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Soil Fertility, Fertilizer, and the Maize Green Revolution in East Africa

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Abstract

This paper investigates the reasons for the low application of external fertilizers on farms in Kenya and Uganda. The analysis uses a large panel of household data with rich soil fertility data at the plot level. The authors control for maize seed selection and household effects by using a fixed-effects semi-parametric endogenous switching model. The results suggest that Kenyan maize farmers have applied inorganic fertilizer at the optimal level, corresponding to the high nitrogen-maize relative price, in one of the two survey years and also responded to the price change over time. In Uganda, even the low application of inorganic fertilizer is not profitable because of its high relative price. The authors conclude that policies that reduce the relative price of fertilizer could be effective in both countries, while the efficacy of policies based on improving farmers' knowledge about fertilizer use will be limited as long as the relative price of fertilizer remains high.

This paper—a joint product of Japan's National Graduate Institute for Policy Studies and the World Bank's Agriculture and Rural Development Team, Development Research Group—is part of a larger efforts at both institutions to understand policies that promote productivity gains and growth in agriculture. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at Tom.Matsumo@worldbank.org.

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Soil Fertility, Fertilizer, and the Maize Green Revolution in East Africa

1. Introduction

The low application of inorganic fertilizer in Sub-Saharan Africa (hereafter Africa) is one of the major constraints to achieving a Green Revolution in this region (IFDC, 2006). Although there have been many studies to ascertain the reasons behind the low application of the inorganic fertilizer, some competing hypotheses remain (Morris et al., 2007; Kelly, 2006). Market-based hypotheses suggest that farmers are responding to the high fertilizer price, which has been the result of high transportation and marketing costs in Africa (Jayne et al., 2003; Gregory and Bumb, 2006). Non-market based hypotheses emphasize farmers' lack of knowledge on inorganic fertilizer and high yielding varieties, as well as financial constraints (surveyed in Morris et al. 2007).

One of the non-market constraints is the land degradation which could lower the returns to the fertilizer application (Adesina, 1996; Marenya and Barrett, 2007). Degraded soils have low capacity to hold water and external soil nutrients, and, thus, external fertilizers have low returns on degraded soils. The low returns on the degraded soils would force farmers to reduce the already low inorganic fertilizer application, which in turn may contribute to further land degradation (Smaling et al., 1997; Henao and Baanante, 2006; IFDC, 2006).[1] A recent study by Marenya and Barrett (2007) advances the research on this issue by employing plot level soil carbon content data in western Kenya and finds that the marginal return to the inorganic fertilizer is low and not profitable in maize production when the soil carbon content is low. Their results suggest that conventional policies to encourage farmers to use inorganic fertilizer would be ineffective on depleted soils. Their analyses, however, are based on cross sectional

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[1] Although there is a debate over the possible overestimations of the previous estimates of soil losses, many experts agree that the land degradation is a critical constraint to African agriculture (Koning and Smaling, 2005; Pender et al., 2006).

data and do not control for the possible endogeneity of the input use or the selection of high yielding variety (HYV) seeds.

In this paper, we follow the approach taken by Marenya and Barrett (2007) but use two-year panel data of farm households in Kenya and Uganda where we have maize production data on 6,329 plots, of which we have soil fertility data for more than 70 percent of the plots. Kenya and Uganda provide an interesting comparison because Kenya has one of the highest productivities for maize in Africa, while Uganda has one of the lowest (Smale and Jayne, 2003; Sserunkuuma, 2005). We control for the HYV selection by using the household fixed effects semiparametric endogenous switching model, developed by Kyriazidou (1997). In particular, we estimate the direct impact of the soil fertility on the maize yield and examine if the soil fertility increases the returns to inorganic and organic fertilizer. The results of the analyses indicate that the Kenyan maize farmers have applied the inorganic fertilizer roughly at the optimal level in one out of the two survey years on both the purchased HYV and local/recycled HYV maize.[2] In Uganda, even the low application of inorganic fertilizer is not profitable because of the high relative price. Regarding the returns to external fertilizers on degraded soils, we do not find any increasing marginal returns of external fertilizers to the soil fertility.

The paper is organized as follows. Section 2 explains the production model that captures the interactions between the soil fertility and the fertilizer inputs and describes the semi-parametric endogenous switching model used in this paper. Section 3 explains the household panel data and soil fertility data. The surveys in both countries were conducted by the same research project which employs comparable questionnaires

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[2] Many farmers in Kenya and Uganda recycle purchased HYV maize after harvesting. We group the recycled HYV maize with the local maize as we explain later in Section 2.

across countries and time. Section 4 presents the estimation results on maize production in both countries. Finally, we discuss the policy implications based on the results in Section 5.

2. Model on Soil Fertility and Returns to Fertilizer on Maize

2.1 Soil Fertility and Crop Production

There are several pathways though which soil fertility contributes to crop production. Directly, soil provides nutrients to crops, and, indirectly, soil affects how easily external inputs are absorbed by the crops (Tiessen et al., 1994; Palm et al., 2001; Bationo and Mokwunye, 2005). As a proxy for soil fertility, Marenya and Barrett (2007) use the carbon content. The soil carbon content is also a proxy for soil organic matter (SOM), which consists of the decayed tissues of plants and animals taken from animal excreta and is increasingly taken as a strong indicator of soil fertility and land degradation because SOM tightly controls many soil properties and major biogeochemical cycles (Ngugi et al., 1990; Manlay et al., 2007).

Some soil characteristics are not fixed over the long run. Organic fertilizer, for instance, can directly alter soil characteristics. Thus, the impacts of organic fertilizer application have a long-term impact on crop production through changing the soil characteristics. Thus, the current soil characteristics reflect the past applications of organic fertilizer to some extent. In the following analysis, therefore, we consider the organic fertilizer application as a flow variable and the soil carbon content as a stock variable.

2.2 Production Function

Regarding the production function, we consider a soil nutrient indicator which is a function of three factors. Let us denote N_{pit} as the soil nutrient indicator of plot *p* of household *i* at time *t*:

$$N_{pit} = N(E_i, C_{pit}, O_{pit}), \tag{1}$$

where E_i is the basic soil condition, such as the soil carbon content, assumed to be time-invariant for a short time period; C_{pit} is the quantity of the inorganic fertilizer application (kg/ha), and O_{pit} is the quantity of the organic fertilizer application (ton/ha). We assume that the basic soil condition, E_i, is common across the maize plots within a household and fixed over time. As we discussed in the previous sub-section, we use the soil carbon content as a single indicator of the soil condition in the following analyses by following Marenya and Barrett (2007).[3]

For the production function, we consider a simple yield function of the Cobb-Douglas form. The yield, kilograms per ha, denoted by Y_{pit}, is given as follows:

$$Y_{pit} = A_i L_{pit}^{\beta_L} S_{pit}^{\beta_S} N_{pit}^{\beta_N} e^{\omega_{ipt}}, \tag{2}$$

where L_{pit} is the plot size (ha), S_{pit} is the seed quantity planted (kg/ha), *A* is the Hicks neutral technology parameter or the total factor productivity.[4] We assume that *A* is

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[3] As we discuss in Section 3, we have only one soil observation per household. Thus, we assume that the soil carbon content is fixed across maize plots within a household and over time. Although it is not clear how long the soil carbon content is stable over time, it seems that the soil carbon content is more stable than other soil nutrients, such as nitrogen content.

[4] We do not include family labor in the model because family labor information was not sought in the second round of the surveys in both Kenya and Uganda. The family labor module was removed from the questionnaire in the second round because the quality of the family labor information was considered poor in the first round of the surveys. We implicitly assume that family labor input is adjusted optimally when the other input levels change. In the regression models, we estimate the household fixed effect models. Thus, as long as the family labor input remains at the same level, the omission of the family labor may not cause a serious bias.

time-invariant at least for the short time period of 2 to 3 years. ω is assumed to capture a productivity shock affected by weather conditions or other idiosyncratic factors. By taking logs of the yield function (2), we have

$$y_{ipt} = a_i + \beta_L l_{ipt} + \beta_S s_{ipt} + \beta_N n_{ipt} + \omega_{ipt}, \tag{3}$$

where the lowercase variables represent the logs of their corresponding uppercase variables. The functional form of the nutrient indicator given by equation (1) is unknown but we take a second-order approximation of the log of N so that it captures the interaction effects of the external inputs and the soil carbon content, which is given by,

$$n_{pit} = \ln N(E_i, C_{pit}, O_{pit}) = \gamma_0 + \sum_x \gamma_x x + \sum_x \sum_{x'} \gamma_{xx'} x x' \tag{4}$$

for $x,\ x' \in \{E, C, O\}$. We expect that the interaction terms between the soil carbon content and the external inputs have positive impacts on the crop production. By plugging equation (4) into equation (3), we have

$$y_{pit} = a_i + \beta_L l_{pit} + \beta_S s_{pit} + \sum_x \delta_x x_{pit} + \sum_x \sum_{x'} \delta_{xx'} x_{pit} x'_{pit} + \omega_{pit}, \tag{5}$$

where the coefficients δs are the product of β_N and γs; that is, $\delta_v = \beta_N \gamma_v$, $v \in \{E, C, O, EC, EO, CO, EE, CC, OO\}$.

Simple OLS regression of y on the observables with pooled samples, however, may provide biased estimates. First, the unobservable total factor productivity, a_i, could be correlated with the inputs. Fortunately for us, we have panel data. Thus, by estimating the fixed effects model, we can at least remove the time-invariant unobserved factors, although we cannot identify the coefficients of the time-invariant independent variables, such as E_i and E_i^2, in the fixed effects (FE) model. We rewrite the estimation equation (5) as:

$$y_{ipt} = \alpha_i + \beta_L l_{ipt} + \beta_S s_{ipt} + \sum_{x \neq E} \delta_x x_{ipt} + \sum_{x \neq E} \sum_{x'} \delta_{xx'} x_{ipt} x'_{ipt} + \omega_{ipt}, \qquad (6)$$

where $\alpha_i = a_i + \delta_E E_i + \delta_{EE} E_i^2$. The fixed effects factors, collected in α_i, will be dropped from the FE model.

Another issue to be considered is the correlation of the productivity shock with the input variables. Specifically, rainfall would be correlated with the input applications and yield simultaneously because the agriculture production in our survey regions is predominantly rain-fed, and farmers determine the level of input use according to the level of rainfall. In this paper, this issue is dealt with by introducing time-region dummies as covariates. With this treatment, we can control for other region level time-variant factors as well. For notational simplicity, we denote z as a vector of the independent variables, including the time-region dummies and φ as a vector of parameters corresponding to z. Subsequently, we describe the model simply as follows:

$$y_{ipt} = \alpha_i + z'_{ipt}\varphi + \varepsilon_{ipt}. \qquad (7)$$

2.3 Endogenous Switching Model

We also need to consider the effect of HYV seed adoption in the yield function. As shown by previous studies on maize in Kenya and Uganda, HYV and local seeds have different yields (Hassan and Karanja, 1997; Nyoro et al., 2004; Sserunkuuma, 2005). Farmers in Kenya and Uganda also recycle HYV seeds for many seasons. After one season, the newly purchased HYV seeds lose their high responsiveness to inorganic fertilizer. Indeed, we find that the recycled HYV seeds have a yield distribution which is more similar to the local seeds than the newly purchased HYV seeds (Appendix Figure A1). Thus, in this paper, we group the recycled HYV maize seeds with the local maize seeds and label them as “local/recycled HYV” maize seeds, and we label the newly purchased HYV maize seeds as “purchased HYV” seeds. To consider the differences in yield and returns to fertilizer use according to seed type, the extended model is given by

$$y_{pit} = d_{pit} y^1_{pit} + (1 - d_{pit}) y^0_{pit}, \tag{8}$$

where d_{pit} is a binary indicator taking 1 if the purchased HYV seeds are planted on plot *p* of household *i* at time *t* and 0 otherwise: $y^j_{ipt}\ (j \in \{0,1\})$ is the potential outcome when the HYV adoption status *j* is exogenously given. Then the yield function is expressed as follows:

$$y^j_{ipt} = \alpha^j_i + z'_{ipt}\varphi^j + \varepsilon^j_{ipt},\ j \in \{0,1\}. \tag{9}$$

We observe only either one of the two potential outcomes. Plugging $y^j s$ into Equation (8), we obtain

$$y_{ipt} = \alpha^0_i + d_{ipt}(\alpha^1_i - \alpha^0_i) + z'_{ipt}\varphi^0 + d_{ipt} z'_{ipt}(\varphi^1 - \varphi^0) + \varepsilon^0_{ipt} + d_{ipt}(\varepsilon^0_{ipt} - \varepsilon^1_{ipt}). \tag{10}$$

There are two possible problems: the presence of the unobserved effects α^j_i and the potential endogeneity of the independent variables specifically on the HYV adoption and its interaction terms. To obtain consistent estimates, we apply the two-step estimation method for the panel data sample selection model, developed by Kyriazidou (1997). To apply her model, we need to obtain consistent estimates of the selection equation with individual fixed effects. In our case, the selection equation will be given by $d_{ipt} = 1\{\eta_i + w'_{ipt}\xi + v_{ipt}\}$, where η_i is a time-invariant household-specific effect, *w* is a vector of independent variables, and *v* is unobserved disturbance. Specifically, we use Logit estimation to obtain the consistent estimates, ξ. In the second step, using ξ, the parameters of the yield equation are estimated by

$$\varphi^j = \left[\sum_{i=1}^{n} \frac{1}{M_i(M_i-1)} \sum_{m \neq m'} \phi_{imm'}(z_{im} - z_{im'})(z_{im} - z_{im'})' d_{im}^j d_{im'}^j \right]^{-1}$$
$$\times \left[\sum_{i=1}^{n} \frac{1}{M_i(M_i-1)} \sum_{m \neq m'} \phi_{imm'}(z_{im} - z_{im'})(y_{im} - y_{im'})' d_{im}^j d_{im'}^j \right], \qquad (11)$$

where M_i is the number of observations of household *i*, the subscript *m* is a substitute for the subscript *pt* solely for notational simplicity, $d^1 = d$ and $d^0 = 1 - d$, and $\phi_{imm'}$ is a kernel weight that becomes large when $w'_{im}\hat{\zeta}$ and $w'_{im'}\hat{\zeta}$ are close. Namely, $\phi_{imm'} \equiv \frac{1}{h} K\left(\frac{(w_{im} - w_{im'})'\hat{\zeta}}{h} \right)$, where $K(\cdot)$ is a kernel function and *h* is a bandwidth. The intuition behind this estimation method is that by taking the difference in the yield function between two observations within a household when their predicted single indexes $w'\hat{\zeta}$ obtained in the first stage regression for the selection model take the same value, not only do time-invariant household fixed-effects, α_i, disappear but so do the selection biases. Using the variables transformed by taking the difference in the above manner, we may be able to apply OLS regression and obtain consistent estimators. In practice, there may not be two observations taking exactly the same value of the predicted single indexes within an individual. To handle this issue, the Kyriazidou estimation applies a weighted regression in which heavier weights are assigned to the differences of the two samples with closer values on their predicted single indexes.

3. Data and Descriptive Analysis

3.1. Data

The data used in this paper come from household-level panel surveys in Kenya and Uganda, collected as part of the Research on Poverty and Environment and Agricultural Technology (R*e*PEAT) Project. All surveys employ comparable questionnaires across countries and time. In addition, soil samples were collected from maize fields when the first rounds of the surveys were conducted. The surveys in Kenya were conducted in 2004 and 2007. The first round of the surveys covered 899 randomly selected households located in 100 sub-locations scattered in central and western regions of Kenya.[5] In the second round, seven sub-locations in Eastern province were dropped because of the scale reduction of the survey project. Thus, in this paper, we drop the samples from Eastern province in Kenya for the analysis below since we apply statistical methods relying on the longitudinal aspects of the data. In addition, attrition also reduced the number of households interviewed. As a result, out of the 777 targeted households, 725 households were revisited for the survey, resulting in an attrition rate of 6.7 percent.[6]

The surveys in Uganda cover 94 rural Local Council 1 (LC1)s that are located across most regions in Uganda, except the North where security problems exist.[7] From each rural LC1, ten households are randomly selected, resulting in a total of 940 small farm households. The second round was conducted in 2005, and 895 households out of the 940 original households visited in the first round were interviewed. Thus, the attrition rate was low at 4.8 percent.[8]

Along with the first rounds of the surveys in Kenya and Uganda, we collected soil samples from the largest maize plot or one of the other cereal plots if maize was not cultivated at each sample household. If no cereal crops were cultivated by a household,

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[5] These two waves of surveys in Kenya were conducted by Tegemeo Institute, with financial and technical help from National Graduate Institute for Policy Studies (GRIPS).

[6] We estimated the determinants of the attrition from the surveys and found that none of the independent variables is significant at the 5 percent level (Appendix Table A1). Thus, we think that the attrition mostly occurred randomly and do not expect serious attrition biases.

[7] The surveys in Uganda were conducted jointly by Makarere University, Foundation for Advanced Studies on International Development (FASID), and National Graduate Institute for Policy Studies (GRIPS).

[8] The attrition rate is less than 5 percent. None of the independent variables in the determinants of the attrition model is significant even at the 10 percent level (Appendix Table A1). Thus, we do not think the attrition biases serious.

no soil samples were taken. The soil samples were collected at a depth of 0-20 cm from five different positions within each plot of a sample household and mixed. Later, the samples from Kenya and Uganda were sent to the soil laboratory at the World Agroforestry Center (ICRAF) in Nairobi and were tested by a new method called near-infrared reflectance spectroscopy (NIRS), following protocols developed by Shepherd and Walsh (2002) and Cozzolino and Morton (2003).

We have matched the soil information to 77 percent of the maize plots in Kenya and 67 percent of the maize plots in Uganda. The major reason for not having the soil information on some of the maize plots is simply because some soil samples were either lost or spoiled before being tested in the laboratory. Because the soil samples were collected at the time of the first survey, we do not have soil information on the maize plots of households who did not produce maize or any other cereals in the first round of the surveys. The Probit regression models for the soil sample attrition indicate that most of the household variables are not correlated with the attrition (Appendix Table A1). The major determinants of the soil sample attrition are the region dummies which represent the soil sample losses and spoilages. Thus, we do not think that the soil sample attrition is systematically correlated with the household characteristics to create attrition biases. In addition, because we estimate the household fixed effects models, we think that if any attrition biases exist, they would be small.

In Table 1, we compare the maize production and input applications between the purchased HYV seeds and the local/recycled HYV seeds. The adoption of the newly purchased HYV is about 59 percent in Kenya, while it is 21 percent in Uganda. As expected, the maize yield is higher for the purchased HYV seeds than the local/recycled HYV seeds, and it is higher in Kenya than in Uganda. In Kenya, the yield of the purchased HYV maize is about 2.2 tons per ha, which is 0.5 tons higher than the yield of the local/recycled HYV maize. The difference between the two groups is statistically significant and partly driven by the differences in the quantities of the input applications. For instance, 86 percent of the purchased HYV maize plots receive at least some inorganic fertilizer, while only 58 percent of the local/recycled HYV maize plots do so. In terms of the quantity, the average amount of inorganic fertilizer applied on the purchased HYV maize plots is about 119 kilograms per ha, which is about twice as much as the amount applied on the local/recycled HYV maize plots.

In contrast, in Uganda, the maize yield is low for the two maize seed groups, and the difference between the two groups is small, at about 0.2 tons per ha. The small difference between the two maize seed groups may be due to the low applications of external fertilizer on both seed groups in Uganda. For instance, only three and six percent of the maize plots receive inorganic and organic fertilizer, respectively. Although the purchased HYV maize plots receive more inorganic fertilizer than the local/recycled HYV maize plots, the average quantity of the inorganic fertilizer application on the HYV maize plots is only nine kilograms per ha.

Among the maize plots with soil data, we find that the average carbon content is 2.5 percent in Kenya and 2.4 percent in Uganda (Table 1). Thus, the average carbon content is about the same in the two countries. In Kenya, the purchased HYV seeds are cultivated in better soils than the local/recycled HYV seeds, while in Uganda the purchased HYV seeds are cultivated on poorer soils than the local/recycled HYV seeds in Uganda. The average carbon content is not so different across seed types within country and across countries. To examine the relationship between the soil fertility and the maize production further, we divide the samples based on the soil carbon content next.

3.2. Soil Fertility and Maize Inputs and Outputs

In Table 2, we divide the samples into four quartiles based on the carbon content. Note that we only include those samples with soil carbon content information in Table 2. In Kenya, the soil carbon content increases from 1.3 percent in the lowest quartile to 4.0 percent in the highest quartile. The proportion of the purchased HYV adoption increases from 46 to 68 percent from the lowest to the highest carbon content quartiles, respectively. Thus, the Kenyan farmers plant the purchased HYV maize seeds on fertile plots. The maize yields of both the purchased HYV and the local/recycled HYV seeds are highest in the highest quartile, and the maize yields remain about the same level among the lowest three quartiles. In particular, the maize yield of the local/recycled HYV seeds is very high at 3.6 tons per ha in the highest quartile, while it remains around 1.3 tons per ha among the lowest three quartiles. We have checked if the high yield in the highest quartile is due to outliers but find the results robust. Although the information is not reported in Table 2, we find that the median yield of the local/recycled HYV seeds is 1.4 tons per ha in the highest quartile, while it is about 0.8 tons per ha in the other three quartiles. Thus, it seems that the local/recycled HYV maize seeds are responsive to the soil carbon content at the high soil carbon content level, even though we need to be careful not to link the high maize yield directly to the soil carbon content only. The quantity of the organic fertilizer application, for instance, is about 3.4 tons per ha in the highest quartile, while it is about 1.3 tons per ha in the lowest quartile.

In contrast, the maize yield and input applications have no clear correlation with the soil carbon content in Uganda. The average maize yield is around 1.5 tons per ha, regardless of the seed types and the soil carbon content quartiles. Inputs also do not have any clear relationships with the soil carbon quartiles. The geological distribution of the maize production in Uganda may explain why no clear relationships exist between the soil carbon content quartiles and the maize inputs and outputs. In the eastern region of Uganda, the soil is poor, but the maize technology is much more advanced than the maize production in the Central and Western regions because it is closer to the Kenyan border. In the western region, where banana is the most important staple crop, the soil is good, but the maize production technology is not advanced. To control for the geographical differences and other observed characteristics of the maize production in Kenya and Uganda, we rely on regression analyses.

4. Regression Results

4.1. Adoption of Purchased HYV

First, we present the regression results of the (purchased) HYV adoption in Table 3, separately for Kenya and Uganda. For each country, we present the results from the random-effects (RE) Logit estimation and the household level fixed-effects (FE) Logit estimation. As the basic explanatory variables, we include household, plot, and community level variables. In addition, to control for the region-specific time-variant effects, such as climate and market conditions, we include seven region dummies, a season dummy, a second survey round dummy, and the interaction terms of these dummies. Because the RE Logit model allows us to estimate the coefficients of time-invariant variables, we add some time-invariant household and soil characteristics into the model. Although the RE model has the advantage of providing the estimation results on time-invariant variables, the RE model estimates could be biased because of omitted variables. Indeed, the Hausman test, presented at the bottom of Table 3, indicates that the RE model estimates are not consistent with the FE estimates. Thus, on the time-varying independent variables, we interpret the results from the FE model.

The RE model results indicate that the soil carbon content has no relationship with HYV adoption in both Kenya and Uganda. Farmers do not appear to consider the soil quality when they choose to apply the purchased HYV. The other results from the RE model are consistent with the common observations. The education level of men in the household has a positive association with the HYV adoption in both countries, and the numbers of men and women in the household increase the HYV adoption in general in both countries. The female education level of women in the household in Uganda has a negative association with the HYV adoption. This is the only unexpected result, and the reason for this finding is not clear. The results from the RE model indicate that the asset value has a positive association with the HYV adoption in both countries. In the FE model, the estimated coefficient of the asset value becomes smaller and not significantly different from zero. The land size, which is another wealth indicator, has no significant impacts on the HYV adoption in both countries. In Uganda, the results of both the RE and FE models indicate that the farmers adopt the HYV maize more frequently on the rented-in plots than the owned plots, which may reflect the possible actions taken by the tenant farmers who want to maximize the immediate returns from the rented-in plots.

Regarding the community level price variables, we find that the relative price variables do not have significant impacts on HYV maize adoption in Kenya. This could be because the input market is well developed in Kenya and the relative prices are nearly constant across regions. Thus, the regional and time dummies may absorb the impacts of the relative prices. In Uganda, on the other hand, the input market is not well developed. Thus, in the central and western regions of Uganda, we do not even have information on the relative price of DAP simply because it is not available. DAP is the most commonly used fertilizer type in Kenya and Uganda, according to our panel surveys. Indeed, the results indicate that the HYV adoption rate is significantly lower in areas where the DAP price information is missing. The relative price of DAP over the maize output price also has a negative impact on the HYV maize adoption. Because HYVs use fertilizer intensive technology and require a certain amount of inorganic fertilizer application, a high relative price of DAP is likely discourage the farmers from adopting the purchased HYV seeds more than the price of the HYV seeds itself.

4.2. Maize Yield Function

Next, we present the results from the yield model, separately for Kenya and Uganda in Table 4 and 5, respectively. In each table, we present the results from the three models: the pooled OLS, the household fixed effects model, and the household fixed semiparametric endogenous switching model. In general, all three estimation models provide robust estimates, with a few exceptions. In the pooled OLS model, all the independent variables are interacted with the purchased HYV maize dummy, and we present the total impacts, not the differential impacts, of the interaction terms with the HYV dummy to make comparisons between the pooled OLS and the other models possible. The switching model controls for the household fixed effects as well as the selection between the purchased HYV and the local/recycled HYV maize, as we explained in Section 3.

Because the soil carbon content (measured in the natural log), the nitrogen content of the inorganic fertilizer (100 kg/ha), and the organic fertilizer application (ton/ha) are all interacted with each other and have the squared terms, interpretations of the results could be complicated. Thus, at the bottom of the tables, we present the partial derivative of one input evaluated at the means. We also indicate if the partial derivates are jointly significant.

Regarding the soil carbon content, the results from the pooled OLS model suggest that the soil carbon content has a positive impact on the maize yield with a decreasing return on both of the seed types in Kenya. The elasticity evaluated at the means is about 0.32 for the purchased HYV maize, while it is about 0.57 for the local/recycled HYV maize. Because the average carbon content levels are about the same for the two seed types, according to the HYV adoption model in Table 3, the results suggest that the local/recycled HYV maize has a greater physical responsiveness to the soil carbon content than the purchased HYV maize. The impact of the organic fertilizer is also greater on the local/recycled HYV maize than on the purchased HYV maize. According to the endogenous switching model, the average impact of an additional one ton of organic fertilizer application per ha increases the maize yield by 4.1 percent for the local/recycled HYV maize and 2.2 percent for the purchased HYV maize. The estimated coefficients are robust across the estimation models. Thus, it seems that the local/recycled HYV maize is more physically responsive to the organic matter, i.e., the soil carbon content and the organic fertilizer, than the purchased HYV maize.

The sizes of the estimated impacts of organic fertilizer may seem small. But note that the estimated coefficients of the organic fertilizer could be biased toward zero because of the possible attenuation biases created by the measurement errors in the organic fertilizer variables. First, it is difficult to measure the quantity of the applied organic fertilizer. Farmers may not remember clearly how much of the organic fertilizer they applied. Second, the quality of the organic fertilizer varies from one farmer to another. The quality of the organic fertilizer depends on the contents and how it is prepared. Thus, we should treat the estimated average impact of the organic fertilizer as a conservative estimate.

As expected, we find a large impact of the inorganic fertilizer application on the maize yield. The evaluated average impacts of the nitrogen content of the inorganic fertilizer, measured in 100 kg per ha, is 0.82 for the purchased HYV maize and 1.13 for the local/recycled HYV maize, according to the results of the endogenous switching model. Because of the decreasing return to the inorganic fertilizer, the smaller average impact on the purchased HYV maize than the local/recycled HYV maize could be explained partially by the larger quantity of the nitrogen application on the purchased HYV maize than on the local/recycled HYV maize. The average nitrogen application on the purchased HYV maize is about 17.9 kg per ha, while the average nitrogen application on the local/recycled HYV maize is about 9.8 kg per ha. To investigate the different application rates, we need to calculate the Marginal Physical Product (MPP) and the profitability of the nitrogen application. We do that in Table 6, together for Kenya and Uganda.

Unlike the results from Marenya and Barrett (2007), the yield effect of external fertilizers does not differ depending on the soil fertility. The interaction terms between the carbon content and the inorganic and organic fertilizer applications are generally not significant. Although the interaction term between the organic fertilizer application and the soil carbon content is positive and significant in the pooled OLS model, it becomes insignificant once we control for the household fixed effects and the seed selection. Similarly, the interaction term between the nitrogen application and the organic fertilizer application loses its significance once the seed selection is controlled for.

In Table 5, we present the results from Uganda. Regarding the soil carbon content, we find that the elasticity of the carbon content, evaluated at the means, is 0.23 on the local/recycled HYV maize. We do not find, however, any significant impacts of the soil carbon content on the purchased HYV maize. These results are consistent with those in Kenya that the soil carbon content has a larger impact on the local/recycled HYV maize than on the purchased HYV maize. We do not find any significant impacts, either individually or jointly, of the organic and inorganic fertilizer applications on the maize yield in Uganda. This is not surprising because of the very low applications of both fertilizers. As we show in Table 1, only 3 and 4 percent of the maize plots in Uganda received the inorganic or organic fertilizer, respectively.

4.3. Optimality of Nitrogen Fertilizer Application

Is the nitrogen fertilizer application at the optimal level? We answer this question by testing if the MPP of the nitrogen application is equal to the nitrogen-maize relative price. Thus, for each year and a given maize seed type, we calculate the MPP by multiplying the average maize yield with the partial derivative of the nitrogen application evaluated at the means:

$$MPP(kg/kg)_t^j = \bar{Y}_t^{\,j} \times E\left[\frac{\partial \ln(Y_t^{\,j})}{\partial \, Nitrogen(100kg)_t^j}\right]/100\,, \tag{12}$$

and conduct a test to see if the MPP is equal to the relative price.[9]

By reviewing numerous technical studies by agricultural scientists, Yanggen et al. (1998) report that the typical yield response rate, which is the additional output obtained in kg divided by the additional nitrogen applied, is 17 in East and Southern Africa. In Kenya, Mbata (1997) reports response rates of 12 to 18 in Central and

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[9] To obtain the nitrogen price, we have divided the DAP price by 0.18 because 100kg of DAP contain 18kg of nitrogen.

Western Kenya. Marenya and Barrett (2007) report the average MPP at 22 in Western Kenya, although they find considerable heterogeneity.

In Table 6, we find that the MPP varies from 11 to 20 in Kenya and 21 to 25 in Uganda. Compared with the previous estimates, these estimates are within a reasonable range. The MPP is 14 for the purchased HYV during the first wave of the panel surveys in Kenya. The nitrogen-maize relative price is 13 during this period. The t-test indicates that the MPP is not different from the relative price, suggesting that the nitrogen application is roughly at the optimal level for the purchased maize during this period in Kenya. For the local/recycled maize, the MPP is lower than the relative price, suggesting a slightly over-application of the nitrogen. During the next survey period, the results are the opposite. We find an almost optimal application on the local/recycled HYV maize but somewhat an under-application for the purchased HYV maize. Because of unexpected events, both agro-ecologically and economically, it is not surprising that Kenyan farmers miss the optimal application levels occasionally. It is more important to point out that the MPPs move in the same direction as the relative-price over time. From the first to the second wave, the relative price increased from 13 to 16 and the MPPs of the purchased and local/recycled HYV maize also increased from 14 to 20 for the purchased HYV maize and from 11 to 16 for the local/recycled HYV maize. Thus, the results indicate that the Kenyan farmers are responding to the change in the relative price and successfully achieving the near optimal application level in one of the two years for both the purchased and local/recycled HYV maize.

The relative price is much higher in Uganda than in Kenya: it is 22 and 34 in the first and second wave, respectively. Because of the low use of the nitrogen fertilizer in Uganda, the MPPs are not precisely estimated. Despite the low precision, we find that the MPP on the purchased HYV maize during the first wave is 23, which is close to the relative price at 22. During the second wave in Uganda, the MPP is around 25 for both the purchased HYV and local/recycled HYV maize, when the relative price is 33. Thus, assuming a decreasing marginal return, even the low application of the nitrogen fertilizer is over-application and not profitable. The relative price in Uganda is simply too high to apply the inorganic fertilizer. The high relative price in Uganda is mostly because of the low maize price in Uganda, which is about 60 percent of the Kenyan price (see Appendix Table A2). Because it would cost more to send the inorganic fertilizer from eastern Uganda to central and western Uganda, the potential relative price would be higher in the central and western Uganda. Thus, to decrease the relative price, the maize price has to increase. Otherwise, the relative price remains too high for any farmers to apply the inorganic fertilizer.

5. Conclusions

To dramatically improve maize productivity in Sub-Saharan Africa, the current level of external fertilizer application is considered to be too low. Thus, we estimate the maize yield function in Kenya and Uganda to investigate the reasons for the low external fertilizer application on maize. Kenya has one of the highest productivities for maize in Sub-Saharan Africa, while Uganda has one of the lowest. Thus, a comparison between the two countries provides valuable lessons for other African countries. By comparing the marginal physical product (MPP) of the nitrogen application on the maize yield and the nitrogen-maize relative price, we find that Kenyan farmers have successfully achieved the optimal nitrogen application level in one of the two survey years on both the purchased and local/recycled HYV maize. We also find that they have responded to the relative price change over time. Thus, the results suggest that a market-based approach, such as reducing the inorganic fertilizer price or increasing the maize price or both, would be effective in encouraging farmers to use more inorganic fertilizer in Kenya. In Uganda, the application levels of external fertilizers are too low to identify precise estimates. Nonetheless, we find that the low inorganic fertilizer application is already over-application in Uganda because of the very high relative price. In both Kenya and Uganda, the potential success of a non-market approach, such as credit or extension provision, would be limited as long as the relative price remains at the present level.

Another major contribution of this paper is the determination of whether the returns to external fertilizers differ depending on the soil fertility. According to the results in this paper, we do not find any significant differences in the returns to the organic and inorganic fertilizer application depending on the soil fertility. Thus, the results suggest that policies that encourage inorganic fertilizer application would be effective even on degraded soils where maize farmers in our samples cultivate maize. This does not suggest, however, that the soil fertility is not important. We also find that the soil carbon content directly increases the maize yield both in Kenya and Uganda. Especially, we find larger impacts on the local/recycled HYV maize than on the purchased HYV maize. Thus, improving the soil fertility has a direct impact on the maize production. In this paper, we are not able to identify the costs of improving the soil fertility. Because of the high relative price of the inorganic fertilizer, it is worth estimating the relative costs of improving the soil fertility. This remains to be investigated in the future.

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Table 1. Summary Statistics

		Seed Type		
	All (1)	Purchased HYV (3)	Local/ Recycled HYV (2)	Difference (2)-(3) (4)
Kenya				
Number of Plots	3,131	1,848	1,283	
Maize Yield (kg/ha)	1,986	2,172	1,718	454*
Maize Plot Size (ha)	0.33	0.34	0.30	0.05**
Seed Planted (kg/ha)	28.4	26.5	31.0	-4.5+
Proportion of Chemical Fertilizer Used	0.74	0.86	0.58	0.28**
Chemical Fertilizer Use (kg/ha)	94.7	119.4	59.2	60.2**
Nitrogen Chemical Fertilizer (kg/ha)	18.41	23.17	11.56	11.62**
Proportion of Organic Fertilizer Used	0.50	0.50	0.50	0.00
Organic Fertilizer Use (kg/ha)	1,935	2,258	1,471	787**
Proportion of Samples with Soil Data	0.77	0.74	0.80	-0.06
Carbon Content (%)	2.48	2.59	2.33	0.26**
pH	6.15	6.08	6.25	-0.18**
Nitrogen-maize price ratio in 2004	13.4			
Nitrogen-maize price ratio in 2007	16.0			
Uganda				
# Plots	3,198	680	2,518	
Maize Yield (kg/ha)	1,561	1,719	1,518	202
Maize Plot Size (ha)	0.31	0.37	0.29	0.08**
Seed Planted (kg/ha)	24.7	22.9	25.2	-2.3*
Proportion of Chemical Fertilizer Used	0.03	0.12	0.01	0.11**
Chemical Fertilizer Use (kg/ha)	2.4	9.1	0.6	8.5**
Nitrogen Chemical Fertilizer (kg/ha)	0.76	2.95	0.17	2.78**
Proportion of Organic Fertilizer Used	0.06	0.07	0.06	0.01
Organic Fertilizer Use (kg/ha)	86	142	71	71
Proportion of Samples with Soil Data	0.67	0.66	0.68	-0.02
Carbon Content (%)	2.35	2.15	2.40	-0.25**
pH	6.64	6.69	6.63	0.05*
Nitrogen-maize price ratio in 2003[A]	22.3			
Nitrogen-maize price ratio in 2006[A]	33.7			

Note: The recycled HYV seeds are grouped together with the local seeds. The yield distribution of the recycled HYV seeds has a similar distribution to the local seeds rather than the purchased HYV seeds (Appendix Figure A1). A The nitrogen-maize price ratios are obtained from eastern Uganda, where farmers apply inorganic fertilizer.

Table 2. Input and Output Level by Soil Carbon Content

	All	Quartile of Soil Carbon Content			
		Lowest	2nd	3rd	Highest
	(1)	(2)	(3)	(4)	(5)
Kenya					
Number of Plots	2,403	545	533	647	678
Carbon Content (%)	2.48	1.28	1.82	2.42	4.01
Ratio of Purchased HYV	0.57	0.46	0.46	0.65	0.68
Yield (kg/ha): Purchased HYV	2,109	2,125	1,841	1,962	2,374
Yield (kg/ha): Local/Recycled HYV	1,765	1,216	1,266	1,326	3,634
Seed Use (kg/ha)	26.8	23.1	28.8	26.8	28.2
Ratio of Chemical Fertilizer Used	0.70	0.64	0.62	0.74	0.79
Chemical Fertilizer Use (kg/ha)	87.0	96.1	76.0	84.5	90.7
Ratio of Organic Fertilizer Used	0.56	0.53	0.58	0.54	0.57
Organic Fertilizer Use (kg/ha)	2,287	1,293	2,016	2,144	3,436
Uganda					
Number of Plots	2,151	595	606	491	459
Carbon Content (%)	2.35	1.33	1.82	2.43	4.27
Ratio of Purchased HYV Adopted	0.21	0.25	0.18	0.20	0.20
Yield (kg/ha): Purchased HYV	1,532	1,786	1,536	1,255	1,413
Yield (kg/ha): Local/Recycled HYV	1,579	1,377	1,954	1,380	1,531
Seed Use (kg/ha)	25.3	25.7	26.2	27.3	21.2
Ratio of Chemical Fertilizer Used	0.03	0.03	0.02	0.02	0.03
Chemical Fertilizer Use (kg/ha)	1.4	0.8	2.6	0.7	1.3
Ratio of Organic Fertilizer Used	0.04	0.03	0.03	0.05	0.07
Organic Fertilizer Use (kg/ha)	42	23	62	35	48

Note: In this table, we only include maize plots that are matched with the soil samples.

Table 3. Determinants of the newly purchased HYV seed adoption.

	Kenya		Uganda	
	RE Logit (1)	FE Logit (2)	RE Logit (3)	FE Logit (4)
Plot Characteristics				
Carbon content	0.1216		0.1100	
	(1.30)		(0.70)	
1{The maize plot is rented}	0.0476	0.2849	0.8961	1.0079
	(0.19)	(1.17)	(2.62)**	(2.86)**
Walking time to the plot (minutes)	0.0103	0.0093	0.0045	-0.0035
	(1.72)	(1.74)	(1.23)	(0.81)
Household Characteristics				
ln(Total size of owned land in ha)	0.3199	0.5724	0.0357	0.1516
	(1.38)	(1.35)	(0.15)	(0.48)
ln(Value of physical assets in USD)	0.1824	0.0333	0.4568	0.2580
	(1.73)	(0.28)	(2.52)*	(1.19)
1{Female household head}	-0.3745		0.4160	
	(1.36)		(0.82)	
Years of schooling of male adult	0.0551		0.1349	
	(1.94)		(2.64)**	
Years of schooling of female adult	0.0209		-0.1455	
	(1.02)		(2.80)**	
Number of adult males	0.0228		0.2644	
	(0.25)		(2.39)*	
Number of adult females	0.1947		0.3680	
	(2.22)*		(3.29)**	
Community Characteristics				
1{DAP price info.NOT available}	-0.8827	-1.5551	-4.0430	-2.8287
	(0.61)	(0.86)	(4.46)**	(2.97)**
DAP price/ maize price	0.0339	-0.5149	-0.5429	-0.4402
	(0.06)	(0.79)	(3.69)**	(2.94)**
Male hourly wage/ maize price	-0.6268	-0.0315	0.1469	0.2025
	(1.76)	(0.06)	(0.60)	(0.85)
1{HYV seed price info.NOT available}	-55.3951	-15.9666	-28.4899	-30.5371
	(0.00)	(0.01)	(0.00)	(0.03)
HYV seed price/ maize price	0.2163	0.0775	0.0768	0.0211
	(4.13)**	(1.27)	(2.87)**	(0.69)
Constant	-3.7599		-2.0889	
	(2.59)**		(1.79)	
Region * Season * Year dummies	Included	Included	Included	Included
Hausman's test for FE vs. RE on coefficients of common covariates	$\chi^2(11)= 35.37$**		$\chi^2(11)= 48.90$**	
Observations	2156	1295	2015	978
Number of households	591	286	486	199

Note: Absolute value of z statistics in parentheses. * significant at 5%; ** significant at 1%. [a] In the fixed-effects Logit estimation, the households who do not alter the state of the HYV seed adoption across plots or seasons are dropped. In addition, the (almost) time-invariant explanatory variables are excluded.

Table 4. Determinants of log of maize yield (Kg/Ha) in Kenya

	Pooled OLS Model		FE Model[a]		FE Endogenous Selection Model [a]	
	Purchased HYV plots	Local/ Recycled HYV plots	Purchased HYV plots	Local/ Recycled HYV plots	Purchased HYV plots	Local/ Recycled HYV plots
	(1)	(2)	(3)	(4)	(5)	(6)
ln (Maize plot size in ha)	-0.2578	-0.2980	-0.3440	-0.4068	-0.3512	-0.4218
	(8.60)**	(8.16)**	(7.21)**	(7.32)**	(6.87)**	(6.29)**
ln (Seed kgs/ha planted)	0.3803	0.3554	0.3571	0.3749	0.4092	0.4321
	(7.75)**	(7.49)**	(5.70)**	(6.03)**	(4.79)**	(5.49)**
ln (Carbon content)	0.4568	1.0130				
	(2.30)*	(5.60)**				
ln^2 (Carbon content)	-0.0696	-0.2901				
	(0.78)	(3.08)**				
Nitrogen content of chemical	1.3971	1.6396	1.3891	1.3417	0.5926	2.0820
Fertilizer input (100kg/ha)	(4.33)**	(4.01)**	(2.67)**	(2.21)*	(0.95)	(3.44)**
Nitrogen^2	-0.5735	-0.3037	-0.5508	0.0336	-0.0921	-0.7703
	(3.09)**	(1.10)	(2.21)*	(0.10)	(0.24)	(1.45)
Organic fertilizer (tons/ha)	-0.0066	0.0657	0.0230	0.0676	0.0383	0.0751
	(0.48)	(3.05)**	(1.30)	(2.67)**	(1.88)	(2.24)*
Organic^2	-0.0004	-0.0019	-0.0007	-0.0020	-0.0005	-0.0015
	(1.56)	(3.22)**	(2.21)*	(3.17)**	(1.12)	(1.25)
Nitrogen x *ln* (Carbon content)	-0.4130	-0.5494	-0.2562	-0.2366	0.3497	-0.9179
	(1.65)	(1.53)	(0.66)	(0.47)	(0.84)	(1.39)
Organic x *ln* (Carbon content)	0.0268	0.0214	0.0154	0.0254	-0.0004	0.0047
	(2.32)*	(1.21)	(1.03)	(1.25)	(0.03)	(0.17)
Nitrogen x Organic	0.0047	-0.0930	-0.0034	-0.1306	-0.0116	-0.0590
	(0.46)	(3.27)**	(0.27)	(3.96)**	(0.63)	(1.06)
Constant	4.2312	3.5159	5.0117	4.4756		
	(24.52)**	(21.95)**	(28.25)**	(25.98)**		
Region x Season x Year dummies	Included		Included	Included	Included	Included
Observations	2371		1165	773	1165	773
Number of Households			356	220	356	220
E[Maize yield (Kg/Ha)| HYV/ non-HYV]	2065.0	1391.1	2080.2	1387.5	2080.2	1387.5
E[∂ lnY/ ∂ lnCarbon| HYV/ non-HYV] [b]	0.32**	0.57**				
E[∂ lnY/ ∂ Nitrogen| HYV/ non-HYV] [b]	0.81**	1.03**	0.92**	0.964**	0.82**	1.13**
E[∂ lnY/ ∂ Organic| HYV/ non-HYV] [b]	0.019 *	0.025**	0.028*	0.011**	0.022*	0.041*
Hausman's test vs. FE Model					$\chi^2(9)$=-	$\chi^2(9)$=15.6

Absolute value of t statistics in parentheses. * significant at 5%; ** significant at 1%. [a] Households with less than 2 observations in the same state of HYV seed adoption are excluded from the regression. [b] The significance level attached to the mean value corresponds to the test statistic for the joint test of the related coefficients being equal to zero simultaneously.

Table 5. Determinants of log of maize yield (Kg/Ha) in Uganda

	Pooled OLS Model		FE Model[a]		FE Endogenous Selection Model[a]	
	Purchased HYV plots	Local/ Recycled HYV plots	Purchased HYV plots	Local/ Recycled HYV plots	Newly Purchased HYV plots	Local/ Recycled HYV plots
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Maize plot size in ha)	-0.1700	-0.1550	-0.1696	-0.3004	-0.2886	-0.2996
	(2.97)**	(5.56)**	(2.14)*	(8.51)**	(2.84)**	(5.72)**
ln(Seed kgs/ha planted)	0.6203	0.6071	0.6151	0.5772	0.5891	0.4848
	(10.76)**	(23.09)**	(7.58)**	(16.71)**	(5.14)**	(9.23)**
ln (Carbon content)	-0.0723	0.1445				
	(0.21)	(1.02)				
ln^2 (Carbon content)	-0.0726	0.0392				
	(0.35)	(0.58)				
Nitrogen content of chemical Fertilizer input (100kg/ha)	0.1469	-7.5816	3.8045	-13.5939	3.0635	-19.9570
	(0.03)	(0.82)	(0.73)	(1.50)	(0.67)	(0.01)
Nitrogen^2	3.7317	0.8901	-3.8466	1.8568	-0.5241	2.3248
	(0.80)	(0.36)	(0.73)	(0.90)	(0.02)	(0.00)
Organic fertilizer (tons/ha)	0.9868	-0.1206	-0.6800	0.2552	1.5585	-0.0612
	(1.28)	(0.45)	(0.18)	(0.88)	(0.16)	(0.18)
Organic^2	-0.0468	0.0077	0.0727	-0.0304	-1.1731	0.0323
	(0.43)	(0.30)	(0.05)	(0.97)	(0.15)	(0.54)
Nitrogen x *ln* (Carbon content)	1.2016	11.2553	-1.2713	18.9528	-1.7808	28.0156
	(0.30)	(1.00)	(0.27)	(1.66)	(0.44)	(0.02)
Organic x *ln* (Carbon content)	-0.9244	0.1687	0.5763	-0.0097	-0.4270	0.0934
	(1.78)	(0.68)	(0.21)	(0.04)	(0.04)	(0.33)
Nitrogen x Organic	-17.7050	0.0000	-14.8094		-20.3941	
	(0.73)	(.)	(0.61)		(0.01)	
Constant	5.0469	4.6093	5.0797	4.4380		
	(24.48)**	(43.12)**	(24.35)**	(45.97)**		
Region x Season x Year dummies	Included		Included	Included	Included	Included
Observations	2084		356	1461	356	1461
Number of Households			112	366	112	366
R-squared	0.98		0.34	0.40	0.34	0.40
E[Maize yield (Kg/Ha)| HYV/ non-HYV]	1532.0	1338.2	1572.0	1403.0	1572.0	1403.0
E[∂ lnY/∂ lnCarbon| HYV/ non-HYV] [b]	-0.20	0.23**				
E[∂ lnY/∂ Nitrogen| HYV/ non-HYV] [b]	0.20**	0.92	2.62	0.46	1.35	0.80
E[∂ lnY/∂ Organic| HYV/ non-HYV] [b]	-0.41	0.007	-0.97	0.25	0.36	0.010
Hausman's test vs. FE Model					$\chi^2(9)=0.23$	$\chi^2(8)=6.12$

Absolute value of t statistics in parentheses. * significant at 5%; ** significant at 1%. [a] Households with less than 2 observations are excluded from the regression. [b] The significance level attached to the mean value corresponds to the test statistic for the joint test of the related coefficients being equal to zero simultaneously.

Table 6. Relative Prices and Marginal Returns of Nitrogen Application

	Marginal Physical Product (MPP) [a]	Average Relative Price (RP)	Test Statistics if MPP = RP
	(1)	(2)	(3)
Kenya - Wave 1			
Purchased HYV Maize	14.10** (0.60)	13.4	*t* = 1.17
Local/Recycled HYV Maize	11.05** (0.91)	13.4	*t* = -2.59**
Kenya - Wave 2			
Purchased HYV Maize	19.89** (0.67)	16.0	*t* = 5.77**
Local/Recycled HYV Maize	16.13** (0.87)	16.0	*t* = 0.15
Uganda - Wave 1			
Purchased HYV Maize	23.44 (1.68)	22.3	*t* = 0.68
Local/Recycled HYV Maize	20.78 (10.80)	22.3	*t* = -1.88
Uganda - Wave 2			
Purchased HYV Maize	24.96 (4.70)	33.7	*t* = -0.14
Local/Recycled HYV Maize	25.23 (9.37)	33.7	*t* = -0.90

Note: [a] MPP = $E[Y^* \partial \ln Y / \partial \text{Nitrogen} | \text{HYV/ non-HYV}]$, where Y is maize yield per ha.
* significant at 5%; ** significant at 1%. The * and ** in column (1) indicate that the estimated coefficients for the evaluated MPPs are jointly significant in Table 4 and 5. The * and ** in column (3) indicate that the MPP and RP are statistically different.

Appendix Table A1: Determinants of Sample Attrition (Probit)

	Kenya		Uganda	
Dependent variable	Soil sample not available	Not interviewed in wave 2	Soil sample not available	Not interviewed in wave 2 [b]
	(1)	(2)	(3)	(4)
Household characteristics in the initial survey year				
Log of land size (ha)	0.0039	-0.0239	-0.0240	0.0008
	(0.13)	(1.02)	(0.88)	(0.44)
Log of asset holdings (USD)	-0.0257	0.0074	0.0167	0.0002
	(1.80)+	(0.67)	(0.95)	(0.14)
1{female headed}	-0.0071	0.0265	0.0425	
	(0.19)	(0.94)	(0.80)	
Years of schooling of male adult	-0.0051	-0.0056	0.0000	0.0005
	(1.13)	(1.71)+	(0.00)	(0.87)
Years of schooling of female adult	0.0103	-0.0020	-0.0140	-0.0008
	(2.13)*	(0.56)	(2.39)*	(1.26)
Number of adult males	0.0074	-0.0199	-0.0109	0.0015
	(0.51)	(1.71)+	(0.74)	(1.43)
Number of adult females	-0.0297	-0.0073	-0.0176	0.0007
	(1.98)*	(0.64)	(1.17)	(0.85)
Kenya region dummies (reference region: Nyanza)				
Western	-0.2663	-0.0450		
	(6.19)**	(1.22)		
Rift Valley	-0.1036	-0.0604		
	(2.53)*	(1.85)+		
Central	-0.1177	-0.0109		
	(3.00)**	(0.35)		
Uganda region dummies (reference region: East)				
Central			0.2190	-0.0005
			(5.54)**	(0.15)
West/South western			0.1545	
			(3.67)**	
E[y]	0.26	0.13	0.41	0.01
Number of households	825	825	938	621

Note: Reported coefficients are the change in probability for an infinitesimal change in each independent, continuous variable and the discrete change in the probability for dummy variables. Absolute value of z statistics in parentheses. + significant at 10%; * significant at 5%; ** significant at 1%. [a] The sample households living in Rift Valley are dropped from the regression since there is no variation in the dependent variable within the region. [b] The sample households living in West/South western are dropped from the regression since there is no variation in the dependent variable within the region.

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Table A2. Input and Output Prices on Maize Production by Region

Region	Maize Price		DAP Price		Nitrogen Price		HYV Seed Price	
	Wave 1 (1)	Wave 2 (2)	Wave 1 (3)	Wave 2 (4)	Wave 1 (5)	Wave 2 (6)	Wave 1 (7)	Wave 2 (8)
	USD/100kg		USD/100kg [DAP/Maize]		USD/100kg [Nitrogen/Maize]		USD/100kg [HYV/Maize]	
Kenya								
Central	17.4	17.7	42.1	50.7	233.9	281.7	178.9	183.6
			[2.4]	[2.9]	[13.4]	[15.9]	[10.3]	[10.4]
Rift Valley	14.3	16.3	34.8	50.9	193.3	282.8	170.8	174.4
			[2.4]	[3.1]	[13.5]	[17.3]	[11.9]	[10.7]
Western	15.8	18.4	40.8	51.9	226.7	288.3	163.6	178.8
			[2.6]	[2.8]	[14.3]	[15.7]	[10.4]	[9.7]
Nyanza	19.2	19.8	42.2	53.7	234.4	298.3	155.5	193.3
			[2.2]	[2.7]	[12.2]	[15.1]	[8.1]	[9.8]
All	16.7	17.8	40.3	51.2	223.9	284.4	167.1	182.3
			[2.4]	[2.9]	[13.4]	[16.0]	[10.0]	[10.2]
Uganda								
East	9.4	8.8	38.2	59.4	212.2	330.0	73.0	91.9
			[4.1]	[6.7]	[22.6]	[37.5]	[7.8]	[10.4]
Central	9.9	10.4	n.a.	n.a.	n.a.	n.a.	49.7	64.0
							[5.0]	[6.1]
West/SW	8.6	10.8	n.a.	n.a.	n.a.	n.a.	35.8	30.6
							[4.2]	[2.8]
All	9.5	9.8	38.2	59.4	212.2	330.0	59.8	72.1
			[4.0]	[6.1]	[22.3]	[33.7]	[6.3]	[7.4]

Note: the prices are the region average of the community level prices. The community level prices are the median of prices reported by respondents at the household level.

Nitrogen price is calculated by DAP price divided by 0.18 based on the fact that the nitrogen content in 100 kg of DAP is 18kg

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Appendix Figure A1. Log of Maize Yield (kg/ha) by Seed Type