The Possibility of a Maize Green Revolution in the Highlands of Kenya: An Assessment of an Emerging Intensive Farming System

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Abstract: This study aims to explore the determinants of the new maize farming system, which is characterized by adoption of high-yielding maize varieties, application of chemical fertilizer and manure produced by stall-fed improved dairy cows, and intercropping, especially the combination of maize and legumes, and its impact on land productivity and household income. We examine not only the impacts of new technologies and production practices but also the impacts of the entire new maize farming system by generating an agricultural intensification index based on a principal component analysis. Our estimation results show that an increase in sub-location level population density and a decrease in the land-labor ratio of an individual household accelerate farming intensification, and that adoption of each new technology and production practice has positive and significant impacts on land productivity. These findings are further supported by the significantly positive impacts of the agriculture intensification index on land productivity.

Keywords: Farming system・Agricultural intensification・Population pressure・Maize・Green Revolution・Kenya

1 Introduction

The improvement of agricultural productivity is imperative for poverty reduction in developing countries in general, and in sub-Saharan Africa, in particular, considering its high rate of population growth, increasingly limited availability of cultivatable lands, and the rise of food prices in the international market (Otsuka, Estudillo, and Sawada, 2008; Barret, Carter and Timmer, 2010). Asia experienced a rapid rise of agricultural productivity, known as the "Green Revolution," characterized by adoption of chemical fertilizer and fertilizer-responsive high-yielding varieties in the 1970s and 1980s, along with expansion of irrigation infrastructure (Hayami and Kikuchi, 1978; David and Otsuka, 1994; Evenson and Gollin, 2003c; Hayami and Godo, 2005; Otsuka and Larson, 2013b). In contrast, Africa is the only continent experiencing the stagnation of agricultural productivity. Researchers, therefore, continue to look for ways to enhance agricultural productivity in Africa. Widely emphasized in the literature as major constraints on the productivity growth, underdeveloped marketing infrastructure leads to high transaction costs for purchase of chemical fertilizer and seeds of high-yielding varieties and the poor access to irrigation (Jayne et al., 2003; Kydd et al., 2004; Reardon et al., 1999; Gregory and Bumb, 2006). This results in harsh and unstable production environments.

Yet, under these circumstances, some farmers have begun adopting a new farming system of maize production in the highlands of Kenya characterized by application of organic fertilizer, i.e., manure produced from improved dairy cattle in addition to use of hybrid seeds, chemical fertilizer, intercropping with legumes, and crop rotation (Otsuka and Yamano, 2005). A typical farmer in this system grows Napier grass, which is a common feed crop for cattle that can also repel pests, feeds it to improved cattle that are raised in stalls, collects manure from the stalls, and applies it on maize fields, where intercropping hybrid maize with nitrogen-fixing legumes is practiced. This farming system is similar not only to the Green Revolution in Asia in the 1970s and 1980s whose essence is application of high-yielding varieties and chemical fertilizer, but also to the agricultural revolution in U.K. in the 18th century, which is based on application of manure produced from stall-fed cattle as well as production of feeds on crop fields (Timmer, 1969). It may not be unrealistic to assume that this new farming system, which embodies the essence of the two preceding revolutions in agricultural history, will bring about "revolutionary" changes in farm productivity in Sub-Saharan Africa.

To our knowledge, however, no study, except Otsuka and Yamano (2005), has statistically examined the determinants of adoption and productivity impacts of this emerging farming system in Sub-Saharan Africa. Therefore, this study aims to identify the determinants of adoption of this new farming system and to estimate its impact on productivity of maize, the major staple crop in Kenya. The unique parcel level panel dataset, in which an agricultural land parcel is divided into multiple pieces of land plots for multiple crop cultivations, allows us to apply land parcel level fixed effects regression analysis which could control year-invariant and also year-variant parcel level unobservable characteristics. In addition to estimating the effects of each element of the new farming system on productivity, this study attempts to measure the impact of the entire system by creating a single agriculture intensification index that captures this multidimensional input intensification. Our approach will provide insights into the effects of the new farming system on the land productivity of maize farming, which should assist policy makers in constructing new effective strategies for agricultural productivity improvement in Sub-Saharan Africa.

We hypothesize that population pressure on land, measured by sub-location level population density and land-labor ratio of a household, accelerates agricultural intensification. We also hypothesize that the adoption of hybrid maize seed, intercropping legumes with maize, manure application, and chemical fertilizer application, as well as measured aggregate intensification index have positive and significant impacts on land productivity measured in value of production, net income per hectare and household total income per capita.

The remainder of the chapter is structured as follows. Section 2 outlines the background of this study, while Section 3 describes the data collection method and provides descriptive statistics. Section 4 explains how the maize farming system index is constructed, Section 5 describes our identification strategies, and Section 6 presents estimation results. Finally, Section 7 discusses conclusions and policy implications of this study.

2 Background Information

In the 18th century, the agricultural revolution was realized by introduction of the turnip as a feed crop, the stall-feeding of cattle, and ample application of manure to crop fields (Timmer, 1969). In contrast to cattle grazing under a three-field system, stall-feeding of cattle is labor intensive as it requires the production of feed crops, care of stall-fed cows, the collection of manure from stalls, and its application to crop fields. Stall-feeding of cattle makes it possible to fully collect manure. Therefore, a farming system based on stall-feeding of cattle is more labor-using and yield-enhancing than the traditional three-field farming system based on grazing. This method seems to fit with densely populated areas in Sub-Saharan Africa, which have been experiencing rapid population growth, shrinkage of cultivatable lands per capita, and declining soil fertility (Otsuka and Place, 2015).

Asia has experienced rapid productivity growth mainly in rice and wheat since the late 1960s (David and Otsuka, 1994; Hayami and Godo, 2005), which is called the Green Revolution. This high growth in agricultural productivity was realized by application of chemical fertilizer, adoption of high-yielding modern rice varieties, and development of irrigation. Farmers used modern varieties and chemical fertilizer simultaneously because provision of soil nutrients is necessary to realize high yield potential of the modern varieties. Rice farmers also adopt such improved cultivation practices as bunding, leveling, straight-row planting, and timely application of fertilizer. Therefore, the important lesson from the Green Revolution in Asia is not only adoption of high-yielding varieties and application of chemical fertilizer but also improved cultivation practices are necessary to increase crop yields significantly (Otsuka and Larson, 2015).

However, in a country where infrastructure is underdeveloped, it is difficult for poor farmers in rural area to amply apply to chemical fertilizer due to its high transaction costs. Moreover, unlike lowland rice farming, which is most sustainable due to the ability of water-stored fields to sustain soil fertility, upland farming requires maintenance of soil fertility by applying organic fertilizer in addition to chemical fertilizer (Otsuka and Larson, 2015). Hence, many farmers in the highlands of Kenya apply organic fertilizer which is made from feces collected from stall-fed cows. Farmers grow feed grass such as Napier grass, which repels pests, and feed it to improved cows in the stalls. Then, farmers collect the cows' feces and create manure from it. Many of them plant a hybrid maize variety and apply both manure and chemical fertilizer on the field. Moreover, they often intercrop maize with legumes that fix nitrogen from the atmosphere, which improves soil fertility. It is important to emphasize that this system combines technological advantages from two agricultural revolutions, one that occurred in England in the 18th century and another that was achieved in Asia in the 20th century. We hypothesize that the emerging farming system has potential to boost maize productivity significantly in Sub-Saharan Africa.

3 Data and Descriptive Analysis

3.1 Data

In order to analyze the determinants of adoption of the new maize farming system and its impact on maize and entire crop yields, including yield of leguminous crops, and milk production, data are taken from a survey called RePEAT. This data set was jointly collected by the National Graduate Institute for Policy Studies (GRIPS), the World Agroforestry Center, and Tegemeo Institute of Agricultural Policy and Development in Kenya. The RePEAT survey is originally based on a survey conducted by the Smallholder Diary Project (SDP) that collected data from more than 3,300 households randomly selected from communities in the Central, Rift Valley, Nyanza, and Western, and Eastern provinces in Kenya by the International Livestock Research Institute. In 2004, the RePEAT survey randomly selected 99 sub-locations, which is the smallest administrative unit, and up to 10 households from each of the selected sub-locations, which results in a sample of 899 households. The second round of the RePEAT survey was conducted in 2012, which revisited 751 households that were interviewed in 2004. Thus, the attrition rate is 16.5%. Attrition weights are estimated and used to control for potential attrition bias in all regressions in this study. Because our focus is on maize farmers, we limit our sample to farmers who grow maize on at least 20% of their farm land in our analysis. After this eligibility rule is applied, our final panel sample is composed of 622 panel households in 96 sub-locations in 2004 and 2012.

The RePEAT survey includes detailed household information on agricultural activities, land use, demographics, education, assets, nonfarm income, agricultural expenditure, and consumption. In the survey area, farmers have farm land parcels and they often divide a land parcel into multiple small plots to grow multiple crops. Thus, the survey team defines a land parcel as a main unit of a farm land and a land plot as a component of a land parcel. The survey enumerator gave unique ID for each land parcel that is traceable over time, which makes it possible to compare the maize production on the same parcel across two crop seasons within the same year or over the two survey years. However, plot IDs are given season by season and year by year by enumerators arbitrarily and thus these plot IDs are not traceable even across crop seasons in a year. In our sample, 622 households had 958 parcels in 2004 and had 880 parcels in 2012. There are main and short cropping seasons in the survey area. The agricultural production data were collected for all crops in all plots for both the main and the short seasons. In 2004, 991 plots were grown with maize in the main season and 561 were grown with maize in the short seasons. In 2012, the corresponding figures are 877 plots and 479 plots, respectively. This gives us 1,552 maize plot level sample observations in 958 parcels in 2004 and 1,356 maize plot observations in 880 parcels in 2012. To address extreme values or outliers, we drop the outcome variables if their values are more than the 99th percentile of each variable.

Table 1 shows socioeconomic characteristics of the sample households and sub-locations. According to this table, the proportion of female-headed households increased from 22% to 29% and that of household's head who completed primary education increased from 35% to 41% from 2004 to 2012. The typical household head has become older by 5 years. The average values of productive assets and total non-land assets have decreased by about 14,000 Kenyan Shieling (KSh) and 15,000 KSh, respectively, from 2004 to 2012.[1] The average household size and the number of household working age (15-64 years) members increased by 0.5 and 0.8 respectively, and the number of dependents has decreased by 0.2 over time. The size of owned land was small already in 2004, i.e., 1.7 hectares, indicating that the population pressure was severe in highlands in Kenya. Owned land size has shrunk to 1.5 hectares over the eight-year period, which clearly leads to a decrease in the land-labor ratio over time. The sub-location population density (persons per square kilometer (km^2)) has increased from 744 to 1,101 over time. Due to the fact that the

[1] Throughout this chapter, all prices are converted to the real price setting 2009 as a base year. The consumer price index for 2004 is 66.03 and that for 2012 is 103.53.

land-labor ratio has declined and, consequently, the population pressure has risen over time, it is clear that it is necessary to increase productivity per unit of land to avoid food insecurity in rural Kenya. Transportation infrastructure has improved over time in Kenya as evidenced by the shortened time distance from the center of sub-location to the nearest big town by a motor vehicle by 9 minutes, which indicates that accessibility to agricultural inputs and output markets would have improved over time.

3.2 Maize and Milk Production in Kenya

Table 2 provides production data based on maize plot data per cropping season in 2004 and 2012. The size of a maize plot has shrunk over time, which is consistent with the declining trend in the owned land size from 2004 and 2012. The adoption rate of hybrid maize has increased from 49% to 72%, expenditures for chemical inputs other than chemical fertilizer, which include herbicides, pesticides, and fungicides, have risen from 88 KSh per hectare to 176 KSh per hectare, and expenditure of hired labor also has increased from 2,941 KSh per hectare to 3,973 KSh per hectare. Though the ratio of intercropping with legumes has declined by 6 percentage point, the quantity of intercropped legume seeds has been raised by 5 kg per hectare over time. Both the adoption rate of manure and the quantity of manure applied per hectare have risen significantly over time. In contrast, the adoption rate of chemical fertilizer and its applied quantity, which is converted into the total weight (in kg per hectare) of primary nutrients in terms of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O_5) contained in fertilizers (hereafter, NPK), have stagnated from 2004 to 2012. It is important to point out that the maize yield has increased by about 40% and value of all crop production including maize and all other intercropped crops of a maize plot has increased by 21%. Similarly, sample households experienced a growth in their net crop income, defined as total value of all crop production minus all paid-out costs associated with crop production including costs of chemical and organic fertilizer, other chemical inputs, seed, and hired labor, by 21% over time.

Table 3 shows the amount of fertilizer application and land productivity by the type of maize seeds on a maize plot per cropping season. The adoption of hybrid maize seeds is associated with a higher yield and value of harvest than that of local seeds by about 63% and 68%, respectively. Consistently, the proportion of plots with chemical fertilizer application is higher for hybrid seeds than for local seeds by 37 percentage point, and the quantity of chemical fertilizer applied per hectare is also greater for the hybrid seed plots than for the local seed by 31 kg per hectare. In contrast to chemical fertilizer use, the proportion of manure used is the same for local seed and hybrid seed plots. However, when we look at the quantity of manure applied per hectare, it is greater for hybrid seeds than for local seeds. This indicates that rural farmers in Kenya know the importance of applying both chemical and manure to realize the yield potential of the hybrid seeds.

Overall, it is indicated that maize farmers in the highlands of Kenya spontaneously began exerting efforts to intensify land use under the increasing population pressure on the limited land resources.

It is a mistake to examine only maize fields if we are interested in the impacts of new maize-based farming system because keeping improved dairy cows is an integral part of this farming system. Table 4 displays the slight decline in the number of improved cows and the total number of cows from 2004 to 2012 in the RePEAT data, though these changes are not statistically significant. However, the quantity of milk produced per cow by local, improved, and both local and improved cows all increased over time. Milk production per improved dairy cow is about four times greater than that of a local cow, which demonstrates the much higher productivity of improved cows over local cows. The use of improved dairy cows is reminiscent of the White Revolution realized in India a few decades ago (Kajisa and Palanichamy, 2013).

4 The Agricultural Intensification Index

It is difficult to measure the overall effect of the farming system, which consists of multiple changes in input uses and production practices, by simply looking at individual elements of the new farming system separately because their effects on agriculture production could be interactive. In fact, many changes are expected to be complementary. In such a case, if we analyze the impacts of each change on outcome variables by estimating the production function, we could miss the interacting effects of multiple changes. Although it is theoretically possible to specify the general form of production function, such as translog, it is empirically difficult to estimate such a function due to the limited degree of freedom and high correlation among various elements of the new farming system.[2] Therefore, it will be useful to construct a single index that represents the intensity of adoption of the new maize farming system. This single index should incorporate the important multiple indicators from each dimension of agricultural intensification in the system.

This study uses principal component analysis (PCA) to construct an index of agricultural intensification. PCA is a variable reduction procedure which decomposes variations in the

[2] Table A1 shows both household and plot level matrices of the pairwise correlation coefficients of input uses that consist of the new maize farming system. All the inputs are positively correlated and the correlation coefficients are mostly significant.

variables included in the analysis into components (Darnell, 1994). A component is a linear combination of weighted explanatory variables, in such a way that the component accounts for a maximal amount of variance in the explanatory variables (Cavatassi, Davis, and Lipper, 2004). Since the first component captures the greatest proportion of total variation, it will be used as an agricultural intensification index in our analysis. The component is constructed based on the factor scores which are used as weights for each explanatory variable to calculate an index which represents the degree of agricultural intensification.

For this study, we generate two agricultural intensification indices, one at the household level and the other at the plot level. The household level agricultural intensification index is computed by the following formula (Filmer and Prichett, 1998):

$$HI_{it} = \sum_{k=1}^{5} F_k \left[\frac{(x_{itk} - X_k)}{S_k}\right], \qquad (1)$$

where HI_{it} is the household level agricultural intensification index for household i in year *t* which follows a normal distribution with a mean of zero, F_k is the factor score for the variables k in the PCA model, x_{itk} is the variable k of household i in year *t,* and X_k and S_k are the mean and standard deviation of the variable k. The PCA model includes a dummy variable for hybrid maize seed adoption, quantity of intercropped legume seeds with maize, quantity of manure per hectare, quantity of chemical fertilizer converted in NPK per hectare, and the number of improved cows per hectare, as these input variables represent household level agricultural intensification of the new maize farming system.

Similarly, the plot level agricultural intensification index is constructed as follows:

$$PI_{ipst} = \sum_{l=1}^{4} G_l \left[\frac{(z_{ipstl} - Z_l)}{T_l}\right], \qquad (2)$$

where PI_{ipst} is the plot level agricultural intensification index of household i on maize plot *p* in the cropping season *s* in year *t*, G_l is the factor score for the variables l in this model, z_{ipstl} is the variable l of household i on maize plot *p* in cropping season *s* in year *t*, and Z_l and T_l are the mean and standard deviation of the variable l. This PCA model includes the same variables as in the household level intensification index with exception of the number of improved cows per hectare. This is because although the number of improved cows per hectare is one of the key variables of the new maize farming system, this variable is only observable in the household level data. As both HI_{it} and PI_{ipst} becomes greater, farming is supposed to be more intensified. Since the data used for the analysis consist of two rounds of panel data, it is necessary to create indices which can be compared over time. Therefore, the pooled data from two rounds of panel data are used to generate both intensification indices.

Table 5 shows the factor loadings of the individual elements accounting for both household and plot level agricultural intensification indices. The principal components explain 31% of the variance in the 5 variables for the household level model and 35% of that in the 4 variables for the plot level model. Factor loading, which provides direction and weight for each variable, shows that the quantity of chemical fertilizer applied and number of improved cows account for a large part of the agricultural intensification in the household level model and hybrid seed adoption and the quantity of chemical fertilizer applied contribute greatly to the agricultural intensification in the plot level model. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy takes a value between 0 and 1, and higher KMO values indicate that the correlation between pairs of the explanatory variables could be explained by the other explanatory variable (Kaiser, 1974). The KMO of the household level index is 0.60 and that of the plot level index is 0.56, and it is usually considered that PCA is acceptable if a value of KMO is more than 0.5. The factor loadings for both indices obtained from the pooled samples of the 2004 and 2012 surveys display similar patterns, which indicates that it is acceptable to use the indices created from pooled data. The result shows that agricultural intensification indices have increased from -0.126 to 0.124 from 2004 to 2012 at the household level and from -0.181 to 0.204 at the plot level, indicating that agricultural intensification has advanced even in the short period of 8 years.

Table 6 indicates evidence that the agricultural intensification index captures the degree of intensification of each input quite well by looking at crop production on maize plots per cropping season by the quartile of the plot level index in 2012. As shown in the table, there are upward trends in all individual input uses, as the quartile of the agricultural index goes up. Consistently, outcome variables such as maize yields, value of production from all crops, and net crop income increase as the degree of agricultural intensification deepens. These findings indicate that the farmers' effort of agricultural intensification is likely to pay off in rural Kenya. Furthermore, it is interesting to note that households that belong to the greatest quartile of the index have the smallest operated maize plot size, which is consistent with the negative correlation between farm size and agricultural intensification widely observed in Sub-Saharan Africa in recent years (Larson et al., 2014).

5 Estimation Strategies

5.1 Determinants of the New Maize Farming System Adoption

Following the literature on agricultural intensification, this study focuses on population pressure as the driving force that accelerates agricultural intensification. Boserup (1965) argues that a rise in population density will change the relative prices of land and labor, which increases the demand for new inputs such as fertilizer, irrigation water, improved seeds, and herbicide in order to intensify land use. This leads to an increase in input use per unit of area, which is regarded as agricultural intensification. In this way, population pressure accelerates intensive use of labor and other non-land inputs, which facilitates a shift of farming system from extensive, such as slash and burn farming, to intensive, such as sedentary multi-cropping farming with higher agricultural productivity (Otsuka and Place, 2001). Similarly, Hayami and Ruttan (1985) argue that changes in relative input scarcities would bring about changes in behaviors of farmers and supporting institutions to adapt to new conditions, which is called the “induced innovation hypothesis.” In their hypothesis, it is postulated, as in the Boserupian view, that population pressure decreases a wage rate relative to a land price, which increases the demand for labor and non-land input use, thereby enhancing land productivity. Empirical evidence shows that population pressure is associated with smaller land size and higher agricultural intensification (Josephson, Ricker-Gillbert, and Florax, 2014; Muyanga and Jayne, 2014; Ricker-Gillbert, Jumbe, and Chamberlin, 2014). Following the existing literature, this study employs the community level population density and the ratio of a household’s own land to family labor as proxies for population pressure on land in order to explore its impact on agriculture intensification.

To assess the effects of the population pressure and other variables to explain agricultural intensification, we consider estimation of the following reduced form equation based on seasonal maize plot level data:

$$I_{iphvdst} = \alpha_0 + \alpha_1 Pop_{vdt} + \alpha_2 LL_{hvdt} + \alpha_3 PL_{iphvdst} + \alpha_4 Pr_{vdt} + \alpha_5 X_{hvdt} + \alpha_6 Dist_{vdt} + \alpha_7 Div_d + \alpha_8 D_t + \alpha_9 Div_d * D_t + SS_s + \beta_{phvd} + \varepsilon_{iphvdst}, \quad (3)$$

where $I_{iphvdst}$ is the agricultural intensification index or one of the four agriculture input or practice variables of interest, i.e., the amount of manure applied per hectare, amount of chemical fertilizer converted into the NPK applied per hectare, adoption of hybrid maize seed, and amount of intercropping legume seed planted. All variables pertain to maize plot *i* in parcel p of household *h* in sub-location *v* in division *d* in cropping season *s* in year *t*.[3] Pop_{vdt} is a sub-location level population density (persons per km^2). LL_{hvdt} is a ratio of household's own land size to a number of working age (15-64) household members. $PL_{iphvdst}$ is plot land size. Pr_{vdt} is a vector of sub-location level output and input prices including a maize price, a diammonium phosphate (DAP) price, which is the price of most popular chemical fertilizer in the survey area, an average hybrid maize seed price, and a wage rate of hired labor in agriculture. X_{hvdt} is a vector of household control variables including a number of working age (15-64) household members, a dummy variable for female head, household head's age, a dummy variable for head with primary education, value of livestock, and a soil carbon content of the main maize plot which represents soil fertility of household's farm land. Some soil samples were lost or spoiled in the laboratory and thus a dummy variable for no soil information is created and included in the regressors in order to avoid the loss of the observations without soil sample information. $Dist_{vdt}$ is a travel time from the center of sub-location to the nearest big town by a motor vehicle. Div_d and D_t are division and time dummies. Division and time interaction terms are also added to control for the impact of time specific localized shocks that could affect both agricultural intensification and population pressure. SS_s is a short season dummy. β_{phvd} is a household-parcel fixed effect that intends to capture time-invariant parcel characteristics such

[3] Both division and sub-location are types of administrative regions in Kenya. There are 43 divisions, which divided into 96 sub-locations in our sample data.

as soil type and land quality and time-invariant household level factors such as farmer management ability, household risk preferences, and unmeasured household wealth, which could be correlated with population density and the land-labor ratio and input use simultaneously. The existence of β_{phvd} would cause OLS estimates to be biased and inconsistent. Because of the availability of plot level production data for the same parcel in different seasons and different years, we can purge β_{phvd} by estimating equation (3) using a household-parcel level fixed effects estimation approach. Our main interest is the estimated parameters of α_1 and α_2.

5.2 Impact of the New Maize Farming System on Agricultural Production

To examine the impact of the new maize farming system on agricultural productivity, the impact of each individual element of the new farming system is estimated separately. Additionally, in order to measure the impact of the entire farming system, the effect of the agricultural intensification index is also estimated. The following model is used to examine individual and overall effects:

$$Q_{iphvdst} = \delta_0 + \delta_1 I_{iphvdst} + \delta_2 PL_{iphvdst} + \delta_3 X_{hvdt} + \delta_4 Dist_{vdt} + \delta_5 Div_d + \delta_6 D_t + \delta_7 Div_d * D_t + SS_s + \theta_{phvd} + \mu_{phvdt} + \varepsilon_{iphvdst}, \quad (4)$$

where $Q_{iphvdst}$ is one of the three output variables of interest, which are the physical maize yield per hectare, value of all crop production, and net crop income which is defined as value of all crop production minus all paid costs. As in the determinants of intensification regression models, the existence of the time-invariant unobservable factor (θ_{phvd}) would cause the OLS estimates to be biased and inconsistent. To deal with this, we first estimate equation (4) using household-parcel fixed effects model approach. However, even after the time-invariant household-parcel characteristics are controlled for, there are still concerns that the year-variant household and parcel level factors, μ_{phvdt} could affect both intensification and agricultural outputs simultaneously. To deal with this problem, we take advantage of a subsample of parcels for which the production data is available for at least one plot from both seasons or more than one plot in any one cropping season in a given year. Such subsamples of parcels allow us to estimate δ_1 from within household-parcel-year variation.

Outputs from a new maize farming system accrue not only from crop production but also from milk production. Therefore, the following models are also employed in order to capture the effect of the maize-based farming system on total value of crop and milk production and net income from the crop and milk production:

$$Y_{hvdt} = \pi_0 + \pi_1 HI_{hvdt} + \pi_2 L_{hvdt} + \pi_3 X_{hvdt} + \pi_4 Dist_{vdt} + \pi_5 Div_d + \pi_6 D_t + \pi_6 Div_d * D_t + \rho_{hvd} + \varepsilon_{hvdt}, \quad (5)$$

where Y_{lkjt} is alternately the value of crop and milk production per hectare or net income per hectare defined as value of crop and milk production minus all paid costs associated with crop and milk production. HI_{hvdt} is the household level intensification index. L_{hvdt} is household's land endowment. As indicated above, the unobservable fixed effects, ρ_{hvd}, would result in inconsistent estimates. Hence, the household fixed effects model is estimated for equations (5).

Even though the intensification appears to increase land productivity and profitability, it is not clear whether agricultural intensification also contribute to overall household income. Though intensification increases crop income, household income could decrease in total if intensification requires large amount of family labor and a household reduces labor allocation to non-farm activity. Therefore, we also conduct household fixed effects estimation to examine the effect of maize farming intensification on household net non-farm income and net total income, which is a sum of net crop income, net livestock income, wage income, net income from self-owned business and transfer income such as remittances and pensions, by using same specification of equation (5). The dependent variables are household net non-farm per capita and net total income per capita.

6 Estimation Results

6.1 Determinants of Adoption of the New Maize Farming System

Table 7 shows the estimation results of the new maize-based farming system adoption model. In columns (1) to (5), the specifications explaining quantity of manure per hectare, quantity of NPK equivalent chemical fertilizer use per hectare, adoption of hybrid maize seed dummy, quantity of intercropped legume seeds planted per hectare, and the agriculture intensification index on a maize plot per cropping season are estimated by the household-parcel level fixed effects model.

The econometric results confirm that population pressure is indeed the driving force for the emergence of the new farming system. For example, sub-location level population density has a positive and significant impact on hybrid seeds adoption and the agriculture intensification index. Additionally, the land-labor ratio has a negative and significant effect on chemical fertilizer use and the agriculture intensification index. These estimation results support our hypothesis that population pressure encourages input use intensification. It is observed that plot size has consistently negative and significant impacts on all technology adoption except hybrid maize seed, which also indicates that scarcity of land facilitates agricultural intensification.

As expected, the chemical fertilizer use is negatively and significantly affected by DAP price (price of the most popular chemical fertilizer in the survey area). It also appears that the chemical fertilizer and organic fertilizer are substitutes, which is indicated by the positive coefficient of DAP price in the model of quantity of manure, even though it is significant only at 10% level. While the hybrid seed price has the expected negative sign in the coefficient of adoption of hybrid seed, it is statistically insignificant, suggesting seed price is not a major factor affecting farmers' decision on whether to adopt hybrid seed varieties or not. On the other hand, farmers' adoption decisions of hybrid maize are positively and significantly influenced by maize price, which is not surprising if farmers are profit maximizers and hybrid seed varieties have yield advantages over the conventional varieties.

6.2 Impact of the New Maize Farming System on Agricultural Production

Table 8 shows the impact of individual input use and intercropping on land productivity alternatively measured by maize yield per hectare, value of all crop production per hectare, and net crop income per hectare on a maize plot per cropping season. The equation (4) is estimated in two ways. We first present the household-parcel fixed effects results for each of three measures of land productivity (columns 1, 3, and 5) and then the household-parcel-year fixed effects results (columns 2, 4, and 6).

The household-parcel fixed effects model shows that adoption of hybrid maize is found to contribute to 12% and 13% increases in maize yield and value of all crop production. Additionally, the household-parcel-year fixed effects estimation indicates that the adoption of hybrid maize would increase net crop income by 16%. Quantity of intercropped legume seeds is shown to have an almost zero impact on maize yield. This is not surprising because by intercropping maize with legume, the "effective" maize planted area becomes smaller in an intercropped field than a pure-stand field. Thus, no effect on maize yield seems to indicate that the fertility-enhancing effect of intercropping, as offset by the effect of the shrinkage of "effective" maize area. However, farmers could obtain revenue from legume harvest in addition to revenue from maize and thus total crop revenue from an intercropped field could be more than a pure-stand field. In fact, an increase in intercropped legume seeds by 10 kg raises value of crop production by from 3 to 4% and net crop income by about 4%. Hence, although intercropping with legumes on a maize plot does not increase maize yield, farmers can obtain higher revenue and income from the intercropped production of legumes. In addition, as legumes enhance soil nutrients by fixing nitrogen from the atmosphere, intercropping with legumes could contribute to a gain in total crop revenue in the longer run.

Both household-parcel fixed effects and household-parcel-year fixed effects estimations show that the additional application of manure by one ton per hectare is expected to increase maize yield, value of all crop production, and net income from all crops by about 2-3%, 3%, and 3%, respectively. Similarly, additional application of chemical fertilizer by 10 kg per hectare is expected to increase maize yield and value of all crop production by about 2-3% and 2%, respectively. However this positive impact disappears in net crop income, implying that chemical fertilizer application does not increase as much as maize yield and crop revenue dues to its high costs. There are consistent negative effects of farm size on all outcome variables, which demonstrates the inverse relationship between farm size and agricultural productivity.[4]

[4] In order to check if there are interacted effects of adoption of hybrid maize seeds and other input use, Table A2 shows the estimation results of the effects of input intensification including interaction terms between adoption of

It may not be possible to capture the whole impact of the new maize farming system only by estimating the impact of an individual practice on agriculture production. In order to examine the effect of the entire new maize farming system, we re-estimated equation (4) by replacing all the individual intensification practices by the single agricultural intensification index on the right hand side of the equation. The estimation results using both the household-parcel fixed effect and household-parcel-year fixed effect panel estimation methods are reported in Table 9. The results show significant and positive effects of the agricultural intensification index on all outcome variables consistently for both models. However, estimated coefficients in parcel-year fixed effect models are smaller than those of parcel fixed effect models, suggesting possible positive bias in parcel fixed effect models which fail to control year variant household and parcel level unobservables. An increase in the intensification index by one standard deviation would raise maize yield per hectare by 18% and 10%, value of all crop production per hectare by 22% and 15%, and net crop income per hectare by 15% and 10% in the parcel fixed effects model and in the parcel-year fixed effect model, respectively. Consistent with the results in Table 8, we observe the negative impacts of the farm size on outcome variables, which confirms the inverse farm size-productivity relationship.

Since the new maize farming system aims to increase output not only from crop production but also from milk production, Table 10 exhibits the impacts of agricultural intensification on the total value of crop and milk production per hectare (column 1) and the sum

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hybrid maize seeds with intercropping with legume, manure application, and chemical fertilizer application. Though individual effects of each input still remains mostly positive and significant, most effects of the interaction terms are insignificant. This seems to contradict with the descriptive finding in which many farmers use hybrid seeds and fertilizers at the same time and they achieve higher yields than those who don't. One possible explanation is that there are mainly two types of farmers, who use inputs all together and achieve high yields and who don't. Thus, interaction effects might be difficult to observe in the interaction terms.

of crop and milk net income per hectare (column 2) estimated from household level panel data. Consistent with the findings in Table 9, the effects of agriculture intensification on both outcome variables are positive and significant. A rise in the intensification index by one standard deviation would increase the value of crop and milk production per hectare by 36% and net crop income per hectare by 34%. The estimation results also indicate that the household head's age is negatively related to both crop and milk production and net income, indicating that a household with a younger head tends to have higher agricultural productivity.

Furthermore, Table 11 shows the estimation results of the effect of maize farming intensification on the net non-farm income per capita (column 1) and the net total household income per capita (column 2) based on household level panel data. There is a potential concern that the positive effect of increase in agricultural intensification on crop income could be offset by a reduction of non-farm income if intensification requires large amount of family labor and a household reduces its labor allocation to non-farm activities. The positive and insignificant coefficient on intensification index in the off-farm equation allays such concern (column 1). Finally, intensification has significant and positive effect on total income as supported by the positive and statistically significant coefficient of intensification index on the total income equation (column 2). In terms of the magnitude of effect, one standard deviation increase in the intensification index causes net total income to increase by 21%. The results on other variables are also mostly consistent with expectation. For example, land access is significantly and positively related to both non-farm income and total income. Female-headed households are worse off than male-headed households, as they earn 50% and 31% less non-farm income and total income than male-headed households holding other factors constant. The value of productive assets is positively associated with non-farm income and total income.

6.3 Impact of the New Maize Farming System on Profit

One limitation of the data is that it did not collect information on family labor use on crop production and thus we could not estimate an impact of the new farming system on profits netted of family labor cost[5] If intensification requires households to use more family labor which is not captured by data, an impact of intensification on agricultural production or income would overestimate the impact on production efficiency. Though the survey team did not collect family labor use data from all plots, they collected it from the largest pure stand maize plot in the main cropping season. If a household does not have a pure-stand maize plot, family labor use information on the largest intercropped maize plot in main season was collected. Based on this additional information in the dataset, we could compute a profit, which is defined as value of crop production minus all the costs associated with production including family labor on the largest maize plot. This enables us to check if the impact of agricultural intensification differs between net crop income and profit at least for the largest plot.

Table 12 displays crop production data on the largest pure-stand maize plot or the largest intercropped maize plots in the main cropping season. The means of most inputs and outputs have the same trend as in Table 2; crop yield and revenues increased with the level of intensification over time. Additionally, crop profit has increased by 26% over time. In contrast to other input use, family labor use and live-in and exchange labor use have decreased significantly over time. This means that intensification occurs in a rather unexpected manner in that the

[5] The concern is mainly related to the quantification of the net effects on agricultural productivity and agricultural income. The results on off-farm income and total income are not affected as the labor use is internalized in the measurement of off-farm income and total income.

intensified system increases the use of capital inputs to save the cost of labor through input substitution.

Table 13 compares the effect of the new farming system on net crop income, which is defined as value of crop production minus all paid costs, and crop profits, which is defined as value of crop production minus all costs including family labor cost, using the same subsample of plots. The results indicate that one standard deviation increase in the intensification index would raise net crop income by about 9% and crop profit by 12%, suggesting that the potential biases of the estimated effects of the intensification system based on the large sample without accounting for family labor are likely to be small.

7 Conclusion and Policy Implications

As population pressure grows rapidly in Kenya, rural farmers have started to intensify a farming system by adopting new inputs and production practices, including adoption of high-yielding maize varieties, application of manure produced by improved dairy cows, and intercropping of maize with legumes that could fix nitrogen. Though the phenomenon of the new farming system has started to receive attention among researchers, the empirical research that assesses the driving forces and impacts of this system is limited. Hence, this study aims to quantify the determinants of the new maize farming system and its impact on agricultural productivity. To assess the impact of the new farming system, this study examines the impacts of inputs individually as well as the impact of the new maize farming system by using an agricultural intensification index constructed by PCA.

Our estimation results show that an increase in sub-location level population density raise the rate of hybrid maize seed adoption and the extent of agricultural intensification, meanwhile a decrease in the land-labor ratio increases chemical fertilizer application and the degree of agricultural intensification. These findings indicate that population pressure accelerates farming intensification, consistent with the Boserupian and induced innovation hypotheses. Furthermore, it is found that the adoption of hybrid maize seed, intercropping legumes with maize, manure application, and chemical fertilizer application have positive and significant impacts on land productivity. These impacts are confirmed and reinforced by the consistently positive and significant impacts of the agriculture intensification index not only on land productivity in terms of value of production and net income per hectare but also on the household total income per capita.

Therefore, we conclude that the new farming system has significantly improved the productivity of small-scale farmers in the highlands of Kenya. We must recognize, however, that there has been little research on the “optimum” farming system, despite the fact that new seeds, inorganic and organic fertilizer, and intercropping with leguminous crops are likely to be complementary. It can be expected that much more significant increase in the productivity of farming could be achieved if appropriate research is carried out and appropriate technical support and extension services regarding this new maize farming system are provided for small-scale maize farmers in Kenya.

Table 1 Sample household and sub-location characteristics

	2004		2012		Testing difference in means[a]
	Mean	S.D.	Mean	S.D.	
Household characteristics					
Number of households	622		622		
Female-headed households (%)	22%	(41)	29%	(46)	***
Head completed primary education (%)	35%	(48)	41%	(49)	**
Age of the head (years)	55.89	(13.9)	61.01	(14.2)	***
Value of productive asset (KSh)	49,394	(184,421)	35,050	(155,685)	
Value of asset (KSh)	80,829	(201,970)	65,933	(169,348)	
Household size	6.6	(2.9)	7.1	(3.2)	***
Household members between 15 & 64	3.6	(2.0)	4.4	(2.4)	***
Number of dependents	2.8	(1.9)	2.6	(1.7)	**
Owned land size (ha)	1.7	(2.4)	1.5	(1.8)	**
Owned land size per household members between 15 & 64 (ha)	0.6	(0.9)	0.4	(0.7)	***
Sub-locations characteristics					
Number of sub-locations	96		96		
Sub-location population density (persons/km^2)	744	(1,123)	1,101	(1,616)	***
Time to the nearest big town (min by car)	98	(48)	79	(37)	***

*** and ** indicate significance at 1 and 5%, respectively.
[a] Significance testing of the difference in means between 2004and 2012.

Table 2 Crop production of the maize plots per cropping season

	2004		2012		Testing difference in means[a]
	Mean	S.D.	Mean	S.D.	
Number of plots	1,552		1,356		
Maize plot size (ha)	0.38	(0.42)	0.34	(0.31)	***
Hybrid maize seeds (%)	49%	(50)	72%	(45)	***
Intercrop with legumes (%)	78%	(42)	72%	(45)	***
Manure applied (%)	39%	(49)	48%	(50)	***
Chemical fertilizer applied (%)	70%	(46)	71%	(45)	
Intercropped legumes seeds (kg/ha)	20	(25)	25	(25)	***
Quantity of manure (kg/ha)	970	(2,554)	1385	(2,729)	***
Quantity of chemical fertilizer (kg/ha) [b]	46	(62)	44	(50)	
Cost of other chemical inputs (KSh/ha) [c]	88	(376)	176	(506)	***
Cost of hired labor (KSh/ha)	2,941	(5,625)	3,973	(5,684)	***
Quantity of maize yield (kg/ha)	1,363	(1,452)	1,909	(1,446)	***
Value of crop production (KSh/ha)	41,733	(43,285)	50,701	(43,652)	***
Net crop income (KSh/ha) [d]	32,101	(39,441)	38,918	(39,589)	***

*** and * indicate significance at 1 and 10%, respectively.

[a] Significance testing of the difference in means between 2004and 2012.

[b] Quantity of chemical fertilizer is measured in NPK equivalent.

[c] This includes herbicides, pesticides, fungicides, and other chemical input.

[d] Net crop income is defined as the value of all crop production minus all paid costs associated with crop production.

Table 3 Means of yield and fertilizer application by seed type in the maize plots per cropping season in 2012

	Type of maize seeds			Testing difference in means[a]
	Local seeds	Hybrid seeds	All	
Number of maize parcels	381	975	1,356	
Maize yield (kg/ha)	1,315	2,143	1,909	***
Value of crop production (KSh/ha)	34,151	57,215	50,701	***
Manure				
Manure applied (%)	48%	48%	48%	
Quantity Applied (kg/ha)	1,070	1,509	1,385	***
Chemical fertilizer				
Chemical fertilizer applied (%)	45%	82%	71%	***
Quantity Applied (kg/ha)	22	53	44	***

*** and * indicate significance at 1 and 10%, respectively.

[a] Significance testing of the difference in means between local seeds and hybrid seeds.

Table 4 Milk production per household in a year

	2004		2012		Testing difference in means[a]
	Mean	S.D.	Mean	S.D.	
Number of households	662		662		
Number of local cows	1.3	(4.8)	1.3	(4.5)	
Number of improved cows	1.9	(2.9)	1.8	(2.5)	
Number of total cows	3.2	(5.2)	3.1	(4.8)	
HH with improved cows (%)	0.57	(0.5)	0.56	(0.5)	
Quantity of milk produced per cow for HH owning only local cows (liter/cow)	154	(222)	182	(211)	
Quantity of milk produced per cow for HH owning only improved cows (liter/cow)	695	(619)	841	(665)	***
Quantity of milk produced per cow for HH owning local & improved cows (liter/cow)	336	(307)	396	(296)	
Quantity of milk produced per cow for all HH (liter/cow)	511	(570)	624	(627)	***
Value of milk produced (KSh/cow)	29,268	(35,912)	27,683	(35,729)	
Net milk income (KSh/cow)[b]	20,922	(29,498)	22,127	(30,916)	

*** indicates significance at 1%.

[a] Significance testing of the difference in means between 2004and 2012.

[b] Net milk income is defines as the value of milk produced minus all the paid costs associated with milk production.

Table 5 Factor loading for maize production intensification index in maize plots

	Pooled years	2004	2012
Household level			
Individual elements		**Factor loadings**	
Hybrid maize seeds (=1)	0.46	0.48	0.41
Quantity of intercropped legume seed (kg/ha)	0.09	0.03	0.10
Quantity of manure (kg/ha)	0.41	0.38	0.45
Quantity of chemical fertilizer (kg/ha)[a]	0.59	0.60	0.59
Number of improved cows (numbers/ha)	0.51	0.51	0.52
KMO	0.60	0.59	0.57
Proportion variation explained	0.31	0.32	0.29
Mean of agriculture intensification index generated from pooled data	0.00	-0.126	0.124
SD of agriculture intensification index	1.24	1.32	1.14
Plot level			
Individual elements		**Factor loadings**	
Hybrid maize seeds (=1)	0.56	0.56	0.57
Quantity of intercropped legume seed (kg/ha)	0.43	0.38	0.45
Quantity of manure (kg/ha)	0.34	0.27	0.36
Quantity of chemical fertilizer (kg/ha) [a]	0.62	0.69	0.59
KMO	0.56	0.49	0.57
Proportion variation explained	0.35	0.34	0.36
Mean of agriculture intensification index generated from pooled data	0.00	-0.181	0.204
SD of agriculture intensification index	1.19	1.22	1.12

[a] Quantity of chemical fertilizer is measured in NPK equivalence.

Table 6 Mean of crop production by quartile of the agriculture intensification index in maize plots in 2012

	Quartile of agriculture intensification index			
	1st	2nd	3rd	4th
Hybrid maize seeds (%)	11%	85%	95%	96%
Intercrop with legumes (%)	50%	66%	79%	91%
Manure applied (%)	39%	44%	46%	60%
Chemical fertilizer applied (%)	32%	69%	87%	96%
Intercropped legumes seeds (kg/ha)	11	17	26	45
Quantity of manure (kg/ha)	528	762	1042	3134
Quantity of chemical fertilizer (kg/ha) [a]	9	23	49	94
Cost of other chemical inputs (KSh/ha) [b]	54	118	189	334
Cost of hired labor (KSh/ha)	2,083	3,458	4,709	5,213
Quantity of maize yield (kg/ha)	1,247	1,664	2,064	2,606
Value of crop production (KSh/ha)	27,503	40,384	52,122	79,475
Net crop income (KSh/ha) [c]	23,901	32,076	38,142	58,648
Maize plot size (ha)	0.32	0.38	0.37	0.28

[a] Quantity of chemical fertilizer is measured in NPK equivalence.
[b] This includes herbicides, pesticides, fungicides, and other chemical inputs.
[c] Net crop income is defined as crop production minus all paid costs associated with crop production.

Table 7 Estimation results of the determinants of input intensification per cropping season (parcel fixed effects model, plot level data)[a]

Explanatory variables	Manure (t/ha) (1)	Chemical fertilizer (10kg/ha)[b] (2)	Hybrid maize seeds (=1) (3)	Intercropping legume seeds (kg/ha) (4)	Intensification index (5)
Log of sub-location population density (ppl/km^2)	0.470	0.340	0.152*	5.227	0.328*
	(0.722)	(0.907)	(0.0782)	(4.364)	(0.194)
Log of owned land size per working adult (ha)	0.0688	-0.370**	-0.00952	-1.056	-0.0681*
	(0.118)	(0.177)	(0.0167)	(0.973)	(0.0387)
Log of cultivated plot size (ha)	-0.544***	-0.985***	0.0172	-4.513***	-0.231***
	(0.104)	(0.198)	(0.0159)	(0.923)	(0.0425)
Log of maize price (KSh/kg)	0.205	0.0141	0.0421*	-0.397	0.0570
	(0.209)	(0.290)	(0.0221)	(1.491)	(0.0605)
Log of DAP price (KSh/kg)	1.087*	-2.450**	-0.0203	1.971	-0.150
	(0.604)	(1.032)	(0.104)	(5.492)	(0.232)
Log of hybrid maize seed price (KSh/kg)	0.0197	0.550	-0.0834	-1.316	-0.0460
	(0.466)	(0.940)	(0.103)	(4.556)	(0.213)
Log of farm wage rate (KSh/day)	-0.0932	-1.785	-0.0497	2.083	-0.201
	(0.466)	(1.193)	(0.0853)	(5.167)	(0.216)
Log of HH size	0.277	0.610*	0.0391	-0.144	0.137
	(0.269)	(0.328)	(0.0426)	(2.025)	(0.0847)
Female-headed (=1)	-0.333	0.0621	0.0318	1.893	0.0349
	(0.250)	(0.532)	(0.0525)	(2.340)	(0.113)
Head's age	-0.00688	0.0139	-0.00182	0.135	0.00229
	(0.00895)	(0.0226)	(0.00166)	(0.0827)	(0.00447)
Head completed primary education (=1)	-0.104	0.679	-0.00915	-1.420	0.0275
	(0.237)	(0.550)	(0.0388)	(2.309)	(0.101)
Log of value of productive assets (KSh)	0.138**	0.0964	0.0105	-0.147	0.0391
	(0.0688)	(0.124)	(0.0106)	(0.642)	(0.0252)
Log of carbon in the soil	-0.145	1.090	0.0119	1.401	0.104
	(0.491)	(0.842)	(0.0738)	(4.539)	(0.176)
Log of time to big town (min by car)	-1.846	-4.778*	-0.0979	-2.723	-0.711
	(1.812)	(2.505)	(0.278)	(18.52)	(0.640)
Constant	0.147	30.34**	0.487	-19.76	1.011
	(8.946)	(12.02)	(1.344)	(85.02)	(3.022)
Observations	2,879	2,884	2,908	2,883	2,831
R-squared	0.068	0.164	0.189	0.106	0.155
Number of parcels	1,118	1,119	1,122	1,120	1,113

The numbers in parentheses are robust standard errors.
***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Interaction terms between year 2012 and divisions, and year 2012, short season, and no carbon information dummies are included in all regressions.
[b] Quantity of chemical fertilizer is measured in NPK equivalence.

Table 8 Estimation results of the effects of input intensification on crop production per cropping season (parcel and parcel-year fixed effects models, plot level data)[a]

	Log of maize yield (kg/ha)		Log of value of crop production (KSh/ha)		Log of net crop income (KSh/ha)[c]	
Type of fixed effects model	Parcel	Parcel -year	Parcel	Parcel -year	Parcel	Parcel -year
Explanatory variables	(1)	(2)	(3)	(4)	(5)	(6)
Hybrid maize seeds (=1)	0.124**	0.0792	0.125**	0.0806	0.0835	0.156*
	(0.0526)	(0.0646)	(0.0582)	(0.0848)	(0.0672)	(0.0924)
Intercropping legume seeds (kg/ha)	0.000314	-0.00100	0.0039***	0.00290**	0.0041***	0.00429***
	(0.0009)	(0.00114)	(0.00100)	(0.00135)	(0.00112)	(0.00149)
Manure (t/ha)	0.0275***	0.0176*	0.0321***	0.0313***	0.0324***	0.0194
	(0.00843)	(0.00949)	(0.00903)	(0.0116)	(0.0107)	(0.0120)
Chemical fertilizer [b] (10kg/ha)	0.0290***	0.0180***	0.0215***	0.0103	0.00533	-0.00974
	(0.00522)	(0.00631)	(0.00614)	(0.00915)	(0.00633)	(0.00868)
Log of cultivated plot size (ha)	-0.457***	-0.530***	-0.387***	-0.450***	-0.333***	-0.435***
	(0.0406)	(0.0447)	(0.0470)	(0.0555)	(0.0434)	(0.0646)
Log of household size	0.128		0.116		0.0784	
	(0.0964)		(0.0904)		(0.0822)	
Female-headed (=1)	-0.0960		-0.0858		-0.0510	
	(0.114)		(0.110)		(0.103)	
Age of head	0.00154		0.00130		-0.000914	
	(0.00416)		(0.00407)		(0.00366)	
Head completed primary education (=1)	0.0907		0.0197		0.188*	
	(0.101)		(0.0873)		(0.103)	
Log of value of productive assets (KSh)	0.00802		-0.0387		-0.00229	
	(0.0247)		(0.0250)		(0.0269)	
Log of carbon	0.0499		-0.0789		0.250	
	(0.172)		(0.153)		(0.199)	
Log of time to big town (min by car)	-0.692		-0.691		-0.256	
	(0.496)		(0.467)		(0.549)	
Constant	8.721***	6.266***	12.89***	9.680***	10.18***	9.405***
	(2.232)	(0.0777)	(2.129)	(0.0973)	(2.506)	(0.113)
Observations	2,810	2,810	2,810	2,810	2,809	2,809
R-squared	0.732	0.737	0.522	0.532	0.810	0.782
Number of fixed-effects	1,110	1,803	1,113	1,805	1,113	1,805

The numbers in parentheses are robust standard errors.
***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Short season dummy is included in all regression. Interaction terms between year 2012 and divisions, and year 2012, and no carbon information dummies are included in regression of (2), (4) and (6).
[b] Quantity of chemical fertilizer is measured in NPK equivalence.
[c] Net crop income is defined as crop production minus all paid costs associated with crop production.

Table 9 Estimation results of the effects of the intensification index on crop production per cropping season (parcel and parcel-year fixed effects models, plot level data)[a]

	Log of maize yield (kg/ha)		Log of value of crop production (KSh/ha)		Log of net crop income (KSh/ha)[b]	
Type of fixed effects model	Parcel	Parcel -year	Parcel	Parcel -year	Parcel	Parcel -year
Explanatory variables	(1)	(2)	(3)	(4)	(5)	(6)
Intensification index	0.155***	0.0817***	0.185***	0.126***	0.129***	0.0864**
	(0.0214)	(0.0261)	(0.0248)	(0.0360)	(0.0263)	(0.0366)
Log of cultivated plot size (ha)	-0.463***	-0.534***	-0.397***	-0.457***	-0.342***	-0.430***
	(0.0399)	(0.0441)	(0.0459)	(0.0546)	(0.0426)	(0.0638)
Log of household size	0.137	-	0.115		0.0748	
	(0.0960)		(0.0900)		(0.0826)	
Female-headed (=1)	-0.103		-0.0892		-0.0521	
	(0.113)		(0.109)		(0.102)	
Age of head	0.00138		0.00148		-0.000736	
	(0.00411)		(0.00405)		(0.00370)	
Head completed primary education (=1)	0.102		0.0202		0.180*	
	(0.102)		(0.0868)		(0.102)	
Log of value of productive assets (KSh)	0.0104		-0.0384		-0.00188	
	(0.0245)		(0.0249)		(0.0269)	
Log of carbon	0.0574		-0.0771		0.245	
	(0.171)		(0.153)		(0.200)	
Log of time to big town (min by car)	-0.747		-0.704		-0.219	
	(0.504)		(0.470)		(0.543)	
Constant	9.192***	6.386***	13.23***	9.864***	10.20***	9.580***
	(2.268)	(0.0605)	(2.138)	(0.0755)	(2.476)	(0.0897)
Observations	2,810	2,810	2,810	2,810	2,809	2,809
R-squared	0.730	0.736	0.521	0.530	0.810	0.780
Number of fixed effects	1,110	1,803	1,113	1,805	1,113	1,805

The numbers in parentheses are robust standard errors.
***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Short season dummy is included in all regression. Interaction terms between year 2012 and divisions, and year 2012, and no carbon information dummies are included in regression of (2), (4) and (6).
[b] Quantity of chemical fertilizer is measured in NPK equivalence.
[c] Net crop income is defined as crop production minus all paid costs associated with crop production.

Table 10 Estimation results of the effects of the intensification index on agriculture production per year (household fixed effects model, household level data)[a]

	Log of value of crop & milk production (KSh/ha)	Log of net crop & milk income (KSh/ha)[b]
Explanatory variables	(1)	(2)
Intensification index	0.293***	0.277***
	(0.0302)	(0.0382)
Log of owned land size (ha)	-0.0354	-0.0146
	(0.0446)	(0.0655)
Log of household size	0.0274	-0.0430
	(0.0791)	(0.105)
Female-headed (=1)	-0.0284	-0.161
	(0.0986)	(0.107)
Head's age	-0.00477*	-0.00897***
	(0.00282)	(0.00344)
Head completed primary education (=1)	-0.00583	-0.0262
	(0.0701)	(0.0919)
Log of value of productive assets (KSh)	0.00929	-0.0125
	(0.0218)	(0.0289)
Log of carbon	-0.104	-0.189
	(0.158)	(0.225)
Log of time to big town (min by car)	-0.337	-0.541
	(0.451)	(0.552)
Constant	12.65***	13.89***
	(2.038)	(2.447)
Observations	1,195	1,195
R-squared	0.389	0.524
Number of households	619	619

The numbers in parentheses are robust standard errors.
***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Interaction terms between year 2012 and divisions, and year 2012, short season, and no carbon information dummies are included in all regressions.
[b] Net crop and milk income is defined as the value of crop and milk production minus all paid costs associated with crop and production.

Table 11 Estimation results of the effects of the intensification index on non-farm and total household income per year (household fixed effects model, household level data)[a]

	Log of net non-farm income per capita (KSh)	Log of net total income per capita (KSh)[b]
Explanatory variables	(1)	(2)
Intensification index	0.0787	0.168***
	(0.0820)	(0.0386)
Log of owned land size (ha)	0.231*	0.172***
	(0.118)	(0.0447)
Log of household size	-0.295	-0.545***
	(0.199)	(0.0889)
Female-headed (=1)	-0.496*	-0.305***
	(0.266)	(0.117)
Head's age	-0.0128	-0.00703*
	(0.00873)	(0.00374)
Head completed primary education (=1)	-0.251	-0.117
	(0.223)	(0.0921)
Log of value of productive assets (KSh)	0.0931*	0.0631**
	(0.0538)	(0.0250)
Log of carbon	-0.181	-0.176
	(0.402)	(0.218)
Log of time to big town (min by car)	1.003	-0.490
	(1.132)	(0.640)
Constant	-0.964	-0.730**
	(0.656)	(0.312)
Observations	5.095	13.25***
R-squared	(5.120)	(2.886)
Number of households	1,192	1,192

The numbers in parentheses are robust standard errors.
***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Interaction terms between year 2012 and divisions, and year 2012, short season, and no carbon information dummies are included in all regressions.
[b] Net total income is computed as the sum of net crop income, net livestock income, wage income, net income from self-owned business and transfer income.

Table 12 Crop production of the largest pure-stand maize plot or the largest intercropped maize plot in the main cropping season

	2004		2012		Testing difference in means[a]
	Mean	S.D.	Mean	S.D.	
Number of plots	426		426		
Maize plot size (ha)	0.48	(0.45)	0.41	(0.34)	***
Hybrid maize seeds (%)	52%	(50)	76%	(43)	***
Manure applied (%)	44%	(50)	60%	(49)	***
Chemical fertilizer applied (%)	71%	(46)	75%	(43)	
Quantity of manure (kg/ha)	942	(2,567)	1525	(2,464)	***
Quantity of chemical fertilizer (kg/ha)[b]	53	(66)	43	(42)	***
Family labor (hours/ha)	991	(859)	706	(724)	***
Live-in & exchange labor (hours/ha)[c]	237	(398)	84	(207)	***
Cost of other chemical inputs (KSh/ha)[d]	106	(411)	184	(407)	***
Cost of hired labor (KSh/ha)	3,878	(6,042)	4,911	(6,370)	**
Quantity of maize yield (kg/ha)	1,661	(1,330)	2,071	(1,404)	***
Value of crop production (KSh/ha)	47,541	(40,774)	58,546	(44,362)	***
Net crop income from all crops (KSh/ha)[e]	36,920	(39,759)	45,246	(39,623)	***
Crop profit from all crops (KSh/ha)[f]	34,225	(38,841)	42,992	(39,542)	***

*** and * indicate significance at 1 and 10%, respectively.

[a] Significance testing of the difference between columns (b) and (c)

[b] Quantity of chemical fertilizer is measured in NPK equivalent.

[c] Live-in labor means live-in agricultural workers who live with the households.

[d] This includes herbicides, pesticides, fungicides, and other chemical input.

[e] Net crop income is defined as the value of all crop production minus all paid costs associated with crop production.

[f] Net crop income is defined as the value of all crop production minus all costs associated with crop production including family labor costs.

Table 13 Estimation results of the effects of the intensification index on crop production in the main cropping season (parcel fixed effects models, the largest maize plot level data)[a]

Explanatory variables	Log of net crop income (KSh/ha)[b] (1)	Log of crop profit (KSh/ha)[c] (2)
Intensification index	0.0789*	0.101*
	(0.0468)	(0.0539)
Log of cultivated plot size (ha)	-0.441***	-0.433***
	(0.0922)	(0.0988)
Log of household size	0.170	0.107
	(0.107)	(0.115)
Female-headed (=1)	-0.0492	-0.0726
	(0.158)	(0.176)
Age of head	-0.00187	-0.00613
	(0.0256)	(0.0275)
Squared age of head	-0.0000145	0.0000156
	(0.000216)	(0.000230)
Head completed primary education (=1)	0.223	0.347*
	(0.155)	(0.179)
Log of value of productive assets (KSh)	-0.0224	-0.00587
	(0.0386)	(0.0389)
Log of carbon	0.0583	0.00378
	(0.193)	(0.209)
Log of time to big town (min by car)	-0.415	-0.461
	(0.446)	(0.501)
Constant	-0.0109	-0.142
	(0.240)	(0.259)
Observations	0.0328	0.0379
R-squared	(0.124)	(0.141)
Number of fixed effects	11.50***	11.75***

The numbers in parentheses are robust standard errors.

***, **, and * indicate significance at 1, 5, and 10%, respectively.

[a] Year 2012 and no carbon information dummies are included in all regressions.

[b] Net crop income is defines as the value of crop production minus all paid costs associated with crop production.

[e] Crop profit is defined as the value of all crop production minus all costs associated with crop production including family labor costs.

Appendix

Table A1 Pairwise correlation coefficients matrix of input use

		(1)	(2)	(3)	(4)	(5)
Household level						
(1)	Hybrid maize seeds (=1)	1				
(2)	Quantity of intercropped legume seed (kg/ha)	0.0044	1			
(3)	Quantity of manure (kg/ha)	0.0899***	0.0598**	1		
(4)	Quantity of chemical fertilizer (kg/ha)[a]	0.2571***	0.0041	0.1428***	1	
(5)	Number of improved cows (numbers/ha)	0.1115***	0.0286	0.163***	0.2439***	1
Plot level						
(1)	Hybrid maize seeds (=1)	1				
(2)	Quantity of intercropped legume seed (kg/ha)	0.0716***	1			
(3)	Quantity of manure (kg/ha)	0.0739***	0.0826***	1		
(4)	Quantity of chemical fertilizer (kg/ha)[a]	0.2695***	0.1653***	0.0828***	1	

***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Quantity of chemical fertilizer is measured in NPK equivalence.

Table A2 Estimation results of the effects of input intensification on crop production per cropping season (parcel and parcel-year fixed effects models, plot level data)[a]

	Log of maize yield (kg/ha)		Log of value of crop production (KSh/ha)		Log of crop net income (KSh/ha)[c]	
Type of fixed effect model	Parcel	Parcel -year	Parcel	Parcel -year	Parcel	Parcel -year
Explanatory variables	(1)	(2)	(3)	(4)	(5)	(6)
Hybrid maize seeds (=1)	0.234***	0.157*	0.167**	0.0943	0.0751	0.0939
	(0.0703)	(0.0860)	(0.0770)	(0.106)	(0.0902)	(0.116)
Intercropping legume seeds (kg/ha)	0.00153	-0.000797	0.00403**	0.00179	0.00393**	0.00240
	(0.00139)	(0.00171)	(0.00168)	(0.00225)	(0.00187)	(0.00235)
Manure (t/ha)	0.0314**	0.0313*	0.0288*	0.0400*	0.0210	0.0167
	(0.0136)	(0.0169)	(0.0158)	(0.0207)	(0.0180)	(0.0210)
Chemical fertilizer (10kg/ha)[b]	0.0407***	0.0279***	0.0298***	0.0178	0.00890	-0.00841
	(0.00853)	(0.00936)	(0.00888)	(0.0135)	(0.0108)	(0.0137)
Hybrid seed * intercropping legume seeds (kg/ha)	-0.0159*	-0.0129	-0.0114	-0.0106	-0.00492	-0.00273
	(0.00896)	(0.0101)	(0.0100)	(0.0143)	(0.0119)	(0.0150)
Hybrid seed * manure (t/ha)	-0.00581	-0.0212	0.00474	-0.0134	0.0163	0.00497
	(0.0171)	(0.0199)	(0.0186)	(0.0248)	(0.0214)	(0.0250)
Hybrid seed * chemical fertilizer (10kg/ha)	-0.00203	-0.000432	-0.000261	0.00192	0.000365	0.00331
	(0.00167)	(0.00212)	(0.00186)	(0.00252)	(0.00229)	(0.00291)
Log of cultivated plot size (ha)	-0.454***	-0.526***	-0.386***	-0.449***	-0.334***	-0.437***
	(0.0407)	(0.0447)	(0.0471)	(0.0558)	(0.0436)	(0.0653)
Log of household size	0.128		0.115		0.0777	
	(0.0963)		(0.0901)		(0.0820)	
Female-headed (=1)	-0.0931		-0.0813		-0.0472	
	(0.114)		(0.110)		(0.103)	
Age of head	0.00192		0.00154		-0.000806	
	(0.00416)		(0.00407)		(0.00368)	
Head completed primary education (=1)	0.0887		0.0174		0.187*	
	(0.102)		(0.0873)		(0.103)	
Log of value of productive assets (KSh)	0.00876		-0.0386		-0.00272	
	(0.0247)		(0.0250)		(0.0268)	
Log of carbon	0.0490		-0.0789		0.252	
	(0.173)		(0.153)		(0.198)	
Log of time to big town (min by car)	-0.696		-0.677		-0.230	
	(0.498)		(0.469)		(0.548)	
Constant	8.776***	6.227***	12.80***	9.674***	10.06***	9.436***
	(2.243)	(0.0831)	(2.135)	(0.106)	(2.496)	(0.119)
Observations	2,810	2,810	2,810	2,810	2,809	2,809
R-squared	0.733	0.738	0.523	0.532	0.811	0.783
Number of fixed effects	1,110	1,803	1,113	1,805	1,113	1,805

The numbers in parentheses are robust standard errors.
***, **, and * indicate significance at 1, 5, and 10%, respectively.
[a] Short season dummy is included in all regression. Interaction terms between year 2012 and divisions, and year 2012, and no carbon information dummies are included in regression of (2), (4) and (6).
[b] Quantity of chemical fertilizer is measured in NPK equivalence.
[c] Net crop income is defined as crop production minus all paid costs associated with crop production.

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