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Abstract

Kenya is one of the few countries in Sub-Saharan Africa to experience an impressive rise in fertilizer use following a series of input market reforms in the early 1990s. Two major consequences of these reforms were declining fertilizer marketing margins and distances between farmers and fertilizer dealers. We quantify the effects of these changes on commercial fertilizer use and maize production in Kenya by estimating fertilizer demand and maize supply response functions using nationwide household survey data. Our results indicate that between 1997 and 2010, the estimated 27% reduction in real fertilizer prices that can be attributed to falling marketing margins associated with market reforms led to a 36% increase in nitrogen use on maize fields and a 9% increase in maize production resulting from both yield and acreage effects. On the other hand, decreasing distances to fertilizer retailers from the perspective of a given household did not appear to raise fertilizer use or maize supply, although a comparison across households using average distances over the panel indicate that those closer to retailers do apply more fertilizer on their maize fields.

***Key words**: agricultural productivity, fertilizer, input market reforms, Kenya, policy*

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Acronyms

APE	Average Partial Effects
CAN	Calcium Ammonium Nitrate
CIF	Cost, Insurance, and Freight
CPC	National Weather Service Climate Prediction Center
CPI	Consumer Price Index
DAP	Di-ammonium Phosphate
DFID	Department for International Development
FAO	Food and Agriculture Organization of the United Nations
FEWS	Famine Early Warning System
GoK	Government of Kenya
GPS	Global Positioning System
GRUMP	Global Rural-Urban Mapping Project
IFDC	International Fertilizer Development Center
KIPPRA	Kenya Agricultural Sector Data Compendium
KNBS	Kenya National Bureau of Statistics
KSH	Kenyan Shillings
MOAFL	Ministry of Agriculture, Livestock, and Fisheries
MLE	Maximum Likelihood Techniques
MSU	Michigan State University
NAAIAP	National Accelerated Agricultural Inputs Access Program
NCPB	National Cereals and Produce Board
OLS	Ordinary Least Squares
SSA	Sub-Saharan Africa
TLU	Tropical Livestock Units
USAID	United States Agency for International Development
USD	United States Dollars

1. Introduction

Raising agricultural productivity remains a major challenge in developing countries. Farm productivity is especially low in Sub-Saharan Africa (SSA), where fertilizer use, on average, lags far behind the rest of the world. Identifying effective strategies for raising fertilizer use in Africa has been a longstanding and increasingly topical policy priority, especially in light of new evidence providing the empirical link between fertilizer use and economic growth at the country level (McArthur and McCord 2014). While most of the continent has struggled to raise fertilizer use in a sustainable manner, there are several countries in the region with relatively high levels of fertilizer use, suggesting that there may be important success stories from which to learn (Sheahan and Barrett 2014). When such cases are 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 national fertilizer use more than doubled between the early 1990s and 2010 (see Figure 1a) and maize production and yields have been on a mostly upward trajectory (see Figure 1b). Analysis of Kenyan household survey data shows that fertilizer use per hectare of cultivated maize rose by 34 percent and maize yields rose by 18 percent over the same period. In the maize breadbasket areas specifically, over 90 percent of smallholder farmers use fertilizer on maize with application rates comparable to areas of Green Revolution Asia (Ariga and Jayne 2009). The doubling of fertilizer use in Kenya was achieved mainly by smallholder farmers as a result of growth in commercial purchases in response to widespread reforms in the fertilizer market, rather than to input subsidy programs.

Given great attention to currently fashionable fertilizer subsidy programs (see synthesis pieces, including Jayne and Rashid 2013; Ricker-Gilbert, Jayne, Shively 2013), the Kenyan story may serve as a good example of an alternative approach to achieving the same end goal: widespread uptake of yield-enhancing fertilizer. Reforming markets through the elimination of price, import license, and other controls is a relatively contentious issue politically, although one without much empirical evidence on either side, particularly in SSA. These issues remain both topical and widely debated, and providing such evidence could be highly germane to other public efforts to promote small farm input use and staple crop productivity.
Prior research has documented the role of Kenyan government-led input market reforms of the 1990s in reducing domestic fertilizer distribution costs and encouraging significant new entry in rural fertilizer retailing (Ariga and Jayne 2009, 2010). Alene *et al.* (2008) show how

transactions costs affect fertilizer demand through joint estimation of output supply and input demand models, but with specific attention to market participation outcomes. Omamo and Mose (2001) explore the impact of reforms 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 these studies have looked at some aspect of fertilizer use in Kenya, there currently exists no rigorous evidence that has quantified the nationwide impacts of input marketing policy reforms on fertilizer use and national maize production. Moreover, there may be several pathways through which these input market reforms may have affected farmers' use of fertilizer and maize response, implying the need for careful econometric analysis beyond what is currently available in the literature on input markets in SSA. We seek to fill these knowledge gaps by using five waves of household panel survey data for the years directly following the reforms to isolate the specific contributions to fertilizer use and maize production resulting from (1) a reduction in distance traveled by farmers to acquire fertilizer due to new entry of private fertilizer retailers and (2) a decrease in the retail price of fertilizer attributed to falling marketing margins observed between the Port of Mombasa and retail distribution points.

Our study first documents these two changes as experienced by farmers, linking both outcomes to the input market reform period. We then estimate a double-hurdle model of demand for commercial fertilizer on maize fields and maize output supply models, controlling for unobserved household heterogeneity. Finally, using the parameter estimates from these models, we predict the *ex post* impacts on fertilizer use and maize production resulting from increases in fertilizer market accessibility and decreases in the marketing margins portion of fertilizer prices.

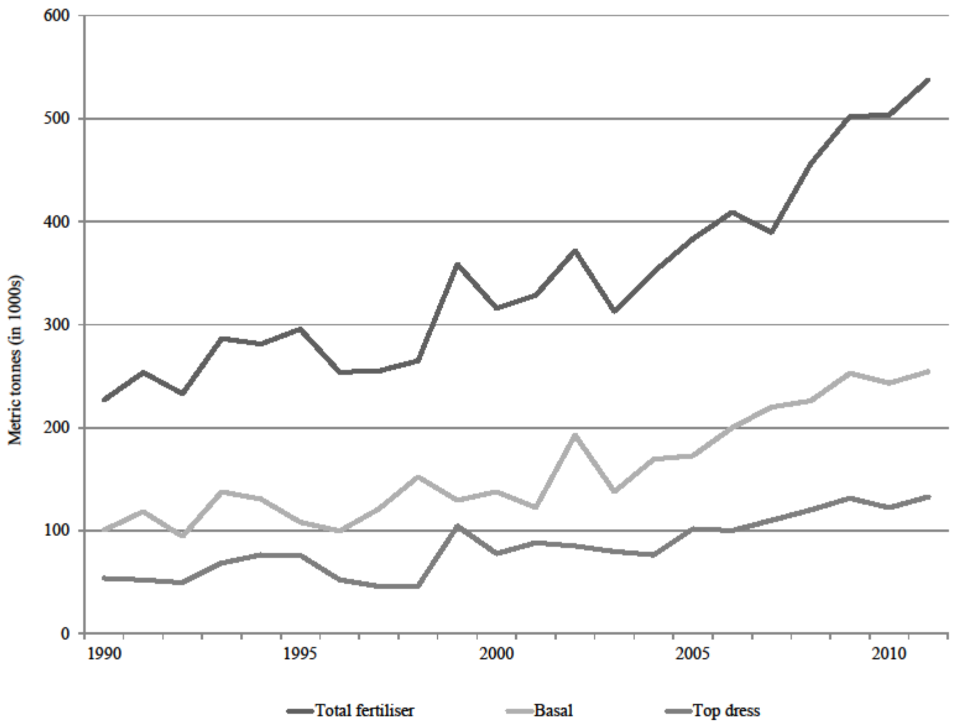
2. Fertilizer market development in Kenya

Prior to reform, fertilizer and maize markets in Kenya were dominated 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 country's single license for fertilizer importation. 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 continued to control which firms could receive licenses.

The reform process was initiated after growing realization that rent-seeking behavior was negatively affecting farmers' access to fertilizer 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 measures, including the elimination of import quotas, the removal of fertilizer price and foreign exchange controls, and the relaxation of import license restrictions, leading to full government retreat from the fertilizer market by 1994. There were also virtually no input subsidy programs in Kenya between 1990 and 2007.

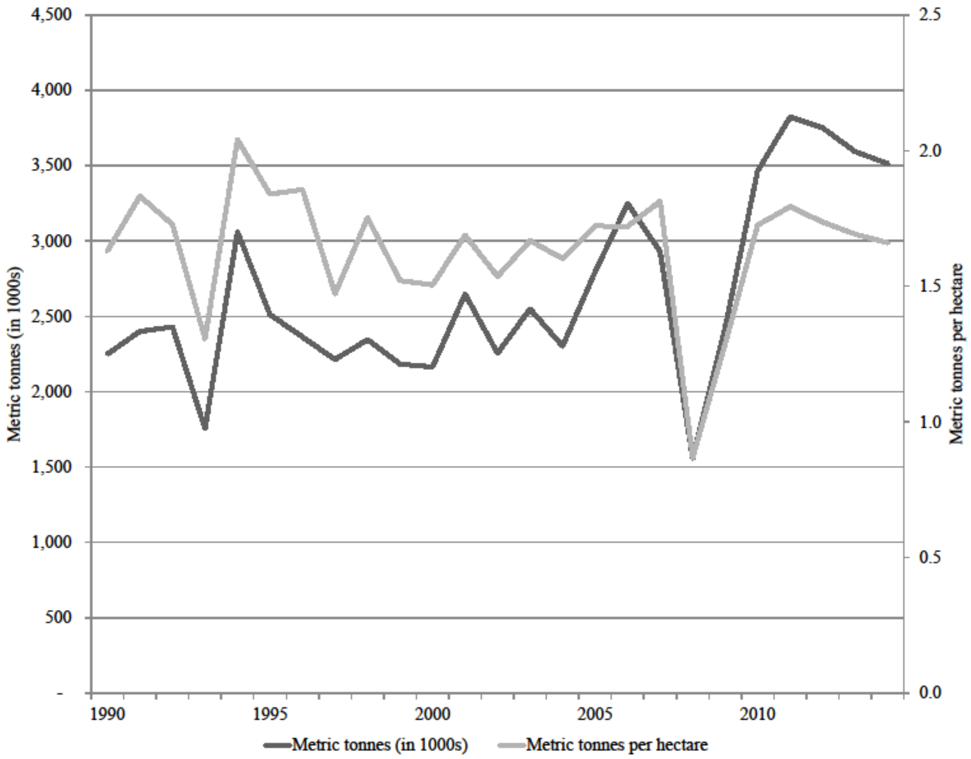
Following the reforms, fertilizer supply channels evolved to accommodate private sector entry, and the distribution of commercial fertilizer to farmers throughout the country increased significantly. Wanzala *et al*. (2001) studied four fertilizer marketing channels in western Kenya in the late 1990s and used 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 limited private sector investment in fertilizer supply chains and various taxes on fertilizer coming through the Port of Mombasa. After the elimination of fixed maximum retail selling prices, opportunities expanded for profitable investment in fertilizer supply chains which ultimately improved competition.

Figure 1a. National fertilizer use trends



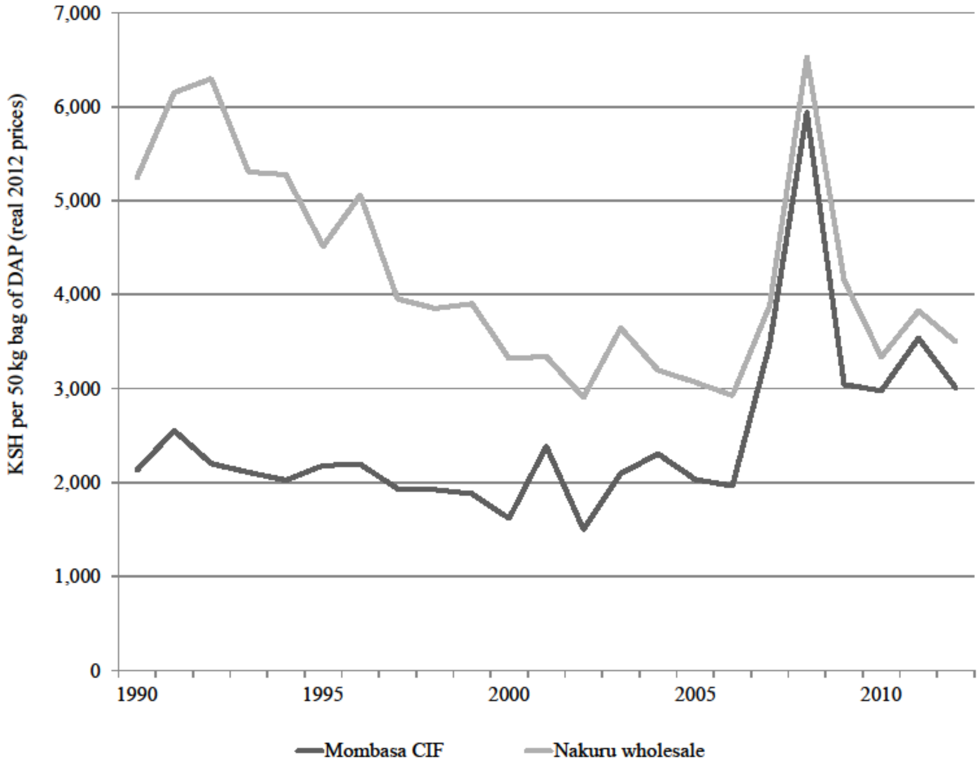
Source: Ministry of Agriculture, Livestock, and Fisheries in Kenya.

Figure 2b. National maize production trends



Source: Ministry of Agriculture, Livestock, and Fisheries in Kenya.

Figure 3. 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, Livestock, and Fisheries in Kenya for all years in Nakuru and through 2009 in Mombasa. After 2009, the Mombasa prices were estimated using a time trend, crude oil prices (a proxy for international transport costs), the current and lagged international DAP price, and a AR(1) adjustment to correct for autocorrelation. Prices were deflated to 2012 levels using the CPI from the Kenya National Bureau of Statistics (KNBS).

In the decade following the fertilizer marketing reforms, domestic marketing costs declined leading to a reduction in real fertilizer costs for farmers. Comparing di-ammonium phosphate (DAP) fertilizer cost, insurance, and freight (CIF) prices in the Port of Mombasa with wholesale prices in Nakuru (a major fertilizer consuming area of the Rift Valley), Figure 2 shows that domestic marketing costs declined from roughly 50 percent of the Nakuru price in 1997 to about 25 percent in 2008. Based on key informant interviews in the fertilizer supply chains, 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 sources of international finance; (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 as more firms entered the market. Key informants indicated that local and international private companies' commitment to long-term cost-reducing investments in fertilizer distribution was largely due to the greater scope for commercial fertilizer sales after the elimination of fertilizer price controls and other policy related restrictions on the marketing of fertilizer, the concurrent liberalization of agricultural commodity markets, and the perception of reduced risks to investment in fertilizer supply chains after the government phased out non-commercial fertilizer distribution programs in the mid1990s (Ariga and Jayne 2009).

Not only did fertilizer prices decline from the perspective of farming households (until the major international price spike in 2008), but the number of rural fertilizer retailers also 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. Fertilizer retailers moved further into rural areas and became more accessible to farmers, leading to lower costs incurred by farmers in moving fertilizer from retail shops to the farm-gate. Based on evidence that transport and transactions costs are significant deterrents to participation in input markets by Kenyan farmers (Alene *et al*. 2008), the observed reduction in transport costs is likely to have increased fertilizer demand over time.

Despite what appears to be a demonstrable response by the private sector to incentives emanating from these reforms, in 2007 the GoK initiated a large-scale fertilizer and certified seed subsidy scheme, the National Accelerated Agricultural Inputs Access Program (NAAIAP), aimed at increasing national maize production and decreasing rural poverty by supporting input access for the most vulnerable and resource-poor farmers.[2] Running parallel to the NAAIAP, 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 mitigate the effect of the spike in international fertilizer prices in 2008 and the disruption in private fertilizer retailing following the post-election violence of 2007/08.[3] While these government programs are not the focus of this analysis, it is important to note that some of the gains from the earlier withdrawal of the government from participation in input markets was somewhat reversed starting in 2007 through the implementation of these two subsidy programs.

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[2] This is an ongoing "smart" subsidy program using vouchers through the private agro-dealer distribution system. For more details on the NAAIAP program, see Sheahan *et al.* (2014).
[3] For more details on the NCPB fertilizer subsidy program, see Peter and Rotich (2013).

3. Conceptual framework

Policy changes, such as those initiated in Kenya in the 1990s, are designed to affect behavior through changes in incentives. The specific input marketing policy changes under study may have affected farmer input demand behavior indirectly, through the ways in which the reforms affect trader behavior and retail prices. We study two pathways linking the outcomes of market reforms with farmer fertilizer demand. Then, we describe the two ways in which increase in fertilizer demand can lead, ultimately, to increases in maize output at the household level.

Pre-reform controls on the retail price of fertilizer were intended to protect farmers from predatory practices of traders, and it might at first seem paradoxical that the removal of price controls would lead to a reduction in the price of fertilizer. However, if the maximum retail prices were insufficient to cover traders' costs of distributing fertilizer from wholesale points to remote areas, then we might expect traders to significantly limit their reach and/or farmers to incur high costs and long distances to access fertilizer on their own, costs that might easily outweigh benefits from buying fertilizer at the controlled price. In other words, economies of scale in distribution might allow traders to more cheaply distribute fertilizer to remote areas closer to the farmer if given the incentives to do so. Hence, the first pathway we explore concerns how the distance necessary for farmers to travel between the nearest fertilizer retail store back to the farm affected fertilizer demand.

Our second pathway of interest concerns changes in retail fertilizer prices. Fertilizer prices experienced by farmers may also fall if private firms make investments along the supply chain given confidence in a stable and liberalized market environment. These investments may reduce costs in distribution and, when markets are sufficiently competitive, may be transmitted directly to farmers. While changes in retail fertilizer prices may reflect exogenous changes in world prices and domestic transport costs, changes in internal marketing costs over time are more easily attributable to changes in the domestic enabling environment. This paper, therefore, explores the link between the reduction in fertilizer retail prices via domestic port-to-retail margins that can be credibly associated with the input market reforms and the resulting impacts on fertilizer demand.

The link between fertilizer use and maize production is relatively more straightforward: increased use of fertilizer should increase yields (output per hectare); reduced fertilizer prices could also encourage farmers to increase their maize area.

After describing our data, the following sections are devoted to first establishing the link between the input market reforms in Kenya and our main measures of interest: the extent to which the retail price of fertilizer and farmers' accessibility to retail outlets were affected by the input marketing policy reforms. We then estimate the impact of these price and market access changes on the quantity of fertilizer demanded by Kenyan farmers for use on maize and the household level maize production impacts of these changes, both on yield and area under cultivation.

4. Data and sample selection

Our data come from the nationwide Rural Household Indicator Survey of Egerton University's Tegemeo Institute. This longitudinal farm household survey was implemented in 1997, 2000, 2004, 2007, and 2010, and covers 24 administrative districts, 39 divisions, and 120 villages where standard proportional sampling using census data for rural divisions formed the basis of sampling at the household level (for more details on survey design, see Argwings Kodhek *et al*. 1998). The panel started with 1,500 households but, due to attrition over the thirteen years, 1,243 are consistently interviewed through the most recent 2010 wave.

Our analysis, however, does not make use of the strict five-round panel. Instead, we limit our sample to an unbalanced panel of maize-producing households. Because most agricultural data in the survey is observed at the field level, we narrow our focus to specifically defined maize fields, then aggregate across maize fields to the household-level for analysis.[4] The focus on maize reduces our sample to a possible 1,468 households across any of the five rounds. From this sample of maize producers, all households in the Coastal province are dropped (n=83) because it the Coast quite different from the other maize-producing areas of the country. We further drop households which do not meet the econometric considerations described in Section 5 (n=254). Our final sample includes an unbalanced panel of 1,131 households, with a total of 4,629 observations across all five rounds, implying that the average household cultivated maize fields in four of the five survey rounds.[5] More details on the distribution of our sample can be found in Table 1. Difference-in-means analysis across the dropped and remaining maize producing households is found in Table A.2 of the Appendix.[6]

Several external data sets are matched to the household survey data using Global Positioning System (GPS) coordinates recorded during data collection. We also utilize a range of

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[4] Fields are categorized as "maize fields" if they meet the following criteria: (1) have maize and no more than six other crops, (2) maize is not produced alongside a major cash crop (i.e., tea, sisal, rice, pyrethrum, cotton), and (3) maize constitutes at least 25 percent of the calculated value of total harvest from the field. We place great emphasis on identifying which fields appear to be primarily comprised of maize. Otherwise, it could be the case that commercial fertilizer, observed at the field level, may be applied to other non-maize crops on the field instead.

[5] Because our selected sample is drawn from a nationwide sample, we expect our estimates to be broadly representative of maize producers in Kenya

[6] Given statistically significant differences across a number of variables (as expected), we perform robustness checks by varying our included sample in estimation.

international, national, and market-level data sources, matched to our sample at the district or province level. These data sets are explained in more detail below.

Table 1. Distribution of maize-producing households in our sample by survey year and overall

Province	Districts	1997	2000	2004	2007	2010	Overall no. of households	Overall no. of observations
Eastern	Kitui, Machakos, Makueni, Meru, Mwingi	123	160	182	135	143	192	743
Nyanza	Kisii, Kisumu, Siaya	144	189	223	222	206	235	984
Western	Bungoma, Kakamega, Vihiga	214	218	271	250	235	273	1,188
Central	Muranga, Nyeri	102	65	81	75	86	110	409
Rift Valley	Bomet, Nakuru, Narok, Trans Nzoia, Uasin Gishu, Laikipia	189	274	306	292	244	321	1,305
	Total nationwide sample	772	906	1,063	974	914	1,131	4,629

Note: See Section 4 for more details. We use an unbalanced panel of the 1,131 households in our analysis. This results in 4,629 observations, defined as a household in a given survey year.

5. Estimation strategy

Our aim is to quantify the impacts of reduced prices and costs associated with procuring fertilizer resulting from market reforms on fertilizer use and maize production in Kenya. Our methodology relies on a profit maximization framework to derive input demand and output supply equations. The profit function dual approach is appropriate to our focus on the variable costs of production associated with reforms to the input sector. We assume maize-producing households not only maximize profits over all possible income-generating opportunities, but also with respect to maize production in particular. As such, we specify a profit function for one output y (maize), a vector of fixed and variable inputs $\boldsymbol{x}$ (including but not limited to fertilizer), output price p, and a vector of input prices $\boldsymbol{r}$, where y is conditional on $\boldsymbol{x}$:

(1)
$$\pi(p,\boldsymbol{r}) = \max_{y}\left\{py - \sum_{i=1}^{n} r_i x_i\right\}$$

Using the envelope theorem and Hotelling's lemma, the first order conditions of the profit function yield output supply and input demand equations:

(2)
$$y^* = \frac{\partial \pi}{\partial p} = y(p,\boldsymbol{r})$$

(3)
$$x_i{}^* = \frac{-\partial \pi}{\partial r_i} = -x_i(p,\boldsymbol{r})$$

5.1. Attributing changes in fertilizer accessibility and prices to input market reforms

Our analysis focuses specifically on the reduction in the farm gate price of fertilizer $r_1$and its impact on fertilizer demand $x_1$and maize supply y. Microeconomic theory contends that a reduction in fertilizer price should, under normal assumptions, positively increase both fertilizer demand and maize supply. For our purposes, the farm gate price of fertilizer r_1 can be further broken into two central components: the price paid at retail markets for the product $m_1$and the cost of transport back to the farm d_1 ($r_1 = m_1 + d_1$).

But, to what extent can changes in the magnitude of these values be credited to input market reforms *per se*? While key informant interviews of private fertilizer companies highlight the influence of changing policies in the 1990s and the phase-out of state fertilizer programs as the impetus for both the reduction in fertilizer marketing costs and the rapid investment by retailers in rural areas, it is still difficult to show direct causation between private investments and policy reforms. Existing studies and simple descriptive analysis help to better establish the link. For instance, the substantial decline in the distance traveled by farmers to the nearest retail fertilizer seller over this period corresponds with the substantial increase in the number of fertilizer retailers operating in Kenya's rural areas immediately following the reform period (Allgood and Kilungo 1996; Arwings-Kodhek 1996; Freeman and Kaguongo 2003), as described above. For this reason, it seems appropriate to credit the reduction in travel distance necessary to access fertilizer to the reforms.

Likewise, as shown in Figure 2, inflation-adjusted CIF prices of fertilizer at the Port of Mombasa did not decline between the mid-1990s and 2007; the decline in wholesale prices in maize production areas was almost entirely due to reductions in the marketing margins over time between CIF import prices and up-country wholesale prices. To be sure that we exclude other possible reasons for changes in local prices of fertilizer, we estimate two simple linear fertilizer price determinants models for maize-producing household j during main cropping season t:

(4) $$m_{1jt} = \vartheta_0 + \vartheta_1 m_t^{world} + \vartheta_2\left(m_{1jt} - m_t^{Mombasa}\right) + \vartheta_3 f_t + e_{jt}$$

(5) $$r_{1jt} = \Phi_0 + \Phi_1 m_t^{world} + \Phi_2\left(m_{1jt} - m_t^{Mombasa}\right) + \Phi_3 f_t + \Phi d_{jt} + \varepsilon_{jt}$$

where the retail price (m_1) and farm gate price (r_1) of fertilizer experienced by Kenyan farmers are functions of the observed world price of fertilizer (m^{world}), the difference between the fertilizer price experienced by farmers and the import price of fertilizer into Mombasa ($m^{Mombasa}$) (the gap between which represents domestic marketing margins), the price of diesel fuel in Nairobi (f) (a proxy for domestic transport costs), a local retail-to-farm transport cost (d) (for the farm gate price model only), and error terms e and ε. Using the coefficient estimates, we also calculate Shapley values, which decompose the explained variance (measured by the overall model R^2) into mean marginal contributions over particular individual or groups of regressors (Huettner and Sunder 2012), a more direct way of ascertaining the influence of marketing margins and local transport costs on farmer fertilizer prices.

In addition, key features of our empirical approach further allow us to isolate this specific variation in prices and accessibility across time in Kenya, those most consistent with the input policy reforms, as described in more detail below. Beyond what we are able to control, we fully acknowledge that other factors may have played some part, directly or indirectly, in the increase in fertilizer accessibility and decrease in prices, including trade liberalization, maize and other market reforms, and expanded promotion of fertilizer by extension services.

5.2. Estimating the fertilizer demand and maize supply functions

Our profit function takes a generalized quadratic functional form, from which linear input demand and output supply equations can be derived. We estimate the following maize supply and fertilizer demand equations for maize-producing household j during main cropping season t:

(6)
$$y_{jt}^* = \beta_0 + \beta_1 p_{jt} + \sum_{i=1}^{n} \gamma_i r_{ijt} + \sum_{k=1}^{q} \delta_k z_{kjt} + \tau_t + \mu_{jt}$$

(7)
$$x_{1jt}^* = \alpha_0 + \alpha_1 p_{jt} + \sum_{i=1}^{n} \theta_i r_{ijt} + \sum_{k=1}^{q} \sigma_k z_{kjt} + \tau_t + \nu_{jt}$$

where y is the maize harvest across all maize fields, x_1 is the amount of commercial fertilizer applied to all maize fields, p is the output price of maize, r_1 is the farm gate price of fertilizer (with both m_1 and d_1 components), z includes all farm, community, agro-ecological, and market characteristics that also are hypothesized to affect both outcome variables (our notation allows time-variation here, but some of which may be observed as fixed), and μ and ν are the error terms. The foreseen non-separability of maize production and consumption decisions by Kenyan households is partially accommodated by allowing socio-demographic characteristics of the household to be included in z (de Janvry and Sadoulet 2006; Singh, Squire, Strauss 1986).[7]

Important for this analysis, the inclusion of cropping year effects τ allows us to control for, among other things, international and import prices of fertilizer and diesel costs that are passed on to all Kenyan households in a given year. This means that all remaining variation in r_1 is specific to within-Kenya effects representing, to a large extent, the variation across time and space in internal marketing margins and fertilizer accessibility. The coefficients γ_1 and θ_1, therefore, largely reveal the magnitude of household maize supply and fertilizer demand response, respectively, associated with input market reforms as distinct from other external forces.

The maize supply equation can be estimated using ordinary least squares (OLS). However, despite an observed increase in the use of fertilizer over time in Kenya, a non-trivial number

[7] While the non-separability assumption remains untested in our sample of Kenyan households, we rely on consistent evidence of multiple market failures in several other countries in the region (Dillon and Barrett 2014).

of maize-producing households did not use commercial fertilizer in any given year. The relatively large number of zeros in the dependent variable (about 32 percent) leads to inconsistent estimates via OLS, creating the need for a “corner solution” fertilizer demand model. Like many other studies of fertilizer demand with similar restrictions (e.g., Croppenstedt, Demeke, Meschi 2003; Ricker-Gilbert, Jayne, Chirwa 2011), we rely primarily on Cragg’s double hurdle model (Cragg 1971). The decision to use fertilizer is first estimated using a binary probit model. Then, for those households that use commercial fertilizer in a given year, a truncated normal regression is run on the continuous variable describing the amount of fertilizer applied. The two-tiered model takes the following form:

(8) $$P(D_{jt} = 1|x_{jt}) = \omega \boldsymbol{X_{jt}}$$

(9) $$x_{jt} = \varphi \boldsymbol{X_{jt}} \; if \; D_{jt} = 1$$

where D_{jt} is the participation decision variable which takes the value one if the household used commercial fertilizer on maize fields and zero otherwise, and $\boldsymbol{X_{jt}}$ represents all variables and vectors in the fertilizer demand model described in equation (7). Since it is possible that the factors influencing farmers’ decisions to use fertilizer may differ from those influencing the quantities of fertilizer applied by users, the $\boldsymbol{X_{jt}}$vector has two separate sets of coefficients; ω is associated with the first hurdle while φ is associated with the second hurdle. Both hurdles are estimated using maximum likelihood techniques (MLE).

The error terms μ and ν in equations (6) and (7) are functions of two components. The first part contains unobserved time-constant factors, also called unobserved heterogeneity c_j, which affect household j’s demand for commercial fertilizer or maize supply response and create concerns about endogeneity. These factors might include household-specific soil quality, the farmer’s management ability, and degree of risk aversion. The second element of the error term is composed of random variables ε_{jt}. The use of panel data makes it possible to control for c_j. We use the correlated random effects (CRE) estimator, which allows for correlation between the unobserved omitted variable c_j and included explanatory variables. The CRE estimator uses 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:

(10) $$c_j = \rho + \rho \overline{\boldsymbol{M}} + a_{jt}$$

where $\overline{\boldsymbol{M}}$ is a vector of household-averaged values for all variables in both the maize supply and fertilizer demand equations across all waves of the panel.[8] For this estimation, the CRE method is preferred because it allows for estimation of time-invariant variables unlike fixed effects methods but without the strong assumptions of traditional random effects techniques.

The CRE approach provides an intuitive way of estimating changes that occur "within" the panel unit over the time period of interest and measuring the differences "between" units on average, further useful to our goal of understanding the impact of policy changes from the perspective of a given household. Because sufficient household-level variation is necessary for the CRE device to be employed, households with qualifying maize fields in less than three survey years are dropped from the sample.[9] Robust standard errors are estimated at the household level to account for potential heteroskedasticity and serial correlation (Wooldridge 2009).

[8] 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 $\overline{\boldsymbol{M}}$ the means of the binary survey year variables as well. We use this technique when estimating any non-linear models, but drop these variables in the linear models.

[9] This decision rule drops 254 households from our sample. 97 of these households only have qualifying maize fields in one survey round and would drop out from any estimation using household averages across time regardless. The remaining 157 households (in two survey rounds) are later brought back into the sample for robustness checks.

6. Variables in the fertilizer demand and maize supply models

In this section, we describe the variables used in the input demand and output supply models, summarized in Table 2. Outliers in excess of the 99th percentile of the distribution for a given variable are replaced with the value at the 99th percentile so as to limit their leverage. Otherwise, all data remains as the household reported. In our descriptive statistics, all nominal prices are converted to real 2010 levels using the yearly consumer price index (CPI) values from the Kenya National Bureau of Statistics (KNBS).

6.1. Commercial fertilizer use

We measure fertilizer use as the total kilograms of nitrogen from all commercially purchased fertilizer types applied to maize fields.[10] Farmers use a range of fertilizers with varying nutrients, hence conversion to nitrogen is warranted. Because very little applied phosphorus is taken up by the maize plant in the year of application, agronomic studies of fertilizer response tend to focus on response rates to nitrogen specifically. Moreover, nitrogen is considered to be the most constraining nutrient in maize production in most areas of Kenya. We perform robustness checks using total kilograms of fertilizer as well. Table A.1 in the Appendix shows the percent of households with maize fields receiving commercial nitrogen application by year and province and the average application rates for fields receiving fertilization. Except for 1997 in Eastern and all years in Nyanza Province, the rest of the provinces and year combinations show at least half of maize producing households using commercial nitrogen on their maize fields.

6.2. Maize supply

We are interested to disentangle the two pathways through which an increase in fertilizer use at the household level associated with the reforms contributed to changes in maize supply outcomes (see Section 3). To that end, we measure maize harvest across all maize fields in total kilograms of dry and green maize.[11] The total harvest amount at the household level merely describes the overall production response. But, where the total hectares under maize at the household level is controlled, this effect can be interpreted as a productivity impact, the total increase in maize output per unit of land. Then, to the extent that changes in total

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[10] Only in the 2010 survey could farmers obtain fertilizer from one of the government's subsidy programs (only relevant to n=77). Since the interest of our study is to understand how *commercial* demand was affected by the changes in prices and market access conditions, we subtracted the subsidized quantities from total fertilizer use.

[11] Green maize includes cobs picked fresh for eating before the main harvest period.

production can be attributed, instead, to changes in area under maize fields, we also specify a model where the outcome is simply acreage.

6.3. Fertilizer (retail) market prices

Instead of including the full farm gate price of fertilizer r in our models, we separate out the market price m_1 from the transport component d_1 in order to study their separate effects. Including the market price of fertilizer m_1 allows us to measure the contribution of changes in overall prices resulting from the reduction in marketing margins as a consequence of policy reforms, particularly when combined with results from equation (4). We compute m_1 as the price of nitrogen based on the two main types of fertilizer applied to maize fields, DAP and CAN, weighted by the relative shares of over 30 types of basal and top dress fertilizers found on maize fields, averaged at the district and year level.[12] This weighting scheme allows us to create nitrogen prices that more accurately mimic the local supply environment and the fertilizer type preferences of farmers. 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. Robustness checks are performed using other definitions of the fertilizer price. Fertilizer market prices are based on farmer recall. For households that did not purchase a given type of fertilizer, a district median value derived from purchasers is substituted.[13] Average nitrogen prices by province and survey year can be found in Table A.1 of the Appendix.

6.4. Transporting fertilizer from the (retail) market to the farm

Our second key explanatory variable and the remaining component of farm gate fertilizer prices is the cost of transporting fertilizer from the retail market to farm gate d_1. In our analysis, d_1 is proxied as the distance between these two locations. We choose not to use the actual transport cost because while changes in transport costs are due to factors other than fertilizer market reform (e.g., local transport market environment), the changes in distance traveled from the farm to fertilizer retailers reflect changes in the number and location of retailers operating in rural areas, which is indicative of changes in the enabling environment in the fertilizer supply chains. Our identification strategy for d_1 rests on the assumption that entry and exit of rural fertilizer retailers are due, directly or indirectly, to input market policy

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[12] DAP is 18 percent and CAN is 26 percent nitrogen. We, therefore, calculate the market price of nitrogen as: $m_1 = \left(\frac{m_{DAP}}{0.18}\right) w_{basal} + \left(\frac{m_{CAN}}{0.26}\right) w_{topdress}$ where w_{basal} and $w_{topdress}$ are the weights and sum to one.

[13] 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.

changes, though we cannot definitively rule out other potential explanations.[14] In each survey year, the household-reported distance (in kilometers) between the farm and nearest fertilizer seller is recorded. Table A.1 shows averages by province and survey year.[15] Distance for most areas in the sample declined dramatically between 1997 and 2007 and then largely leveled off between 2007 and 2010.

6.5. Expected maize prices

Future post-harvest maize prices are not known at the time fertilizer use decisions are made in Kenya, hence a reasonable proxy for expected maize prices is needed in the input demand and output supply models. We assembled wholesale maize prices by month and year across six major markets in Kenya (Eldoret, Kisumu, Kitale, Nairobi, Nakuru, Taveta), then matched each included district in our analysis with the most relevant of these markets. We create an average of observed market prices in the six months prior to planting, accounting for the differences in planting time across the country (e.g., October in the eastern areas and March in the Central, Rift Valley, and Western areas).

6.6. Characteristics of the production system

Because fertilizer application and maize yields may vary with other market and agroecological conditions, we include dummy variables for provinces and five broadly classified soil types.[16] We also include household-specific elevation levels, as collected during the 2010 survey. Rainfall expectations, necessary since fertilizer application decisions are made without full knowledge of how the season will unfold, are proxied at the village level using a six-year moving average of past rainfall levels acquired from the National Weather Service Climate Prediction Center (CPC) as part of the Famine Early Warning System (FEWS) project. We also derive a village level population density variable using population counts from the Global Rural-Urban Mapping Project dataset (GRUMP) in 1995,

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[14] Relocation of households is not a possible explanation because of the panel nature of households in the sample.

[15] The distance to the nearest fertilizer seller variable is not necessarily expected to reflect changes in more general market access conditions. Using this same data, Chamberlin and Jayne (2013) show the very low degree of correlation across market access indicators, including several other distance measures.

[16] These five groups include: (1) Regosols and Podzols found in volcanic areas, (2) high humus Phaeozems, Luvisols, and Greyzems with highly productive Cambisols, (3) Leptosols with high sand content, (4) Leptosols with less sand content, and (5) "poor soils" meaning both Vertisols, Ferralsols, and Podzols with high clay and inadequate drainage as well as very shallow or very poorly drained soils found in swamps, reefs, or erosional plains. For more details, see Sheahan, Black, and Jayne (2013).

2000, 2005, and 2010 and the total arable land from GlobCover2009, a global land cover dataset.[17,18]

We also control for village-median casual daily wages, a measure of the opportunity cost of hiring labor. Several other quasi-fixed characteristics of the farm are used as controls, including total area under cultivation (in hectares) and total livestock availability (measured in tropical livestock units, TLUs).[19] Because the maize fields are not comprised entirely of maize, the total number of crops on these maize fields is used to control for the fact that some portion of the fertilizer may have been applied to other crops. The inclusion of this variable helps to capture how fertilizer decisions can vary across maize fields with different crop compositions but similar maize seeding rates.

6.7. Characteristics of the household

A number of variables describing household characteristics are included in the model following de Janvry and Sadoulet (2006) and Singh, Squire, and Strauss (1986) and the substantial literature linking the socio-economic status of the household with the ability or decision to use fertilizer (e.g., Feder and Umali 1993; Feder, Just, Zilberman 1985). The age of the household head is included as a proxy for human capital and experience, and sex of the household head is used as a proxy for household access to inputs complementary to fertilizer (Doss and Morris 2001). We control for household size (in adult equivalents) as both a measure of quasi-fixed household agricultural labor availability and household consumption needs. Because available income and, in particular, the flow of available income over the year, are difficult to accurately specify for agricultural households, the value of household asset wealth at data collection time is used as an indicator of households' purchasing power.[20]

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[17] For further details on this data set, see Balk and Yetman (2004).

[18] While one might expect considerable fluctuations in expected rainfall conditions and variable population density estimates across time, we find very high correlation coefficients (above 0.9) between year-specific and averages across all survey years (necessary for the CRE device) of these two village-level variables. Due to multicollinearity, we opt to only include the average values in our estimation.

[19] We include only cattle, goats, and sheep in this aggregate due to changes in the survey across years. The TLU conversion used here is 1 cattle = 0.7 TLU and 1 goat or sheep = 0.1 TLU.

[20] Assets consistently included in all five survey years are used to construct the asset wealth variable, including the total value of livestock, farm equipment, and large household assets.

Table 2. Mean (and standard deviation) of variables in models split by binary commercial fertilizer use decision

Variable	Level of observation	Household did use commercial fertilizer on maize fields (obs=3,163: 68 percent)	Household did not use commercial fertilizer on maize fields (obs=1,466: 32 percent)	Statistical significance of difference in mean between two groups (t-test)
Total hectares under maize fields (hectares)	Household	0.85 (1.61)	0.66 (0.72)	***
Total maize production across maize fields (kg)	Household	1914.55 (2922.54)	796.00 (1388.08)	***
Maize yield (kg/ha)	Household	2488.15 (1583.35)	1356.68 (1237.78)	***
Total nitrogen applied to maize fields (kg)	Household	30.93 (60.23)	-	-
Nitrogen application rate on maize fields (kg/ha)	Household	34.85 (29.47)	-	-
Real retail price of nitrogen (KSH/kg) (weighted N portion of DAP and CAN)	Household (or district median)	331.86 (84.79)	351.81 (107.00)	***
Distance from household to nearest fertilizer dealer (km)	Household (or village median)	3.14 (3.50)	6.10 (7.36)	***
Real (estimated) expected price of maize (KSH/kg)	District	25.41 (4.17)	27.68 (5.57)	***
Village casual daily wage rate (KSH/day)	Village	141.83 (51.79)	130.68 (54.08)	***
Average number of crops on maize fields (range 1-7; 1=monocropped maize)	Household	2.92 (1.52)	3.09 (1.55)	***
Area under cultivation (hectares)	Household	1.60 (1.63)	1.29 (1.24)	***
Tropical livestock units (TLUs)	Household	3.21 (3.45)	3.14 (4.12)	
Household size (adult equivalents)	Household	5.37 (2.37)	5.13 (2.47)	***
Real asset wealth of household (in 1000 KSH) for subset of all household assets	Household	212.57 (382.07)	143.65 (291.57)	***
Sex of household head: Female=1; male=0	Household	0.16 (0.37)	0.26 (0.44)	***
Age of household head (years)	Household	55.52 (13.72)	56.29 (14.03)	*
Expected total rainfall in main growing season (mm)	Village	609.25 (162.19)	546.46 (188.58)	***
Elevation (meters above sea level)	Household	1817.70 (284.32)	1471.73 (353.06)	***
Population density (persons per square kilometer of arable land)	Village	542.19 (447.11)	593.88 (623.77)	***

Note: These statistics are pooled across all survey years. Each observation in this table represents one household and year combination, and therefore individual households can show up as users in some survey years and non-users in others. *, **, and *** denote that difference in mean between groups is statistically significant using t-values of 1.645, 1.96, and 2.58 respectively. For more detail on how each of these variables is calculated, see Section 5. All prices and values are converted to real 2010 levels for this table.

7. Results

7.1. Fertilizer price determinants models

We estimate equations (4) and (5) with respect to the price of DAP, since this price is consistently available at the household, national, and international levels. The world price of DAP is observed in November and December before the main planting season (when domestic importers likely place orders on the international market), as obtained from the World Bank Commodity Price Data and converted from USD to KSH using official exchange rates from the Government of Kenya. The price of DAP at import into Mombasa is obtained from FMB weekly fertilizer reports via the Ministry of Agriculture, Livestock, and Fisheries (MoAFL) for the first calendar year of the main cropping season. Year-averaged retail prices of diesel in Nairobi were collected from the Kenya National Bureau of Statistics.[21] Due to data limitations, the farm gate price of DAP is estimated by adding to the observed retail price an estimated transport cost (extrapolated by multiplying the distance recorded in each survey year by the village median transport cost per kilometer, only observed in 2010).

The results of our two fertilizer price determinants model are shown in Table 3. In the retail price of DAP specification, all included regressors are significant at the 1 percent level. The Shapley values indicate that 60 percent of the variation in retail DAP prices is explained by changes in domestic marketing margins between Mombasa and the farmers' point of purchase which is considerable given the significant narrowing of marketing margins in the later survey years (Figure 2). It is this part of the variation that we peg to the market reforms, acknowledging that other unobserved factors may have also contributed as well.

Moreover, we find that 68 percent of the variation in estimated farm gate prices can be explained by the distance traveled between the retail point of sale and farm household. Because these transport costs can only be estimated due to data limitations, this finding merely points to the importance of the costly "last leg" of transport in determining the cost of inputs from the perspective of farmers, even after controlling for the cost of fuel. The change in marketing margins and accessibility of fertilizer are clearly major determinants of the full retail and farm gate costs. By controlling for the remaining variation specific to all

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[21] Ideally we would observe spatial variation in diesel prices for each year of interest, but have been unable to secure these data, should they exist. More recent prices (2013-15) from the Energy Regulatory Commission in Kenya, however, show very limited spatial variation. For the most recent set of prices across 70 Kenyan towns, the coefficient of variation is only 0.02.

households in Kenya through the use of survey year fixed effects, we isolate the contribution from these left-over local portions in our fertilizer demand and maize supply models.

Table 3. Estimation results of determinants models for DAP prices (retail and estimated farm gate) paid by farmers

	Retail price of DAP (KSH/kg)	Estimated farm gate price of DAP (KSH/kg)
Domestic marketing margin of DAP (KSH/kg)	0.92***	1.16***
	(0.00)	(0.08)
Distance from hh to nearest fert dealer (km)		14.92***
		(0.16)
World DAP price (KSH/kg)	0.170**	0.45***
	(0.01)	(0.17)
Diesel price (KSH/liter) in Nairobi	-0.29***	-0.15**
	(0.00)	(0.07)
Constant	65.93***	-39.14***
	(0.39)	(11.48)
District fixed effects	Yes	Yes
N	4,629	4,629
R^2	0.99	0.76
Shapley values		
Domestic marketing margin of DAP (KSH/kg)	*60.06*	*9.99*
Distance from hh to nearest fert dealer (km)		*67.97*
World DAP price (KSH/kg)	*31.02*	*5.66*
Diesel price (KSH/liter) in Nairobi	*3.25*	*0.43*
District fixed effects	*5.67*	*15.95*

Notes: *** p<0.01, ** p<0.05, * p<0.1. Standard errors included in parentheses. All models include 1,131 households with 4,629 observations pooled across years. All prices are specified in real 2010 values (given the necessary exclusion of year fixed effects). Estimated farm gate prices of DAP represent the sum of observed retail prices plus an estimated transport cost back to the farm gate. The domestic marketing margins are calculated as the difference between the DAP price that farmers pay at local retail markets minus the import (CIF) DAP price in Mombasa. The numbers included in the bottom panel represent Shapley values, or the percentage of the R^2 that can be explained by the regressor (or group of regressors, in the case of district fixed effects). We calculate these values using the "rego" user-written command in Stata.
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis and several external data sets described in Section 7.

7.2. Fertilizer demand model

Table 4 presents the unconditional average partial effects (APEs) of our preferred nitrogen demand model specification, the double hurdle model (with raw regression coefficients in Table A.4 of the Appendix).22 We focus on the unconditional APEs because they represent the effect of particular variables on the full sample of maize-producing household, not just those who use commercial fertilizer, to identify the contribution of input market reform outcomes to population-scale fertilizer use. The average partial effects are estimated using the

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[22] The APEs for the same model estimated as OLS and Tobit are included in Table A.3 of the Appendix. We confirm via a likelihood ratio test that the unrestricted double hurdle model is a better fit for our data then the restricted Tobit model. For this reason, all further analysis of the fertilizer demand model will draw exclusively on the double hurdle estimates.

approach described in Burke (2009). The standard errors and related *p*-values are bootstrapped using 200 repetitions. For robustness, a number of other specifications were estimated where the key dependent and independent variables were redefined (Table A.5 of the Appendix).[23] No major differences in statistical significance across these models were identified. We limit the discussion that follows to our main variables of interest and refer readers to the tables for details on control variables.

Model results reveal that the market price of nitrogen exhibits the expected negative sign only in the second hurdle, meaning an increase in the price of nitrogen reduces the amount applied to maize fields but not necessarily the likelihood of using commercial fertilizer on maize (Table A.4 of the Appendix). When translating into unconditional APE terms across the full sample, a one KSH/kg drop in retail nitrogen prices leads to a statistically significant increase of 0.16 kilograms of commercial fertilizer applied to maize fields (elasticity of -1.13 at sample average prices, see Table 7). We provide context to the magnitude of these values later in this section.

The distance to the nearest fertilizer dealer variable is not statistically significant in either hurdle (Table A.4 of the Appendix) or as an unconditional APE (Table 4). While the lack of significance may be surprising given the importance often given to market accessibility, these results are consistent with 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. Moreover, the lack of significance in these partial effects (both conditional and unconditional in their case) was also observed by Mather and Jayne (2011) who use the same base data set but a more broadly defined sample of households (not specific to maize fields) and without the inclusion of 2010. This provides further support that our somewhat strict definition of "maize field" is not affecting the results. Our results are somewhat at odds with Minten, Koru, and Stifel (2013) who show the importance of changing distance in the decision to use inputs in a particularly remote area of Ethiopia. In that setting, however, households face transport distances of well over 10 kilometers, as compared with a high-end average of about 6 kilometers in 1997 and 3

[23] These robustness checks include (1) a model with total commercial fertilizer application (not nutrient availability) as a dependent variable and an average of actual DAP and CAN prices used as the key independent price variable, (2) 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, and (3) a final model specification with the nitrogen to maize price ratio.

kilometers in 2010 in Kenya. We expect that the differences in our results arise from the vast dissimilarities in operating environment.[24]

Table 4. Unconditional average partial effects (APEs) of double hurdle nitrogen fertilizer demand model

	Dep. variable= N fert applied to maize fields (kg)		
	APE	se	sig
Time varying effects:			
N retail market price (KSH/kg)	-0.16	0.06	***
Distance to fert dealer (km)	0.07	0.18	
Expected maize price (KSH/kg)	0.96	0.58	*
Village wage rate (KSH/day)	-0.03	0.05	
Average no. crops on maize fields (1-7)	0.06	0.60	
Area under cultivation (hectares)	3.48	0.60	***
Tropical livestock units	0.38	0.25	
Household size (adult equivalents)	0.24	0.39	
Value of all hh assets (1000 KSH)	0.00	0.00	
Female headed household (1=yes)	7.74	7.82	
Age of hh head (years)	-0.03	0.17	
Expected rainfall (total mm)	-0.02	0.02	
Elevation (meters above sea level)	0.03	0.01	***
Population density of village	0.00	0.01	
Time averaged effects (CRE device):			
N retail market price (KSH/kg)	-0.43	0.16	***
Distance to fert dealer (km)	-0.68	0.37	*
Expected maize price (KSH/kg)	-4.52	1.05	***
Village wage rate (KSH/day)	-0.17	0.14	
Average no. crops on maize fields (1-7)	-1.46	1.53	
Area under cultivation (hectares)	1.30	0.75	*
Tropical livestock units	0.35	0.40	
Household size (adult equivalents)	0.35	0.59	
Value of all hh assets (1000 KSH)	-0.00	0.01	
Female headed household (1=yes)	-9.52	6.27	
Age of hh head (years)	-0.05	0.19	

Notes: *** p<0.01, ** p<0.05, * p<0.1. "se" denotes robust standard errors clustered at the household level. Standard errors were bootstrapped using 200 replications; unconditional APEs, bootstrapped standard errors, and p-values were calculated using the procedure outlined in Burke (2009). The household level "time averaged effects" represent the CRE device described in Section 5. All models were also estimated with dummy variables by province, soil group, and survey year. Raw regression results can be found in Table A.4 of the Appendix. The model includes 1,131 households with 4,629 observations across years (pooled and unbalanced panel). Total hectares under maize fields is omitted from this model given endogeneity (simultaneity) concerns. Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

These APE estimates do not mean, however, that distance does not matter to commercial fertilizer demand. When examining the household-average distance to the nearest fertilizer

[24] The Kenyan equivalent to the Ethiopian example could be the dropped Coastal areas, where the travel distances are far more substantial (Table A.2 of the Appendix), particularly in the earlier years. When adding the qualifying maize producers from this province back in to our sample, however, we still find no statistically significant effect on nitrogen use (Table A.7 of the Appendix).

dealer (as included in the CRE device), we find a negative and statistically significant relationship in the first hurdle, signaling that households further from fertilizer dealers are less likely to use fertilizer relative to their more accessible neighbors (Table A.4 of the Appendix), and also a negative and statistically significant unconditional APE value (Table 4). This cross-sectional result is unrelated to our goal of specifically identifying how the quantity of fertilizer demanded by a given household changed as its distance to the nearest fertilizer retailer dropped. Further, this discrepancy between time-averaged and contemporaneous distance effects illuminates the importance of controlling for the effects of unobserved household-level heterogeneity, which would have otherwise biased our time-varying estimates.

7.3. Maize supply model

In order to distinguish the two pathways through which maize production could change (intensification versus extensification), we first estimate the response as measured in total household maize production, then separately by maize yield (controlling for maize area) and hectares under maize. Table 5 includes the resulting APEs while Table 7 displays the elasticities calculated at the sample means.

As in the fertilizer demand model, it is the retail nitrogen price that contributes significantly to the maize supply response, not the local transport distance.25 We find that the total production effect (APE of -2.90 kg, elasticity of -0.33) is inclusive of both a productivity effect (APE of -1.89 kg, elasticity of -0.21) and an area planted to maize effect (APE of -0.002 hectares, elasticity of -0.35). The direction and significance of these effects holds when re-specifying the models with respect to a non-nutrient specific fertilizer price, although not across all three models when using fertilizer-to-maize price ratio (Table A.6 of the Appendix).

[25] Unlike the sample selection robustness checks on the fertilizer demand model, the statistical significance of these APEs vanish when including the dropped households from the Coast and with fewer than three years of maize production (Table A.8 in the Appendix). We interpret this to mean that maize production conditions are quite different on the Coast and, therefore, the inclusion of these households attenuates our estimates. Moreover, more than half of the 157 households with maize fields in only two years do not fall out of the overall survey sample after only two years, implying that maize production is not (long-run) important for these households. Our preferred sample and estimates are, therefore, exclusive of these very marginal maize producing households.

Table 5. Unconditional average partial effects (APEs) of maize supply models

	Total production response			Productivity/yield response			Acreage response		
	Dep. variable=Maize output (kg)			Dep. variable=Maize output (kg)			Dep. variable=Area under maize fields (ha)		
	APE	se	sig	APE	se	sig	APE	se	sig
Time varying effects:									
N retail market price (KSH/kg)	-2.90	1.14	**	-1.89	1.03	*	-0.002	0.001	***
Distance to fert dealer (km)	0.87	5.26		0.71	5.29		0.001	0.003	
Expected maize price (KSH/kg)	2.88	26.87		18.93	23.77		-0.019	0.012	
Village wage rate (KSH/day)	-0.18	1.37		-0.31	1.26		0.000	0.001	
Total area under maize fields (hectares)				519.63	145.23	***			
Average no. crops on maize fields (1-7)	-22.74	14.49		-25.58	13.76	*	0.005	0.006	
Area under cultivation (hectares)	615.24	54.12	***	407.80	74.59	***	0.399	0.033	***
Tropical livestock units	51.41	19.93	***	35.75	18.18	**	0.029	0.017	*
Household size (adult equivalents)	25.55	15.60		20.04	15.14		0.011	0.012	
Value of all hh assets (1000 KSH)	0.32	0.51		0.42	0.48		0.000	0.000	
Female headed household (1=yes)	-56.08	103.71		-89.30	96.19		0.071	0.044	
Age of hh head (years)	-4.02	4.45		-3.06	4.06		-0.001	0.002	
Expected rainfall (total mm)	1.47	0.63	**	1.55	0.52	***	0.000	0.000	
Elevation (meters above sea level)	1.57	0.24	***	1.34	0.19	***	0.000	0.000	
Population density of village	0.19	0.10	***	0.14	0.09		0.000	0.000	
Time averaged effects (CRE device):									
N retail market price (KSH/kg)	7.94	2.42	***	5.06	1.92	***	0.003	0.001	**
Distance to fert dealer (km)	-4.25	18.90		-7.11	17.05		0.002	0.020	
Expected maize price (KSH/kg)	-113.43	26.51	***	-105.29	21.89	***	-0.008	0.017	
Village wage rate (KSH/day)	-2.93	3.81		0.69	3.07		-0.004	0.002	*
Total area under maize fields (hectares)				453.54	113.44	***			
Average no. crops on maize fields (1-7)	-53.95	47.68		-54.64	38.10		-0.001	0.023	
Area under cultivation (hectares)	308.62	100.54	***	-32.65	81.76		0.164	0.089	*
Tropical livestock units	84.76	37.00	**	74.57	30.56	**	-0.003	0.031	
Household size (adult equivalents)	-27.68	29.98		-21.39	25.49		-0.012	0.021	
Value of all hh assets (1000 KSH)	0.11	0.80		-1.05	0.53	**	0.001	0.001	*
Female headed household (1=yes)	87.85	136.94		26.48	114.26		0.026	0.068	
Age of hh head (years)	-7.04	5.40		-5.87	4.77		-0.001	0.002	

Notes: *** p<0.01, ** p<0.05, * p<0.1. "se" denotes standard errors clustered at the household level. The household level "time averaged effects" represent the CRE device described in Section 5. All models were also estimated with dummy variables by province, soil group, and survey year. All models estimated with ordinary least squares (OLS) and household-level correlated random effects (CRE). All models include 1,131 households with 4,629 observations across years (pooled and unbalanced panel).
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

As a check on the size of these maize production APEs, we use a "chain rule" approach that combines the marginal effects estimates from our nitrogen demand model with those from a maize production function, the dual of the profit function, using the same base data set by Sheahan *et al.* (2013).[26] The two marginal effects can be multiplied together to produce an indirect estimate as follows:

(11) $$\frac{\partial x_1}{\partial m_1}\frac{\partial Y}{\partial x_1}=\frac{\partial Y}{\partial m}$$

The product of these two partial effects can be interpreted as how a one KSH/kg change in the retail market price of nitrogen leads to change in maize output via a change in nitrogen applied to maize fields.

On average across the sample, Sheahan *et al*. (2013) estimate a one kilogram per hectare increase in the amount of nitrogen applied to a maize field leads to a 17.5 kilogram per hectare response in maize production. While we recognize that there exists considerable heterogeneity in possible response rates across space and over time, we use this national average in order to better link with our nationwide estimate and produce a statistic relevant to national-level policy changes and outcomes. The outcome of the indirect "chain rule" method alongside our directly estimated maize supply response effects can be found in Table 6 for comparison. The indirect approach yields a value of -2.78, as compared to our directly estimated total maize production estimate of -2.90 and maize yield estimate of -1.89.

Table 6. Comparison of direct and indirect methods of computing change in maize production/yield on account of changing nitrogen prices

Change in nitrogen use (kg) resulting from an increase in real nitrogen price (KSH/kg)[a]				Response of maize (kg/ha) to nitrogen application (kg/ha)[b]		Change in maize yield (kg/ha) from a 1KSH/kg decline in retail nitrogen price	
						Chain rule method[c]	Maize supply function estimation method[d]
APE	se	sig.	elasticity	MP	se		
-0.16	0.06	***	-1.33	17.5	2.43	+2.78	Range: +1.89 to 2.90

Notes: *** p<0.01, ** p<0.05, * p<0.1. [a]Estimates correspond with the regression results from the Cragg's double hurdle model specification of the nitrogen demand model in Table 4. "se" denotes bootstrapped standard errors using 200 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 in Sheahan *et al*. (2013). [c]See equation (11) in the main text for details. [d]These values represents the average products from the total maize production and maize production/yield response models found in Table 5. Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

[26] See Sheahan *et al.* (2013) for a full explanation of the production function and marginal product estimation.

7.5. Fertilizer and maize outcomes from decreasing marketing margins

The partial effects on the nitrogen prices from both models can be combined with actual changes in nitrogen prices to explore how the observed decline in farmer-experienced retail prices, namely the domestic marketing margin portion, have directly contributed to changes in fertilizer use and maize output. Table A.1 in the Appendix summarizes the real average retail nitrogen prices (in 2010 levels) at the province level by survey year. Using the two end point survey years (1997 and 2010), we calculate a 210 KSH drop in real nitrogen prices across the thirteen years under study, equivalent to a 45 percent reduction in real price of nitrogen, a decline consistent with the GoK reported trends in up-country wholesale prices shown in Figure 2. We estimate that 60 percent of the variation in DAP prices can be attributed to domestic marketing margins. For this reason, we consider about 60 percent of the overall 45 percent reduction in prices to have emanated from the reforms, equivalent to about 27 percent.

Table 7. Estimated household-level outcomes resulting from change in real nitrogen prices between 1997-2010

Outcome		Maize supply function estimates[a]			Estimated increases in outcome on account of observed changes in nitrogen prices from domestic marketing margins portion (%)[b]	Observed total increases in outcome at national-level not specific to input reform pathways (%)
		APE	elasticity	sig		
Fertilizer	Total nitrogen use on maize (kg)	-0.16	-1.33	***	35.9	97.4[c]
Maize	Total production response (kg)	-2.90	-0.33	**	8.9	58.2[d]
	Productivity/yield response (kg)	-1.89	-0.21	*	5.7	17.6[d]
	Maize acreage response (ha)	-0.002	-0.35	***	9.5	49.3[d]

Notes: *** p<0.01, ** p<0.05, * p<0.1. [a]These estimates come from the models shown in Tables 4 and 5. [b]This column includes the product of the predicted elasticities and the portion of the observed change in real prices attributed to the reforms between 1997 and 2010 (see text for details). [c]This value represents the total change in national fertilizer use, not specific to maize, using data from the Ministry of Agriculture, Livestock, and Fisheries in Kenya as shown in Figure 1a. [d]These values include the actual/total percent increases in maize supply outcomes between the highest and lowest values observed in any of the survey years between 1997 and 2010 using official data from The Kenya Agricultural Sector Data Compendium (KIPPRA) as shown in Table A.1 of the Appendix.
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis and other official data sources described in the table notes.

Table 7 displays the products of this observed percent decrease in nitrogen prices specific to decreases in domestic marketing margins over time and the elasticity estimates from the model, the *ex post* impacts of the reforms. Between 1997 and 2010, the observed fall in real nitrogen prices largely on account of the reforms led to a 36 percent increase in nitrogen use on maize fields, a 9 percent increase in total maize production, a 6 percent increase in maize yields, and a 10 percent increase in area under maize. Using the highest and lowest values from the survey years between 1997 and 2010, total national fertilizer use (not specific to maize) nearly doubled, the total area under maize increased by 49 percent, total yield by 18 percent, and total maize production by 58 percent. Our estimates, therefore, show the substantial contribution of falling fertilizer marketing margins indicative of the input reform period to fertilizer demand and maize production outcomes, but also leave considerable room for other effects to have also been instrumental.

8. Conclusions

The importance of raising staple crop productivity and modern agricultural input use in Sub-Saharan Africa warrants efforts to identify and potentially replicate those strategies that have been successful in the region. Large-scale input subsidy programs have proven themselves effective in raising national fertilizer use, but many African governments are finding them increasingly difficult to sustain due to fiscal constraints, difficulties in implementation, and questionable effects on the development of commercial distribution systems. In light of these challenges, policy makers are searching for alternative policy tools for promoting fertilizer use. Motivated by descriptive evidence showing a substantial increase in inorganic fertilizer use by smallholder farmers in Kenya subsequent to several input market reforms, which targeted the root causes of high prevailing prices instead, we provide quantitative evidence linking the reform policies with smallholder fertilizer use and maize supply outcomes.

Using five waves of nationwide household panel data for the years directly following the reforms in Kenya, we first establish the relationship between the policy changes (e.g., elimination of price and other government controls) and changes in retail fertilizer prices and accessibility. We then estimate models of nitrogen demand and maize supply while controlling for unobserved household heterogeneity. Our results show that decreases in the portion of real nitrogen prices that can be attributed to the reforms (internal port-to-retail marketing margins) were significant in contributing to increases in fertilizer demand by smallholder farmers. These decreasing fertilizer prices also resulted in increased maize production, higher yields, and greater area under maize. On the other hand, decreasing distances to fertilizer retailers from the perspective of a given farming household did not appear to raise fertilizer use or maize supply, although relatively less accessible households (on average, across time) do apply less fertilizer to their maize.

More specifically, we find that 60 percent of the variation in retail fertilizer prices can be ascribed to changes in domestic marketing margins between import and fertilizer consumption points in farming communities. Combined with actual decreases in observed prices of nitrogen nutrient in fertilizer and elasticity estimates from our models, we estimate that reductions in internal marketing margins associated with input market reforms resulted in a 36 percent increase in nitrogen use on maize fields and a 9 percent increase in maize production resulting from both maize yield and area under maize effects. Our estimates can be credibly pegged to the input reforms, although uncontrolled effects may have also plausibly contributed to decreases in the marketing margins under study.

We also find discrepancies in the relative magnitudes of fertilizer and maize yield response values. While nitrogen use on maize has increased significantly in Kenya, maize yield levels have not risen proportionately. This finding points to the continued challenge of increasing fertilizer (and other input) use in a sustainable, efficient, and productive manner, a theme echoed throughout the literature on fertilizer response rates in SSA (e.g., Sheahan *et al.* 2013; Snapp *et al.* 2014; Liverpool-Tasie *et al.* 2015). Simply raising fertilizer use, through whatever policy levers, is not necessarily enough to achieve staple food crop productivity goals, particularly when soils are poor and complementary inputs are lacking.

Kenya represents a case of how major reforms to agricultural input markets, resulting in substantial new entry by the private sector, have promoted the achievement of important national policy objectives at little or no fiscal cost to the government. This policy approach to increasing fertilizer use contrasts sharply with other tactics—namely input subsidy program—that have been adopted recently by many African countries, including Kenya in more recent years. We believe that other African countries have comparable potential to significantly raise fertilizer use and agricultural output in their countries by providing similar incentives to private firms through improving the enabling environment in which they operate.

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Appendix

Table A.1 Summary statistics using survey and government data, by province and year

Province	Statistic	1997	2000	2004	2007	2010
Eastern	Area under maize (in 1,000 ha)	395	504	504	436	455
	Production (in 1,000 tons)	244	213	213	419	339
	Average yield (tons/ha)	0.6	0.4	0.4	1.0	0.7
	% of households applying N to maize fields	46.3	51.9	68.7	64.4	58.0
	Mean N application rate (kg/ha)	21.4	29.7	20.1	23.6	25.1
	Mean N price (KSH/kg)	424	363	306	297	282
	Mean distance to fertilizer dealer (km)	8.4	3.5	2.2	2.4	2.5
Nyanza	Area under maize (in 1,000 ha)	159	205	245	83	327
	Production (in 1,000 tons)	369	465	740	150	455
	Average yield (tons/ha)	2.3	2.3	3.0	1.8	1.4
	% of households applying N to maize fields	37.5	43.9	41.2	44.6	43.2
	Mean N application rate (kg/ha)	18.0	18.4	25.0	25.9	40.4
	Mean N price (KSH/kg)	631	409	327	327	268
	Mean distance to fertilizer dealer (km)	9.7	7.9	5.0	3.0	3.5
Western	Area under maize (in 1,000 ha)	116	181	182	202	233
	Production (in 1,000 tons)	274	465	465	581	463
	Average yield (tons/ha)	2.4	2.6	2.6	2.9	2.0
	% of households applying N to maize fields	50.0	75.7	78.2	86.4	86.0
	Mean N application rate (kg/ha)	32.3	38.6	42.1	45.3	46.6
	Mean N price (KSH/kg)	450	351	302	267	264
	Mean distance to fertilizer dealer (km)	4.9	3.8	2.6	3.5	3.9
Central	Area under maize (in 1,000 ha)	132	131	109	139	176
	Production (in 1,000 tons)	126	83	68	164	126
	Average yield (tons/ha)	1.0	0.6	0.6	1.2	0.7
	% of households applying N to maize fields	88.2	86.2	85.2	92.0	79.0
	Mean N application rate (kg/ha)	40.4	33.2	38.3	35.2	34.7
	Mean N price (KSH/kg)	417	357	301	275	302
	Mean distance to fertilizer dealer (km)	3.5	1.4	1.5	1.5	1.4
Rift Valley	Area under maize (in 1,000 ha)	448	486	569	664	675
	Production (in 1,000 tons)	1,064	979	1,253	1,800	1,903
	Average yield (tons/ha)	2.4	2.0	2.2	2.7	2.8
	% of households applying N to maize fields	76.1	85.4	82.4	84.9	73.3
	Mean N application rate (kg/ha)	29.2	32.3	39.3	39.0	37.5
	Mean N price (KSH/kg)	494	374	301	277	249
	Mean distance to fertilizer dealer (km)	5.8	4.1	3.3	3.8	5.4
National/ Sample average	*Area under maize (in 1,000 ha)*	1,250	1,507	1,609	1,524	1,866
	Production (in 1,000 tons)	2,077	2,205	2,738	3,115	3,286
	Average yield (tons/ha)	1.7	1.5	1.7	2.0	1.8
	% of households applying N to maize fields	*58.5*	*68.5*	*70.6*	*73.8*	*67.9*
	Mean N application rate (kg/ha)	*29.8*	*31.9*	*35.0*	*36.9*	*38.9*
	Mean N price (KSH/kg)	*486*	*372*	*308*	*288*	*267*
	Mean distance to fertilizer dealer (km)	*6.7*	*4.5*	*3.2*	*3.1*	*3.8*

Notes: See main 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 United Nations between June 2009 and June 2010 was 76KSH/1USD. All prices and values are converted to real 2010 levels for this table.
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 by the authors from the Tegemeo Rural Household Survey using the sample selected for this analysis.

Table A.2. Means testing across included and excluded households in our sample

	Household average values across all survey years with viable maize fields				
	Households in analysis sample n=1,131	Households dropped for geography reasonsa n=83	Stat. sig. diff	Households dropped for econometric reasonsb n=254	Stat. sig. diff
Total hectares under maize fields	0.77	0.93		0.48	***
Total maize production (kg)	1499.20	756.67	***	702.95	***
Maize yield (kg/ha)	2114.21	958.20	***	1686.51	***
Portion use nitrogen fertilizer (0-1)	0.68	0.08	***	0.58	***
Total nitrogen applied (kg)	19.38	0.30	***	8.70	***
Nitrogen application rate (kg/ha)	23.12	0.49	***	18.03	***
N retail market price (KSH/kg)	337.54	272.05	***	389.85	***
Distance to fert dealer (km)	4.06	16.06	***	5.02	***
Village wage rate (KSH/day)	140.15	220.37	***	148.89	***
Average no. crops on maize fields (1-7)	2.99	3.56	***	2.91	
Area under cultivation (hectares)	1.48	1.48		1.11	***
Tropical livestock units	3.18	2.45	*	2.46	***
Household size (adult equivalents)	5.23	7.54	***	4.66	***
Value of all hh assets (1000 KSH)	191.94	121.88	**	170.93	
Female headed household (1=yes)	0.20	0.17		0.19	
Age of hh head (years)	55.87	55.70		54.76	
Expected rainfall (total mm)	580.07	263.73	***	507.61	***
Elevation (meters above sea level)	1709.87	286.05	***	1699.37	
Population density of village	559.94	411.49	***	562.89	

Notes: *** p<0.01, ** p<0.05, * p<0.1. The statistical significant refers to difference in means between the dropped households and the households included in the analysis. See Section 5 and Table 1of main text for more detail on sample selection. The included values represent household means of the variables pooled across all survey years since not all households necessarily were maize producers in the first survey round (year=1997). All monetary values are expressed in real 2010 KSH. The fact that we find significant differences across these variables suggests that our main results are most attributable to farming households for which maize is not a marginal crop. aThese households were dropped from the sample because they are located in the Coastal province. 57 of the 83 households had maize fields in at least two survey rounds. bThese households from the remaining provinces were dropped because they had maize fields in two or fewer survey rounds. 157 of the 254 households were maize producers in two survey rounds.

Table A.3. Unconditional average partial effects (APEs) of OLS and Tobit specifications of nitrogen demand model

	OLS-CRE Dep. variable= N fert applied to maize fields (kg)			Tobit Dep. variable= N fert applied to maize fields (kg)		
	APE	se	sig	APE	se	sig
Time varying effects:						
N retail market price (KSH/kg)	-0.13	0.02	***	-0.02	0.01	
Distance to fert dealer (km)	0.19	0.09	**	0.01	0.08	
Expected maize price (KSH/kg)	-1.18	0.54	**	0.38	0.26	
Village wage rate (KSH/day)	-0.01	0.03		-0.01	0.01	
Average no. crops on maize fields (1-7)	0.14	0.36		0.28	0.18	
Area under cultivation (hectares)	9.38	1.31	***	4.16	0.54	***
Tropical livestock units	1.13	0.40	***	0.62	0.19	***
Household size (adult equivalents)	0.16	0.35		0.11	0.17	
Value of all hh assets (1000 KSH)	0.01	0.01		0.00	0.00	
Female headed household (1=yes)	3.75	2.63		1.29	1.59	
Age of hh head (years)	-0.05	0.08		-0.05	0.04	
Expected rainfall (total mm)	0.06	0.01	***	0.04	0.01	***
Elevation (meters above sea level)	0.04	0.01	***	0.03	0.00	***
Population density of village	0.00	0.00	**	0.01	0.00	***
Time averaged effects:						
N retail market price (KSH/kg)	0.24	0.06	***	-0.02	0.04	
Distance to fert dealer (km)	-0.71	0.45		-0.99	0.30	***
Expected maize price (KSH/kg)	-2.39	0.62	***	-2.94	0.63	***
Village wage rate (KSH/day)	-0.16	0.09	*	-0.16	0.05	***
Average no. crops on maize fields (1-7)	-1.51	1.04		-0.66	0.54	
Area under cultivation (hectares)	9.36	2.46	***	4.00	0.96	***
Tropical livestock units	-0.52	0.87		-0.19	0.42	
Household size (adult equivalents)	-0.60	0.65		-0.28	0.32	
Value of all hh assets (1000 KSH)	0.03	0.02		0.01	0.01	
Female headed household (1=yes)	-2.88	3.26		-2.57	1.95	
Age of hh head (years)	-0.03	0.11		0.02	0.06	

Notes: *** p<0.01, ** p<0.05, * p<0.1. "se" denotes robust standard errors clustered at the household level. The household level "time averaged effects" represent the CRE device described in Section 5. All models were also estimated with dummy variables by province, soil group, and survey year. These models includes 1,131 household with 4,629 observations across years (pooled and unbalanced panel). Total hectares under maize fields is omitted from this model given endogeneity (simultaneity) concerns.
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

Table A.4. Nitrogen fertilizer demand double hurdle model raw regression results

	Hurdle 1	Hurdle 2
	Dep var=Nitrogen only (kg)	
N retail market price (KSH/kg)	0.00160	-2.218***
	(0.00150)	(0.570)
Distance to fertilizer dealer (km)	-0.000674	0.983
	(0.00632)	(1.261)
Expected maize price (KSH/kg)	-0.00142	13.04**
	(0.0205)	(5.971)
Village wage rate (KSH/day)	-0.00294**	-0.192
	(0.00130)	(0.480)
Average no. crops on maize fields (1-7)	0.0448***	-2.205
	(0.0158)	(5.132)
Area under cultivation (hectares)	0.0643**	43.12***
	(0.0293)	(5.334)
Tropical livestock units	0.0220**	3.845*
	(0.0109)	(2.011)
Household size (adult equivalents)	-0.000398	3.188
	(0.0145)	(2.955)
Value of all hh assets (1000 KSH)	0.000157	0.0207
	(0.000234)	(0.0312)
Female headed household (1=yes)	-0.280**	114.4**
	(0.140)	(57.84)
Age of hh head (years)	-0.00837**	0.300
	(0.00400)	(1.160)
Expected rainfall (total mm)	0.00265***	-0.434*
	(0.000502)	(0.246)
Elevation (meters above sea level)	0.00193***	0.305***
	(0.000207)	(0.0759)
Population density of village	0.000407***	-0.0115
	(9.90e-05)	(0.0835)
Household-level averages (CRE device)		
N retail market price (KSH/kg)	0.000464	-5.797***
	(0.00337)	(1.880)
Distance to fertilizer dealer (km)	-0.0787***	-4.530
	(0.0179)	(3.418)
Expected maize price (KSH/kg)	-0.138***	-52.60***
	(0.0361)	(12.64)
Village wage rate (KSH/day)	-0.00613	-1.865
	(0.00384)	(1.357)
Average no. crops on maize fields (1-7)	-0.0356	-16.99
	(0.0498)	(15.99)
Area under cultivation (hectares)	0.197***	5.673
	(0.0536)	(7.276)
Tropical livestock units	-0.0819***	9.575***
	(0.0195)	(3.453)
Household size (adult equivalents)	-0.00490	4.865
	(0.0259)	(5.290)
Value of all hh assets (1000 KSH)	5.78e-05	-0.0627
	(0.000353)	(0.0662)
Female headed household (1=yes)	0.0916	-144.7**
	(0.170)	(72.58)
Age of hh head (years)	0.00679	-1.368
	(0.00489)	(1.319)
Soil group dummy variables	Yes	Yes
Province dummy variables	Yes	Yes
Survey year dummy variables	Yes	Yes
Number of households	1,131	913
Number of observations	4,629	3,163

Notes: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at the household level displayed in parentheses. See Table 4 in main text for marginal effects estimates and all other relevant notes.
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

Table A.5. Nitrogen demand model (double hurdle only) robustness checks (fertilizer price and amount definitions)

	(1)		(2)		(3)	
	Hurdle 1	Hurdle 2	Hurdle 1	Hurdle 2	Hurdle 1	Hurdle 2
	Dep var=Total fertilizer(kg)		*Dep var=Nitrogen only (kg)*		*Dep var=Nitrogen only (kg)*	
Average DAN and CAN retail market price (KSH/kg)	0.00679	-40.98***	0.00672	-11.77***		
	(0.00799)	(8.680)	(0.00797)	(3.160)		
Distance to fertilizer dealer (km)	0.00169	2.190	-0.000881	1.051	-0.00112	1.786
	(0.00604)	(4.228)	(0.00633)	(1.275)	(0.00619)	(1.330)
Expected maize price (KSH/kg)	0.0100	38.65**	-0.000184	12.12*		
	(0.0211)	(16.88)	(0.0207)	(6.333)		
Nitrogen-to-maize price ratio					0.0123	-19.64***
					(0.0106)	(4.187)
Village wage rate (KSH/day)	-0.00295**	-0.578	-0.00284**	-0.228	-0.00307**	-0.414
	(0.00131)	(1.301)	(0.00130)	(0.496)	(0.00132)	(0.475)
Average no. crops on maize fields (1-7)	0.0464***	-24.79	0.0451***	-2.518	0.0455***	-4.335
	(0.0159)	(15.34)	(0.0157)	(5.344)	(0.0157)	(5.469)
Area under cultivation (hectares)	0.0570**	147.3***	0.0640**	43.95***	0.0623**	44.17***
	(0.0286)	(15.65)	(0.0293)	(5.498)	(0.0293)	(5.648)
Tropical livestock units	0.0205*	15.04**	0.0219**	3.720*	0.0232**	3.514*
	(0.0110)	(7.308)	(0.0110)	(2.043)	(0.0109)	(1.953)
Household size (adult equivalents)	-0.00232	11.50	-0.000429	3.414	0.000293	3.342
	(0.0146)	(8.908)	(0.0145)	(3.039)	(0.0144)	(2.941)
Value of all hh assets (1000 KSH)	2.14e-05	0.117	0.000158	0.0173	0.000142	0.00830
	(0.000240)	(0.108)	(0.000234)	(0.0314)	(0.000232)	(0.0279)
Female headed household (1=yes)	-0.274**	250.2*	-0.278**	115.9**	-0.274**	117.9**
	(0.139)	(129.3)	(0.139)	(58.53)	(0.140)	(57.27)
Age of hh head (years)	-0.00879**	1.989	-0.00837**	0.234	-0.00831**	0.246
	(0.00400)	(3.976)	(0.00399)	(1.205)	(0.00400)	(1.296)
Expected rainfall (total mm)	0.00267***	-0.665	0.00268***	-0.270	0.00284***	0.0454
	(0.000497)	(0.592)	(0.000500)	(0.223)	(0.000505)	(0.175)
Elevation (meters above sea level)	0.00189***	1.185***	0.00190***	0.373***	0.00206***	0.403***
	(0.000202)	(0.227)	(0.000204)	(0.0805)	(0.000205)	(0.0708)
Population density of village	0.000420***	0.0378	0.000409***	-0.0171	0.000312***	-0.341***
	(9.73e-05)	(0.243)	(9.78e-05)	(0.0924)	(8.79e-05)	(0.115)
Soil group dummy variables	Yes	Yes	Yes	Yes	Yes	Yes
Province dummy variables	Yes	Yes	Yes	Yes	Yes	Yes
Survey year dummy variables	Yes	Yes	Yes	Yes	Yes	Yes
Hh correlated random effects	Yes	Yes	Yes	Yes	Yes	Yes
Number of households	1,131	913	1,131	913	1,131	913
Number of observations	4,629	3,163	4,629	3,163	4,629	3,163

Notes: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at the household level displayed in parentheses. See Table 4 in the main text for all other relevant notes.
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

Table A.6. Maize supply model robustness checks (fertilizer price and quantity definitions)

	Total production response		Productivity/yield response		Acreage response	
	Dep variable=Maize output (kg)		*Dep variable=Maize output (kg)*		*Dep variable=Area under maize fields (ha)*	
	(1)	(2)	(3)	(4)	(5)	(6)
Average DAN and CAN retail market price (KSH/kg)	-16.10***		-12.21**		-0.00580*	
	(6.069)		(5.473)		(0.00307)	
Distance to fertilizer dealer (km)	1.492	1.861	1.125	1.110	0.000889	0.00134
	(5.239)	(5.113)	(5.287)	(5.141)	(0.00290)	(0.00284)
Expected maize price (KSH/kg)	19.40		31.36		-0.0154	
	(26.15)		(23.29)		(0.0122)	
Nitrogen-to-maize price ratio		1.384		3.862		-0.00739*
		(10.04)		(9.102)		(0.00431)
Village wage rate (KSH/day)	-0.0147	-0.413	-0.152	-0.00529	0.000378	-0.000196
	(1.338)	(1.421)	(1.229)	(1.263)	(0.000646)	(0.000688)
Total area under maize (hectares)			520.3***	521.0***		
			(145.3)	(145.4)		
Average no. crops on maize fields (1-7)	-22.45	-26.97*	-24.98*	-27.49**	0.00413	0.00176
	(14.51)	(14.40)	(13.77)	(13.62)	(0.00593)	(0.00627)
Area under cultivation (hectares)	615.2***	615.1***	407.4***	405.5***	0.399***	0.402***
	(54.10)	(54.02)	(74.59)	(74.64)	(0.0330)	(0.0330)
Tropical livestock units	50.94**	51.07**	35.36*	35.77**	0.0294*	0.0288*
	(19.81)	(19.96)	(18.09)	(18.18)	(0.0165)	(0.0167)
Household size (adult equivalents)	25.48	26.85*	19.89	19.98	0.0108	0.0122
	(15.61)	(15.67)	(15.14)	(15.15)	(0.0122)	(0.0122)
Value of all hh assets (1000 KSH)	0.334	0.342	0.429	0.443	-0.000172	-0.000178
	(0.511)	(0.511)	(0.474)	(0.475)	(0.000372)	(0.000378)
Female headed household (1=yes)	-49.87	-57.91	-84.20	-77.84	0.0714	0.0550
	(103.4)	(103.5)	(95.95)	(95.80)	(0.0444)	(0.0438)
Age of hh head (years)	-3.449	-3.974	-2.623	-1.940	-0.00136	-0.00285
	(4.443)	(4.432)	(4.048)	(3.981)	(0.00187)	(0.00191)
Expected rainfall (total mm)	1.355**	1.525**	1.469***	1.532***	-0.000125	2.35e-06
	(0.616)	(0.640)	(0.509)	(0.527)	(0.000401)	(0.000425)
Elevation (meters above sea level)	1.590***	1.643***	1.360***	1.425***	0.000236	0.000221*
	(0.238)	(0.234)	(0.188)	(0.188)	(0.000149)	(0.000134)
Population density of village	0.186*	0.148*	0.140	0.105	5.01e-05	4.34e-05
	(0.0954)	(0.0820)	(0.0859)	(0.0741)	(5.77e-05)	(4.44e-05)
Soil group dummy variables	Yes	Yes	Yes	Yes	Yes	Yes
Province dummy variables	Yes	Yes	Yes	Yes	Yes	Yes
Survey year dummy variables	Yes	Yes	Yes	Yes	Yes	Yes
Hh correlated random effects	Yes	Yes	Yes	Yes	Yes	Yes
Number of households	1,131	1,131	1,131	1,131	1,131	1,131
Number of observations	4,629	4,629	4,629	4,629	4,629	4,629

Notes: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at the household level displayed in parentheses. See Table 5 in the main text for all other relevant notes.
Source: Authors' calculations from the Tegemeo Rural Household Survey using the sample selected for this analysis.

Table A.7. Nitrogen demand model robustness checks (sample selection)

	Dep. variable=Nitrogen fertilizer applied to maize fields (kg)								
	OLS-CRE			Tobit-CRE			Double hurdle-CRE		
	APE	se	sig	APE	se	sig	APE	se	sig
Add Coastal households (new=67 hh, total=1,198 hh)									
N retail market price (KSH/kg)	-0.03	0.01	***	-0.01	0.01	*	-0.07	0.03	
Distance to fert dealer (km)	0.09	0.07		-0.03	0.07		0.04	0.19	
Add households with only two years in panel (new=157 hh, total 1,288 hh)									
N retail market price (KSH/kg)	-0.03	0.01	***	-0.01	0.01	***	-0.08	0.03	***
Distance to fert dealer (km)	0.23	0.08	***	0.02	0.07		0.05	0.18	
Add households with only two years in panel, including Coastal households (new=234 hh, total=1,365 hh)									
N retail market price (KSH/kg)	-0.03	0.01	***	-0.01	0.01	***	-0.08	0.02	***
Distance to fert dealer (km)	0.10	0.07		-0.02	0.07		0.04	0.16	

Notes: *** p<0.01, ** p<0.05, * p<0.1. See Table 4 in main text for all notes about control variables and estimation and for comparison with estimates. Bootstrapping standard errors for the model with only Coastal households added was dropped to 75 replications for convergence reasons. See Table A.2 of the Appendix for relevant summary statistics for added households. See Table 1 and Section 4 in main text for sample distribution considerations.

Table A.8. Maize supply model robustness checks (sample selection)

	Total production response			Productivity/yield response			Acreage response		
	Dep. variable=Maize output (kg)			Dep. variable=Maize output (kg)			Dep. variable=Area under maize fields (ha)		
	APE	se	sig	APE	se	sig	APE	se	sig
Add Coastal households (new=67 hh, total=1,198 hh)									
N retail market price (KSH/kg)	-0.60	0.51		-0.56	0.46		0.000	0.000	
Distance to fert dealer (km)	0.62	4.98		-0.79	4.39		0.003	0.003	
Add households with only two years in panel (new=157 hh, total 1,288 hh)									
N retail market price (KSH/kg)	-0.10	0.49		-0.132	0.44		0.000	0.000	
Distance to fert dealer (km)	1.05	4.83		0.382	4.84		0.001	0.003	
Add households with only two years in panel, including Coastal households (new=234 hh, total=1,365 hh)									
N retail market price (KSH/kg)	-0.77	0.48		-0.757	0.43	*	0.000	0.000	
Distance to fert dealer (km)	2.72	5.07		1.024	4.41		0.003	0.003	

Notes: *** p<0.01, ** p<0.05, * p<0.1. See Table 5 in main text for all notes about control variables and estimation and for comparison with estimates. See Table A.2 of the Appendix for relevant summary statistics for added households. See Table 1 and Section 4 in main text for sample distribution considerations.