Are Farmers Under-Utilizing Fertilizer? Evidence from Kenya

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Abstract

It is widely perceived that sub-Saharan African farmers are under-utilizing inorganic fertilizer. Using five waves of nationwide household survey data from Kenya collected over thirteen years, we estimate the profitability of nitrogen application on maize and compare to observed use patterns. In general, we find that farmers have been consistently and steadily increasing nitrogen application rates towards rates where the risk-adjusted marginal revenue equals the marginal cost of fertilizer application and that, in some areas, farmers have reached and possibly surpassed that point. Fertilizer use rates may nevertheless be profitably raised in many areas, but doing so will require the adoption of complementary practices that raise response rates to nitrogen application.

1. Introduction

In the last 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.

This paper provides a policy-relevant assessment of fertilizer profitability and use in Kenya. 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 et al. 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 et al. 2006, 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. Answering these questions 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. While our study is specific to Kenya, researchers and policy makers from other countries where fertilizer might be important for improving smallholder income and national food security can benefit from the framework we develop for investigating the appropriateness of fertilizer use expansion, particularly in countries considering the use of fertilizer subsidies.

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 et al. (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 et al. (2008, 2010) 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 these 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: (i) How does the response of maize to fertilizer application rates vary across Kenya? (ii) Are households in Kenya using fertilizer on maize fields where it is profitable to do so, and is there room for profitably expanding fertilizer use in certain areas? (iii) What are economically optimal levels of fertilizer application, and does a "gap" exist between observed and estimated optimal levels? The remainder of the text will proceed as follows: Section 2 describes trends in fertilizer use and prices in Kenya; Section 3 describes the data set and sample; Section 4 includes our conceptual framework and describes the methods used to examine fertilizer profitability; Section 5 details how we estimate maize response to fertilizer application from a production function; Section 6 reports the results of various profitability measures; Section 7 includes a comparison between estimated optimal and actual fertilizer use rates; and Section 8 provides conclusions and policy recommendations.

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

Like many other African countries, virtually all fertilizer consumed in Kenya is imported. Fertilizer price data from the Ministry of Agriculture show that prices in Mombasa, representing international prices plus port charges, have stayed relatively constant over time (apart from a large spike in international prices in 2007/08) while prices in Nakuru, a major agriculture market in the Rift Valley, 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 observed narrowing of margins: (1) less expensive transportation options after the introduction of brokerage services, (2) private importers moving to international 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 inflation-adjusted fertilizer prices have fallen, despite a 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 incentive to use fertilizer. Using monthly real prices of maize grain at two major wholesale markets in Kenya (Nakuru and Eldoret) we find that, like fertilizer prices, real maize prices also have fallen over time, even with considerable price increases in 2000, 2004, and 2009. 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. The remainder of this paper seeks to tell the more complete story of fertilizer profitability across Kenya.

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 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” for simplicity), 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 percent 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 percent are monocropped. On average across years, about 75 percent of households have one maize field per year, 20 percent have two, and the remaining 5 percent 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 4714 maize fields over five survey years.

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

[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).

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 percent 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}. 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:

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

where Y_{ijt} is the output index of maize field i at household j at time t, 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.

The framing of functional form choice in agronomic and economic production function studies has generated a large literature. Berck and Helfand (1990) develop the theme that heterogeneity in nutrient inputs to the plant as a result of spatial and temporal variation typically leads to a smooth "aggregate" production function at the field level irrespective of the functional form for a given year and point within a field. Kastens et. al (2005) provide an example using the response of winter wheat to the application rate of nitrogen from a long-term trial. The annual responses were linear up to a plateau but varied from year to year. They point out that the farmer does not know which year will be "drawn" from nature so a smoothed function that captures the temporal variability is an appropriate approach. A quadratic form is widely used for crop yield response to nutrient functions (e.g., Traxler and Byerlee 1993; Kouka et al. 1995) and can be viewed as an approximation to the underlying functional form.

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 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 instead of treating the omitted variable as a parameter to estimate:

$$c_j = \tau + \overline{x}_k \gamma + a_{ijt} \quad (3)$$

where $\overline{x}_k$ is a vector of average values of each input x_k at the household level j across all waves of the panel. If the household knows c_j and is an optimizer, the level of all other variables x_k and z_k will be responsive to c_j if there are external drivers such as price that change across waves or a shock followed by learning and execution. 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 ordinary least squares (OLS). 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.

Using estimates from the production function, we calculate the expected marginal and average physical products of fertilizer (MPP and APP) and, subsequently, the expected marginal and average value cost ratios (MVCR and AVCR) of the following forms:

$$E(MVCR_{fijt}) = \frac{E(p_{yt}) * E(MPP_{xijt})}{w_{fijt}} \qquad (4)$$

$$E(AVCR_{fijt}) = \frac{E(p_{yt}) * E(APP_{xijt})}{w_{fijt}} \quad (5)$$

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 et al. 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):

$$E(MVCR_{fijt}) \geq 1 + \rho \quad (6)$$

$$E(AVCR_{fijt}) \geq 1 + \rho \quad (7)$$

Then, because MVCRs and AVCRs are measures of relatively profitability (i.e., use the ratio of input and output prices), we compute an additional measure of absolute profitability, the total revenue on maize fields added from the use of fertilizer (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

[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.

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. This value is computed as:

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

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

5. 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 1 includes a complete list of the variables included in the production function, what they measure, and the associated descriptive statistics. 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. 23 percent of total fields were dropped after applying these exclusion rules.

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,[4] the two nutrients limiting in most SSA soils (Stoorvogel and Smaling 1990; Sanchez et al. 1997), components 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 percent of the applied phosphorous in the first year of application (Griffith), 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).[5] 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

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

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 both 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. Then, using data on the 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: (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.[6] 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.

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

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.[7] 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.[8]

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 percent of farms use fertilizer in some amount, and most farms chose to use both hybrid seeds and fertilizer together.[9] Our estimation approach was to include a dummy variable for seed type; we did not attempt to parse

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

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

[9] The principal exceptions are (1) Narok district (Rift Valley) where over 90 percent of fields had hybrids but at most 50 percent were fertilized and (2) Mwingi district (Eastern Province) where hybrid use has increased from 5 to 75 percent but fertilizer use has remained low.

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 et al. 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 et al. 2006) 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.

5.1. Econometric results

The production function estimation results can be found in Table 2.[10] 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

[10] 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.

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 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. The asset variable, measured per hectare, exhibits a positive and diminishing relationship, meaning more asset-rich households (per hectare) up to about the 99th percentile have a yield advantage, likely due to the higher soil organic matter levels.

5.2. 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.[11] Table 4 includes the marginal and average products of applied nitrogen averaged by district and soil group (for standard errors of the marginal products, see Table 3). 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 et al. 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.

[11] 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.

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.

6. Profitability of Fertilizer Use

Using the marginal and average products of nitrogen at the district and soil group level, the profitability of fertilizer is calculated in this section 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 (or 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. The next two sections provide more detail on how these prices are calculated, followed by the results of the profitability analysis.

6.1. Price of nitrogen

We compute a district-averaged price of nitrogen using the observed price paid by households for DAP and CAN.[12] 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 et al. 1991; Key et al. 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. 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 nitrogen.

The average distance from the household to the nearest fertilizer dealer fell considerably over the survey years in Kenya, particularly in the three lowlands zones. The average reduction in real transport costs across zones was estimated at 35 percent between 1997 and 2010, varying between 17 percent in the High Potential Maize area to over 50 percent in the Western Lowlands, providing further justification for incorporating transport costs into the full acquisition cost. The year with the shortest average distance to the nearest fertilizer dealer was 2007, not

[12] All prices used in this analysis are adjusted to 2010 levels using the CPI from the Ministry of Finance in Kenya.

2010, where real transport costs were an average 45 percent lower than those estimated for 1997. In some areas and years, the cost of transport creates a significant wedge between the market and acquisition prices of nitrogen. On average, though, the cost of transport adds between 50 and 100 KSH to the market price of fertilizer. Over the 1997-2010 period for the entire sample, about 20 to 22 percent of the farm-gate acquisition price is accounted for by transport costs from the retail purchase point to the farm, covering between 3 and 8 kilometers on average.

6.2. Price of maize

While fertilizer prices and transport costs are known at the time of purchase, the price for which maize will sell on the market months later is not known to the farmer. We use *expected* maize selling prices as calculated by Muyanga (forthcoming) who regresses 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.[13] With estimates at the household level, we average to the district level and use these values as expected maize selling prices in our profitability analysis.

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 this 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 (Jayne et al. 2001). In this dataset, we find between 38 and 57 percent of households are net buyers in any given survey year, with the Eastern Lowlands as high as 80 percent in 1997 and the High Potential Maize zone as low as 19

[13] These variables include current and lagged NCPB (government maize board) and regional market prices, distances from the regional markets, and the type of buyer to which farmers normally sell their maize.

percent in 2007. For the majority of households, then, a better measure of the opportunity cost of growing maize is 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 buying prices to arrive at an expected buying price. Because we do not observe maize buying prices before 2004, we predict these values using an average observed difference between expected maize buying and selling prices in the last three survey years. Like the nitrogen prices, maize prices are averaged at the district level. In general, the buying price of maize is between 5 and 10 KSH more than the selling price (16 to 22 percent difference), with a much larger wedge in 2004 than other years.[14]

6.3. Relative fertilizer profitability measures

Before looking specifically at the profitability calculations, we calculate the relative price of nitrogen to maize. 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. 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, but still not in line with 2000 and 2004 levels. This trend is somewhat amplified when adding the transport cost of fertilizer; 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

[14] One value we do not capture 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. In 2010, over 70 percent of households sold their maize directly at the farm-gate. Furthermore, we never observe how far a household needs to travel to purchase maize. For these reasons, the transport costs of selling and purchasing maize are not included in our analysis.

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 1 shows how the relative accessibility of fertilizer has changed over the survey years for the entire sample. While there are statistically significant differences across districts for most of the variables included in this plot, this figure shows how sample-averaged real prices of nitrogen and maize and distance traveled to the nearest fertilizer dealer in 2010 were about half of what they were in 1997. 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 provides further justification for investigating the difference between relative profitability (MVCR and AVCR measures) and absolute profitability (income gains from nitrogen use).

MVCRs and AVCRs are calculated by year and averaged across each district and soil group; Table 4 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 4 and 6, this suggests vast increases in household income from the use of fertilizer on maize and that the last unit of fertilizer was very profitable, implying that households are not quite at 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 2). Interestingly, the least most profitable zone, on average, is the High Potential Maize zone where AVCR values are above 1 but MVCR values are either at 1, 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 rate of fertilizer application might be the most profitable strategy for farmers.

7. 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, and (3) examine the size of the "gap" between calculated optimal and observed fertilizer application rates. Then, as a measure of absolute profitability, we calculate the revenue levels possible should farmers increase their nitrogen application rates from observed to calculated optimal ones.

7.1. Summary statistics of relative fertilizer profitability and use

Table 4 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 percent 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 percent 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 very large and range from 7 and 142 percent, with most values between 20 and 50. 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 percent difference), although there is room to increase use by 5-10 kilograms per hectare in order to achieve the condition MVCR=1 (30-50 percent 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 percent) 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.

7.2. Revenue added from fertilizer use at current and optimal levels

The MVCR and AVCR estimates 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 substantially over the survey years, the relative profitability of fertilizer is unable to capture the actual monetary returns to fertilizer use experienced in a given year, an important consideration for smallholder farmers. Because of this, we calculate an additional absolute profitability measure, the household revenue from maize production added through the use of nitrogen fertilizer, using the acquisition price of nitrogen and both the selling and buying prices of maize. This calculation is a measure of the value of the additional output provided by fertilizer application minus the cost of fertilizer at the chosen use level. Figure 2 shows the sample-averaged revenue added from nitrogen application using the acquisition price of nitrogen and maize price specific to the household (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.

Even at a high level of aggregation, Figure 2 shows how inflation-adjusted revenue values can change considerably between years, even when fertilizer application rates remain fairly constant, a feature much less apparent when only considering relative profitability measures. Real revenues from actual fertilizer use rates stayed fairly constant over the full sample, apart from a substantial drop in 2007, while revenue values derived from calculated optimal nitrogen rates varied much more between years. When looking at revenue values by district and soil group, swings in revenue values calculated at actual use rates appear much larger than the sample-averaged values, although still do not have the variation found in the optimal use levels. Because farmers are likely more conscious of household revenue than value-cost ratios, the fact that revenue from observed nitrogen rates does not vary as considerably might be an indication that households seek to minimize variation (i.e., risk) in income level over time. Even so, this figure provides further evidence that the gap between observed and optimal use rates closed over the course of the survey years given the difference in revenue between the observed and optimal rates is much smaller in the more recent survey years.

Disaggregating revenue values between net maize buyers and sellers provides another interesting look at absolute profitability. Because net maize sellers are more likely to apply more fertilizer than net maize buyers, the benefits of valuing maize at the higher buying price are often dwarfed by the gains in output from applying fertilizer nearer to optimal levels. As such, net maize sellers, who also function as more aggressive fertilizer users, generally see higher revenue under current management practices than their net buying counterparts. Most of the households in this sample switch between net buying and net selling status between survey years, signaling greater variability in household income between years and an overall riskiness of investing in expensive inputs given uncertainly about household maize stocks at the end of the season.

8. Conclusions and Policy Implications

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 percent of maize fields in 2010 were fertilized at levels less than 25 percent 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 percent of maize fields in some lowlands districts but 65 percent in others remained unfertilized in 2010, and that households in some districts are using around 90 percent 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 et al. 2010) and do improve household income in the long run. Moreover, we believe that analyses similar to that conducted in this study could provide important policy guidance to other African governments grappling with how to promote sustainable agricultural intensification in their countries.

Table 1: Distribution of variables in the production function across all survey 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			

Table 2: 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.

Table 3: Expected marginal products of nitrogen and associated standard errors by district and soil group

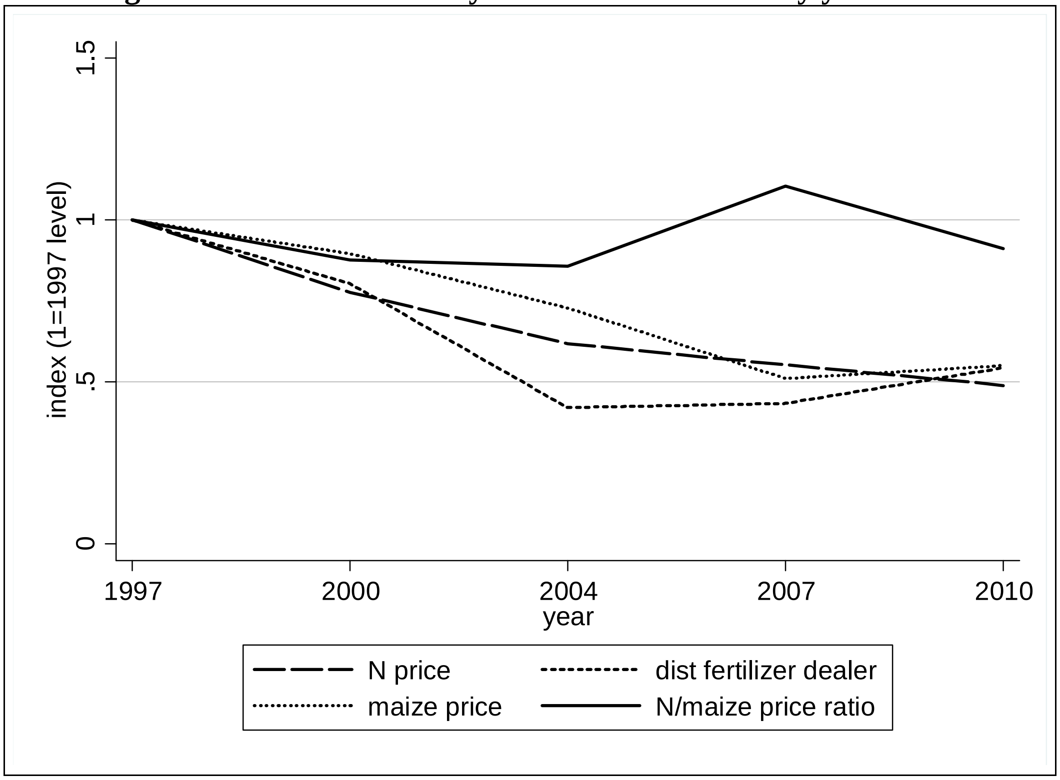
	District	Soil group	Zone group	Number of households	Expected marginal product (MP)	Standard error (SE)	Ratio of SE/MP
Eastern	Machakos	3	1	19	41	13.2	0.32
	Makueni	3	1	56	36	13.9	0.39
	Meru	1	3	51	18	4.1	0.23
	Mwingi	2	1	15	48	11.9	0.25
	Mwingi	3	1	13	42	12.0	0.29
Nyanza	Kisii	2	3	25	18	4.4	0.24
	Kisii	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	3	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

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

Table 4: Relative nitrogen profitability and current use levels by district and soil group

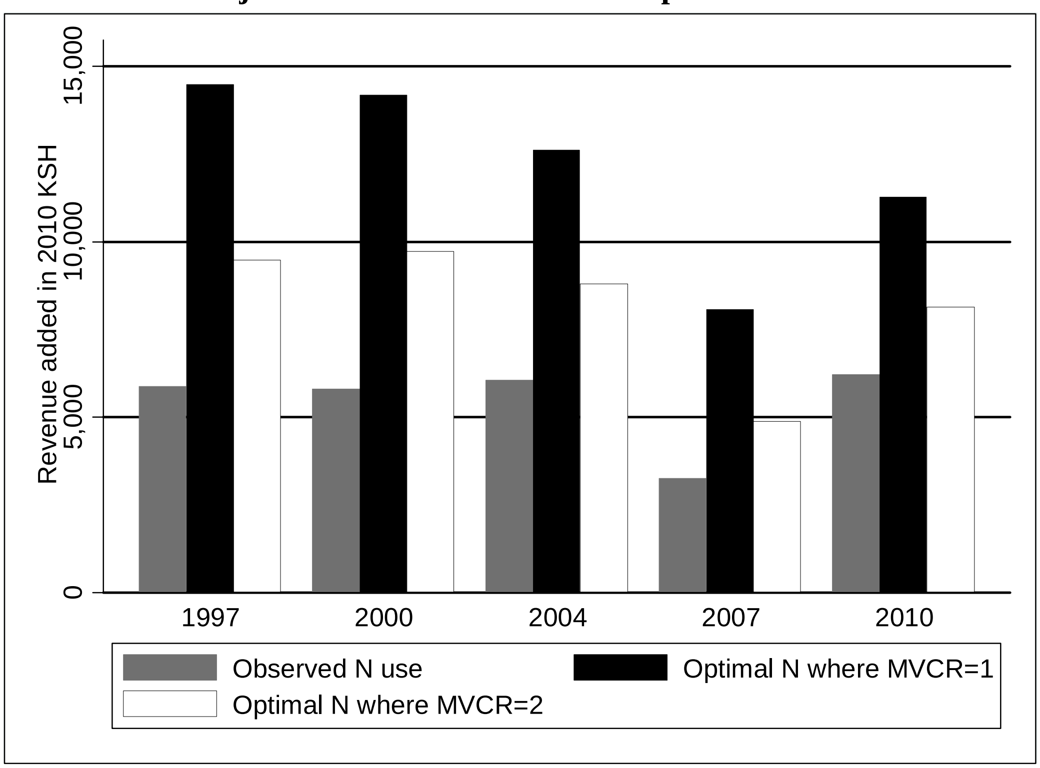
Region	District	Soil group	Mean across survey years				Estimated optimal N (kg/ha)		Mean observed commercial N (kg/ha, excludes zeros)					% maize fields with commercial N application				
			MP	AP	MVCR	AVCR	MVCR=2	MVCR=1	1997	2000	2004	2007	2010	1997	2000	2004	2007	2010
Eastern	Machakos	3	41	44	3.5	4.2	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	3	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

Figure 1: Changes in relative accessibility of fertilizer over survey years for all households



Note: Nitrogen and maize prices were adjusted to 2010 levels using the CPI.

Figure 2: Inflation-adjusted revenue added to maize production from use of nitrogen



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