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What is the Scope for Increased Fertilizer Use in Kenya?

by

Megan Sheahan, Roy Black, and T.S. Jayne

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Any views expressed or remaining errors are solely the responsibility of the authors.

EXECUTIVE SUMMARY

Despite upward trends in fertilizer application rates on maize fields over the last twenty years, there remains a perception in Kenya that fertilizer use is not expanding quickly enough and that application rates are not high enough to reverse the country's growing national food deficit. In 2007, this manifested in the creation of a comprehensive multi-million dollar fertilizer and improved seed subsidy and training program, the National Accelerated Agricultural Inputs Access Program (NAAIAP), with the objective of raising food production and farm productivity. However, little nationwide and longer term evidence exists to determine whether higher fertilizer application rates are profitable for farmers and whether they would have an incentive to continue using it on commercial terms after graduating from the subsidy program.

Using five waves of nationally representative household survey data covering thirteen years, this paper estimates the profitability of fertilizer application on maize fields and compares with observed fertilizer use patterns over time. Marginal and average products of nitrogen are estimated from a production function and disaggregated by district and soil type in order to approximate local level agro-ecological conditions. In an environment where the real prices of both fertilizer and maize have decreased since the late 1990s, relative input to output prices have stayed fairly constant over the survey years, apart from a spike in fertilizer prices in 2007. Transportation costs of fertilizer, on the other hand, have decreased 35% over the survey years given the proliferation of fertilizer retailers in rural areas, leading to a decrease in the overall acquisition price of fertilizer.

By estimating economically optimal nitrogen application rates under both risk neutral and risk averse scenarios and comparing with actual observed application rates, we find households across Kenya have consistently and steadily adjusted their fertilizer use towards optimal application rates over time. Over the entire sample, only about 16% of maize fields in 2010 were fertilized at levels less than 25% below our risk averse optimal values. This trend is most pronounced in the Eastern and Western Lowlands areas where we find an appreciable increase in the percentage of fertilized fields over time as well as an increase in the rate of commercial nitrogen applied per hectare by fertilizer users, with a particularly large jump in 2010. Still, however, we estimate room for profitable expansion in these areas. In the High Potential Maize and Western Transitional Zones, households see a gain in household income from using fertilizer, however the last unit is generally at break-even profitable levels, or not profitable at all, meaning households are applying fertilizer at optimal or slightly more than optimal levels. Expanding fertilizer use in these areas is not a profitable strategy unless coupled with complementary inputs and soil management practices.

Because relative prices do not show much variation over time, we also calculate two absolute measures of fertilizer profitability, (1) the total revenue added from fertilizer application and (2) the gain to fertilizer use at the margin. Results show that, despite an increase in fertilizer application rates over time in some areas and the leveling off in others, the estimated total revenue added from fertilizer application and the net gain to the last unit of fertilizer have both eroded over time. With evidence from both relative and absolute profitability measures, we find that tremendous additional expansion of fertilizer application rates on maize in Kenya should not necessarily be sought after unless it is possible to raise the average physical response rates of maize to fertilizer.

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ACRONYMS

AP	average (physical) product
AVCR	average value cost ratio
CAN	calcium ammonium nitrate
cif	cost, insurance, and freight
CPC	Climate Prediction Center
CPI	consumer price index
CRE	correlated random effects
DAP	diammonium phosphate
FAO	Food and Agriculture Organization of the United Nations
FEWS	Famine Early Warning System
GISAMA	Guiding Investments in Sustainable Agricultural Markets in Africa Project
GoK	Government of Kenya
GPS	Global Positioning System
IFPRI	International Food Policy Research Institute
KSH	Kenyan shilling
MP	marginal (physical) product
MSU	Michigan State University
MVCR	marginal value cost ratio
NAAIAP	National Accelerated Agricultural Inputs Access Program
NCPB	Kenya's National Cereal Produce Board
NGO	non-governmental organization
OLS	ordinary least squares
SSA	Sub-Saharan Africa
USAID	United States Agency for International Development
VCR	value cost ratio

1. MOTIVATION

In the past several years, the promotion of fertilizer has become a pervasive theme across Sub-Saharan Africa (SSA), particularly following the first African Fertilizer Summit in Abuja, Nigeria in mid-2006. A resurgence of interest in fertilizer as a yield-enhancing input has led to the revival of large-scale fertilizer subsidy programs in a growing number of countries, including Malawi, Nigeria, Zambia, Tanzania, and Ghana, and a refocusing on agricultural input intensification by international donors. Increased fertilizer use has been singled out as the main avenue for raising the yields and incomes of smallholder farmers, improving national food security, and capturing the benefits of green revolutions that have been achieved in other parts of the world. However, we are increasingly concerned that the absence of a more holistic strategy involving the adoption of complementary inputs and management strategies on farmers' fields and that the promotion of higher fertilizer application rates in isolation may be not cost-effective, profitable for farmers, or sustainable. Therefore, analyses of incentives and returns to using fertilizer incorporating evidence from farmers' fields can potentially provide useful guidance for developing practical and effective input intensification policies.

Kenya's fertilizer market reform program contributed to a dramatic increase in fertilizer use on smallholder farms starting in the mid-1990s and a substantial decline in the farm-gate price of fertilizer, all of which was achieved largely without government subsidies (Ariga, Jayne, and Nyoro 2006). The number of fertilizer wholesalers and retailers operating in rural Kenya expanded rapidly starting in the 1990s, resulting in a major decline in the distance that farmers had to travel to access fertilizer (Ariga and Jayne 2009). National fertilizer consumption doubled between 1990/91 and 2007/08 (Ministry of Agriculture 2008) with the growth driven by commercial demand from smallholder farmers (Ariga, Jayne, and Nyoro 2006; Ariga et al. 2008; Ariga and Jayne 2009). Despite upward trends in fertilizer application rates on maize fields over the last twenty years, the Government of Kenya (GoK) had, by the mid-2000s, become increasingly concerned that fertilizer use was not expanding quickly enough and that application rates were not high enough to reverse the country's growing national food deficit. In response to its food self-sufficiency concerns and reports on the apparent success of Malawi's input subsidy program (e.g., Dugger 2007), the GoK in 2007 initiated a comprehensive multi-million dollar fertilizer and improved seed subsidy and training program, the National Accelerated Agricultural Inputs Access Program (NAAIAP), with the objective of raising food production and farm productivity.

Important research questions flow from this line of inquiry. Principally, it is critical to understand whether higher fertilizer application rates are profitable for farmers and whether they would have an incentive to continue using it on commercial terms after graduating from the subsidy program. If it were possible to compute optimal fertilizer use rates on farmers' maize fields, we could then understand the degree to which actual use rates are sub-optimal and the extent to which the NAAIAP could contribute to farm productivity by closing this gap between observed and optimal application rates. This line of inquiry can help the GoK identify complementary investments and programs to raise the efficiency of farmers' use of fertilizer and hence achieve greater food production and farm productivity from the same or even less public expenditure on the NAAIAP.

The yield response from applied plant nutrients, both inorganic and organic, in Kenya has been investigated by several researchers; however, there are no studies to our knowledge that systematically study inorganic fertilizer application rates on farmers' fields across more than a decade throughout all maize growing regions in order to assess fertilizer profitability and use across time and space. Hassan, Murithi, and Kamau (1998) utilized several years of data from experiment stations, an excellent starting point but limited by the gap that frequently exists between experimental plots and farmer applications. Increasingly, agronomic investigators are studying returns to fertilizer use in specific areas of Kenya, often using a mix of designed experiments and computer systems models (e.g., Wanderi et al. 2011; Delve and Probert 2004; Bationo 2004). Several researchers have conducted studies similar to ours but with limited geographic scope and data collected over relatively short periods of time. Using econometric methods, Marenya and Barrett (2009) conducted a single cross-section of observational data focusing, particularly, on soil conditions within a small area of western Kenya. Matsumoto and Yamano (2011) use a two-year panel of observational data and confine their discussion to areas of western and central Kenya where fertilizer application rates tend to be relatively high. Well-known work by Duflo, Kremer, and Robinson (2008, 2011) relies on controlled field experiments with a small number of prescribed fertilizer rates in another small area of western Kenya and calculates rates of return to those application rates. No econometric studies, to our knowledge, cover the eastern part of the country where the number of users has increased steadily over the past several years. Also, because previous studies were conducted over short time periods, the response data do not reflect the impact of a range of possible weather conditions, particularly rainfall stress, and changes in prices that are more typically observed in longer data sets. This paper adds to the literature by investigating fertilizer profitability and use across Kenya using variation over time (five waves of panel data covering thirteen years) and space (120 villages in 24 districts), including eastern Kenya, using an econometric model that controls for unobserved heterogeneity and incorporates previous findings about the importance of agro-ecological conditions to fertilizer response. With this type of focus, we are able to provide a big picture story of fertilizer profitability across Kenya, complementing the micro-level studies done by others. In doing so, we address the following questions:

1. How does the response of maize to fertilizer application vary across Kenya? What are the impacts of specific field level, household, community, and agro-ecological factors on maize response and maize response to fertilizer use?
2. Are households in Kenya using fertilizer on maize fields where it is profitable to do so? Or, is there room for profitably expanding fertilizer use in certain areas?
3. What are economically optimal levels of fertilizer application? For those households that are using fertilizer on maize fields, are they doing so at these economically optimal levels? Or, does a gap exist between optimal and observed fertilizer application rates?

Using a nationally representative household panel dataset, we estimate fertilizer profitability on maize fields then compare with observed fertilizer use patterns over time. We examine profitability, both relative and absolute levels, after taking into account the transportation cost of fertilizer and using the maize price specific to household net buying or selling behavior. We estimate district level optimal fertilizer use rates using the distribution of rates among households in each district and compare with actual use levels to establish where a gap exists between observed and estimated economically optimal levels so as to provide pragmatic guidance to the GoK agricultural extension systems on room for profitably expanding fertilizer use across Kenya.

2. FERTILIZER TRENDS IN KENYA

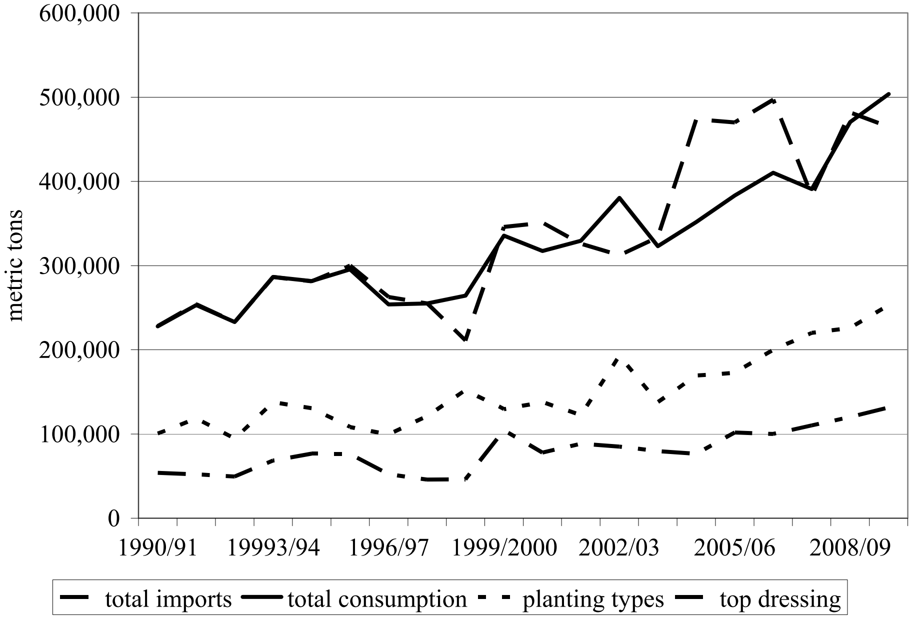
Fertilizer application rates in SSA are far below any other region in the world. Minot and Benson (2009) find that the average fertilizer application rate was only 13 kilograms per hectare in 2008 compared with an average 94 kilograms per hectare in other developing countries. While prices, infrastructure, and biophysical environments can vary in important ways across locations, this statistic has prompted considerable discussion about low fertilizer use in SSA. Researchers provide a long list of reasons why this might be the case including high fertilizer prices, low maize output prices, high transport costs, credit and information constraints, lack of complementary inputs and management practices, risky production environments and the fact that, in contrast to most other developing areas, only a small proportion of cropped area in SSA is under irrigation (Larson and Frisvold 1996; Kherallah et al. 2002; Crawford et al. 2003; Morris et al. 2007). Others have examined the profitability of fertilizer use in SSA at high levels of aggregation using relative input to output prices and value cost ratios (VCRs) finding fertilizer use to be unprofitable in many parts of Africa due to high fertilizer prices and transportation costs (Heisey and Mwangi 1997; Yanggen et al. 1998; Meertens 2005; Morris et al. 2007; Heisey and Norton 2007).

Aggregate fertilizer use trends for SSA may be unimpressive, but country-level statistics show greater variation and some success stories, Kenya among them. Ariga, Jayne, and Nyoro (2006) group countries in Africa by intensity of fertilizer use and percentage growth in fertilizer amount and find that of the four countries which use an average of 25 kilograms per hectare, three have had a growth rate of less than 30% over the 1990-2003 period (Swaziland, Malawi, and Zimbabwe) while one (Kenya) has had both high use and high growth. In our nationwide sample, over 90% of smallholder farmers in western Kenya use fertilizer on fields containing maize (definition in Section 3) and, across all fields where at least 25% of the value of harvest came from maize, 67% were fertilized in 2010 with an average application rate of over 100 kilograms per hectare.

Figure 1 summarizes national level trends over time. Notice that between the mid-1990s and 2005, fertilizer consumption increased by about one-third. Then from 2005 to 2010, fertilizer consumption again increased by one-fourth. The momentary drop in both fertilizer consumption and imports in the 2007/08 season is attributed to both high international prices and the post-election violence in Kenya. Ariga, Jayne, and Nyoro (2006) identify some factors accounting for the impressive growth in fertilizer use, including a stable fertilizer policy environment, a reduction in marketing margins following liberalization, a major increase in the number of fertilizer retailers operating in rural areas (reducing the average distance traveled from farm to acquisition source), and a noticeable shift from monocropping to intercropping in some areas.

Like many other African countries, virtually all fertilizer consumed in Kenya is imported (see Figure 1), making fertilizer prices particularly susceptible to swings in international commodity prices. Imported fertilizer arrives at the port in Mombasa and makes its way to the more agriculturally productive areas in central and western Kenya via private traders and the government. Figure 2 shows the trends in price of fertilizer observed at Mombasa and Nakuru; the difference between the two represents the margins absorbed by traders, transporters, packagers, and marketers. In general, prices in Mombasa (representing international prices plus port charges) have stayed constant over time while prices in Nakuru have fallen dramatically since the late 1990s, signaling a reduction in fertilizer marketing margins over time. By asking key informants in the fertilizer sector, Ariga et al. (2008) report four reasons for the narrowing of margins over time: (1) less expensive transportation options after the introduction of brokerage services, (2) private importers moving to international

Figure 1. National Level Fertilizer Consumption and Imports over Time

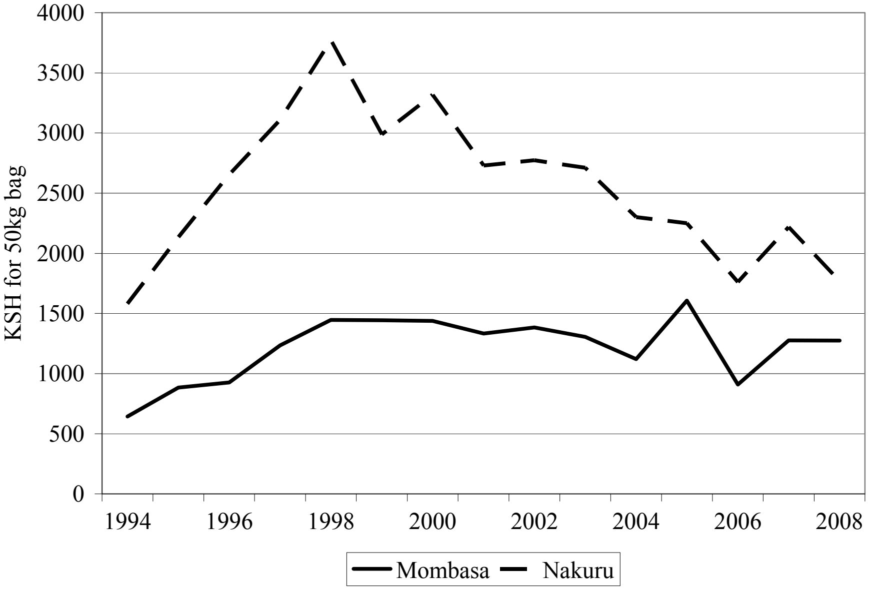


Source: Ministry of Agriculture in Kenya.

connections for credit which are able to offer lower rates and cheaper financing, (3) a concentration in international fertilizer distributors enabling economies of scope and cost savings, and (4) increased competition at the local distribution level since the mid-1990s.

Taken together, fertilizer consumption has increased while fertilizer prices have fallen, despite the price shock in 2007/08. Fertilizer prices, however, are only one part of the economic profitability calculation; the price of output is just as important in assessing the

Figure 2. Real Price of DAP at Mombasa and Nakuru (in 2009 Prices)

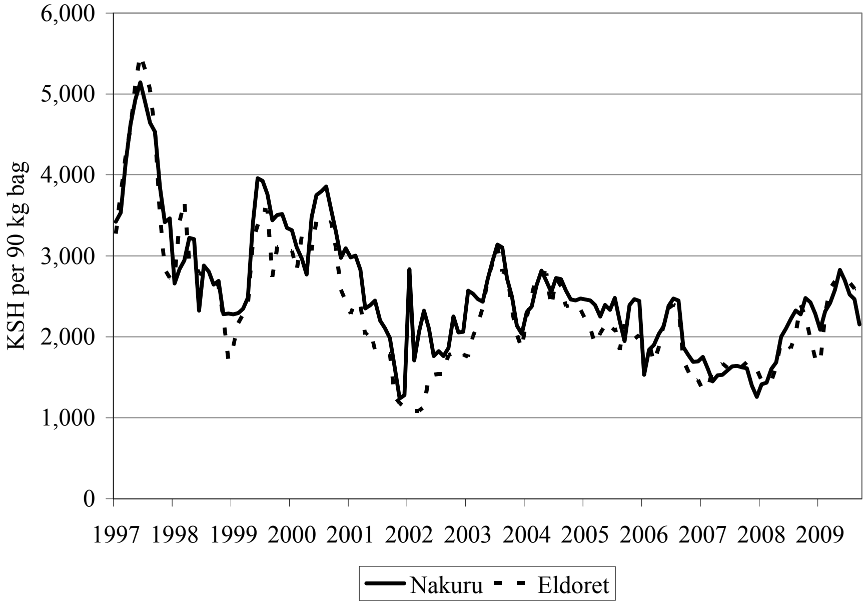


Source: Prices from Ministry of Agriculture in Kenya. Mombasa prices represent cost, insurance, and freight (cif). Nakuru prices represent those at wholesale market. Consumer price index (CPI) from the Kenya National Bureau of Statistics was used to compute real fertilizer prices.

incentive to use fertilizer. Figure 3 shows the real price of maize grain at two major wholesale markets in Kenya (Nakuru and Eldoret), measured monthly. This graph shows that, like fertilizer prices, maize prices also have fallen over time, even with considerable price spikes in 2000, 2004 and 2009. Moreover, Kirimi et al. (2011) show that marketing margins for maize millers and retailers have also been declining over time in Kenya. Together, this provides evidence that post-liberalization food and agricultural policy in Kenya has largely favored consumers over producers and others along the maize value chain.

With a downward trend in both inflation-adjusted fertilizer and maize prices, this calls into question how relative and absolute prices and, therefore, relative and absolute incentives to use fertilizer have changed over time. Moreover, focusing only on prices obscures the differences in conditions necessary for maize growth—particularly soil type and rainfall distribution—and the profitability of using fertilizer given the combination of those conditions and prices. This analysis will expand on the work of others by using variation across space and time in observed prices and fertilizer use to determine fertilizer profitability. Our estimates will help the GoK to produce more accurate location-specific recommendations for fertilizer application rates for farmers operating under the heterogeneous agro-ecological and market environments found in Kenya.

Figure 3. Real Wholesale Maize Grain Prices in Major Maize Producing Areas (in 2009 Prices)



Source: Maize prices from Market Information Bureau, Ministry of Agriculture Kenya. The CPI from the Kenya National Bureau of Statistics was used to compute real maize prices.

3. DATA AND SAMPLE SELECTION

The data used in our analysis comes from Egerton University's nationwide Tegemeo Rural Household Survey where households are asked a range of questions about their agricultural activities for the years 1997, 2000, 2004, 2007, and 2010. The surveys cover 24 administrative districts and 120 villages where standard proportional sampling using census data for rural divisions of the country formed the basis of extraction of the sample households. The panel started with 1500 households but, due to attrition, 1243 are consistently interviewed through the most recent panel. Because of the way survey data was collected, most inputs are observed at the field level. Supplemental data on yearly rainfall levels comes from the National Weather Service Climate Prediction Center (CPC) as a part of their Famine Early Warning System (FEWS) project. Rainfall values are available at the village level based on extrapolations from weather station data using Global Positioning System (GPS) coordinates taken during data collection. Soil data comes from the Kenya Soil Survey and the Ministry of Agriculture from data originally collected in 1980 and is also available at the village level.

From this data set, we narrow our focus to fields containing maize (hereafter referred to as maize fields), our unit of analysis, instead of averaging to the household level, and include only fields from the main long season given variation in bi-modal systems throughout Kenya. We limit the sample to fields that 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% of the calculated value of total harvest from the field. This criterion allows a larger number of fields to be considered given less than 10% are monocropped. We conclude that these fields are principally comprised of maize given little variation in maize seed rate between fields with different numbers of crops. On average across years, about 75% of households have one maize field per year, 20% have two, and the remaining 5% have three or more. Furthermore, areas of the country where agro-ecological conditions are generally incompatible with fertilizer use on maize (very low average rainfall or very poor soil conditions) are excluded from analysis.[1] Because we choose a population of fields from a random sample, the resulting data set is representative of the maize producing regions of Kenya. Our final sample includes 906 households and 4,714 maize fields over five survey years. For a distribution of households and fields included in this sample, see Table 1.

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[1] These areas include all of Coastal Province, Kitui district (Eastern Province), Laikipia district (Rift Valley), Kisumu district (Nyanza), and some parts of Siaya district (Nyanza) and Narok district (Rift Valley).

Table 1. Distribution of Households (and Fields) Used in Analysis

Agro-ecological zones	Districts	Original panel	Balanced panel	Fertilizer profitability analysis sample
Coastal Lowlands	Kilifi, Kwale	80	74	0
Eastern Lowlands	Machakos, Mwingi, Makueni, Kitui, Taita-Taveta	166	141	103 (528)
Western Lowlands	Kisumu, Siaya	188	149	41 (248)
Western Transitional	Bungoma (lower elevation), Kakamega (lower elevation)	172	145	154 (822)
High Potential Maize Zone	Kakamega (upper elevation), Bungoma (upper elevation), Trans Nzoia, Uasin Gishu, Bomet, Nakuru, Narok	411	331	341 (1,841)
Western Highlands	Vihiga, Kisii	156	128	135 (738)
Central Highlands	Nyeri, Muranga, Meru	268	241	132 (537)
Marginal Rain Shadow	Laikipia	59	34	0
Total sample		1,500	1,243	906 (4,714)

4. CONCEPTUAL FRAMEWORK AND METHODS

The aim of this paper is to understand whether or not farmers are making decisions about fertilizer use consistent with relative and absolute economic profitability measures within reasonable bounds of risk and uncertainty. To calculate those profitability measures, we first frame the fertilizer use decision by starting at the household level. Households in Kenya typically function as multiproduct firms, deriving income from the production of various crops and often a range of off-farm activities. We assume households are optimizers subject to constraints across all activities. Given the importance of maize in the Kenyan production system, this analysis focuses on the maize enterprise or, more specifically, maize fields where at least 25% of the value of production comes from maize.

The yield *Y* on maize field *i* from household *j* at time *t* is a function of several vectors:

$$Y_{ijt} = f(x_{kijt}, z_{kijt}, \mu_{ijt}) \tag{1}$$

where the vector x_{kijt} is comprised of inputs chosen by the household (including fertilizer) as well as agro-ecological conditions; the vector z_{kijt} includes those characteristics of the household that likely influence yield; and the vector μ_{ijt} is the error term containing unobservable characteristics of the production system which include both time constant c_j and truly random variables ε_{ijt}. Given evidence that quadratic production functions are appropriate for capturing heterogeneity across space (Berck and Helfand 1990; Kastens et. al 2005) and the frequency of use in crop yield response to nutrient functions (e.g., Traxler and Byerlee 1993; Kouka, Jolly, and Henao 1995), we utilize a quadratic production function in this set up, which can be viewed as an approximation to the underlying functional form.

Because the maize fields included in the sample are typically not monocropped, we transform observed kilograms harvested of other crops into their maize equivalents using an output index used by Liu and Myers (2009) of the following form:

$$Y_{ijt} = \frac{\sum_s Y_{is} P_s}{P_m} \tag{2}$$

where Y_{ijt} is the output index of maize field *i*, Y_{is} is the total kilograms harvested of crop *s* on field *i*, P_s is the market price of crop *s*, and P_m is the market price of maize. For monocropped fields, the output index is simply total kilograms of maize harvested; for intercropped fields, the output index is conditional on the relative output prices and volume harvested of other crops.

With production function estimates, we then calculate the expected marginal and average physical products of fertilizer (MP and AP) and, subsequently, the expected marginal and average value cost ratios (MVCR and AVCR) of the following forms:

$$E(MVCR_{fijt}) = \frac{E(p_{yt}) * E(MP_{xijt})}{w_{fijt}} \tag{3}$$

$$E(AVCR_{fijt}) = \frac{E(p_{yt}) * E(AP_{xijt})}{w_{fijt}} \tag{4}$$

where w_f is the price of fertilizer and p_y is the output price of maize.[2] An expected AVCR of greater than one means that a risk neutral household could increase its income as a result of fertilizer use (i.e., the average gain per unit); an expected MVCR of greater than one indicates income would be increased with an increase in the rate of fertilizer application.[3] However, given the fact that households in Kenya may be risk averse, we include a risk premium ρ in the set up (e.g., Anderson, Dillion, and Hardaker 1977). An MVCR of two (meaning a risk premium of one) has been used in the literature (e.g., Xu et al. 2009; Sauer and Tchale 2009; Bationo et al. 1992) dating back to work by the FAO (1975) in order to better accommodate risk and uncertainty, adjust for the many unobserved costs associated with fertilizer use, and serve as an approximation for the rate at which fertilizer is profitable *enough* for farmers to want to use it (see Kelly 2005):

$$E(MVCR_{fijt}) \geq 1 + \rho \qquad (5)$$

$$E(AVCR_{fijt}) \geq 1 + \rho \qquad (6)$$

Then, because MVCRs and AVCRs are measures of relatively profitability (i.e., use the ratio of input to output prices), we compute two additional measures of absolute profitability: the net gain in revenue to the last unit of fertilizer used (equation 7) and the total revenue added from the quantity of fertilizer applied (equation 8). With the noted real reduction in both fertilizer and maize prices following liberalization, the ratio of the two prices has not changed dramatically over this time period meaning the profitability of using fertilizer as calculated from those relative prices may not show a great deal of variability over time. However, a fall in both prices may have contributed to changes in net income levels of households and, therefore, a measure of absolute profitability provides a better sense of how changes in fertilizer and maize prices independently affect the actual gains to fertilizer use and income levels of smallholder farmers. These values are computed both at the margin and overall:

$$\text{net gain to last unit of fertilizer} = E(MP_{xijt}) * E(p_{yt}) - w_{fijt} \qquad (7)$$

$$\text{net gain to total fertilizer application} = [E(Y^F) - E(Y^{NF})] * E(p_{yt}) - x_{ijt} * w_{fijt} \qquad (8)$$

where Y^F is yield with fertilizer application and Y^{NF} is yield without fertilizer application.

4.1. Production Function Estimation Techniques

One of the important gains from panel data is the ability to control for unobservable household-specific effects which are expected to be correlated with the explanatory variables (Hausman and Taylor 1981). Unobserved variation in soil characteristics within a broad soil group and managerial skill are two important unobserved individual effects in our study. If households are optimizers and recognize the individual differences in their production functions, the farms with positive effects will use more fertilizer per hectare, all else equal, and there will be correlation between the unobserved individual effect in the error term and the rate of application of fertilizer resulting in a bias in ordinary least squares (OLS) estimators. The correlated random effects (CRE) estimator provides an approach to allow for correlation between the unobserved individual omitted variable c_j and included explanatory

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[2] These equations require independence between the included terms, which is a reasonable first order approximation where markets are not entirely localized.

[3] In our set up we assume there are no other costs to using or increasing fertilizer application rates. While this is not the focus of our analysis, we do acknowledge that there are a number of possible transactions costs, particularly when using for the first time, and that expenditure on labor may change with an increase in fertilizer application.

variables provided the unobserved effect is time-invariant. A class of CRE models developed by Mundlak (1978) and Chamberlain (1980) allows for modeling the distribution of the omitted variable conditional on the means of the strictly exogenous variables. The remaining portion of the error term ε_{ijt} includes random unobserved effects that vary over time at the household level and between maize fields.

Given we do not observe the same field over time and that the composition and number of maize fields at the household level can vary between survey years, the resulting panel is unbalanced. Wooldridge (2010) shows that correlated random effects can be employed with unbalanced panels in linear models, such as the quadratic production function estimated here. Moreover, because Mundlak-Chamberlain is used to control for unobserved heterogeneity at the household level and variation in the explanatory variables is necessary for household level averages to be a viable control, a household must have maize fields in at least three of the five survey years to be included in the sample. We estimate the CRE model using the OLSs. The adequacy of the functional form was evaluated using residual plots. The potential for multicollinearity serious enough to preclude estimation was explored by plotting relationships by geographic area with similar characteristics and the use of condition scores. We account for non-constant variance by computing robust standard errors clustered at the household level, a common solution to heteroskedasticity (Wooldridge 2009). Clustering at the household level has the added benefit of making standard errors robust to serial correlation.

5. SUMMARY STATISTICS

As a prelude to econometric analysis, this section reports how maize productivity and fertilizer use have changed over time and across space in Kenya using statistics from households in our dataset as a complement to the national level trends described in Section 2. First, Table 2 shows the average maize output index by year and agro-ecological zone, split between maize monocropped and intercropped fields. Partially as a function of the output index itself, we observe a lot of variability across zones and survey years. The central motivation of the production function estimation is to isolate the extent to which fertilizer application contributed to these observed differences in output on maize fields.

Table 3 shows how the percent of households using fertilizer in each zone has changed over the survey years. The first row in each agro-ecological zone shows the percentage of households that used fertilizer on any crop or field while the second row is specific to application on maize fields. Notice how percentages and changes vary considerably across zones. In the higher potential maize regions (i.e., Western Transitional, High Potential Maize Zone, Western Highlands and Central Highlands), over 70% of households currently use fertilizer with some zones closer to 95%. In the generally lower potential maize production areas (i.e., Coastal Lowlands, Eastern Lowlands, Western Lowlands and Marginal Rain Shadow), percentages are often much lower, although more varied. A higher portion of households in the Eastern Lowlands use fertilizer on maize (almost 50% currently) compared to the other lowland areas where 10 to 20% is more common. These areas, however, have seen a doubling or more of households using fertilizer between 1997 and 2010.

Table 2. Mean Output Value as Defined by Liu-Myers Yield Index (kg/ha)

		1997	2000	2004	2007	2010
Coastal Lowlands	Maize mono	434	1,146	649	873	895
	Maize inter	856	1,701	949	1,892	1,253
Eastern Lowlands	Maize mono	521	1,407	1,289	1,094	2,611
	Maize inter	711	1,762	1,352	2,047	2,489
Western Lowlands	Maize mono	712	720	473	1,407	1,124
	Maize inter	942	1,053	1,064	2,336	1,721
Western Transitional	Maize mono	1,250	1,979	2,272	2,038	3,253
	Maize inter	1,609	2,538	2,623	3,204	3,106
High Potential Maize	Maize mono	3,655	2,551	3,554	3,335	2,297
	Maize inter	3,015	3,021	3,875	3,657	2,662
Western Highlands	Maize mono	1,241	1,944	1,102	1,552	1,584
	Maize inter	1,654	2,118	2,067	3,156	3,311
Central Highlands	Maize mono	1,877	2,484	1,925	2,547	2,454
	Maize inter	2,337	3,080	2,811	3,530	4,831
Marginal Rain Shadow	Maize mono	-	1,778	593	-	1,368
	Maize inter	1,060	1,709	2,124	2,760	2,068
Total sample	Maize mono	2,214	2,049	2,442	2,644	2,078
	Maize inter	1,934	2,338	2,471	3,063	2,789

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Table 3. Percent of Fields Where Fertilizer Was Applied in Any Amount by Type of Field

		1997	2000	2004	2007	2010
Coastal Lowlands	Any field	2	3	4	7	8
	Maize field	3	5	5	11	17
Eastern Lowlands	Any field	21	18	24	33	27
	Maize field	23	24	41	40	51
Western Lowlands	Any field	3	4	4	9	10
	Maize field	2	3	5	12	13
Western Transitional	Any field	20	29	31	39	36
	Maize field	38	63	74	80	77
High Potential Maize	Any field	53	43	48	51	47
	Maize field	78	87	87	90	89
Western Highlands	Any field	45	52	47	45	44
	Maize field	72	88	91	93	94
Central Highlands	Any field	57	59	51	57	63
	Maize field	87	86	86	90	84
Marginal Rain Shadow	Any field	14	15	11	23	11
	Maize field	4	4	4	13	6
Total sample	Any field	38	37	37	41	40
	Maize field	52	56	64	68	67

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Table 4. Mean Kilograms of Nitrogen and Phosphorus Applied per Hectare for those that Used Fertilizer

		1997	2000	2004	2007	2010
Coastal Lowlands	N	0.6	6.3	0.9	8.2	8.5
	P	0.0	0.0	0.4	8.6	5.6
Eastern Lowlands	N	7.3	11.2	10.4	15.7	25.5
	P	3.5	4.1	4.6	6.0	11.2
Western Lowlands	N	17.1	8.4	8.7	11.0	21.4
	P	7.8	7.6	8.7	9.6	17.6
Western Transitional	N	33.0	32.9	43.1	49.0	46.3
	P	20.6	19.0	20.0	21.2	21.4
High Potential Maize	N	31.3	39.2	42.2	43.8	44.4
	P	17.6	15.0	19.0	20.2	25.0
Western Highlands	N	16.2	17.8	27.9	28.0	41.9
	P	17.6	15.0	19.0	20.2	25.0
Central Highlands	N	36.8	29.4	30.6	30.4	66.7
	P	16.4	14.2	15.7	15.2	16.3
Marginal Rain Shadow	N	-	-	126.4	12.6	22.2
	P	-	-	39.6	10.1	24.8
Total sample	N	29.9	32.0	34.9	37.6	44.5
	P	20.7	19.8	19.7	20.2	21.4

Source: Authors' calculations from the Tegemeo Rural Household Survey

Table 4 shows the average kilograms per hectare of nitrogen and phosphorous[4] applied to maize fields across all five waves of the panel. Using only non-zero fertilizer application values, this table shows that households generally choose fertilizers where the nitrogen component is greater than the phosphorous component, due in part to the presence of top dressing fertilizers. Again, these numbers show great diversity across Kenya. In the high potential areas, farmers apply between 20 and 40 kilograms per hectare of nitrogen and 15 and 25 kilograms per hectare of phosphorous. Farmers in the Western Highlands fertilize at rates similar to those in the Western Lowlands, the former considered high potential and the latter low potential. Otherwise, in the Coastal Lowlands and Marginal Rain Shadow, fertilizer has been applied only in the recent past while the Eastern Lowlands has seen a tremendous increase in application rates since 1997.

In 2010, all households were asked in what year they started using inorganic fertilizer on any crop, not just maize. The distribution of responses is found in Figure 4. Again, differences across agro-ecological zones are immense. On average, households in the High Potential Maize Zone and Central Highlands claim to have been using fertilizer for about 25 years as compared to about 10 in the Eastern and Western Lowlands. This history of diffusion closely follows how fertilizer came to exist in Kenya.[5] While these years represent when the household first used inorganic fertilizer, it does not necessarily mean that the household consistently used fertilizer in every subsequent growing season thereafter. Of the 1,467 households who provided a response in 2010, we find that between 8 and 12% *disadopted* in any one survey year specifically on maize fields following their first application of inorganic fertilizer.

While the incidence of fertilizer use and associated fertilizer application rates are much lower in some zones than in others, the maize yield response associated with fertilizer use in those areas might be such that using more fertilizer is not profitable or not profitable at the same levels of application. In the next section, we econometrically model maize production as a function of various inputs, fertilizer among them, to better understand the differences in fertilizer application rates, maize response, and fertilizer profitability across Kenyan households.

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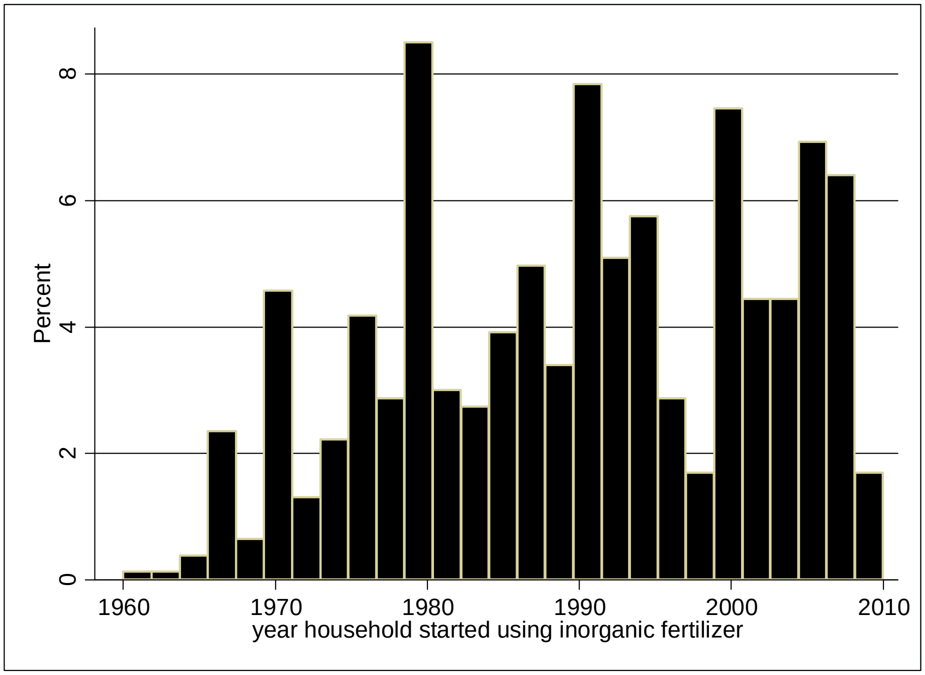
[4] Throughout the text, we refer to phosphorous as the amount of actual elemental phosphorous (P) from the compound P_2O_5 found in inorganic fertilizers, unless otherwise specified. The P portion of P_2O_5 is equivalent to 43.6% of the total phosphate compound.

[5] Fertilizer was first used only by European colonists, who preferred growing conditions in the Rift Valley and surrounding highlands, on cash crops, then was taken up by Kenyan farmers on their own cash crops following independence in 1963 (Hassan, Murithi, and Kamau 1998). A government fertilizer subsidy coupled with the release of hybrid seeds further encouraged Kenyan farmers to start using fertilizer on their maize in the 1960s (Kimuyu, Jama, and Muturi 1991). The lowlands areas, furthest from where fertilizer was initially introduced, were the last to start using fertilizer.

Figure 4. Distribution of Year in which Household Started Using Inorganic Fertilizer on Any Crop for those that Used Fertilizer during or before 2010



Source: Authors' calculations from the Tegemeo Rural Household Survey.

6. ECONOMETRIC MAIZE YIELD RESPONSE MODEL

In this section, we discuss the implementation of the econometric model used to develop estimates of the marginal and average products of nitrogen. Table 5 includes a complete list of the variables used in the production function and what they measure. The distribution of these variables across all maize fields in all years can be found in the Appendix 1. Most inputs in the production process were collected at the field level. In order to utilize as much field level variation as possible, estimation is done at the field level while accounting for unobserved household level characteristics using correlated random effects and clustering at the household level.

A number of fields with missing and extreme values are dropped from the dataset prior to estimation in order to limit the leverage of potentially erroneous observations. Observations are dropped if they satisfy any of the following conditions: (1) any missing value in the regressed variable set, (2) plot size less than 0.06 hectares or greater than 7 hectares, (3) yield per hectare of greater than 9,700 kilograms, (4) maize seed per hectare of zero or greater than 60 kilograms, (5) nitrogen per hectare of greater than 120 kilograms, or (6) phosphorous per hectare greater than 50 kilograms. These ranges were determined based on an understanding of reasonable values in the Kenyan context and government input recommendations. Twenty three percent of total fields were dropped after applying these exclusion rules.

Table 5. Variables in Maize Yield Response Model

Y		Output (yield)	Maize yield computed using Liu and Myers index
x	continuous	Nitrogen (N)	Nitrogen content of applied fertilizers (kg/hectare)
		Phosphorous (P)	Phosphorous content of applied fertilizers (kg/hectare)
		Seed (seed)	Seed rate (kg/hectare)
		Hectares (hect)	Number of hectares in given maize field
		Rainfall stress (rain stress)	Proportion of 20-day periods when rainfall was less than 40 mm during the main growing season (range 0-1)
		Asset wealth (asset)	Value of assets at household-level per hectare (proxy for household soil fertility and capital availability)
	categorical	Hybrid seed (hybrid)	1=new hybrid, 0=other seed (retained hybrid, OPV, local variety)
		Manure or compost (manure)	1=manure or compost applied to field, 0=none
		Legume intercrop (legume)	1=legume intercropped with maize; 0=none
		Crops per field (crop)	Number of crops included on field (range 1-7)
		FAO soil classification (FAO)	Type of soil: Cambisols, Ferralsols, Phaeozems, Luvisols, Greyzems, Podzols, Regosols, Rankers
		Soil groups (soil)	Soils grouped into four based on above classification system: 1=volcanic, 2=high humus or highly productive, 3=Rankers with high sand, 4=Rankers with less sand
		Agro-ecological zone groups (zone)	Six agro-ecological zones grouped into three: 1=lowlands, 2=transitional and high potential, 3=highlands
		Years (year)	Each survey year included as a dummy
		Districts (dist)	Each district included as a dummy

We observe the amount of each fertilizer *applied* to a field in a given year, not the amount of key nutrients *available* in the soil or *absorbed* by the crops. The amount of fertilizer applied to a field is separated into its nitrogen and phosphorous, the two nutrients limiting in most SSA soils (Stoorvogel and Smaling 1990; Sanchez et al. 1997), components (see Table 4) because the ratio of nitrogen to phosphorous in fertilizer applied varies across fields. Applied nitrogen generally is used by the plant that season while phosphorous is a far less mobile nutrient, with crops using only about 20% of the applied phosphorous in the first year of application (Griffith n.d.) which leads us to focus only on applied nitrogen in this analysis. The most common types of fertilizer used on maize in Kenya are basal diammonium phosphate (DAP) and top dress calcium ammonium nitrate (CAN).[6] Many households apply only basal, few apply only top dress, and a significant portion apply both basal and top dress in similar fixed proportions.

The econometric model initially was estimated quadratic in both nitrogen and phosphorous. However, given the limited variation in the ratio of the two nutrients (observations clustered around P_2O_5 to N ratios of 2.6 and 1.2) it was difficult to parse out individual partial effects of nitrogen and phosphorous while capturing the diminishing marginal products as application rates increased. Because of concerns about possibly overestimating the partial effects of nitrogen when leaving out phosphorous completely, we ran linear models on small sub-samples of data in relatively homogenous environments. When running models with only nitrogen, we produced marginal effects that were clearly too high. Adding a phosphorous term to these simple localized models brought the marginal effects of nitrogen down significantly and to levels comparable to marginal effects produced in the overall model with a quadratic nitrogen term with a nitrogen and phosphorous interaction term. The comparability of these estimates provides confidence that the nitrogen and phosphorous interaction term in our model adequately controls for the collinearity of the two nutrients and the omitted variable in our specification.

Agro-ecological conditions across Kenya can vary substantially. As such, and with particular interest in the response of maize to fertilizer, we condition the coefficients on nitrogen response on (1) where geographically the field is located, (2) on what type of soil, and (3) the amount of rainfall stress experienced during the main season. To do this, we create zone and soil groups, the resulting combinations having at least 100 households each in an effort to overcome the lack of precision associated with small samples. With information on elevation, rainfall and other agro-ecological conditions, we pool districts into three groups given relative similarity in production conditions:

1) lowlands areas in Nyanza and Eastern Provinces,
2) high potential areas in the Rift Valley and Western Provinces, and
3) highlands areas in Central and Nyanza Provinces.

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[6] For reference, for DAP, the N content is 18% and P content is 20.06% (P_2O_5 is 46%). For CAN, the N content is 26%, with no P. The calcium carbonate component of CAN reduces the potential acidification associated with nitrogen application.

Then, using data on the Food and Agriculture Organization (FAO) soil type found in each village, we pool soils into four groups based on similarities in formation properties, likely soil organic matter levels, and composition[7] (see Table 6 for more information):

1) Regosols and Podzols found in volcanic areas;
2) High humus Phaeozems, Luvisols, and Greyzems with highly productive Cambisols;
3) Rankers with high sand content; and
4) Rankers with less sand content.

Table 6. Soil Groups Created from Soil Data for Use in Nitrogen Interactions

Soil group number and criteria (number of villages)	Number of villages by soil classification	Number of villages by agro-ecological zone
1 Volcanic landform: Regosols and some Podzols (25)	Podzols: 2 Regosols: 23	High Potential Maize Zone: 9 Central Highlands: 16
2 High humus or highly productive: Phaeozems, Luvisols, Greyzems, Cambisols (21)	Cambisols: 4 Phaeozems: 6 Luvisols, 10 Greyzems: 1	Eastern Lowlands: 1 Western Transitional: 1 High Potential Maize Zone: 11 Western Highlands: 2 Central Highlands: 3 Marginal Rain Shadow: 3
3 Rankers with more sand (25)	Rankers: 25	Coastal Lowlands: 4 Eastern Lowlands: 11 Western Lowlands: 2 Western Transitional: 4 High Potential Maize Zone: 1 Western Highlands: 3
4 Rankers with less sand (20)	Rankers: 20	Western Lowlands: 1 Western Transitional: 6 High Potential Maize Zone: 7 Western Highlands: 5 Central Highlands: 1
5 Vertisols, Ferralsols, and Podzols with high clay and inadequate drainage (9)	Ferralsols: 1 Podzols: 7 Vertisols: 1	Eastern Lowlands: 1 Western Lowlands: 7 Marginal Rain Shadow: 1
6 Very shallow or very poorly drained soils found in swamps, reefs or erosional plains (5)	Podzols: 3 Solonetz: 2	Coastal Lowlands: 3 Western Lowlands: 2

Note: The first four groups are included as interaction terms in the model. The last two grayed groups represent conditions inhospitable to maize growth and/or fertilizer response. These villages are excluded from the production function estimation. See Appendix 2 for where they are located.

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[7] This grouping system was accomplished principally using information from Table 1 of IUSS Working Group WRB (2007).

These soil groups are a far from adequate attempt to capture the heterogeneity in soil conditions across Kenya, but represent an effort to understand overall trends in fertilizer response related to general soil type using limited data. Both zone and soil groups in addition to yearly rainfall stress variables are interacted with nitrogen in order to condition fertilizer response on the normal environment in which farmers operate and the events specific to a given main season. We confirm via a Chow Test (p-value of 0.0001) that fertilizer response does, in fact, vary between the constructed zone and soil groups.

Because input data is available at the field level (not specific to maize) and our yield index essentially converts revenue from a field into maize yield equivalents, an approach is needed to recover good approximations of the true maize yield response to applied nitrogen. In our model, we utilize the observed maize seeding rate (for the field) and the number of crops per field (measured as dummy variables) as controls.[8] Monte Carlo investigations were conducted for hypothetical data believed to mirror the underlying, but unknown, data generating process. These control variables mitigated most of the bias which would have occurred had they not been included. Moreover, both control variables cut the coefficient of variation on the yield index within the household in half and to levels more reasonable and likely for maize yield at the household level.[9]

The remaining variables seek to control for other important contributions to differences in maize yield across time and space. New hybrid maize seeds typically increase yield when rainfall stress is limited and have the added benefit of further increasing yield when appropriately paired with nitrogen fertilizers (Hassan et al. 1998; Ellis 1992). This complementarity and joint use decision creates an econometric estimation challenge because of endogeneity between the choice of technique and the expectation the choice will be correlated with unobserved individual effects (see Suri 2011). For many districts in our data, 80 to 100% of farms use fertilizer in some amount, and most farms chose to use both hybrid seeds and fertilizer together.[10] Our estimation approach was to include a dummy variable for seed type; we did not attempt to parse out a differential response function for the small subset of farms that use traditional seed varieties with fertilizer, meaning our marginal products may be slightly understated.

Manure is often used by Kenyan farmers to increase the organic matter and nutrient content of the soil and to slow the rate of fertility decline (Kihanda, Warren, and Micheni 2005; Kimani and Lekasi 2004). Other evidence from Kenya shows that intercropping maize with leguminous crops helps to improve overall maize output (Rao and Mathuva 2000). We control for the differences in conditions over time using the distribution of rainfall in the main season, measured as rainfall stress and observed at the village level. Rainfall stress is used instead of total main season rainfall given the importance of continuous moisture available to the plant throughout the growing season (Kironchi, Mbuvi, and Nguluu 2006)

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[8] About 70% of maize fields in our sample have either one or two crops, 20% have between three and five, and 10% have six or seven.

[9] The coefficient of variation on the yield index within the household is very high at 52% over the entire sample. These two controls reduce the predicted coefficient of variation to about 25%.

[10] The principal exceptions are (1) Narok district (Rift Valley) where over 90% of fields had hybrids but at most 50% were fertilized and (2) Mwingi district (Eastern Province) where hybrid use has increased from 5 to 75% but fertilizer use has remained low. Conversations with those familiar with Narok indicate that farming is relatively recent there, with an influx of households moving from more populated districts in Kenya. Households may believe that the previously uncultivated land is still naturally fertile and does not yet require fertilizer.

and the fact that rainfall stress and total rainfall are highly correlated in this data (correlation coefficient of 0.86). Soil type is controlled for using the FAO soil classification system, also observed at the village level. Furthermore, evidence from Tittonell et al. (2005) and Marenya and Barrett (2009) in Kenya suggests that poorer households generally have more degraded soils. We include a measure of household asset wealth as a proxy for household level variation in soil quality. While we do not find a significant interaction effect between asset wealth and fertilizer application in our data, we do keep the asset variable in the model to control for the contribution of overall soil quality to maize output as well as the potential contribution of productive capital assets to maize yield. Finally, given a long history of research on the inverse relationship between farm size and physical yield (Chayanov 1962; Sen 1962; Berry and Cline 1979; Barrett 1996), we also include a measure of field size, highly correlated with farm size in Kenya, to control for the differences across size of operations. Year and district dummy variables are included to absorb the remaining variation over time (i.e., temperature and pest infestations) and space not accounted for in the rainfall and location-specific variables respectively.

6.1. Econometric Results

The production function estimation results can be found in Appendix 3.[11] Most of the squared terms for nitrogen generate negative and statistically significant estimates, meaning a diminishing marginal returns relationship is appropriate. The lowlands are the areas with the most concave and steepest slope on nitrogen, with the highlands and higher potential areas having less concavity. Furthermore, the lowlands areas have a much higher response to combined nitrogen and phosphorous than the other two areas. Not only does this coefficient pick up on the differences in response to combined nitrogen and phosphorous, but also the differences in the ratio of applied phosphorous to applied nitrogen across space. In the eastern lowlands, for example, households are more likely to use top dress with basal whereas households in the highlands and higher potential areas are more likely to apply only basal.

The interactions between nitrogen and our soil groups do not produce the statistically significant estimates one would expect. There are a number of reasons why this might be the case. First, the individual FAO soil classifications are already included as dummy variables, so it could be the case that while these soils have different inherent productivity levels, their responses to fertilizer are not very different between our constructed soil groups. Second, and probably most likely, we lumped all soils into four different categories, which could be too high a level of aggregation to tease out how soil characteristics contribute to differences in fertilizer response. Third, perhaps soil formation properties are not as important to fertilizer response as the actual nutrient composition of the soil (for example, Marenya and Barrett 2009), for which we do not have data.

The final interaction with nitrogen is rainfall stress. One would hypothesize that areas with high rainfall stress (correlated with low rainfall) would have a lower response to fertilizer than areas with less rainfall stress and higher rainfall. In initial attempts to simply interact nitrogen with rainfall stress, we never found statistically significant results, which led us to include the interaction by zone group. When doing so, we find that these coefficients are not

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[11] The signs and significance level of most squared terms provide further justification for using a quadratic functional form. Moreover, several of the variables in the Mundlak-Chamberlain device are statistically significant, another indication of the importance of controlling for the consequences of unobserved household heterogeneity.

necessarily measures of contemporaneous differences in nitrogen response to different levels of rainfall stress, but actually helping us to control for a left out variable that allow us to estimate the distribution of nitrogen response rates *within* our zone groups. For example, the coefficients on the lowlands and highlands interactions are positive, which is showing the differences in fertilizer response between districts included in those zone groups. In the lowlands group, the Eastern Lowlands have more rainfall stress than the Western Lowlands but also more fertilizer use and, it appears, higher fertilizer response. Similarly, in the highlands, the Central Highlands have more rainfall stress than the Western Highlands, but also more fertilizer use. The sign on the high potential group is negative, which is likely a product of relative similarity in rainfall stress conditions across this group and the fact that districts with slightly less rainfall stress do have higher returns to fertilizer application.

As hypothesized, applied manure contributes positively to maize yield, either as a contemporaneous input or as a proxy for the soil organic matter level of the field. All else equal, using new hybrid maize seeds contributes to higher maize yields. When interacting the hybrid dummy variable with rainfall stress, as hypothesized, this term is negative (although not significant), meaning hybrid seeds are not necessarily a useful choice for households in lower rainfall environments. In terms of other biophysical relationships, the coefficient on rainfall stress is negative and significant, meaning the more intermittent the rainfall, the lower the maize yield, as expected. A quadratic term was tested for and was found to be statistically insignificant; a negative linear relationship was much more appropriate. The hectares variables show that yields, all else equal, are greater for smaller fields (correlated with smaller farms) than medium and larger sized fields, consistent with what others observe in the literature. Moreover, we find that this variable may also be picking up on some other unobserved characteristics of similarly sized fields and should not be interpreted as precise. The asset variables, measured per hectare, are increasing at a decreasing rate up to the largest values in our sample, meaning more asset-rich households (per hectare) have a yield advantage, likely due to the higher soil organic matter levels.

6.2. Marginal and Average Products of Nitrogen

Given that farmers make decisions about input use at planting time with uncertainty about how the season will unfold, we are interested to model *expected* maize response to fertilizer application. Therefore, instead of using contemporaneous rainfall stress in the marginal and average product calculations, we use a six-year moving average of past rainfall stress levels as a measure of expected rainfall conditions in the coming main season. Using these procedures, the overall marginal product of nitrogen is 17.5, meaning a one kilogram per hectare increase in the amount of applied nitrogen will increase maize yield by about 17.5 kilograms per hectare, all else equal. This value is similar to other overall, highly aggregated marginal products of nitrogen found in the literature throughout SSA. For example, Yanggen et al. (1998) find an average maize response to nitrogen of 17 from a large number of research trials and on-farm demonstrations across all of Eastern and Southern Africa.

What we are interested in, though, is local level marginal and average products so that it is possible to examine the degree of correlation between fertilizer profitability and use patterns across space and time. We calculate marginal and average products by district, soil group, and year, where the variation comes from differences in zone, soil group, rainfall stress levels, and ratio of past phosphorous to nitrogen application.[12] Appendix 5 includes the marginal and average products of applied nitrogen averaged by district and soil group (for standard errors of the marginal products, see Appendix 4). Similar to the considerable differences in inputs used by farmers, we find marginal products for various sub-groups ranging from 6 to 48 with similar variations in average products. The ratio of standard errors of estimated marginal products within individual district and soil groups range from 0.17 to 0.83, with most groups within the 0.2 to 0.3 range. In general, we find higher marginal and average products in the lowlands areas where fertilizer has only more recently been a feature of maize production. In the areas where farmers have used fertilizer in large amounts for a much longer period of time, the marginal and average products are much lower. It is well known that persistent use of nitrogen fertilizers without complementary organic inputs or liming leads to an increase in soil acidity and, therefore, a decrease in the capacity of soil to respond to applied nitrogen (Bekunda, Bationo, and Ssali 1997). Moreover, there is preliminary evidence that some areas of western Kenya have more acidic soils due to high use of nitrogen fertilizers without appropriate soil amendments (Esipisu 2011). What our results might suggest, then, is that land more recently brought into a fertilizer rotation could experience higher gains from fertilizer use and that land with a long history of fertilizer application may no longer experience the same gains if complementary inputs have not been part of management practices.

Some of our estimates match others found in the literature. For example, Matsumoto and Yamano (2011) found marginal products varying across the western and higher potential regions between 11 and 20. Their analysis, however, precluded eastern Kenya where we find the highest returns. Marenya and Barrett (2009) found the marginal product of nitrogen to be 17.6 for both Vihiga and South Nande districts. While we estimate the value to be closer to 13.9, they did have a standard error of about 8, meaning our results are well within their confidence interval. Mbata (1997) looked at response to fertilizer in the Rift Valley, finding marginal products between 12 and 18, depending on the district, which again are similar to our estimates.

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[12] The marginal products were estimated using the margins command in Stata and represent average partial effects of nitrogen. The average products were manually calculated at the field level using the coefficient estimates, then averaged to the district, soil group, and year level for use in subsequent analysis.

7. PROFITABILITY OF FERTILIZER USE

Using the marginal and average products of nitrogen at the district and soil group level estimated in the last section, the profitability of fertilizer use is assessed using the market price of nitrogen plus its transportation cost from the market to the farm-gate and a maize price specific to net maize buying (selling) households. If a household is a consistent net seller of maize across all five surveys (114 of 906 households), then the selling price of maize is attributed. If the household is a consistent net buyer of maize (131 of 906), then the buying price of maize is used. If the household is sometimes a net buyer and sometimes a net seller (661 of 906), then a simple average of the two is used. These values seek to mimic the household perception of the opportunity cost of producing maize by attributing the maize price that best matches their observed maize market standing over time. Fertilizer profitability is calculated using the marginal and average value cost ratios of nitrogen as described in equations 3 and 4 with the prices described below.

7.1. Price of Nitrogen

We compute a district-averaged price of nitrogen at the field level using the observed price paid by the household for DAP and CAN, the two most commonly used fertilizers in the dataset.[13] Market prices do not necessarily accurately reflect the cost of acquiring fertilizer, especially in places where fertilizer retail outlets may be few and far between or where infrastructure may be poorly developed. The significance of transactions and transport costs in limiting farmers ability to participate in markets—both input and output—is well-established in the literature (de Janvry, Fafchamps, and Sadoulet 1991; Key, Sadoulet, and de Janvry 2000; Bellemare and Barrett 2006) and has been used to explain why input adoption may be lower than expected (Morris et al. 2007; Winter-Nelson and Temu 2005). Given the stated importance of transactions and transport costs, we create an estimated transport cost, one essential component of the full gamut of transactions costs, from the household to the nearest fertilizer seller. In each survey year, we observe the distance (in kilometers) from the household to the nearest fertilizer seller, but only in 2010 do we know the cost of moving between the locations (via matatu, motorbike, bicycle etc.). To estimate village level transport costs in earlier years, we multiply the median transport cost per kilometer observed in 2010 by the median distance from the farm to the nearest fertilizer seller in the previous years. These calculated transport costs are added to the district level market prices of nitrogen to arrive at what will hereafter be described as the acquisition price of fertilizer.

Table 7 shows the average distance from the household to the nearest fertilizer dealer. In general, distances are low and, in some zones (i.e., the three lowlands zones), falling considerably over time. As evidence from high standard deviations, however, slight increases and decreases should not be the focus, as variation within zones is immense. Instead, one should note the overall smaller distances necessary to access fertilizer over time. Both of these findings provide further justification for incorporating transport costs into the full acquisition costs given the remarkable decline over time in acquisition distances.

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[13] All prices used in this analysis and subsequent tables and figures are adjusted to 2010 levels using the CPI from the Ministry of Finance in Kenya.

Table 7. Mean (and Standard Deviation) Distance (Kilometers) from Household to Nearest Fertilizer Seller

	1997	2000	2004	2007	2010
Coastal Lowlands	25.2	23.8	17.3	8.7	4.6
	(16.8)	(11.5)	(22.3)	(12.0)	(4.4)
Eastern Lowlands	10.1	6.0	3.7	2.8	3.6
	(13.1)	(10.0)	(5.1)	(2.9)	(3.9)
Western Lowlands	16.2	12.5	7.0	3.9	4.3
	(10.5)	(6.2)	(7.0)	(1.6)	(2.6)
Western Transitional	6.7	4.8	2.9	3.6	4.1
	(5.9)	(5.4)	(2.4)	(3.1)	(2.8)
High Potential Maize	5.3	3.8	3.1	3.7	5.2
	(8.2)	(3.9)	(3.2)	(3.6)	(4.3)
Western Highlands	3.3	1.8	1.3	2.3	2.9
	(4.0)	(1.8)	(1.1)	(1.8)	(1.6)
Central Highlands	2.8	1.5	1.3	1.4	1.4
	(3.9)	(1.6)	(0.8)	(1.4)	(1.5)
Marginal Rain Shadow	23.6	2.2	7.0	2.9	4.4
	(8.3)	(1.9)	(9.7)	(2.7)	(5.1)
Total sample	7.5	5.9	3.8	3.4	4.0
	(10.1)	(7.7)	(6.5)	(3.9)	(3.6)

Source: Authors calculations from Tegemeo Rural Farm Household Surveys.

Table 8. Mean Price of Nitrogen per Kilogram (2010 Prices)

	Nitrogen price	1997	2000	2004	2007	2010
Coastal Lowlands	Market	407	230	216	227	258
	Acquisition	771	527	437	261	318
Eastern Lowlands	Market	344	246	217	189	166
	Acquisition	477	299	262	238	219
Western Lowlands	Market	632	450	376	315	234
	Acquisition	951	725	465	388	308
Western Transitional	Market	356	332	273	230	216
	Acquisition	456	378	303	263	258
High Potential Maize	Market	457	351	278	239	224
	Acquisition	507	392	307	273	266
Western Highlands	Market	519	367	247	254	205
	Acquisition	582	411	276	307	258
Central Highlands	Market	314	267	226	216	199
	Acquisition	378	308	267	254	243
Marginal Rain Shadow	Market	285	227	195	182	175
	Acquisition	600	272	236	211	215
Total sample	Market	432	337	268	242	213
	Acquisition	550	418	316	285	263

Source: Authors' calculations from the Tegemeo Rural Household Survey.
Note: Market prices reflect district averages. Acquisition prices reflect market prices plus village level calculated transport cost of fertilizer between households and the nearest fertilizer dealer.

Table 8 shows the average computed market and acquisition price of fertilizer in real 2010 terms. In some areas, the cost of transport creates a significant wedge between the market and acquisition prices of nitrogen (e.g., 1997 in the Coastal Lowlands). On average, though, the cost of transport adds between 50 and 100 Kenyan shilling (KSH) to the market price of fertilizer. Over the 1997-2010 period for the entire sample, about 20 to 22% of the farm-gate acquisition price is accounted for by transport costs from the retail purchase point to the farm, covering between 4 and 8 kilometers. The high per unit costs of the last few kilometers underscores the potential for reducing farm-gate fertilizer prices through innovations to reduce transport costs of the last mile.

7.2. Price of Maize

While fertilizer prices and transport costs are known at the time of purchase and use, the price for which maize will sell on the market months later is not known to the farmer. We model *expected* maize selling prices using a technique employed by Muyanga (forthcoming) of regressing the price at which farmers sell their maize at the end of the season (i.e., what we observe in the data set) on the information available to farmers at the time of planting and other factors that determine the price farmers receive. These include current and lagged Kenya's National Cereal Produce Board (NCPB) prices, regional markets current and lagged prices, distances from the regional markets, and the type of buyer to which farmers normally sell their maize. With the regression estimates, we predict the selling price of maize farmers likely envisioned at the time of planting. With estimates at the household level, we average to the district level and use these values as expected maize selling prices.

While the selling price of maize is the usual metric for calculating the marginal and average value product of output, a significant number of households in the dataset are net maize buyers. The fact that a majority of households, even in agriculturally dominant areas, are net buyers has been well-documented by other researchers with respect to all of SSA (e.g., Christiaensen and Demery 2007) and Kenya specifically (e.g., Jayne et al. 2001). Furthermore, a relatively small number of farming households comprise the total marketable surplus of maize in the country. Jayne et al. (2001) found that 10% of small scale farmers produced 74% of the maize sold by the small scale maize sector. Table 9 shows the percent of net buyers and net sellers in this data set each year.

For the majority of households, then, a better measure of the opportunity cost of growing maize might be its buying price. Instead of modeling expected buying prices using the same method as expected selling prices, we calculate the difference between the expected and actual (observed) selling prices and add that difference to the actual (observed) buying prices to arrive at an expected buying price. Like the prices of nitrogen, maize prices are averaged at the district level to minimize measurement error. Table 10 shows the calculated expected buying and selling price of maize. In general, the buying price of maize is between 5 and 10 KSH more than the selling price (16 to 22% difference), with a much larger wedge in 2004 than the other two years.

Table 9. Percent Net Buyers and Net Sellers of Maize by Zone and Year

		1997	2000	2004	2007	2010
Coastal Lowlands	Net buyer	89	88	91	72	88
	Net seller	2	9	9	17	5
Eastern Lowlands	Net buyer	81	71	54	57	60
	Net seller	13	23	36	31	25
Western Lowlands	Net buyer	75	79	80	60	53
	Net seller	8	12	14	21	30
Western Transitional	Net buyer	77	57	41	32	37
	Net seller	13	34	44	50	42
High Potential Maize	Net buyer	25	26	20	19	36
	Net seller	62	60	71	73	46
Western Highlands	Net buyer	53	55	51	44	36
	Net seller	26	33	32	43	48
Central Highlands	Net buyer	63	52	52	40	53
	Net seller	21	39	33	46	23
Marginal Rain Shadow	Net buyer	80	88	52	26	44
	Net seller	7	13	45	41	34
Total sample	Net buyer	57	51	46	38	47
	Net seller	30	39	44	49	36

Source: Authors' calculations from the Tegemeo Rural Household Survey.
Note: Net buyer defined as a household which purchases more maize than they produce in a given year. Net sellers are defined as households which sell more maize than they purchase in a given year. Households with a balance of zero (autarkic) or ones in which rely exclusively on gifts or aid are the excluded percentage.

Table 10. Mean Expected Selling and Buying Price of Maize per Kilogram (2010 Prices)

		1997	2000	2004	2007	2010
Coastal Lowlands	Sell price	51.6	38.5	31.4	21.7	25.8
	Buy price	-	-	40.5	37.4	29.8
Eastern Lowlands	Sell price	37.1	33.9	27.6	20.0	18.9
	Buy price	-	-	34.9	25.8	27.1
Western Lowlands	Sell price	43.2	37.0	29.8	21.6	22.1
	Buy price	-	-	34.9	22.6	23.5
Western Transitional	Sell price	36.6	33.9	27.4	19.0	20.8
	Buy price	-	-	34.2	21.5	22.7
High Potential Maize	Sell price	37.7	33.0	26.9	18.0	20.5
	Buy price	-	-	33.9	20.4	23.0
Western Highlands	Sell price	40.1	37.6	30.4	21.9	22.0
	Buy price	-	-	35.3	23.2	22.3
Central Highlands	Sell price	42.6	37.0	28.9	21.0	20.4
	Buy price	-	-	34.7	24.1	26.3
Marginal Rain Shadow	Sell price	36.5	-	27.8	17.5	19.4
	Buy price	-	-	33.8	21.3	27.5
Total sample	Sell price	39.4	34.9	28.3	19.8	21.0
	Buy price	-	-	34.7	22.9	24.3

Source: Authors' calculations from the Tegemeo Rural Household Survey.
Note: Purchase prices of maize not observed in 1997 or 2000.

The one remaining value that we do not capture here is the distance a household needs to travel to sell or purchase maize. While we do observe the distance a household traveled to make its largest maize sale in certain survey years, this variable does not necessarily capture the closest alternative for the household. A farmer could make the choice to travel a greater distance in order to make a larger sale, bypassing several other markets along the way, or simply to sell from the farm to other households in the village. In the 2010 dataset, over 70% of households claimed to sell their maize from the farm (the buyer came to them). Furthermore, we never observe how far a household needs to travel to purchase maize. For these reasons, the transport cost of selling and acquiring maize are not included here.

7.3. Profitability Calculations

Before looking specifically at the profitability calculations, it is useful to conceptualize relative prices using the aforementioned specifications. Recall from Figures 2 and 3 that both maize and fertilizer prices have fallen, in general, over time. Table 11 shows the relative price of fertilizer to maize (i.e., the inverse of what is used in the MVCR and AVCR calculation) under three different relative price scenarios. A lower ratio signals that the incentive to use fertilizer is greater: the cost of the input is relatively less than the price of the output. Overall, these ratios do not show an overwhelming decline in the relative price of fertilizer to maize over time.

Table 11. Relative Price Scenarios (Nitrogen/Maize per Kilogram) over Time by Zone

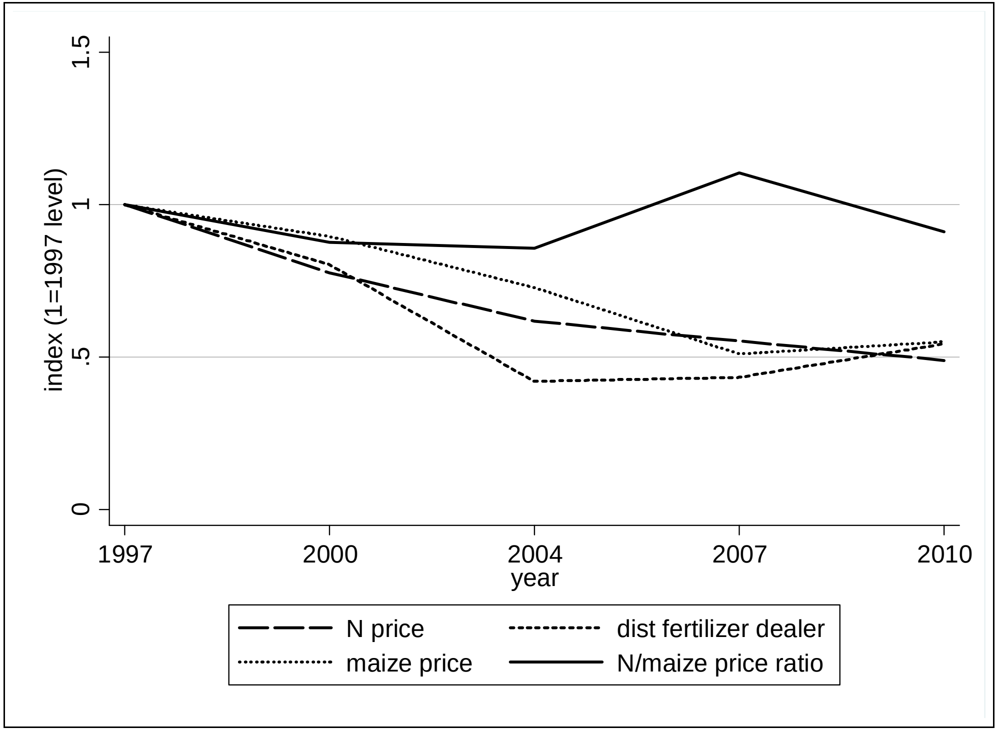
	Nitrogen price	Maize price	1997	2000	2004	2007	2010
Eastern Lowlands	Market	Sell	9.5	7.3	7.9	9.3	8.7
	Acquisition	Sell	13.3	8.8	9.5	11.7	11.4
	Acquisition	Sell or buy	-	-	8.2	10.1	8.9
Western Lowlands	Market	Sell	14.5	12.2	12.8	14.6	10.6
	Acquisition	Sell	21.7	19.3	15.8	18.0	13.9
	Acquisition	Sell or buy	-	-	14.2	17.5	13.4
Western Transitional	Market	Sell	9.7	9.8	9.9	12.1	10.4
	Acquisition	Sell	12.5	11.1	11.0	13.9	12.4
	Acquisition	Sell or buy	-	-	9.7	13.0	11.9
High Potential Maize	Market	Sell	12.2	10.6	10.3	13.3	10.8
	Acquisition	Sell	13.5	11.8	11.4	15.1	12.8
	Acquisition	Sell or buy	-	-	10.4	14.4	12.3
Western Highlands	Market	Sell	12.9	9.8	8.0	11.6	9.3
	Acquisition	Sell	14.4	11.0	8.9	13.9	11.7
	Acquisition	Sell or buy	-	-	8.2	13.5	11.5
Central Highlands	Market	Sell	7.4	7.2	7.8	10.3	9.8
	Acquisition	Sell	8.9	8.3	9.3	12.2	11.9
	Acquisition	Sell or buy	-	-	8.3	11.3	10.2
Total sample	Market	Sell	11.1	9.9	9.7	12.4	10.1
	Acquisition	Sell	13.8	12.0	11.1	14.5	12.5
	Acquisition	Sell or buy	-	-	10.0	13.8	11.7

Source: Authors' calculations from the Tegemeo Rural Household Survey.
Note: Buying price of maize not observed in 1997 and 2000.

Market prices of nitrogen were relatively high in 1997 but declined in 2000 and 2004. In 2007, the price of nitrogen increased much more than the cost of maize, forcing the relative price back up again. By 2010 the relative price had fallen again, but still not in line with 2000 and 2004 levels. This trend is somewhat amplified when adding the transport cost of fertilizer (acquisition price); the decrease in distance traveled to fertilizer retailers over time has steadily decreased the acquisition price of nitrogen. In the highest potential areas, the ratio hovers around 12, consistent with other work in the area. For example, Matsumoto and Yamano (2011) use a value of 13 during the years in their sample across western and central Kenya.

As an overall indication of changes in prices and fertilizer access over time, Figure 5 shows how the relative accessibility of fertilizer has changed over the survey years for the entire sample. While there are statistically significant differences across zones and districts for most of the variables included in this plot, this figure shows the prices of nitrogen and maize and distance traveled to the nearest fertilizer dealer in 2010 were about half of what they were in 1997. Like Table 11, however, the relative nitrogen to maize price has remained fairly constant, even increasing in 2007 relative to 1997. The downward trend in prices versus mostly stable relative prices provide further justification for investigating the differences between the absolute profitability of fertilizer (i.e., net income for households using fertilizer) and relative profitability as defined by the MVCR and AVCR measures.

Figure 5. Changes in Relative Accessibility of Fertilizer over Survey Years for All Households



Source: Authors' calculations from the Tegemeo Rural Household Survey.

Table 12 shows the average MVCRs and AVCRs for each district and soil group in the last three survey years; Appendix 5 shows averages across time. Over the total sample, MVCRs are between 1.37 and 1.88 and AVCRs are between 1.67 and 2.28, depending on the year. The highest MVCRs and AVCRs are found in the Eastern Lowlands due to high marginal and average physical products. With values between four and six, this suggests vast increases in household income from the use of fertilizer on maize and that the last unit of fertilizer was still very profitable, implying that households were still quite far from optimal use rates, where according to theory, the marginal value over the marginal cost equals 1. Fertilizer use is next most profitable in the Central Highlands where, again, both the average and last unit of fertilizer were particularly profitable (in most cases, with AVCRs and MVCRs over two). Interestingly, the least most profitable zone, on average, is the High Potential Maize zone where AVCR values are above one but MVCR values are either at one, slightly above or slightly below. This indicates that while profitable to use, households are likely using at or near the most profitable rates and that there would not be substantial gains (and possibly losses) from increasing dosage. In fact, in some cases, a decrease in the amount of fertilizer applied might be the most profitable strategy.

Table 12. MVCRs and AVCRs by District, Soil Group, and Year

Province	District	Soil group	MVCR			AVCR		
			2004	2007	2010	2004	2007	2010
Eastern	Machakos	3	3.60	3.69	3.27	4.18	4.21	4.34
	Makueni	3	5.09	4.01	3.29	5.88	4.69	4.83
	Meru	1	2.21	1.51	1.46	2.48	1.70	1.67
	Mwingi	2	5.00	5.05	6.13	6.91	6.07	6.36
	Mwingi	3	4.22	4.38	5.91	4.42	5.13	8.17
Nyanza	Kisii	2	2.02	1.49	1.72	2.42	1.69	2.06
	Kisii	4	2.05	1.40	1.48	2.32	1.61	1.82
	Siaya	3	1.97	1.78	1.96	2.34	2.07	2.63
	Siaya	4	2.00	1.84	1.69	2.53	2.31	2.51
Western	Bungoma	2	2.11	1.27	1.54	2.48	1.64	1.90
	Bungoma	3	0.80	0.63	0.71	1.25	0.89	1.03
	Bungoma	4	1.57	1.02	0.96	2.06	1.38	1.38
	Kakamega	2	1.11	1.17	1.04	1.72	1.56	1.58
	Kakamega	3	0.97	0.66	0.76	1.30	0.96	1.11
	Kakamega	4	1.49	1.17	1.30	1.64	1.32	1.44
	Vihiga	3	0.93	0.55	0.64	1.15	0.69	0.83
	Vihiga	4	1.47	0.79	0.98	1.72	0.91	1.20
Central	Muranga	1	2.32	2.04	2.20	2.54	2.16	2.52
	Muranga	4	2.51	2.12	2.44	2.63	2.26	2.55
	Nyeri	1	2.06	1.92	1.90	2.44	2.13	2.16
	Nyeri	2	2.71	2.35	2.52	2.90	2.50	2.69
Rift Valley	Bomet	1	1.26	0.88	0.97	1.42	0.98	1.11
	Nakuru	1	0.71	0.54	0.61	0.92	0.68	0.85
	Nakuru	2	1.10	0.59	0.81	1.30	0.72	1.00
	Nakuru	4	1.05	0.69	0.84	1.24	0.79	1.03
	Narok	1	0.48	0.23	0.31	0.65	0.30	0.44
	Trans Nz.	4	1.04	0.98	1.18	1.51	1.48	1.68
	Uasin Gis.	1	0.99	0.61	0.69	1.34	0.87	0.98
	Uasin Gis.	2	1.34	0.82	0.88	1.84	1.30	1.32

Source: Authors' calculations from the Tegemeo Rural Household Survey.

The average reduction in real transport costs across zones was estimated at 35% between 1997 and 2010. These varied between 17% in the High Potential Maize area to over 50% in the Western Lowlands. Given we observe this considerable decrease in the travel distance necessary to purchase fertilizer over the survey years, how did it contribute to changes in the profitability of fertilizer? We examine this by simulating AVCR measures, holding fixed all variables over the five surveys except the observed change in transport cost between 1997 and 2010. In Table 12 the average product, expected maize price, and nitrogen price *do* vary, meaning our simulation does not show the true contribution of the change in transport cost to the change in profitability. However, we also observe that these values do not change over time by very much, allowing us to make this assumption for the purpose of simulation. In Table 13 we show how the real change in transport costs contributed to changes in these simulated AVCR measures between 1997 and 2010, with the other values fixed at both their average and maximum levels across the five surveys. Because we want to include all five survey years, only the selling price of maize is used in these AVCR calculations. Averaged across the six zones, we observe a 35% drop in the transport cost between 1997 and 2010 which, all else equal, contributed to an estimated 10% increase in the profitability of fertilizer use when the other variables are valued at the average and 7% when they are valued at their maximum. In the Western Lowlands and Transitional zones where the drop in transport cost was the most drastic, the profitability of fertilizer increased between 15 and 20% on account of the change in distance to the nearest fertilizer dealer. The reason these changes might seem smaller than expected is that the transport cost is a relatively small contributor to the total AVCR as compared to the other values held constant.

The MVCR and AVCR estimates presented in Table 12 represent measures of relative profitability, relying on the ratio of nitrogen to maize prices. Given that the relative price of nitrogen to maize has not changed tremendously over the survey years (see Table 11), the relative profitability of fertilizer, as embodied in the MVCRs and AVCRs, mostly varies to the extent that other variables in the formulas change more substantially over time, for example the fertilizer transport cost as shown in Table 13. The relative profitability measures, then, are unable to capture the actual monetary returns to fertilizer use experienced in a given year. Because farmers both pay out to acquire fertilizer then later are paid in the price of maize, the ratio of the two values is unlikely to be the most important value considered by the farmer when making the decision to use fertilizer.

Because of this, we calculate an additional absolute profitability measure as shown in Table 14 the net gain to the last kilogram of nitrogen applied (i.e., gain at the margin) using the acquisition price of nitrogen and both the selling and buying prices of maize for comparison. When using the selling price of maize, the net gain to the last unit of fertilizer application has diminished considerably across time. Even in Eastern Province, where the reduction in transport cost over time has declined considerably, the net gain to fertilizer use over time has fallen. The negative values in some of the more heavily fertilized regions are a function of both lower marginal products of nitrogen and the prices of nitrogen and fertilizer. Again, these results are likely a product of decreased productivity of the soil due to overuse of fertilizer and lack of complementary inputs. Moreover, while nitrogen prices and transport distances are lowest in these areas, the selling prices of maize are relatively low also, making the net gain to the last unit of nitrogen applied not particularly profitable.

Table 13. Simulated Change in AVCR Due to Real Change in Transport Costs (1997-2010)

	% change in real transport cost	Calculated at average levels			Calculated at max levels		
		Simulated AVCR (1997)	Simulated AVCR (2010)	% change in AVCR	Simulated AVCR (1997)	Simulated AVCR (2010)	% change in AVCR
Eastern Lowlands	-38	3.97	4.43	12	4.38	4.76	9
Western Lowlands	-53	1.88	2.22	18	2.01	2.24	11
Western Transitional	-55	1.19	1.38	16	1.37	1.55	13
High Potential Maize	-17	1.16	1.19	2	1.21	1.23	2
Western Highlands	-16	1.35	1.39	3	1.23	1.25	2
Central Highlands	-31	2.15	2.29	7	2.59	2.73	5
Total sample (unweighted)	-35	1.95	2.15	10	2.13	2.29	7

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Using the buying price of maize produces higher net gains given the buying price of maize is generally higher. This does not mean, however, that the net gains to net buyers of maize are greater than those to net sellers given net buying households need to purchase both maize and nitrogen (both cash outflows) while net sellers sell maize but purchase nitrogen (cash inflow and outflow). What this does show is that (1) the net gain to fertilizer use is higher when using the price at which most household purchase maize and (2) the decrease in net gain to the last unit of fertilizer between 2004 and 2010 has been more severe when using the net buying price as opposed to the net selling price. In summary, while relative nitrogen to maize prices have not changed considerably over the survey years, the absolute prices of fertilizer and maize have moved such that the absolute profitability of the last kilogram of fertilizer has declined. In some areas (Eastern Lowlands), expanding fertilizer use appears to be a profitable strategy while in others (High Potential Maize Zone) fertilizer use appears at or even slightly beyond optimal levels. We investigate these findings alongside actual use patterns in the next section.

Table 14. Net Gain to Last Kilogram of Fertilizer Applied (KSH) by District, Soil Group, Year

Province	District	Soil group	Selling price of maize					Buying price of maize				
			1997	2000	2004	2007	2010	1997	2000	2004	2007	2010
Eastern	Machakos	3	1,141	1,111	603	504	433	-	-	837	904	938
	Makueni	3	940	1,019	756	572	341	-	-	989	643	511
	Meru	1	311	327	249	96	68	-	-	370	177	178
	Mwingi	2	1,350	1,418	1,031	815	719	-	-	1,379	1,276	1,202
	Mwingi	3	1,103	1,185	818	666	683	-	-	1,111	1,063	1,147
Nyanza	Kisii	2	77	272	231	123	164	-	-	305	160	159
	Kisii	4	64	207	226	90	115	-	-	296	122	110
	Siaya	3	379	454	338	291	265	-	-	637	333	321
	Siaya	4	414	386	391	340	206	-	-	721	387	259
Western	Bungoma	2	312	254	239	44	97	-	-	386	94	168
	Bungoma	3	-92	-38	-67	-106	-89	-	-	-4	-77	-50
	Bungoma	4	155	183	109	-16	-34	-	-	221	24	15
	Kakamega	2	182	93	15	34	7	-	-	91	67	18
	Kakamega	3	42	5	-43	-106	-67	-	-	21	-86	-58
	Kakamega	4	5	170	94	24	67	-	-	188	55	81
	Vihiga	3	-21	-36	-55	-168	-123	-	-	-9	-164	-111
	Vihiga	4	143	95	96	-84	-17	-	-	168	-78	1
Central	Muranga	1	507	424	304	221	169	-	-	401	265	332
	Muranga	4	704	560	378	265	226	-	-	490	317	423
	Nyeri	1	583	411	245	200	161	-	-	331	253	245
	Nyeri	2	866	690	442	314	293	-	-	567	381	404
Rift Valley	Bomet	1	154	72	89	-35	-23	-	-	121	-57	-2
	Nakuru	1	-146	-85	-113	-146	-130	-	-	-54	-114	-97
	Nakuru	2	-98	48	-11	-147	-78	-	-	85	-107	-34
	Nakuru	4	-56	26	-22	-111	-67	-	-	69	-68	-22
	Narok	1	-330	-143	-192	-243	-205	-	-	-126	-251	-187
	Trans Nz.	4	95	-58	-17	-17	15	-	-	59	17	71
	Uasin Gis.	1	-80	15	-19	-101	-80	-	-	41	-78	-77
	Uasin Gis.	2	-18	50	50	-56	-32	-	-	133	-27	-28
Total sample			220	269	186	61	78	-	-	303	113	144

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Note: The acquisition price of nitrogen is used throughout. Buying price of maize not observed in 1997 and 2000.

8. OPTIMAL AND ACTUAL FERTILIZER USE DECISIONS

In this section, we investigate the relationship between observed fertilizer use and the profitability measures calculated in the last section. Using relative profitability measures, we (1) examine the trends in fertilizer use over time alongside MVCR and AVCR measures, (2) calculate optimal fertilizer use levels at two different profitability scenarios using production function estimates, and (3) examine the size of the gap between calculated optimal and observed fertilizer application rates. Then, using absolute profitability measures, we calculate the revenue that would be possible if farmers increased their fertilizer application rates from observed levels to calculated optimal fertilizer application rates.

8.1. Summary Statistics of Relative Fertilizer Profitability and Use

Appendix 5 contains MVCR and AVCR measures, the percentage of fertilized fields and the average nitrogen application rates by fertilizer users for each survey year, and estimated optimal fertilizer application rates by district and soil group. With the presence of various government fertilizer subsidy programs in 2010, the NAAIAP among them, we limit our calculations of actual use rates to households who purchased commercial fertilizer so as not to confuse overall fertilizer use trends with fertilizer supplied at a subsidized rate. From the sample of households that received a fertilizer subsidy in 2010 from any outlet (including NGOs), 34% of their maize fields were also fertilized with commercial fertilizer. In our total 2010 survey sample, about 150 households received a government fertilizer subsidy which is equivalent to less than 10% of all maize fields in our 2010 production function sample where fertilizer was applied in any amount. Notice, however, that the percent of maize fields with commercial fertilizer dropped in most locations in 2010. Further analysis is needed to determine if this drop is the result of crowding out of the private sector via government subsidy programs.

For the purposes of this paper and with recognition that our use of the term is narrow from a systems perspective, optimal nitrogen application rates are defined as where MVCR=1 and MVCR=2. Technically speaking, the economic optimal level of nitrogen for a risk neutral household is where MVCR=1 (where the marginal cost equals the marginal return), however, we also are interested in how a risk averse household should operate and, therefore, calculate a value where MVCR=2 as well, under the assumption that risk averse farmers require this return to the marginal unit of fertilizer applied on their maize field. Coefficients of variation on the optimal fertilizer use levels within the district and soil group level are large, with most between 20 and 50 percent. These values, therefore, should not necessarily be interpreted as precise but, instead, indicative of overall trends.

As previously mentioned, the areas with the highest MVCRs and AVCRs are in the Eastern Lowlands (Machakos, Makueni, and Mwingi districts) and Western Lowlands (Siaya district) which also happen to have the lowest percentage of fertilizer users and the lowest dosage rates, particularly in earlier survey years where access to fertilizer was hindered by the presence of very few retailers. We find an appreciable increase in the percentage of fertilized fields in these districts over time as well as an increase in the rate of commercial nitrogen applied per hectare by fertilizer users, with a particularly large jump in 2010. This suggests that the gap between where it is profitable to use and what households are actually doing has narrowed over time, although more so in the Eastern Province than the lowland areas of Nyanza. Furthermore, fertilizer users in Machakos, Makueni and Mwingi applied at average rates near what we calculate to be optimal where MVCR=2 (less than a 30% difference), although there is room to increase use by 5-10 kilograms per hectare in order to achieve the condition MVCR=1 (30-50% above current rates). These findings suggest that while fertilizer use has increased markedly in the last few years, there is likely still room for expansion in these lowlands areas of Kenya but, in the absence of other research against which to corroborate, further household level research should be conducted before prescribing fertilizer use at higher levels.

The next highest MVCR and AVCR levels are found in the highlands areas (Central Province, Meru in Eastern Province, Vihiga district in Western Province) where actual fertilizer use levels are considerably higher than the previous group. For example, Kisii district in the Western Highlands has some of the most constantly fertilized fields and at the highest levels. Within the highlands, there appears to be a divide between areas with volcanic soils (soil group one) and other soil types. Those with volcanic soils are more likely to use fertilizer (around 90%) and at higher levels. The MVCRs on the non-volcanic soils are higher, though, suggesting that fertilizer use could be profitably expanded in these areas. However, estimated optimal nitrogen application levels for most of the highlands are unreasonably high where MVCR=1 (>60 kilograms per hectare). The large difference between the MVCR=1 and MVCR=2 scenarios points to the lack of significant concavity in the production function for zone three due to high standard deviations across households for the variables included in the model, meaning changes in relative prices cause large changes in calculated optimal levels. With average application rates in 2010 around 30-40 kilograms per hectare in the highland areas, we cautiously conclude that fertilizer users are likely applying somewhere around optimal levels where profitable, although there appear to be opportunities to increase the percentage of farmers using fertilizer on maize in some areas, including the non-volcanic soil areas of Muranga district.

The remaining zones are the High Potential Maize and Western Transitional Zones, comprising Western and Rift Valley Provinces. Here, we find the lowest MVCRs and AVCRs across the board. On average, households see a gain in household income from using fertilizer (AVCR>1), however the last unit is generally at break-even profitable levels (MVCR=1) or not profitable at all (MVCR<1), meaning those households using fertilizer are already doing so at optimal or slightly more than optimal levels. Estimated optimal levels of nitrogen use where MVCR=1 are generally around or below the observed levels of fertilizer use on maize, providing further evidence that households may be over-using fertilizer in certain districts. Notice, however, that many of the districts exhibit zero optimal levels under the MVCR=2 scenario. This means that there is no positive value of nitrogen application that would make MVCR=2 given the marginal product of nitrogen and observed relative prices. There are some areas of Nakuru and Narok districts (Rift Valley) where, according to the data (which embody existing management practices), fertilizer use is estimated to be not profitable at all (AVCR<1); moreover, estimated optimal levels under both MVCR scenarios are zero. We do find relatively lower levels of fertilizer use in some of these areas (Narok), although some households appear to make the non-profitable choice to use fertilizer on maize fields. Nakuru district may be a case where we are not picking up on some important agro-ecological characteristic that makes farmers want to use fertilizer. Overall, households in these higher potential areas have approached levels of optimality in fertilizer use (consistent with the findings of Matsumoto and Yamano 2011) and perhaps more than optimal levels in some areas due to increasing soil acidity and micro-nutrient depletion where inorganic fertilizer has been used for a long time. Expanding fertilizer use beyond what is already observed is estimated to be unprofitable at market prices prevailing over the sample period in these areas.

Table 15. Percent of Fields with Sub-optimal N Application Rates in 2010 (Including Non-fertilized Fields)

Province	District	Soil group	MVCR=1 any amount below	MVCR=1 >25% below	MVCR=2 any amount below	MVCR=2 >25% below
Eastern	Machakos	3	87	87	87	87
	Makueni	3	87	70	74	62
	Meru	1	100	85	0	0
	Mwingi	2	95	90	95	90
	Mwingi	3	100	100	100	100
Nyanza	Kisii	2	100	87	13	0
	Kisii	4	96	71	0	0
	Siaya	3	97	94	61	42
	Siaya	4	85	85	85	69
Western	Bungoma	2	93	80	3	0
	Bungoma	3	8	0	0	0
	Bungoma	4	44	37	0	0
	Kakamega	2	50	18	0	0
	Kakamega	3	21	15	0	0
	Kakamega	4	98	87	0	0
	Vihiga	3	0	0	0	0
	Vihiga	4	50	38	0	0
Central	Muranga	1	100	95	71	57
	Muranga	4	100	94	100	100
	Nyeri	1	97	0	48	37
	Nyeri	2	100	0	94	82
Rift Valley	Bomet	1	32	0	0	0
	Nakuru	1	0	0	0	0
	Nakuru	2	0	0	0	0
	Nakuru	4	8	0	0	0
	Narok	1	0	0	0	0
	Trans Nz.	4	66	30	2	0
	Uasin Gis.	1	16	0	0	0
	Uasin Gis.	2	38	32	0	0
Total sample			61	48	19	16

Source: Authors' calculations from the Tegemeo Rural Household Survey.

As a final look at the gap between current fertilizer use levels and estimated optimal ones, Table 15 shows the percent of maize fields that were fertilized at any level below and more than 25% below the calculated optimal rates in 2010. Our skepticism remains about the accuracy of estimates for the highlands areas and, as usual, the heterogeneity in household and field characteristics should be considered before blindly applying more fertilizer given very high coefficients of variation in the optimal application estimates, however we believe this table provides a useful picture of where, in general, fertilizer application could profitably be expanded throughout these areas of Kenya.

Table 16. Mean N Application Rates for Fertilizer Users by Net Maize Buying or Selling Status

		1997	2000	2004	2007	2010	Optimal N MVCR=1	Optimal N MVCR=2
Eastern Lowlands	Net sell always	5.1	7.8	10.5	5.1	-	29.3	23.1
	Switch by year	6.3	11.4	11.7	14.3	25.3		
	Net buy always	7.7	10.8	8.7	17.3	22.5		
Western Lowlands	Net sell always	-	-	-	-	55.2	13.8	3.6
	Switch by year	0.7	0.9	10.2	9.3	19.1		
	Net buy always	-	29.6	8.9	9.1	29.2		
Western Transitional	Net sell always	53.5	46.8	53.8	67.0	58.2	41.0	5.1
	Switch by year	29.9	28.4	40.0	44.4	44.4		
	Net buy always	18.0	16.8	39.3	34.0	32.5		
High Potential Maize	Net sell always	35.0	45.0	47.7	43.9	49.7	35.0	4.5
	Switch by year	26.2	32.4	35.1	42.0	42.2		
	Net buy always	17.0	18.7	30.1	20.3	24.1		
Western Highlands	Net sell always	14.9	17.0	21.2	36.2	44.7	49.3	10.4
	Switch by year	15.2	17.3	28.3	27.4	39.0		
	Net buy always	16.4	8.2	22.3	21.0	30.9		
Central Highlands	Net sell always	45.3	30.0	26.1	31.3	28.4	79.6	26.9
	Switch by year	28.4	27.4	28.7	23.9	30.7		
	Net buy always	29.1	27.1	21.5	26.0	35.7		
Total sample	Net sell always	35.6	42.2	44.2	43.8	49.6	41.2	9.8
	Switch by year	24.2	27.3	31.7	35.2	38.8		
	Net buy always	19.7	17.8	22.2	23.1	29.1		

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Again, Eastern and Nyanza provinces remain under-fertilized at both levels of risk, while the higher potential Rift Valley and some areas of Western province have reached and possibly extended beyond optimal levels. Over the entire sample, only about 16% of maize fields in 2010 were fertilized at levels less than 25% below our calculated optimal values where MVCR=2.

In our tables, observed application rates are averaged across all maize fields and households. However, when disaggregating results by net maize buying and selling households, trends are much more pronounced. Table 16 splits average application rates for fertilizer users by net buying and selling status by zone and year. Because the sample of households (and the districts from which they came) included in a given zone can change between years, we chose to focus on trends across the full sample. Households that are consistent net sellers always the highest average fertilizer application rates, consistent net buyers have the lowest application rates, and households switching between the two (most households in our data) have application rates between the two. Across the sample, average application rates for fertilizer users are about 70% higher for consistent net sellers than net buyers. Still, all three groups show a steady increase in application rates over time, with net sellers being more likely to apply fertilizer at rates beyond what we estimate to be profitable.

8.2. Revenue Added From Fertilizer Use At Current And Optimal Levels

Here, we return to the discussion of absolute levels of fertilizer profitability by calculating the household revenue from maize production added through the use of nitrogen fertilizer, both at observed use rates and at estimated optimal levels. This calculation is a measure of the value of the additional output provided by fertilizer use minus the cost of fertilizer at the chosen use level. Table 17 shows the revenue added from fertilizer application using the acquisition price of nitrogen and maize price specific to the household (either selling or buying). These values represent changes in total household income level as a result of fertilizer use at the levels observed by farmers and at calculated optimal application rates where MVCR=1 and MVCR=2.

The negative revenue values observed in some areas and years occur when the additional expense of using fertilizer is higher than the additional value of maize output. As with the rest of this analysis, standard errors and deviations are very high; the coefficients of variation of average revenue as calculated with actual use levels are often around or over 100% within a given district and soil group. As such, these values should be interpreted as averages, realizing that there is high variability across farms in these districts. Even so, one important finding is the huge changes in revenues between years, even when fertilizer use levels remain relatively constant. For instance, a comparison of revenues from actual fertilizer use levels in 2004 and 2007 shows that, in many places, revenues were cut in half in 2007 and sometimes negative due to an increase in fertilizer prices in this year. The relative measures of profitability show that 2007 was a relatively less profitable year; however, these profitability measures, which are representative of actual household income, show a more drastic picture of how those price changes in 2007 affected overall revenues.

Comparing these measures to the rates of application values in Appendix 5 further illuminates the differences between relative and absolute profitability measures. In the lowlands, this table shows that there are still huge revenue gains to increasing fertilizer use to estimated optimal levels. Recall, however, that because most households in these areas are net buyers of maize, maize output is valued at the generally higher level of maize purchasing prices, which translates into relatively higher revenue values. In the higher potential areas, where households sometimes applied more than the estimated optimal level of fertilizer use, this table shows how revenue could improve by reducing fertilizer application rates. Furthermore, gains to changing fertilizer application rates are not nearly as large as they are in the lowlands areas, further evidence that most households in the high-potential zones are already applying near optimal rates.

Table 17. Revenue Added from the Application of Nitrogen (2010 Prices, KSH)

District	Soil group	Actual use rates			Optimal use rates (MVCR=1)			Optimal use rates (MVCR=2)		
		2004	2007	2010	2004	2007	2010	2004	2007	2010
Machakos	3	8,683	8,810	17,128	16,944	16,022	28,582	16,023	15,042	27,211
Makueni	3	10,828	8,904	17,666	19,672	16,324	21,688	19,120	15,607	21,079
Meru	1	9,461	5,027	5,332	18,385	7,635	7,613	12,542	1,094	600
Mwingi	2	39,764	19,672	28,678	56,802	37,536	34,122	55,742	36,522	33,556
Mwingi	3	3,379	16,307	30,541	13,429	25,755	43,233	12,358	24,702	42,667
Kisii	2	13,799	5,530	9,157	21,196	8,149	12,978	15,154	629	6,524
Kisii	4	7,963	4,127	7,641	14,027	5,849	9,778	8,679	279	2,931
Siaya	3	6,605	2,981	7,944	9,284	4,659	13,206	6,608	2,239	11,752
Siaya	4	11,107	7,755	12,114	14,997	9,998	21,738	11,894	7,084	20,008
Bungoma	2	13,398	7,829	8,956	22,582	9186	11,654	16,053	1,860	4,669
Bungoma	3	3,019	-1,584	-215	4,623	436	1,215	45	0	0
Bungoma	4	12,859	4,285	4,833	16,972	5,426	5,876	9,926	201	246
Kakamega	2	14,272	7,086	9,065	16,228	8,151	9,943	7,498	1,040	3,241
Kakamega	3	2,441	-968	1,134	5,129	1,626	2,696	249	0	0
Kakamega	4	4,730	1,778	2,409	6,534	2,521	3,220	763	194	0
Vihiga	3	781	-3,874	-2,500	1,849	49	291	51	0	0
Vihiga	4	5,028	-1,065	2,333	7,540	175	2,679	1,671	0	0
Muranga	1	8,727	4,162	12,394	19,622	11,671	20,046	13,301	4,840	14,712
Muranga	4	5,800	5,700	5,970	22,487	16,402	17,546	15,178	7,710	10,957
Nyeri	1	14,854	7,320	7,638	23,211	13,916	13,975	16,497	6,544	7,120
Nyeri	2	14,184	9,513	14,109	33,231	21,839	27,421	23,073	12,042	20,611
Bomet	1	4,180	211	907	5,144	515	1,024	596	0	0
Nakuru	1	-699	-2,036	-1,815	422	35	156	0	0	0
Nakuru	2	2,442	-2,021	107	2,885	3	279	17	0	0
Nakuru	4	1,903	-963	123	2,245	5	758	162	0	0
Narok	1	-1,618	-1,976	-2,653	0	0	0	0	0	0
Trans Nz.	4	6,528	5,156	7,182	7,760	6,195	7,958	1,584	1,290	3,138
Uasin Gis.	1	2,748	-1,833	-731	3,591	691	1,102	561	0	0
Uasin Gis.	2	10,610	3,808	3,460	13,341	5,062	4,969	7,057	450	507
Total sample		7,559	2,823	5,596	12,081	5,271	8,191	7,374	1,857	4,388

Source: Authors' calculations from the Tegemeo Rural Household Survey.

9. CONCLUSIONS

While other studies have provided micro-level evidence that there is still significant potential to exploit the use of fertilizer in specific areas of Kenya, this paper adds to this literature by providing a national level assessment of fertilizer profitability and use patterns over time and across maize-producing districts in Kenya to help guide fertilizer policy decisions in an environment where heavy subsidy programs are touted as necessary for improving smallholder incomes and national food security. We find fertilizer use at commercial prices to be profitable across a large portion of Kenya's maize producing areas, particularly as transportation costs and the distance necessary to travel to the nearest fertilizer retailer have fallen dramatically over time. Furthermore, we find household commercial purchases are consistently and steadily increasing towards risk-adjusted economically optimal levels of fertilizer application over the survey years. Over the entire sample, only about 16% of maize fields in 2010 were fertilized at levels less than 25% below our calculated optimal values where MVCR=2.

In the lowlands areas, where rainfall levels are substantially lower and fertilizer was introduced much more recently, we find fertilizer to be profitable and households increasing their use significantly in the last few years. We find that about 20% of maize fields in some lowlands districts but 65% in others remained unfertilized in 2010, and that households in some districts are using around 90% of the nitrogen computed to be optimal where MVCR=2. Conversely, we find that most households in the high potential districts of Western Province and Rift Valley use fertilizer at high application rates and that some households might actually benefit from the reduction in the nitrogen amount applied per hectare.

Furthermore, because relative nitrogen to maize prices do not vary considerably over time, we also show how changes in absolute prices meant that total revenue from fertilizer use varied much more substantially between years. High fertilizer prices in 2007 meant farmers' inflation-adjusted revenues, even where application rates remained unchanged, were cut in half compared to 2004 levels. Moreover, while optimal nitrogen application rates are calculated from relative profitability measures, high standard deviations in revenue values between years signal a higher risk involved in always choosing optimal fertilizer rates. This suggests that policy makers should consider both input and output prices, the gap between output buying and selling prices, and how all prices move in relation to one another when developing agricultural policy aimed at incentivizing input intensification, particularly given the large number of households switching between net maize buyer and seller status over time.

While cognizant of the fact that we study average trends and that households and field level heterogeneity should be considered when making decisions on fertilizer use, we find that tremendous additional expansion of average fertilizer application rates on maize in Kenya should not necessarily be sought after unless it is possible to raise the average physical response rates of maize to fertilizer. This brings into focus the importance of complementary inputs and attention to detail in soil conditions (like Marenya and Barrett 2009) as part of an overall strategy to raise the efficiency of farmers' use of fertilizer. In other parts of the world, practices that have helped raise the average physical response rates of fertilizer include soil testing, more specific fertilizer blends appropriate for farmers' specific conditions, investment in drainage to prevent water-logging, ameliorating soil acidity conditions which impede plant uptake of phosphorus, deep placement application, and appropriate plant populations for farmers' specific micro-locations. This implies, at the margin, greater public investment in farmer extension and training programs. In the few areas of Kenya where fertilizer use is still below calculated optimal levels, policy mechanisms may be appropriate to help farmers reach economically optimal rates, so long as they do not undermine farmers' incentive to use commercial fertilizer (like Duflo, Kremer, and Robinson 2011) and do improve household income in the long run.

APPENDICES

Appendix 1. Distribution of Variables in Production Function across All Maize Fields and Years

Variable	Mean	Standard Deviation	
		Overall	Within
Maize yield computed using the Liu and Myers output index (per hectare on field)	2707	1778	1422
Nitrogen content (N) of applied fertilizers (kg/hectare on field)	25.2	26.5	17.5
Phosphorous content (P) of applied fertilizers (kg/hectare on field)	15.0	13.5	8.8
Seed rate (kg/hectare on field)	22.5	8.4	7.0
Number of hectares in given maize field	0.61	0.65	0.42
Manure or compost applied to field=1	0.30	0.46	0.34
New hybrid maize seed used on field=1	0.76	0.43	0.28
Legume intercropped with maize on field=1	0.14	0.35	0.28
Number of crops included on field (range 1-7)	2.8	1.6	1.4
Proportion of 20-day periods when rainfall was less than 40 mm (range 0-1)	0.24	0.22	0.13
Average value of assets at household level across years per hectare (in 1000 KSH)	438	517	0
Other controls (fixed effects)			
FAO soil classification: Cambisols, Ferralsols, Phaeozems, Luvisols, Greyzems, Podzols, Regosols, Rankers			
Survey year			
District			
Other interactions with nitrogen			
Soils groups: 1=volcanic, 2=high humus or highly productive, 3=Rankers with high sand, 4=Rankers with less sand			
Agro-ecological zone groups: 1=lowlands, 2=transitional and high potential, 3=highlands			

Source: Authors’ calculations from the Tegemeo Rural Household Survey.

Appendix 2. Averages of Select Production Function Variables by District and Soil Group

Province	District	Soil group	Yield (kg/ha)	N (kg/ha)	P (kg/ha)	P/N ratio	Fert fields (%)	Manure (%)	Hybrid (%)	Rain total (mm)	Rain stress (%)
Coast	Kilifi	3	1,336	7.4	5.3	0.60	10	29	32	252	56
	Kwale	6	1,156	0.9	0.4	0.44	2	29	9	242	69
	Taita Tav.	5	949	-	-	-	0	31	26	283	50
Eastern	Kitui	3	1,312	-	-	-	0	34	12	289	51
	Machakos	3	1,900	12.9	7.7	0.76	43	59	16	313	47
	Makueni	3	1,607	14.9	5.1	0.36	62	70	46	271	49
	Meru	1	3,145	25.2	14.8	0.66	89	60	98	545	27
	Mwingi	2	1,703	16.6	10.4	0.60	10	69	30	326	40
	Mwingi	3	2,229	10.8	10.6	0.90	19	68	45	334	38
Nyanza	Kisii	2	2,242	29.2	22.5	0.93	98	10	93	889	12
	Kisii	4	2,309	24.2	19.1	0.92	98	6	89	858	14
	Kisumu	5	1,204	15.3	10.8	0.75	3	16	32	719	12
	Siaya	3	1,574	13.9	11.8	1.0	14	36	8	710	16
	Siaya	4	2,008	19.4	16.3	1.0	24	49	23	719	16
	Siaya	5	1,431	5.8	3.7	0.59	3	12	10	655	19
Western	Bungoma	2	2,724	37.3	23.8	0.80	91	18	90	848	6
	Bungoma	3	3,507	45.7	24.2	0.68	90	17	96	828	8
	Bungoma	4	2,733	45.6	22.3	0.68	89	18	94	805	6
	Kakamega	2	3,864	64.4	29.3	0.54	96	15	91	746	11
	Kakamega	3	2,508	45.7	22.4	0.64	64	25	92	876	4
	Kakamega	4	2,453	24.2	10.5	0.56	54	46	44	869	5
	Vihiga	3	2,689	26.5	13.9	0.67	71	33	48	891	7
	Vihiga	4	2,795	26.1	14.8	0.71	87	39	57	893	8
Central	Muranga	1	2,554	28.0	13.4	0.59	91	55	69	378	60
	Muranga	4	2,598	19.1	15.4	0.83	87	50	63	377	56
	Nyeri	1	3,110	31.6	11.0	0.44	93	68	78	381	54
	Nyeri	2	2,807	33.6	12.6	0.41	68	59	68	348	58
Rift Valley	Bomet	1	3,119	21.7	23.3	1.1	100	9	97	858	22
	Nakuru	1	2,891	23.6	22.0	1.0	94	18	98	538	40
	Nakuru	2	1,775	20.1	17.3	1.0	72	17	52	497	50
	Nakuru	4	3,012	20.5	20.6	1.1	97	18	92	527	36
	Narok	1	3,029	11.6	12.3	1.1	28	10	99	469	56
	Narok	2	3,277	11.1	12.4	1.1	3	9	99	484	55
	Trans Nz.	4	3,805	53.8	27.1	0.61	89	17	94	676	18
	Uasin Gis.	1	3,585	36.5	20.5	0.63	86	10	95	618	24
	Uasin Gis.	2	3,048	51.4	25.6	0.62	95	14	91	600	28
	Laikipia	2	2,125	15.0	13.7	0.98	4	56	66	285	62
	Laikipia	5	2,207	-	-	-	0	45	48	289	60

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Note: N per hectare, P per hectare, and P to N ratio values represent averages of fertilizer users (excludes non-users). District and soil group combinations in gray are excluded from estimation due to (1) very low rainfall, (2) poor soil conditions (i.e., soil groups 5 and 6) or (3) practically no fertilizer users (districts with less than 10% fertilized fields). For information on soil groups, see Table 6. All field level observations included in table, not just those used in production function estimation.

Appendix 3. Production Function Estimation Results

	Coefficient Estimate (Robust Standard Error)
N*zone1 (lowlands)	25.45 (17.46)
N*zone2 (high potential areas)	17.58*** (4.90)
N*zone3 (highlands)	14.10** (6.63)
N^2*zone1 (lowlands)	-0.724*** (0.21)
N^2*zone2 (high potential areas)	-0.0938** (0.05)
N^2*zone3 (highlands)	-0.0889 (0.08)
N*P*zone1 (lowlands)	1.379*** (0.42)
N*P*zone2 (high potential areas)	0.256*** (0.08)
N*P*zone3 (highlands)	0.218 (0.15)
N*soil1 (volcanic landform soils)	-2.712 (3.83)
N*soil2 (high humus, productivity soils)	2.317 (3.11)
N*soil3 (Rankers with more sand)	-4.733 (3.17)
N*soil4 (Rankers with less sand)	Base
N*rainstress*zone1 (lowlands)	41.00* (21.43)
N*rainstress*zone2 (high potential areas)	-18.66** (7.42)
N*rainstress*zone3 (highlands)	17.82* (9.22)
Seed rate (kg/ha)	57.17*** (9.80)
Seed rate^2	-0.495** (0.19)
Hectares in field	-944.5*** (99.94)
Hectares in field^2	135.9*** (21.29)
Asset (in 1000 KSH)	0.526*** (0.14)
Asset^2	-0.000105** (<0.01)
Manure on field (=1)	189.2*** (64.16)
Hybrid maize seed used (=1)	568.7*** (92.25)
Rainfall stress (0-1: portion of period<40mm rain)	-1,457*** (269.9)
Hybrid*rainstress	-307.5 (250.9)
Legume intercropped with maize (=1)	-97.99 (79.23)
1 crop on field (maize monocropped) (=1)	Base
2 crops on field (=1)	315.2*** (63.36)
3 crops on field (=1)	636.2*** (81.44)
4 crops on field (=1)	1,025*** (101.4)
5 crops on field (=1)	1,122*** (105.6)
6 crops on field (=1)	1,573*** (131.8)
7 crops on field (=1)	1,700*** (142.6)
District fixed effects	Yes
FAO soil-type fixed effects	Yes
Year fixed effects	Yes
Mundlak-Chamberlain device:	
mean N (kg/ha)	6.537* (3.51)
mean P (kg/ha)	1.859 (7.23)
mean seed rate (kg/ha)	6.801 (7.46)
mean hectares in field (ha)	279.3*** (95.16)
mean rainfall stress (0-1: portion of period<40mm rain)	1,240* (653.1)
mean manure (=1)	69.76 (135.6)
mean hybrid (=1)	-35.85 (153.4)
mean legume (=1)	-411.7** (197.5)
mean number crops on field (1-7)	-73.55 (45.52)
Constant	-199.4 (551.7)
R-squared	0.358
Number of households	906
Number of maize fields	4714

Note: ***, **, * significant at the 1%, 5%, and 10% levels respectively.

Appendix 4. Expected Marginal Products of Nitrogen and Associated Standard Errors by District and Soil Group

	District	Soil group	Zone group	Number of households	Expected marginal product (MP)	Standard error (SE)	Ratio of SE/MP
Eastern	Machakos	3	1	19	41	13.2	0.32
	Makueni	3	1	56	36	13.9	0.39
	Meru	1	3	51	18	4.1	0.23
	Mwingi	2	1	15	48	11.9	0.25
	Mwingi	3	1	13	42	12.0	0.29
Nyanza	Kisii	2	3	25	18	4.4	0.24
	Kisii	4	3	59	16	4.1	0.26
	Siaya	3	1	27	29	5.8	0.20
	Siaya	4	1	14	32	4.8	0.15
Western	Bungoma	2	2	38	18	3.1	0.17
	Bungoma	3	2	13	9	2.7	0.30
	Bungoma	4	2	30	14	2.6	0.19
	Kakamega	2	2	24	14	2.8	0.20
	Kakamega	3	2	60	10	3.1	0.31
	Kakamega	4	2	49	15	3.9	0.26
	Vihiga	3	3	36	9	5.5	0.61
	Vihiga	4	3	15	14	4.8	0.34
Central	Muranga	1	3	25	20	4.6	0.23
	Muranga	4	3	4	24	5.6	0.23
	Nyeri	1	3	35	19	4.7	0.25
	Nyeri	2	3	17	26	6.1	0.23
Rift Valley	Bomet	1	2	36	15	3.9	0.26
	Nakuru	1	2	30	9	3.9	0.43
	Nakuru	2	2	23	12	4.3	0.36
	Nakuru	4	2	44	12	3.6	0.30
	Narok	1	2	12	6	5.0	0.83
	Trans Nz.	4	2	40	11	2.6	0.24
	Uasin Gis.	1	2	41	9	3.6	0.40
	Uasin Gis.	2	2	55	12	2.7	0.23

Source: Authors' calculations from the Tegemeo Rural Household Survey.

Note: Values in table are averaged across the survey years whereas values used to calculate MVCRs and AVCRs in the text are year-specific.

Appendix 5. Relative Nitrogen Profitability and Current Use Levels by District and Soil Group

	District	Soil group	Mean across survey years				Estimated optimal N (kg/ha)		Mean observed commercial N (kg/ha, excludes zeros)					% maize fields with commercial N application				
			MP	AP	MVCR	AVCR	MVCR=2	MVCR=1	1997	2000	2004	2007	2010	1997	2000	2004	2007	2010
Eastern	Machakos	3	41	44	3.5	4.2	24.7	32.3	3.9	3.2	13.4	11.4	21.1	24	17	58	67	80
	Makueni	3	36	42	4.3	5.2	25.9	31.6	8.4	13.7	10.5	15.6	24.7	39	36	77	70	51
	Meru	1	18	20	1.8	2.1	17.9	70.7	24.7	24.3	24.9	27.6	29.8	89	93	95	90	85
	Mwingi	2	48	55	5.4	6.5	37.8	44.0	2.3	5.4	22.2	13.3	29.5	14	9	4	11	19
	Mwingi	3	42	50	4.7	5.6	27.1	33.6	1.8	11.1	3.2	13.1	22.2	11	7	29	14	30
Nyanza	Kisii	2	18	21	1.8	2.1	23.1	76.1	20.8	16.9	36.7	27.5	36.8	86	100	100	100	93
	Kisii	4	16	18	1.7	1.9	12.8	62.9	14.6	15.7	23.2	26.5	42.9	89	98	99	100	87
	Siaya	3	29	36	1.9	2.4	10.7	21.3	0	0	8.6	6.5	20.1	0	0	9	28	25
	Siaya	4	32	41	1.9	2.5	14.6	26.6	0.7	15.3	11.1	12.0	39.8	7	14	20	47	31
Western	Bungoma	2	18	21	1.7	2.1	22.2	76.9	22.4	33.9	34.0	51.4	42.7	86	88	96	95	85
	Bungoma	3	9	13	0.7	1.1	0.1	26.6	38.1	38.5	57.0	41.1	43.4	79	100	79	100	100
	Bungoma	4	14	18	1.3	1.7	12.8	63.1	32.1	34.8	48.1	53.8	54.4	73	88	96	93	85
	Kakamega	2	14	19	1.1	1.6	11.9	70.6	46.9	64.2	72.3	55.5	65.2	88	96	97	93	93
	Kakamega	3	10	14	0.8	1.1	0.2	32.3	32.0	30.8	49.2	52.4	51.1	32	57	67	78	81
	Kakamega	4	15	16	1.3	1.5	1.0	38.9	35.4	18.3	26.5	25.0	21.7	19	62	58	75	63
	Vihiga	3	9	11	0.7	0.9	0.1	9.9	11.2	18.4	28.3	28.4	34.3	53	52	71	87	86
	Vihiga	4	14	16	1.1	1.3	1.7	30.5	16.5	26.4	25.1	24.2	34.8	53	71	100	93	94
Central	Muranga	1	20	23	2.2	2.4	33.6	84.6	38.0	31.6	22.1	15.3	38.6	95	96	89	93	76
	Muranga	4	24	26	2.4	2.5	31.9	90.1	18.4	23.9	12.3	17.8	17.2	100	100	100	75	50
	Nyeri	1	19	22	2.0	2.3	28.4	81.9	30.0	30.8	37.3	26.4	29.6	86	88	97	96	74
	Nyeri	2	26	27	2.5	2.7	45.9	105.7	34.8	27.5	25.0	27.3	34.9	67	30	73	63	53
Rift Valley	Bomet	1	15	17	1.0	1.2	0.4	22.1	26.1	19.5	20.8	18.7	22.1	100	100	100	100	100
	Nakuru	1	9	11	0.6	0.8	0	5.8	22.0	22.7	23.6	22.8	35.8	97	92	95	94	77
	Nakuru	2	12	15	0.9	1.0	0.1	16.9	19.7	17.3	22.8	22.7	17.3	68	79	81	67	38
	Nakuru	4	12	14	0.9	1.0	0.2	13.7	20.5	20.0	21.6	17.3	24.6	95	96	98	98	88
	Narok	1	6	8	0.3	0.5	0	0	11.1	11.5	13.0	9.3	15.9	8	40	24	53	18
	Trans Nz.	4	11	16	1.1	1.6	7.5	57.0	40.0	53.8	55.0	59.5	52.8	69	89	92	90	72
	Uasin Gis.	1	9	13	0.8	1.1	0.5	22.7	23.2	32.8	36.4	44.5	41.0	54	88	92	91	75
	Uasin Gis.	2	12	17	1.0	1.5	7.2	54.9	29.8	49.8	51.1	64.4	56.0	88	98	95	96	96

Source: Authors' calculations from the Tegemeo Rural Household Survey.

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