both internal and external trade (Jayne and Argwings-Kodhek 1997; Freeman and Kaguongo 2003; Ariga and Jayne 2009). Between the mid-1970s and mid-1980s, the Kenya Farmers Association possessed the single import license for fertilizer in Kenya. Then, by the late 1980s, other companies were allowed to enter, but the market was highly regulated by the Government of Kenya (GoK) which set prices at government-run retail locations, set maximum selling prices for private retailers, and still controlled which firms could receive licenses. The liberalization process was initiated upon realization that current government budgets were unsustainable, that rent-seeking behavior was negatively affecting program implementation, and that maximum fixed selling prices were hindering private retailers from selling fertilizer in relatively remote areas. With both pressure and support from international development partners to reform fertilizer markets, in 1990 the GoK initiated a number of reforms (e.g., elimination of import quotas, price control, import licenses, foreign exchange control), leading to full liberalization of the fertilizer market by 1994.

Following liberalization, fertilizer supply channels morphed to accommodate private sector entry and, ultimately, the widespread distribution of commercial fertilizer to farmers throughout the country. Wanzala et al. (2001) study four different fertilizer marketing channels in western Kenya in the late 1990s and use a cost build-up analysis method to determine where in the supply chain there were “bottlenecks” or unnecessary cost accumulation contributing, in the end, to higher fertilizer prices for farmers. Overall, they found slim profit margins for the various actors along the chain (an indication of high competition) but high costs of domestic distribution in an environment of weak transport infrastructure and various taxes on fertilizer coming through the Port of Mombasa. As time went on, domestic marketing costs declined, leading to a reduction in real fertilizer costs for farmers. Comparing DAP fertilizer CIF prices in Mombasa with wholesale prices in Nakuru (a major fertilizer consuming area of the Rift Valley) as reported by the Ministry of Agriculture, we find that domestic marketing costs declined from roughly 50 percent of the Nakuru price in 1997 to about 25 percent in 2008 (see Figure 1). Based on key informant interviews in the fertilizer sector, Ariga et al. (2008) report four reasons for the observed narrowing of margins in commercially distributed fertilizer over this 11-year period: (1) investment by private fertilizer companies in more efficient supply chain operations; (2) local importers’ increased access to less expensive international financing sources; (3) private companies’ expansion into regional fertilizer distribution and value-addition activities, enabling economies of scope and cost savings; and (4) increased competition at the local distribution level. Key informants stressed that private local and international companies’ commitment to long-term cost-reducing investments in fertilizer distribution was largely due to the liberalization of input markets, the concurrent liberalization of output markets of agricultural commodities, which also took place in the 1990s, and the incentives and reduced risks that private firms perceived after concessionary fertilizer distribution programs were phased out in the mid-1990s.

Not only did fertilizer prices go down from the perspective of farming households (until the major international price spike in 2008), but also the number of rural fertilizer retailers increased dramatically. Allgood and Kilungo (1996) estimated there were 5,000 rural retailers operating in 1996; the IFDC (2001) estimated that this number had increased to 8,000 by the year 2000. Investment by the private sector in fertilizer and maize output markets was in response to price de-control and the ensuing arbitrage opportunities even for thin remote markets that were under-served during the state-run regime. Fertilizer retailers moved further into rural areas and became more accessible to farmers, leading to a reduction in the cost of transportation necessary to move fertilizer from the retail shops to the farm-gate. Based on evidence that transport and transactions costs are significantly inversely related to Kenyan farmers' participation in input markets (Alene et al. 2008), the observed reduction in transport costs is likely to have increased fertilizer demand and application rates over time.

Despite what appears to be an effective response by the private sector to improve smallholder farmers' access to fertilizer in Kenya, the GoK had, by 2007, decided to initiate a large-scale fertilizer and certified seed subsidy program, the National Accelerated Agricultural Inputs Access Program (NAAIAP), aimed at increasing national maize production and decreasing rural poverty for the most vulnerable. The NAAIAP has continued through the 2011/12 agricultural season with the stated focus of providing resource poor farmers with access to improved inputs. Concurrently, the government also distributed subsidized fertilizer through the National Cereal and Produce Board (NCPB) in high fertilizer use areas as a short term strategy to alleviate the pains associated with large increases in the international price of fertilizer in 2008 and the disruption in private fertilizer retailing following the post-election violence of 2007/08. While these government programs are not the focus of this analysis, it is important to note that the retreat of the government in the input market during the liberalization area was somewhat reversed by 2007 through these two subsidy programs.

3. DATA

The data used in the analysis comes from Egerton University's nationwide Tegemeo Rural Household Survey from the years 1997, 2000, 2004, 2007, and 2010. The surveys geographically cover 24 administrative districts, 39 divisions, and 120 villages where standard proportional sampling using census data for rural divisions of the country formed the basis of extraction of the sample households (for more details on survey design, see Argwings-Kodhek et al. 1998). The panel started with 1,500 households but, due to attrition, 1,243 are consistently interviewed through the most recent 2010 panel. Most agricultural data in these surveys is observed at the field level. For that reason, we narrow our focus to specifically defined maize fields instead of averaging to the household level. In doing so, the sample used in this analysis identically matches that of Sheahan et al. (2013). More information on our sample can be found in Table 1.

Supplemental data on yearly rainfall levels comes from the National Weather Service Climate Prediction Center (CPC) as a part of their Famine Early Warning System (FEWS) project. Rainfall values are available at the village level based on extrapolations from weather station data using Global Positioning System (GPS) coordinates taken during data collection. Soil data comes from the Kenya Soil Survey and the Ministry of Agriculture from data originally collected in 1980 and is also available at the village level. We utilize population density estimates by year and village using a combination of data from the Global Rural-Urban Mapping Project (GRUMP) (for further details on this data, see Balk and Yetman 2004) and GlobCover2009, a global land cover dataset. Further, net primary productivity (NPP) values at the village level are taken from a University of Montana data set relying on MODIS data spanning 2000-2006 (for further details on this data, see Zhao et al. 2005).

4. CONCEPTUAL FRAMEWORK AND METHODS

To estimate demand for commercial fertilizer on maize fields, we utilize a profit maximization framework where input demand equations are derived by taking the envelope of a profit function. This framework, however, requires that the production and consumption of maize be separable, an assumption unlikely to hold in Kenya where households fluctuate between net maize buyers and sellers in any given year. Non-separability is accommodated by allowing socio-demographic variables of the household to be included in the estimation of the demand function for fertilizer (de Janvry and Sadoulet 2006; Singh, Squire, Strauss 1986) which enables an input demand function of the following form:

$$x_{ijt}(p_{yjt}, p_{xijt}, z_{jt}, \mu_{ijt}) \qquad (1)$$

where x_{ijt} is the amount of commercial fertilizer applied to maize field i by household j at time t, p_y is the output price of maize, p_x is the price of fertilizer, z includes all household, community, agro-ecological, and market characteristics that also are hypothesized to affect the demand for fertilizer. The error term μ_{ijt} in equation (1) is a function of two components. The first component is unobserved time-constant factors, also called unobserved heterogeneity c_j, which affect household j's demand for commercial fertilizer. These factors might include soil quality, the farmer's management ability, and degree of risk aversion. The second component of the error term is composed of truly random variables, ε_{ijt}.

Despite an observed increase in the use of fertilizer over time in Kenya, a non-trivial number of maize fields went unfertilized in any given year. The relatively large number of zeros in the dependent variable (about 25 percent of fields went completely unfertilized across all years) leads to biased and inconsistent estimates under ordinary least squares (OLS), creating the need for a "corner solution" model. Like many other studies of fertilizer demand with similar restrictions (e.g., Croppenstedt, Demeke, Meschi 2003; Ricker-Gilbert, Jayne, Chirwa 2011), we utilize Cragg's double hurdle model (Cragg 1971), which allows the binary use and continuous amount decisions to be estimated separately unlike the often-used Tobit model (Tobin 1958). The decision to use fertilizer is first estimated using a binary probit model. Then, for those households that use fertilizer, a truncated normal regression is run on the continuous variable describing the amount of fertilizer applied. The two-tiered model takes the following form:

$$P(D_{ijt} = 1 | x_{ijt}) = \gamma X_{ijt} \quad (2)$$

$$x_{ijt} = \beta X_{ijt} \text{ if } D_i = 1 \quad (3)$$

where D_{ijt} is the participation decision variable which takes the value one if the household used commercial fertilizer on a given maize field and zero otherwise and X_{ijt} represents all vectors in the fertilizer demand model described in equation (1). Because we expect the reasons for the decision to use may be different from the reasons for applying a specific rate of fertilizer application for users, the X_{ijt} vector has two separate sets of coefficients, γ is associated with the first hurdle while β is associated with the second hurdle. Both hurdles are estimated using maximum likelihood techniques (MLE).

Using panel data, we are able to control for time-constant unobservable characteristics c_j of households that might influence fertilizer demand using the correlated random effects (CRE) estimator, which both allows for correlation between the unobserved omitted variable c_j and included explanatory variables. CRE models use a device modeled by Mundlak (1978) and Chamberlain (1980) which, instead of treating the omitted variable as a parameter to estimate, allows modeling the distribution of the omitted variable conditional on the means of the strictly exogenous variables:

$$c_j = \tau + \overline{x}_k \gamma + a_{ijt} \quad (4)$$

where $\overline{x}_k$ is a vector of average values of each input x_k at the household level j across all waves of the panel. The CRE approach provides an intuitive way of estimating changes that occur "within" the panel unit over the period and measures of differences "across" units. Wooldridge (2010) shows that the CRE device can be used in unbalanced nonlinear models, such as the data set and demand function described here, by adding into the vector $\overline{x}_k$ the number of survey waves each households is present (i.e., the average of each binary variable representing one survey year). This strategy effectively "weights" each maize field relative to how often the household appears in the sample, both in survey years and number of maize fields. We compute robust standard errors at the household level to account for potential heteroskedasticity and serial correlation between fields within the same household (Wooldridge 2009).

With estimates from the demand model, we then simulate how changes in fertilizer prices (via a reduction in marketing margins) and the distance to the nearest fertilizer dealer (via private sector expansion) have contributed, all else equal, to changes in maize production over time in Kenya. We do this by combining the coefficient estimates from this model with a maize yield response model previously estimated using the same data set (Sheahan et al. 2013). With both sets of coefficients, we employ the chain rule to estimate the change in maize output resulting from a change in the price of fertilizer and distance necessary to travel to purchase fertilizer, respectively. In summary, we utilize the chain rule as follows:

$$\frac{dN}{dp_N}\frac{dY_{maize}}{dN} = \frac{dY_{maize}}{dp_N} \tag{5}$$

$$\frac{dN}{ddist_N}\frac{dY_{maize}}{dN} = \frac{dY_{maize}}{ddist_N} \tag{6}$$

where N is the amount of nitrogen fertilizer applied to the field, p_N is the price of nitrogen, $dist_N$ is the distance from the household to the nearest fertilizer dealer, and Y_{maize} is maize output. With these values, we then simulate the impact of these two major policy interventions—an entry of the private sector into fertilizer retailing and a decrease in the cost necessary to move fertilizer from the point of entry to point of sale—on smallholder maize output.

To what extent can effects (5) and (6) be attributed to market liberalization *per se*? While key informant interviews of private fertilizer companies point to the decisive influence of input market reform policies in the 1990s and the phase-out of concessional fertilizer programs as the impetus for both the reduction in fertilizer marketing costs and the rapid investment by retailers in rural areas, it is not possible to rule out that some types of investments would not have been made even if the pre-reform controls were still maintained. However, as shown in Figure 1, inflation-adjusted CIF import prices of fertilizer did not decline between the mid-1990s and 2007; the decline in wholesale prices in maize production areas was due to reductions in the marketing margins over time between CIF import prices and up-country wholesale prices. This declining trend is also observed in fertilizer retail prices from the household survey data. Inflation-adjusted prices of DAP declined by 40 percent between the 1997 and 2007 panel surveys. Moreover, the quite substantial decline in the distance traveled by farmers to the nearest retail fertilizer seller over this period corresponds to IFDC estimates of a 35 percent increase in the number of fertilizer retailers operating in Kenya's rural areas immediately following the liberalization period (Allgood and Kilungo 1996; Freeman and Kaguongo 2003). The weight of the evidence therefore suggest that the effects to be measured in (5) and (6) at least largely reflect the response of the private sector to the improved investment environment resulting from the specified policy changes described in Section 2 (Wanzala et al. 2001; Freeman and Kaguongo 2003; Jayne et al. 2003; Ariga and Jayne 2009).

5. FERTILIZER DEMAND MODEL COMPONENTS

In this section, we detail the variables used in our demand model. Our key variables of interest are the price of fertilizer and distance to the nearest fertilizer dealer while other variables function as controls. Table 2 provides a summary of the variables included in the demand model. Observations with considerable outliers on the high end of a single variable are replaced with the value at the 99th percentile so as to limit their leverage. Otherwise, all variables and observations are kept in the model for estimation.

5.1. Commercial nitrogen fertilizer applied

We measure the total nitrogen from all fertilizer types applied in kilograms per hectare to a given maize field. Despite the relatively high consumption of di-ammonium phosphate (DAP) and calcium ammonium nitrate (CAN) fertilizers as compared with other fertilizer options, we observe households using a range of fertilizer types on their maize fields and, therefore, combine the nitrogen portions of any fertilizer type used on maize fields.[1] Therefore, variation in nitrogen levels across fields comes from both the type of fertilizer used and the total amount of fertilizer applied. The decision to examine the demand for the nitrogen component of fertilizer instead of total fertilizer application is due to the fact that Kenyan farmers are cognizant of the nutrient composition of the fertilizers on the market and that there is growing awareness of the specific nutrient deficiencies, even broadly, in soils. Further, investigating the demand for nitrogen specifically allows direct comparison of results with the production function estimates from Sheahan et al. (2013) as explained in Section 4 above.

With the presence of two government fertilizer subsidy programs in the 2010 survey, we subtract any subsidized fertilizer acquired by the household from the total amount of fertilizer applied to arrive at the portion of applied fertilizer purchased by the household from the commercial fertilizer market. In our data, less than 2 percent of all maize fields received any subsidized fertilizer. Even when limiting the sample to 2010, only about 10 percent of fields were partially fertilized using subsidized fertilizer products. We denote which households received a fertilizer subsidy (from the government or NGO) with a dummy variable.[2] Given our interest in commercial fertilizer demand, the coefficient on this variable will show how receiving subsidized fertilizer effects demand for commercial fertilizer. Other studies of commercial fertilizer demand in countries with far larger fertilizer subsidy programs have used econometric approaches to mitigate the endogeneity of including the amount of subsidized fertilizer received as an explanatory variable (Mason and Jayne 2012; Ricker-Gilbert et al. 2011). There are two main reasons why including this variable may not significantly distort our results: (i) only a very small portion of our sample received subsidized fertilizer under either of the programs and (ii) the two separate subsidy programs were supposedly targeted at very different households with ostensibly different fertilizer demand potential meaning this variable should not be biased towards one "type" of household or producer in particular.

Table 3 shows both the percent of maize fields fertilized with commercial nitrogen by year and province and the average application rates for those that did apply. Apart from a few

---

[1] For example, DAP is 18 percent and CAN is 26 percent nitrogen. For this analysis, we multiply those percentages by the total amount of each fertilizer observed applied to maize fields to arrive at the commercial nitrogen quantity. These values are then added together at the field level to create total nitrogen used per hectare of maize field.

[2] We use a dummy variable instead of a continuous variable because most recipients of one of the fertilizer subsidy programs—NAAIAP—received approximately the same amount of fertilizer: 100 kilograms.

early years in Eastern Province, we consistently observe at least half of the maize fields fertilized with commercial nitrogen in a given year and province. Within-province variation can be immense since the location specific operating (market and agro-ecological) environment will influence fertilizer use decisions, however it is worth mentioning that the seemingly high proportion of fertilized maize fields is partially a function of how our sample was chosen from the full nationwide sample of data. As explained in Sheahan et al. (2013), areas of the country with conditions inhospitable to maize production and where fertilizer use was virtually non-existent were excluded from the sample in order to facilitate production function estimation. Regardless, the upward trend in percentage of fertilized fields and amount of nitrogen applied by fertilizer users speaks to the growing demand for fertilizer observed by many researchers since the onset of liberalization in Kenya.

5.2. Fertilizer prices

One of our key variables of interest is the price of fertilizer which allows us to measures the contribution to changes in overall prices due to the reduction in marketing margins as a consequence of market liberalization policies. Because there are several types of fertilizer used on maize fields, we create a composite “nitrogen price” using the two main types of fertilizer applied to maize fields and sold in Kenya: DAP and CAN. Instead of using the full market price, we extract the “nitrogen price” by multiplying the total price by the ratio of each fertilizer type to the amount of nitrogen in the overall product. This method is similar to that employed by Xu (2008) who creates a nitrogen price using a simple average of the nitrogen components of DAP and CAN. We improve upon this methodology by weighting the prices of DAP and CAN by the relative shares of basal and top dress fertilizers found on maize fields, averaged at the district and year level. The formula used to calculate nitrogen prices is as follows:

$$P_N=((P_{DAP}/0.18*weight_{basal})+(P_{CAN}/0.26*weight_{topdress}))/2 \tag{7}$$

Overall basal and top dress fertilizers are used in our weights instead of only DAP and CAN since a range of other types of fertilizer are found on maize fields, including urea and NPK. This weighting scheme allows us to create nitrogen prices that more accurately mimic the local supply environment and the fertilizer type preferences of farmers.[3] In some districts like Narok and Bomet, practically all fertilizer applied to maize fields is basal. On the other hand, about half of the fertilizer used by farmers in Makueni and Machakos is top dress.

We use fertilizer prices as recalled by farmers instead of government recorded wholesale prices in order to better approach the input retail environment experienced by smallholder farmers. For households that purchased at least one of these types of fertilizer, the actual price paid by that household is used. For households that did not purchase a given type of fertilizer, a district median value from other purchasers is substituted.[4] The price of nitrogen is therefore household specific when a household purchased DAP and/or CAN, with the district level weighting scheme applied, or district level when neither type of fertilizer was purchased. Nominal prices are converted to real 2010 levels using the yearly consumer price index (CPI) values from the Kenya National Bureau of Statistics (KNBS). Average nitrogen prices by province and survey year can be found in Table 3.

5.3. Fertilizer transport distance

We measure the entry of the private sector following fertilizer market liberalization by examining the change in distance from the farm-gate to a retail location where fertilizer is purchased. Not only does this variable signal a rural expansion of the private sector, but also a reduction in the transportation cost of fertilizer for households. In each survey year, we observe the household-reported distance (in kilometers) from the household (farm gate) to the nearest fertilizer seller, which we use as a proxy for the cost of transporting fertilizer between these locations. We use the actual distance reported by individual farmers in each survey year in our model, or replace it with a village median where no value was given. The sample we choose from the available full nationwide sample means that the drop in distance is not as substantial as the mean distances reported by others using the full data set (for example, Ariga et al. 2008). For this reason, our results are specific to the areas where maize fields are most prevalent and where there is suitable variation in nitrogen application rates with which to estimate production and

---

[3] At first glance it may appear that this weighting scheme conflates fertilizer demand with prices, creating an endogeneous variable. This is not the case since the weights are derived as proportions of total fertilizer use (not actual kilograms) and is derived only where commercial fertilizer is used.
[4] We do not observe the price individual households paid for fertilizer in 1997. Instead, we use district level prices of DAP and CAN for all households.

demand models. Average distances to the nearest fertilizer dealer by province and survey year can be found in Table 3.

5.4. Expected maize prices

While fertilizer prices and transportation distances are known at the time of purchase, the price for which maize will sell on the market months later is unknown to the farmer. We model these naïve expectations by calculating an average price across the six months prior to the month when maize is planted in preparation for the main season. For the western and central parts of Kenya, this corresponds with September through February (with planting in March); for the eastern parts, averages across April to September are used (with planting in October). Monthly prices of dry maize were obtained from the Ministry of Agriculture in Kenya for a number of wholesale market locations across the country. We match the available market data with the districts in our data using knowledge of market integration and maize supply movement. For most markets, prices are only available for two or three of the months within the six month range of interest, which we view as an adequate although imperfect approximation of maize price expectations. As with all other price variables, maize prices are deflated to their real 2010 values using the CPI.

5.5. Characteristics of the production system

Because fertilizer application rates should vary with agro-ecological conditions, we control for the differences in biophysical environments across Kenya using dummy variables for individual districts. Within district variation in agricultural potential is controlled using a time-constant measure of net primary productivity (NPP), the average standing biomass observed at the village level between 2000 and 2006. We also control for the differences in expected conditions over time and within districts using the expected distribution of rainfall in the main season, measured as rainfall stress and observed at the village level. We use a six-year moving average of past rainfall levels as a measure of expected rainfall conditions in the coming main season given fertilizer application decisions are made without full knowledge of how the season will unfold. We control for any remaining time-specific determinants of fertilizer demand by including year fixed effects.

In Kenya, an increasing population coupled with limited arable land has created intense pressure on the land to feed more individuals over time. We test Ester Boserup's seminal hypothesis (Boserup 1965) that increased population density leads to increased agricultural intensification through the use of fertilizers. Building on findings by Jayne and Muyanga (2012) and using population counts from the Global Rural-Urban Mapping Project dataset (GRUMP) at the village level in 1995, 2000, 2005, and 2010, we estimate population counts in the other survey years (1997, 2004, 2007) and obtain population density figures by dividing by the total arable land in the village from GlobCover2009, a global land cover dataset.

In our data, fertilizer application is observed at the field (not crop) level. Because our maize fields are not comprised entirely of maize, we control for the fact that some portion of the fertilizer may have been applied to other crops by including dummy variables for the number of crops on the field. This same control approach, albeit for a different purpose, was used in the production function estimated with the same sample in Sheahan et al. (2013). The inclusion of this variable allows us to understand how fertilizer decisions can vary across different compositions of maize fields where the maize seeding rate remains very similar.

5.6. Characteristics of the household

For reasons of non-separability and a substantial literature on how the socio-economic status of the household influences the decision to use fertilizer (Feder and Umali 1993; Feder, Just, Zilberman 1985), a number of characteristics of the household are represented in the model. Here, we include the age of the household head as a proxy for human capital and experience, and sex of the household head as a proxy for household access to inputs complementary to fertilizer (Doss and Morris 2001). We control for the number of adults (age 17-39)[5] in the household in a particular survey year as both a measure of household labor availability and household size. Because available income and, in particular, the flow of available income over the year, are difficult to accurately specify for households, we use a value of household asset wealth at data collection time (in real 2010 terms) as an indicator of financial liquidity and purchasing power of

[5] This age range may seem narrower than usual but is necessary due to how the data was collected in 1997. In all other survey years, we are able to look at a broader age group (i.e., 15-60). We find that the correlation between adults age 15-16 and adults age 17-39 is highly correlated in the last four survey years (correlation coefficient of 0.87), meaning the included measure should be comparable with a fuller range of "adult" ages.

the household.[6] We control for the size of the farm by including the total number of hectares under cultivation in the main growing season as an indicator of the intensity of agricultural operations.[7] While credit constraints are often cited as reasons for not purchasing inputs (e.g., Coady 1995; Croppenstedt et al. 2003; Odhiambo and Magandini 2008), our data does not provide a variable that adequately captures the credit availability at the household or village level that is not endogenous to observed fertilizer purchases. Instead, we rely on household asset levels and farm size as proxies for the ability of households to access credit, should they choose.

6. DEMAND MODEL ESTIMATION RESULTS

Table 4 includes the regression coefficients for three different specifications of our demand model where a series of dummy variables, namely district and survey years, are swapped in and out to compare the robustness of the coefficient estimates of the main variables of interest. We find that, in general, the year dummy variables tend to reduce the significance of certain variables of interest. One hypothesis for why this might happen is that the year dummy variables absorb some of the time-trending downward movement in prices (both maize and nitrogen) and distance to the nearest fertilizer dealer in which we are interested to investigate. We, however, do want to control for any spatial variation that might influence our results, and believe that the inclusion of district dummy variables helps to that end.[8] For these reasons, we focus the rest of our assessment on the coefficient estimates in model 2 (bolded) where the Mundlak-Chamberlain device and district level fixed effects are used, while acknowledging the movement in coefficients across model specifications.

In model 2, the market price of nitrogen exhibits the expected signs across both hurdles, meaning an increase in the price of nitrogen reduces both the likelihood of using commercial nitrogen and the amount applied to maize fields. Interpreting the size of the coefficients in their raw form is not advisable since both hurdles are non-linear; see Section 7.1 for more on the computed average partial effects. Notice, also, that the only model where the coefficient is not

---

[6] Given variability in the types of assets included in the different survey years, asset wealth is defined here as the total value of livestock, farm equipment, and large household assets consistently recorded across all years of the survey and may not constitute the full value of all household assets.
[7] While likely not exactly equivalent to the total farm size, per se, the 2000 survey did not ask about all household land holdings, so this measure functions as our best estimate.
[8] For robustness, we also tried province and agro-ecological zone level fixed effects for comparison. With much broader coverage, the results from these models were more similar to model specifications where no geographic fixed effects are included.

statistically significant is where only yearly dummy variables are used (model 1), likely for reasons we hypothesized above.

The distance to the nearest fertilizer dealer is statistically significant in the first hurdle but not in the second, meaning changes in fertilizer accessibility only affects the decision to use fertilizer not the amount applied. The addition of year fixed effects in the other models seems to suppress these results and pass the significance to the household average term included in the M-C device. While the lack of significance on the second hurdle of model 2 may be surprising given the story often described in Kenya, these results are consistent with those found by Alene et al. (2008) who also find no significant impact of distance to the nearest fertilizer dealer in the second stage of their fertilizer demand model for a sample of farmers in Nyanza and Western Provinces. This suggests that after controlling for a range of other important variables, the expansion of the private sector into rural areas has not been a major contributor to the increase in application rates but has been significant in the decision to use fertilizer.

Also contrary to hypotheses is the sign on some of the expected maize price coefficients. In model 2, an increase in expected maize price has a negative effect on the probability of use but a positive effect on the amount applied. While the sign of the coefficient in the second hurdle does mirror expectations, the coefficient in the first hurdle is puzzling. Like fertilizer prices, we observe a decrease in real expected maize prices over time, but suspect our method of calculating naïve price expectations may not be perfect. Moreover, our findings are directly contrary to the results found in a model by Mather and Jayne (2011) who, like Muyanga (2013), predict expected maize prices using an econometric model. Instead of converting observed prices to real prices, however, they rely on nominal prices in their analysis but deal with yearly inflation through the use of year dummy variables, which is likely the reason for the differences in our findings. For robustness, we ran our same model with the maize prices calculated by Muyanga (2013) who instead predicts expected prices using regression techniques instead of averaged lagged market prices. In this case, the coefficients were never statistically significant in the three model specifications we use. Despite the change of significance in the maize price term, the coefficient estimates on our two main variables of interest remain very similar, leading us to conclude that our maize price expectations are sufficient for control purposes in this model.

As far as other important agro-ecological features, the net primary productivity (NPP) of a village seems to have a very small negative effect when district fixed effects are used. Because we find this variable to be positive when the model is run without district fixed effects (not shown), we interpret this to mean that maize fields in higher productivity districts are more likely to apply fertilizer; however, villages within higher potential districts may use less fertilizer, perhaps due to the inherent productivity of the surroundings relative to others. Recall, too, that this variable is fixed across time, so we only pick up only on spatial variability, not temporal. Further, the expected rainfall stress variable is insignificant in the first hurdle and exhibits the opposite sign as would be expected in the second hurdle. Unlike NPP, this variable has a unique value for each year with an average value included in the M-C device. While the within household variation may be opposite as expected, the household average variables in the M-C device are generally negative for rainfall stress, meaning average rainfall stress is a good indicator of fertilizer use decisions. The population density variable, as hypothesized, does positively and significantly affect fertilizer use, even when controlling for geographic and time fixed effects meaning input intensification has followed from population density increases in Kenya (like Jayne and Muyanga 2012).

The age of a household head is not significant when controlling for household unobserved effects. Female headed households, however, are significantly less likely to use commercial fertilizer across all of our models, regardless of the fixed effects employed. Households with more adults apply more fertilizer in the second hurdle across several model specifications. Maize plots found on larger farms are no more likely to be fertilized when the household average value is included in the M-C device. The same is not necessarily true of household asset wealth, where neither the year specific nor household averages are significant. This means that variation in asset wealth over time does not affect fertilizer use decisions from the perspective from the household, keeping in mind that asset wealth totals from survey data are likely to exhibit error.

The fertilizer subsidy dummy variable is consistently negative and significant, meaning households that received a fertilizer subsidy in 2010 are significantly less likely to use commercial fertilizer on their maize fields and, when they do, apply in lower quantities. Because two types of subsidy programs are included in our sample and a very low proportion of households in our sample did receive the subsidy, we do not believe there is any important economic interpretation to the actual coefficients. Instead, we believe this motivates the need for a more rigorous study of the "crowding out" effects of these simultaneously occurring subsidy programs in Kenya (see Jayne et al. forthcoming).

For robustness, we also estimate a model on total commercial fertilizer application (with no care to the nutrient availability) where an average of actual DAP and CAN prices, although still weighted, are used in place of the nitrogen price. Otherwise applying the same specifications and dummy variable schemes, we find results to mostly be the same. Of most interest is that the coefficient on fertilizer prices remains negative and significant throughout, but that the distance term is not significant in any of the three model specifications. We also estimated a "hybrid" model that predicts nitrogen use but included the full weighted average prices of DAP and CAN instead of our calculated price of nitrogen. While some coefficient estimates changed, the signs and significance of those on our main variables of interest remained the same, meaning there is no significant trade off to using the calculated nitrogen prices as we have. Because of concerns that farmers consider the price of fertilizer and maize relative to one another instead of separately, we estimate a final model specification where the relative price of nitrogen to maize was inserted as one variable. Here, the price ratio is always negative and significant in the second hurdle of the models, but never the first. Further, the distance to the nearest fertilizer dealer is negative and significant in the first hurdle of model 2 only, meaning without year fixed effects. Convincingly, the coefficient on the distance term in the first hurdle of model 2 is almost identical to the coefficient we predict in Table 4, providing further validity to our results.[9]

7. MAIZE OUTPUT SIMULATION RESULTS

In this section, we use the demand function estimates together with previous estimates from a maize production function and government maize production statistics to simulate the effect of fertilizer market liberalization policies on maize output. First we combine the two econometric estimation results then project those values onto government maize production data to arrive at an overall affect of falling fertilizer prices on maize output.

7.1. Average partial effects and chain rule

---

[9] Results of the regressions run as robustness checks are not included in this paper for reasons of space. For more details on their implementation and results, please contact the authors.

With the demand function estimates, we compute the unconditional average partial effects (APEs) of our two variables of interest—nitrogen price per kilogram and distance to the nearest fertilizer dealer—which allows for a linear interpretation of our non-linear model results. We focus on unconditional APEs as opposed to conditional APEs in order to understand the total effect of changes in nitrogen prices on the full sample of maize fields, not just those where commercial fertilizer is applied. As such, these values provide an estimate of the overall impact of liberalization policies on the input management practices of households across a wide section of the maize producing areas of Kenya. The average partial effects are estimated over the full sample used in this analysis and disaggregated by province using the approach described in Burke (2009). The standard errors and related p-valued are bootstrapped using 100 repetitions.

The results of these procedures appear in Table 5 for model 2 of the regression results presented in Table 4 (bolded). Like the regression coefficients, the calculated p-values show that the nitrogen price partial effect estimates are statistically significant both overall and at the province level. On average across the full sample, a one KSH/kg increase in the price of nitrogen leads to a reduction in the total amount of commercial fertilizer applied to maize fields by 0.1 kgs. Or, conversely, a one KSH/kg drop in nitrogen prices leads to an increase in the use of commercial nitrogen by 0.1 kgs, the scenario more relevant to fertilizer price trends since liberalization. The effect has been greater in Rift Valley, Central, and Western Provinces while slightly smaller in Eastern and Nyanza Provinces. However, while the coefficient on distance to the nearest fertilizer dealer from the first hurdle of our demand model was statistically significant, the unconditional (overall) partial effect on fertilizer demand is not. The lack of significance in these partial effects (both conditional and unconditional in their case) was also found by Mather and Jayne (2011) who use the same base data set but a more broadly defined sample of households and fields without the inclusion of 2010 (i.e., 1,115 households and 4,524 fields across four survey years). This provides further support that our somewhat strict definition of "maize field" is not biasing the results. With a lack of significance in this estimate, we only proceed with calculating the effect of changes in nitrogen price on maize yields.

In order to estimate the impact of changes in nitrogen prices on maize output, we require production function estimates which allow us to link the increase in nitrogen observed via a reduction in its price with the maize yield response associated with increased nitrogen application rates. A maize production function is estimated in Sheahan et al. (2013) using the same sample of maize fields to arrive at marginal products of nitrogen at different levels of disaggregation. While the district and soil group geographic level was the disaggregation of interest in that analysis, we recalculate the expected marginal products at the province level to enable a better fit with data presented later in this section. The expected marginal products of nitrogen used in this analysis are presented in Table 5. On average across the sample, a one kg increase in the amount of nitrogen applied to a maize field yields a 17.5 kilogram response in maize production. We recognize that there exists considerable variation in possible response rates within a province and over time in the same location, but use these values as an approximation of average response rates as expected by a household without full knowledge of how the season will unfold. Sheahan et al. (2013) gives a full explanation of the estimation of the production function and ensuing marginal products.

The product of these two partial effects via a chain rule approach (equation 5) give an estimate of how a one KSH/kg change in the price of nitrogen leads to change in maize output via a change in nitrogen applied to maize fields. These values appear in the final column of Table 5. Interestingly, the range of values narrows from the much larger ranges found in the partial effects from which they were derived meaning that while fertilizer response values may vary considerably across space, how farmers respond to changes in prices evens out the impact on maize output. Because the two values are simply multiplied together and no further econometric analysis employed, we are unable to estimate a standard error of these results although, qualitatively, we know that multiplying two error terms together effectively creates an even larger one, so our results, as always, should not be interpreted as precise. Even so, we find that a 1 KSH/kg decrease in the price of nitrogen leads to a 1.8 kg/ha increase in the amount of maize produced on a field via the increase in chemical nitrogen fertilizer applied.

7.2. Simulated change in maize output

This partial effect on the price of nitrogen can now be combined with actual nitrogen price and government maize production statistics to explore how actual changes in prices over time have contributed to changes in maize output. Table 3 summarizes the average nitrogen price, the same calculated values used in the fertilizer demand model, at the province level by year. Because we rely on household survey data for a better representation of the fertilizer prices faced by households in rural areas, we utilize the change in observed prices between survey years (note, however, that the gap between years is not always uniform) as shown in the first set of columns in Table 6. As anticipated, the inflation-adjusted price of nitrogen has consistently declined over the 1997-2010 period, with the largest fall between 1997 and 2000 during the early stages of the input market liberalization period. The decline in real nitrogen prices are consistent with the GoK reported trends in up-country wholesale prices shown in Figure 1.[10]

We then multiply these observed decreases in nitrogen price over time by the calculated change in maize yield from a change in nitrogen prices (last column of Table 5) to arrive estimated changes in maize yield (kg/ha) on account of changes in nitrogen prices via the increase in fertilizer use, as shown in the second set of columns in Table 6. Between 1997 and 2000, the observed fall in real nitrogen prices sometimes led to an extra 50 or 90 kilogram bag of maize from one hectare of land, with variation by and within province. For perspective, at planting time, a 90 kilograms bag of maize was expected to sell for about 1,000 KSH in Nakuru in 2000 (equivalent to about 13 USD in 2010 terms). In more recent survey years, the maize output gain narrowed with more gradually declining prices. Even between 2007 and 2010, an average of 15 kg/ha was added to maize productivity on account of changing nitrogen prices and their effect on fertilizer use. Again, using expected maize prices in Nakuru, 15 kilograms of maize would be equivalent to about 375 KSH or 5 USD (at 25 KSH/kg) per hectare.

With government aggregate data, we are able to link these mechanisms in our sample to province and national level maize production trends. The total hectares under maize and maize harvest levels (in tons) at the province level come from the Kenya Agricultural Sector Data Compendium (KIPPRA) and can be found by survey year in Table 3. We multiply the total hectares under maize at the province level from the last year in the interval (e.g., for the 1997-2000 price change interval, we use the area planted value from 2000) by the estimated increase in maize yields per hectare estimates to arrive at province level estimates of the total increase in maize production on account of decreases in nitrogen prices.[11] These estimates can be found in the third set of columns in Table 6. To put these numbers in perspective, the last set of columns shows how these maize production values relate to the total maize produced in that province by

---

[10] The only exception to this consistently declining trend in fertilizer prices was in Central Province during the 2007-2010 period.
[11] Notice that we are able to multiply by the total maize area under production instead of just the area where fertilizer is used because we calculated unconditional (instead of conditional) APEs from the fertilizer demand model.

survey year, with percentages ranging from less than 1 to about 11 percent. Notice, again, that nitrogen price changes and their contributions to fertilizer use increases were much larger between 1997 and 2000 than in the subsequent survey years.

8. CONCLUSIONS AND POLICY IMPLICATIONS

This study estimates the impact of fertilizer price and market accessibility changes associated with input market liberalization on commercial fertilizer demand and maize productivity using five waves of panel data allowing us to control for unobserved household-level heterogeneity for the years directly following the start of input market liberalization in Kenya. We find that nitrogen prices are significant in contributing to both the decisions by households to use fertilizer and the application rates on maize fields. For some models, including one controlling for household and district effects, the distance to the nearest fertilizer dealer is a significant determinant of fertilizer use, but not of the actual amount of nitrogen applied to maize fields. When computing the overall unconditional average partial effects of these two variables on overall nitrogen demand across all fields and households, the distance to the nearest fertilizer dealer becomes insignificant while the nitrogen price retains its significance. While we suspect our findings are influenced by (i) the selected sample of maize fields from the larger nationwide data set and (ii) potential error in the household reported distances to fertilizer seller, we think it is useful to acknowledge that rural expansion of private sector dealers may not have had a huge influence on fertilizer demand from the perspective of the household once controlling for a range of other variables.

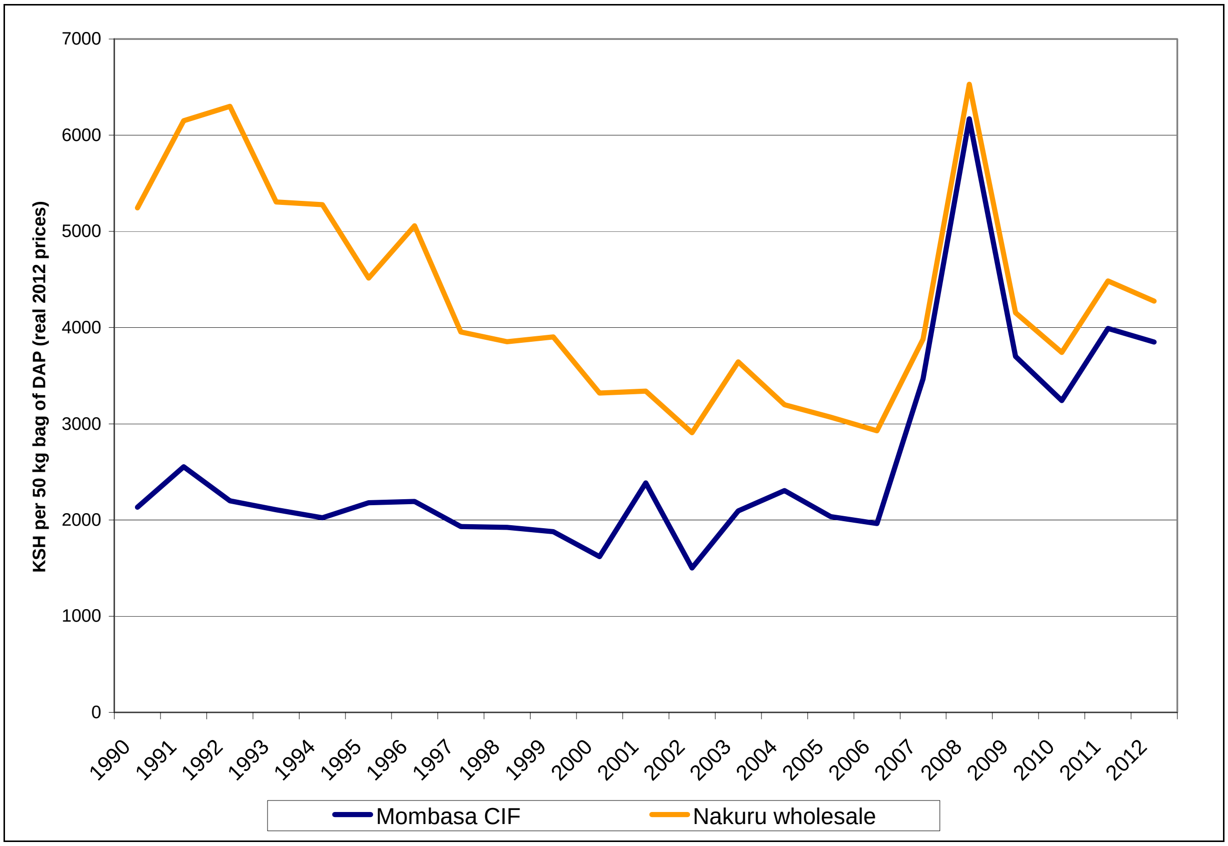
With statistically significant estimates of the effect of the price of nitrogen on the demand for nitrogen, we use the chain rule with related production function estimates to calculate the impact of changing nitrogen prices on maize yields via the expansion of nitrogen use. On average, we find that changes in fertilizer prices between survey years contributed to anywhere between 5 and 135 kilograms per hectare of increased maize output in different years and provinces. These results are downwardly influenced by the sometimes low fertilizer response rates observed in high fertilizer consuming areas of Kenya. Using government estimates of area under maize at the province level, we find that between 1 and 11 percent of total maize output between 1997 and 2010 can be accounted for due to the observed reduction in nitrogen prices via reductions in private sector marketing margins. These estimates represent only those increases in fertilizer use and maize output directly explained by changes in fertilizer prices, with a range of other variables having an effect as well.

The fertilizer demand model and subsequent maize yield response simulations provide perhaps the first quantitative understanding of how liberalization policies directly influence smallholder input use behavior. The price changes used in this study are the result of government policy reforms that led to increased private sector investments and competition which resulted in decreased margins. This approach to increasing fertilizer use remains logistically and fiscally different from the now popular approach that a handful of SSA countries, including Kenya, are implementing to lower fertilizer costs at the household-level via subsidy programs. Such programs are becoming increasingly difficult to financially sustain mostly due to scarce national budgetary allocations that compete with other alternative uses. However, since fertilizer subsidies may be politically difficult to end all together, a combination of policies that encourage private investments in the fertilizer value chains and targeted "smart" subsidies may provide the impetus for increased productivity and incomes in rural communities in a more cost-effective manner.

Kenya represents a solid case study in how liberalization policies can benefit smallholder farmers and national maize output. We recognize, however, that the country specific environment will ultimately affect how successful liberalization policies can be. The framework we develop here can be applied in other SSA countries that have undergone similar transformation with varying results and those who seek to find ways to stimulate input use but have not yet found an appropriate policy mechanism. A regional understanding of smallholder behavior in the midst of changing policies and market environments will help guide our understanding of more appropriate input promotion and staple grain productivity policies.

APPENDIX OF FIGURES AND TABLES

Figure 1. Price of Di-ammonium Phosphate (DAP) in Mombasa and Nakuru (constant 2012 Kenyan shillings per 50 kg bag)



Source: Yearly average fertilizer prices come from the Ministry of Agriculture in Kenya. Prices were deflated to 2012 levels using the CPI from the Kenya National Bureau of Statistics (KNBS).

Table 1. Distribution of Households (and Fields) in Selected Sample

Province	Districts	Original panel	Balanced panel	# of Households (fields) used in this analysis
Coast	Kilifi, Kwale, Taita Taveta	91	83	0 (0)
Eastern	Kitui, Machakos, Makueni, Meru, Mwingi	242	211	154 (738)
Nyanza	Kisii, Kisumu, Siaya	280	226	125 (746)
Western	Bungoma, Kakamega, Vihiga	303	249	265 (1,403)
Central	Muranga, Nyeri	181	162	81 (329)
Rift Valley	Bomet, Nakuru, Narok, Trans Nzoia, Uasin Gishu, Laikipia	403	312	281 (1,500)
	Total sample	1,500	1,243	906 (4,714)

Note: The maize field sample is used in this analysis. For more on how this sample was created from the total available data set, see Sheahan et al. (2013).

Table 2: Mean (and standard deviation) of variables in fertilizer demand model split by binary commercial fertilizer use decision

Variable	Level of observation	Field was not fertilized with commercial fertilizer (n=1,159)	Field was fertilized with commercial fertilizer (n=3,555)
Nitrogen per hectare applied to the maize field (kg/hectare)	Field	-	32.7 (25.7)
Real price of nitrogen (KSH/kg) (average weighted nitrogen portion of DAP and CAN)	Household (or district median)	189 (56)	167 (44)
Distance from household to nearest fertilizer dealer (km)	Household (or village median)	4.62 (4.93)	3.22 (3.48)
Real (estimated) expected price of maize (KSH/kg)	Village	29.6 (9.98)	27.5 (7.76)
Net primary productivity (vegetative biomass measured in grams of carbon per square meter per year)	Village	10,083 (2,350)	11,076 (2,477)
Expected proportion of 20-day periods when rainfall was less than 40 mm during the main growing season (range 0-1)	Village	0.30 (0.21)	0.24 (0.18)
Age of household head (years)	Household	56.3 (13.9)	54.9 (13.4)
Sex of household head: Female=1; male=0	Household	0.23 (0.42)	0.16 (0.37)
Number of adults (age 17-39) in household for at least one month in last year	Household	2.10 (1.54)	2.28 (1.59)
Total size of all fields with cultivation in main season (hectares) as proxy for total farm size	Household	1.41 (1.28)	1.72 (1.62)
Real asset wealth of household (in 1000 KSH) for subset of all household assets	Household	145.2 (262.8)	224.1 (386.0)
Household received a fertilizer subsidy (government or NGO) in main season=1; No=0 (only possible yes in 2009/10)	Household	0.05 (0.22)	0.01 (0.09)
Number of crops on field (1-7, included as dummy variables in model)	Field	2.89 (1.64)	2.80 (1.54)
Population density (persons per square kilometer of arable land)	Village	798.8 (788.4)	530.1 (445.8)
Each district included as a dummy	District	-	-
Each survey year included as a dummy	Overall	-	-

Note: For more detail on how each of these variables is calculated, see the text.

Table 3: Summary statistics using survey and government data split by province and year

Province	Statistic	1997	2000	2004	2007	2010
Eastern	Area under maize (ha)	394,818	504,435	504,435	435,773	454,720
	Production (tons)	244,290	212,710	212,731	419,413	339,008
	Average yield (tons/ha)	0.6	0.4	0.4	1.0	0.7
	% of fields with commercial nitrogen	49.6%	39.9%	66.2%	61.5%	56.7%
	Mean nitrogen application rate (kg/ha)	18.1	18.8	16.5	20.3	23.5
	Mean nitrogen price (KSH/kg)	209	178	154	145	140
	Mean distance to fertilizer dealer (km)	4.3	2.3	2.1	2.1	2.3
Nyanza	Area under maize (ha)	158,764	204,658	245,020	83,333	327,210
	Production (tons)	368,883	465,324	739,900	150,000	455,090
	Average yield (tons/ha)	2.3	2.3	3.0	1.8	1.4
	% of fields with commercial nitrogen	58.0%	66.2%	70.6%	79.9%	68.9%
	Mean nitrogen application rate (kg/ha)	16.0	16.0	26.2	24.4	39.1
	Mean nitrogen price (KSH/kg)	340	239	178	168	142
	Mean distance to fertilizer dealer (km)	5.7	4.3	3.0	1.8	3.4
Western	Area under maize (ha)	116,087	180,680	181,680	201,583	233,494
	Production (tons)	273,583	464,562	464,609	581,321	462,861
	Average yield (tons/ha)	2.4	2.6	2.6	2.9	2.0
	% of fields with commercial nitrogen	52.5%	73.6%	79.3%	85.9%	83.8%
	Mean nitrogen application rate (kg/ha)	29.7	34.7	42.5	42.9	44.2
	Mean nitrogen price (KSH/kg)	226	178	152	135	132
	Mean distance to fertilizer dealer (km)	5.2	4.0	2.6	3.4	3.9
Central	Area under maize (ha)	132,389	130,583	108,823	138,888	175,698
	Production (tons)	126,460	82,989	67,781	163,895	126,201
	Average yield (tons/ha)	1.0	0.6	0.6	1.2	0.7
	% of fields with commercial nitrogen	85.1%	81.8%	90.3%	87.7%	73.2%
	Mean nitrogen application rate (kg/ha)	32.7	30.2	29.4	22.9	32.5
	Mean nitrogen price (KSH/kg)	205	176	149	139	152
	Mean distance to fertilizer dealer (km)	3.7	1.6	1.4	1.6	1.4
Rift Valley	Area under maize (ha)	448,275	486,400	569,260	664,098	675,097
	Production (tons)	1,063,507	979,281	1,253,409	1,800,000	1,902,574
	Average yield (tons/ha)	2.4	2.0	2.2	2.7	2.8
	% of fields with commercial nitrogen	78.9%	89.8%	90.4%	89.6%	80.1%
	Mean nitrogen application rate (kg/ha)	26.0	33.1	34.1	39.5	38.3
	Mean nitrogen price (KSH/kg)	251	185	153	138	125
	Mean distance to fertilizer dealer (km)	5.4	4.1	3.1	3.8	5.4
Sample average	*Area under maize (ha)*	1,250,333	1,506,756	1,609,218	1,523,675	1,866,219
	Production (tons)	2,076,723	2,204,866	2,738,431	3,114,629	3,285,734
	Average yield (tons/ha)	1.7	1.5	1.7	2.0	1.8
	% of fields with commercial nitrogen	*63.9%*	*72.5%*	*79.5%*	*83.0%*	*75.6%*
	Mean nitrogen application rate (kg/ha)	*25.5*	*29.6*	*32.6*	*35.3*	*38.5*
	Mean nitrogen price (KSH/kg)	246	190	157	143	134
	Mean distance to fertilizer dealer (km)	*5.1*	*3.6*	*2.7*	*3.0*	*3.9*

Sources: Area under maize, production, and average yield calculations (white rows) come from The Kenya Agricultural Sector Data Compendium (KIPPRA). Percent of fields with nitrogen, application rates, nitrogen prices, and distance to the nearest fertilizer dealer values (gray rows) are calculated from the maize field sample used in this analysis. We collapse to the household level first when calculating average nitrogen prices and distances to the nearest fertilizer dealers in order to avoid "weighting" towards households with more maize fields.
Notes: The government statistics provided in the "sample average" rows represent a total of the five districts represented here, not the national total. See text for method of calculation for nitrogen prices and distance to the nearest fertilizer dealer. For reference, the average monthly official exchange rate used by the UN between June 2009 and June 2010 was 76KSH/1USD. See http://treasury.un.org/operationalrates/OperationalRates.aspx.

Table 4. Double-hurdle nitrogen demand model regression results under different fixed effects specifications

	(1)		**(2)**		(3)	
	Hurdle 1	Hurdle 2	**Hurdle 1**	**Hurdle 2**	Hurdle 1	Hurdle 2
N market price	-0.000257	-0.412***	**-0.00338*****	**-0.224*****	-0.00247*	-0.345***
(KSH/kg)	(0.00109)	(0.0666)	**(0.000983)**	**(0.0371)**	(0.00144)	(0.0565)
Expected maize	-0.0157*	0.362	**-0.0146****	**0.352***	-0.0146	0.188
price (KSH/kg)	(0.00832)	(0.350)	**(0.00584)**	**(0.182)**	(0.00944)	(0.322)
Distance to nearest	-0.00556	0.162	**-0.0107***	**0.281**	-0.00895	0.169
fertilizer dealer (km)	(0.00522)	(0.292)	**(0.00624)**	**(0.248)**	(0.00642)	(0.249)
Net primary	9.92e-05***	-0.000211	**-0.000140*****	**-0.00302****	-0.000140***	-0.00298**
productivity	(1.70e-05)	(0.000638)	**(3.84e-05)**	**(0.00123)**	(3.83e-05)	(0.00123)
Expected rainfall	-0.00317	-7.121	**-0.698**	**56.31****	-0.329	29.76
stress	(0.603)	(29.43)	**(0.653)**	**(26.83)**	(0.755)	(28.20)
Age of hh head	-0.00313	-0.0188	**-0.00489**	**-0.135**	-0.00440	-0.0240
(years)	(0.00376)	(0.199)	**(0.00472)**	**(0.167)**	(0.00477)	(0.174)
Female headed	-0.250*	3.460	**-0.331****	**1.218**	-0.324**	3.088
household (1=yes)	(0.137)	(5.554)	**(0.156)**	**(4.864)**	(0.156)	(4.949)
Number of adults in	-0.00279	2.373***	**0.00768**	**1.812*****	-0.000148	2.165***
household	(0.0195)	(0.767)	**(0.0210)**	**(0.688)**	(0.0224)	(0.704)
Size of farm (ha)	0.0360	-1.410	**0.0531**	**-1.138**	0.0491	-1.168
	(0.0298)	(1.003)	**(0.0348)**	**(0.920)**	(0.0352)	(0.928)
Household assets	0.000257	0.00535	**0.000236**	**0.00630**	0.000237	0.00561
(1000 KSH)	(0.000178)	(0.00471)	**(0.000182)**	**(0.00461)**	(0.000184)	(0.00455)
Population density of	0.000672**	0.118***	**0.00110*****	**0.0824*****	0.00112***	0.102***
village	(0.000296)	(0.0266)	**(0.000368)**	**(0.0193)**	(0.000417)	(0.0251)
Two crops on field	0.344***	2.025	**0.282*****	**2.730**	0.282***	2.805
(1=yes)	(0.0717)	(2.807)	**(0.0776)**	**(2.503)**	(0.0775)	(2.507)
Three crops on field	0.312***	-2.949	**0.292*****	**-2.309**	0.280***	-1.533
(1=yes)	(0.0870)	(3.164)	**(0.0957)**	**(2.798)**	(0.0959)	(2.825)
Four crops on field	0.395***	-0.261	**0.422*****	**0.245**	0.409***	1.326
(1=yes)	(0.0932)	(3.781)	**(0.100)**	**(3.362)**	(0.101)	(3.423)
Five crops on field	0.348***	-3.239	**0.394*****	**-3.036**	0.381***	-1.807
(1=yes)	(0.0985)	(3.960)	**(0.111)**	**(3.446)**	(0.112)	(3.537)
Six crops on field	0.365***	-1.851	**0.366*****	**-4.024**	0.357***	-3.108
(1=yes)	(0.112)	(4.745)	**(0.124)**	**(4.161)**	(0.126)	(4.224)
Seven crops on field	0.381***	-3.624	**0.332*****	**-4.232**	0.326**	-2.968
(1=yes)	(0.118)	(5.539)	**(0.127)**	**(4.852)**	(0.129)	(4.911)
Fert subsidy in 2010	-1.412***	-56.61***	**-1.558*****	**-51.09*****	-1.518***	-50.38***
(1=yes)	(0.206)	(15.05)	**(0.211)**	**(13.44)**	(0.216)	(13.43)
Year dummies	Y	Y			Y	Y
District dummies			**Y**	**Y**	Y	Y
M-C device	Y	Y	**Y**	**Y**	Y	Y
Households *(n)*	906	906	**906**	**906**	906	906
Maize fields (*n*)	4,714	4,714	**4,714**	**4,714**	4,714	4,714

Notes: Hurdle 1 represents the binary decision to participate in the fertilizer market while Hurdle 2 represents the fertilizer demand model conditional upon participation. Model 2 is bolded because it is used as the basis of further analysis in the text and the APE estimates presented in Table 5. Robust standard errors are found in parentheses: *** p<0.01, ** p<0.05, * p<0.1

Table 5. Unconditional average partial effects (APEs), marginal products of nitrogen, and chain rule calculations by province

District	Nitrogen price (KSH/kg)[a]			Distance to fertilizer dealer (km)[a]			Response of maize to nitrogen application[b]		Calculated change in maize yield (kg/ha) from a 1KSH/kg increase in nitrogen price
	APE	se	p-value	APE	se	p-value	MP	se	
Eastern	-0.044***	0.009	0.000	-0.001	0.060	0.141	33.7	9.43	-1.5
Nyanza	-0.064***	0.014	0.001	0.051	0.090	0.757	21.1	3.07	-1.4
Western	-0.136***	0.025	0.000	0.025	0.179	0.206	13.1	2.24	-1.8
Central	-0.105***	0.022	0.000	0.045	0.139	0.353	21.1	4.64	-2.2
Rift Valley	-0.115***	0.021	0.000	0.069	0.154	0.514	11.2	2.53	-1.3
Sample average	*-0.101****	*0.018*	*0.000*	*0.041*	*0.133*	*0.347*	*17.5*	*2.43*	-1.8

Notes: *** p<0.01, ** p<0.05, * p<0.1. [a] Estimates correspond with the regression results from the second (bolded) model in Table 4. "se" denotes bootstrapped standard errors using 100 replications. Unconditional APEs, bootstrapped standard errors, and p-values were calculated using the procedure outlined in Burke (2009). [b] Marginal products of nitrogen and standard errors are taken from production function analysis on the same data set by Sheahan et al. (2013).

Table 6: Simulated changes in maize output resulting from changes in nitrogen prices by province and year

	Change in household level nitrogen price (KSH/kg)[a]				Change in maize output on account of change in nitrogen prices (kg/ha)				Total change in maize output at province level							
									Tons [b]				As Percent of Province Totals			
	1997-2000	2000-2004	2004-2007	2007-2010	1997-2000	2000-2004	2004-2007	2007-2010	1997-2000	2000-2004	2004-2007	2007-2010	1997-2000	2000-2004	2004-2007	2007-2010
Eastern	-30.9	-24.7	-8.2	-5.9	45.8	36.6	12.2	8.7	23,127	18,445	5,304	3,971	10.9%	8.7%	1.3%	2.4%
Nyanza	-100.6	-61.5	-9.8	-25.6	135.8	83.1	13.3	34.6	27,792	20,353	1,108	11,321	6.0%	2.8%	0.7%	3.6%
Western	-48.6	-25.9	-17.5	-2.9	86.6	46.1	31.1	5.2	15,642	8,382	6,271	1,208	3.4%	1.8%	1.1%	0.6%
Central	-28.9	-27.0	-9.9	12.9	64.1	59.8	22.0	-28.5	8,369	6,513	3,053	-5,016	10.1%	9.6%	1.9%	-1.9%
Rift Valley	-66.4	-31.6	-14.9	-12.8	85.6	40.7	19.2	16.5	41,618	23,151	12,748	11,129	4.2%	1.8%	0.7%	0.9%
Sample average	*-56.3*	*-32.7*	*-14.1*	*-8.4*	*99.5*	*57.8*	*24.9*	*14.8*	*149,938*	*93,008*	*37,973*	*27,708*	*6.8%*	*3.4%*	*1.2%*	*1.3%*

[a] Nitrogen prices are calculated from household survey data used in this analysis. See text for more information on methodology.
[b] Total maize output at the province level comes from the Kenya Agricultural Sector Data Compendium (KIPPRA). See Table 3 for more information.

REFERENCES

Alene, A.D., V. Manyong, G. Omanya, H. Mignouna, M. Bokanga, and G. Odhiambo (2008). Smallholder market participation under transactions costs: Maize supply and fertilizer demand in Kenya. *Food Policy*, 33(4), 318–328.

Allgood, J.H., and J. Kilungo (1996). An Appraisal of the Fertilizer Market in Kenya and Recommendations for Improving Fertilizer Use Practicies by Smallholder Farmers. Muscle Shoals, Alabama: International Fertilizer Development Center.

Argwings-Kodhek, G., T.S. Jayne, G. Nyambane, T. Awuor, and T. Yamano (1998). How Can Micro-Level Household Information Make a Difference for Agricultural Policy Making. East Lansing, Michigan: Michigan State University.

Ariga, J., and T.S. Jayne (2010). Factors Driving the Increase in Fertilizer Use by Smallholder Farmers in Kenya, 1990-2007 in *Yes Africa Can: Success Stories From A Dynamic Continent*, Washington DC: World Bank.

Ariga, J. and T.S. Jayne (2009). Private Sector Responses to Public Investments and Policy Reforms: The Case of Fertilizer and Maize Market Development in Kenya. International Food Policy Research Institute Discussion Paper 00921. Washington DC: IFPRI.

Ariga, J., T.S. Jayne, B. Kibaara, and J.K. Nyoro (2008). Trends and Patterns in Fertilizer Use by Smallholder Farmers in Kenya, 1997-2007. Tegemeo Working Paper Series No. 28. Nairobi, Kenya: Tegemeo Institute.

Balk, D., and G. Yetman (2004). The Global Distribution of Population: Evaluating the gains in resolution refinement. Palisades, New York: Center for International Earth Science Information, Columbia University.

Boserup, E. (1965). *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure.* Chicago, Illinois: Aldine Publishing Company.

Burke, W.J. (2009). Fitting and interpreting Cragg's tobit alternative using Stata. *The Stata Journal*, 9(4), 584–592.

Chamberlain, G. (1980). Analysis of Covariance Data with Qualitative. *The Review of Economic Studies*, 47(1), 225–238.

Coady, D. P. (1995). An Empirical Analysis of Fertilizer Use in Pakistan. *Economica*, 62(246), 213–234.

Cragg, J.G. (1971). Some Statistical Models for Limited Dependent Variables with Application to the Demand for Durable Goods. *Econometrica*, 39(5), 829–844.

Croppenstedt, A., M. Demeke, and M.M. Meschi (2003). Technology Adoption in the Presence of Constraints: the Case of Fertilizer Demand in Ethiopia. *Review of Development Economics,* 7(1), 58–70.

de Janvry, A., and E. Sadoulet (2006). Progress in the modeling of rural households' behavior under market failures. In A. de Janvry & R. Kanbur (Eds.), *Poverty, Inequality, and Development: Essays in Honor of Erik Thorbecke* (pp. 155–181).

Doss, C.R., and M.L. Morris (2001). How does gender affect the adoption of agricultural innovations? The case of improved maize technology in Ghana. *Agricultural Economics*, 25(1), 27–39.

Feder, G., and D.L. Umali (1993). The adoption of agricultural innovations: a review. *Technological Forecasting and Social Change*, 43(3-4), 215–239.

Feder, G., R.E. Just, and D. Zilberman (1985). Adoption of agricultural innovations in developing countries: a survey. *Economic Development and Cultural Change*, 33(2), 255–298.

Freeman, H.A., and J.M. Omiti (2003). Fertilizer use in semi-arid areas of Kenya: analysis of smallholder farmers' adoption behavior under liberalized markets. *Nutrient Cycling in Agroecosystems*, 66, 23–31.

Freeman, H.A. and W. Kaguongo (2003). Fertilizer market liberalization and private retail trade in Kenya. *Food Policy*, 28(5-6): 505-518.

IFDC. (2001). An Assessment of Fertilizer Prices in Kenya and Uganda: Domestic Prices vis-a-vis International Market Prices. Muscle Shoals, Alabama: International Fertilizer Development Center.

Jayne, T.S., and G. Argwings-Kodhek (1997). Consumer response to maize market liberalization in urban Kenya. *Food Policy*, 22(5), 447–458.

Jayne, T.S., J. Govreeh, M. Wanzala, and M. Demeke (2003). Fertilizer market development: a comparative analysis of Ethiopia, Kenya, and Zambia. *Food Policy*, 28(4): 293-316.

Jayne, T.S., and M. Muyanga (2012). Land constraints in Kenya's densely populated rural areas: implications for food policy and institutional reform. *Food Security*, 4(3), 399–421.

Jayne, T.S., D. Mather, N. Mason, and J. Ricker-Gilbert. (forthcoming). How do Fertilizer Subsidy Programs Affect Total Fertilizer Use? A synthesis of the evidence on "crowding in/out" in sub-Saharan Africa. *Agricultural Economics.*

Mason, N.M., and T.S. Jayne (2012). Fertilizer Subsidies and Smallholder Commercial Fertilizer Purchases: Crowding Out, Leakage, and Policy Implications for Zambia. Working Paper 70. Lusaka, Zambia: Indaba Agricultural Policy Research Institute.

Mather, D., and T.S. Jayne (2011). The Impact of State Marketing Board Operations on Smallholder Behavior and Incomes: The Case of Kenya. MSU International Development Working Paper No. 119. East Lansing, Michigan: Michigan State University.

Mundlak, Y. (1978). On the Pooling of Time Series and Cross Section Data. *Econometrica*, 46(1), 69–85.

Muyanga, M. (2013). Effects of population density on smallholder agricultural production and commercialization in rural Kenya. Unpublished Ph.D. dissertation, Agricultural, Food and Resource Economics Department, Michigan State University, East Lansing, Michigan.

Odhiambo, J.J.O., and V.N. Magandini (2008). An assessment of the use of mineral and organic fertilizers by smallholder farmers in Vhembe district, Limpopo province, South Africa. *Journal of Agricultural Research*, 3(5), 357–362.

Olwande, J., G. Sikei, and M. Mathenge (2009). Agricultural Technology Adoption: A Panel Analysis of Smallholder Farmers' Fertilizer Use in Kenya. Working Paper No. AfD-0908. Agriculture for Development. Center of Evaluation for Global Action, UC Berkeley.

Omamo, S.W., and L.O. Mose (2001). Fertilizer trade under market liberalization: preliminary evidence from Kenya. *Food Policy*, 26, 1–10.

Ricker-Gilbert, J., T.S. Jayne, and E. Chirwa (2011). Subsidies and Crowding Out: A Double-Hurdle Model of Fertilizer Demand in Malawi. *American Journal of Agricultural Economics*, 93(1), 26–42.

Sheahan, M., R. Black, and T.S. Jayne (2013). Are Kenyan farmers under-utilizing fertilizer? Implications for input intensification strategies and research. *Food Policy*, 41, 39–52.

Singh, I., L. Squire, and J. Strauss (1986). *Agricultural Household Models*. Baltimore, MD: Johns Hopkins University Press.

Tobin, J. (1958). Estimation of Relationships for Limited Dependent Variables. *Econometrica*, 26(1), 24–36.

Wanzala, M., T.S. Jayne, J.M. Staatz, A. Mugera, J. Kirimi, and J. Owuor (2001). Fertilizer Markets and Agricultural Production Incentives: Insights from Kenya. Working Paper No. 3. Nairobi, Kenya: Tegemeo Institute.

Wooldridge, J.M. (2009). Introductory Econometrics: A Modern Approach, Fourth Edition. Mason, Ohio: South-Western Cengage Learning.

Wooldridge, J.M. (2010). Correlated Random Effects Models with Unbalanced Panels. East Lansing, Michigan: Michigan State University.

Xu, Z. (2008). Essays on Applied Production Analysis in Agriculture. Unpublished Ph.D. dissertation, Agricultural Economics Department, Michigan State University, East Lansing, Michigan.

Zhao, M., F.A. Heinsch, R.R. Nemani, and S.W. Running (2005). Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sensing of Environment,* 95(2), 164–176.