# Economic value of crop residues in African smallholder agriculture

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## Abstract

This paper addresses the use and management of crop residues in the East African Highlands and farmers' decision-making associated with this important on-farm resource. Using data from a socio-economic and household production survey of a sample of 310 households in 15 villages in western Kenya conducted in 2011-2012, the analysis shows that the decision to allocate maize residues to soil fertility management and the amount of such allocation among Kenyan farmers is influenced by the quantity of maize residues produced, as well as conventional inputs into production such as labor and chemical fertilizer. Such allocation decision is also influenced by livestock ownership and purchase of firewood – indicators of other uses of maize residues. The value of maize residues left on the fields is estimated at 3.11 Kenyan shillings or $0.04 per 1 kg, a price that includes not only the value of nitrogen in maize residues but also the value of other environmental benefits that extend beyond fertilizer substitution.

**Keywords:** crop residues, maize production, biomass, value of natural resources, western Kenya.

# Introduction

In order to address the causes of low per capita food production of African smallholder farmers as well as their energy insecurity, measures such as enhancing soil productivity, using cleaner renewable fuels and adapting sustainable agricultural technologies are urgently needed. Many of these measures rely on on-farm biological resources, or biomass (vegetation, cultivated crops and livestock products and their residues), that provide both economic and environmental services in the form of animal feed, residential energy, building materials, and organic soil amendments. In addition, new applications, such as biomass as an input for biofuel production, are rapidly emerging. To reconcile these competing demands and to help address the critical need to improve current on-farm productivity and efficiency without jeopardizing long-term environmental sustainability, we need to better understand farmers' decision-making with respect to biomass management.

Among sources of on-farm biomass, it is perhaps crop residues that have the most competing applications. Crop residues include all inedible phytomass of agricultural production: cereal and legume straws; leaves, stalks, and tops of vegetable, sugar, oil, and tuber crops; and the litter and prunings of nut and fruit trees. Some estimates suggest that over 60% of all crop residues are produced in low income countries, and almost 45% of residues come from the tropics (Smil 1999). Residues are used as cooking fuels, animal feed, and soil fertility management, among other uses. Despite the low energy content of crop residues (compared to wood) and their bulkiness, residues constitute an important source of rural energy in arid, deforested, as well as densely population regions of Africa and Asia. Crop residues are also fed to domestic animals, either chopped and added to residue mixes, or left in the fields for stubble-grazing. Traditional practices in some regions also include the burning of residues, often done to prepare fields for next planting and to destroy phytomass that may carry diseases or pests that could reduce the next season's harvest. According to Smil (1999), about 25% of all residues are burnt in low income countries; this estimate increases to 45% when accounting for their use as fuel.

At the same time, leaving crop residues on the fields together with land fallowing and composting are among the principal strategies to build up soil organic matter that is critical for maintaining soil fertility in many cropping systems and environments. Depletion of soil organic matter is, in fact, often thought to be the fundamental cause for the decline in food production in Africa (Sanchez 2002; Antle and Stoorvogel 2008). Limited use of chemical fertilizer among resource-constrained smallholder farmers aggravates soil nutrient deficiency (Place et al. 2003). There is a growing recognition that soil fertility constraints in Sun-Saharan Africa (SSA) require combined applications of chemical fertilizer and organic resources to simultaneously address short-term crop nutrient demands and long-term increase in soil organic matter (e.g. Vanlauwe and Giller (2006)) and to take advantage of the two resources' economic complementarities (e.g. Marenya and Barrett (2009)). Addition of mineral fertilizer has long been recognized as fundamental to increasing crop yields. More recently, strategies centering on organic resources and crop residue management in particular (e.g. conservation agriculture, application of biochar, etc.) have been widely proposed as part of integrated soil fertility management (ISFM) strategies. Notwithstanding their multiple benefits – including improved yields and yield stability, and carbon sequestration – ISFM technologies centering on crop residues may not be adopted due to labor or land constraints (Place et al. 2003) and unless their profitability is greater than the value of alternative uses of biomass.

This paper examines the use and management of crop residues in the East African Highlands and farmers' decision-making associated with this important on-farm resource. Household survey results show that about 47% of maize residues (both stover and cobs) – the largest source of crop residues on western Kenya farms – is left on the fields as an organic soil amendment, roughly 25% is fed to livestock, 22% is used as cooking fuel, and the remaining residues are allocated to miscellaneous uses. Although considered important to support agricultural productivity, maize residues are thought to be returned to the soil only after other household needs are satisfied. This paper's empirical analysis shows that Kenyan farmers' decisions to allocate maize residues to soil fertility management, and the amount of such allocation, are influenced by the quantity of maize residues produced (in terms of area and yield), as well as conventional inputs into production such as labor and chemical fertilizer. Such decisions are also influenced by livestock ownership and purchase of firewood – indicators of other uses of maize residues. The value of maize residues left on the fields is estimated at about 3.11 Kenyan shillings (KES) or \$0.04 per 1 kg, so that an annual average amount of maize residues allocated to soil fertility management per farm (about 1.3 metric tons) is valued at 3,993 KES, which is equivalent to 48 US dollars.

# Literature Review

Given their importance to farming systems worldwide, there are surprisingly few existing studies analyzing the value of on-farm biological resources. Assigning prices to nonmarket goods and services is a challenging task: environmental externalities, the multiplicity of benefits, and the stream of inter-temporal payoffs all imply methodological complexity (Shiferaw and Freeman 2003). Quantifying crop residue production and accounting for its uses is rarely done even in developed countries (Smil 1999), where agronomic systems are better understood and data sources are typically more complete.

Several studies analyze the value of biological resources in developing countries by calculating changes in overall farm profits or physical changes in production associated with fallowing by including biomass as a production input. For example, López (1997) studies village-level stocks of biomass in Ghana and their decline due to reductions in fallow periods, and concludes that biomass is often exploited beyond socially optimal levels. Goldstein and Udry (2008) demonstrate the importance of fallows for on-farm soil quality and profits, also in Ghana. Using farm-level survey data from the Brazilian Amazon, Klemick (2011) estimates a production function to examine the value of forest fallow ecosystem services and finds that fallows improve productivity both on-farm and downstream. Gavian and Fafchamps (1996) find that manure application has a significantly positive effect on crop yields in Niger.

Two recent studies – Magnan, Larson, and Taylor (2012) and Teklewold (2012) – derive the value of biomass using the observed prices of agricultural products for which biomass can substitute. Both studies extend the method of estimating shadow wages and labor supply functions in the context of non-separable agricultural household models developed by Jacoby (1993) and Skoufias (1994). Violation of the assumption of perfect markets in developing countries leads to the deviation of the shadow wage from the observed market wage and requires a distinct estimation approach. Since the shadow wage equals the value of the marginal product of labor (MPL) regardless of market failure, Jacoby (1993) and Skoufias (1994) propose the following method: 1) estimate the farm production function to determine the MPL; 2) calculate the shadow wage and shadow income based on the MPL; then, 3) estimate the labor supply equations as functions of the shadow wage, shadow income and appropriate preference shifters. Examples of this approach and its extensions include Abdulai and Regmi (2000), Shively and Fisher (2004), Fisher, Shively, and Buccola (2005), and Barrett, Sherlund, and Adesina (2008), among others.

Applying this overall approach to non-market biomass, Magnan, Larson, and Taylor (2012) examine the value of cereal stubble in a mixed crop-livestock farming system in Morocco. Similar to Le (2009), they use the price of a market input, purchased feed, to derive the shadow price of cereal stubble. In the spirit of Shively and Fisher (2004) and Fisher, Shively, and Buccola (2005), Teklewold (2012) models a system of allocation equations for farmyard manure to examine the role of returns to manure in smallholder agriculture in Ethiopia. His model estimates the shadow price of manure and analyzes farmers' allocation of manure to household consumption (as energy), selling, and/or farming.

There are several estimation difficulties associated with the approach developed by Jacoby (1993) and Skoufias (1994) (Le 2009). For example, the potential endogeneity of regressors in the estimation of the production function requires the use of instruments. One of the common strategies is to rely on the value (prices times quantities) instead of the quantities of outputs and inputs; however, this strategy may bias the estimation of the production function if there is any price variation across regions (Jacoby 1993). Data limitations can also lead to challenges in finding appropriate instruments for endogenous regressors. Sherlund, Barrett, and Adesina (2002), for example, note that despite the critical dependence of smallholder agricultural production on largely exogenous environmental conditions, few studies directly control for them. This omission can lead to the omitted variable bias as farmers' decisions and input choices typically respond in part to weather, soils, and other environmental conditions.

A different strand of literature considers the value of biomass as a source of household energy. It is often thought that agricultural residues (crop residues and dung) and improved stoves are substitutes for fuelwood in consumption. However, the empirical evidence as to whether fuelwood and dung, or fuelwood and crop residues, are substitutes or complements is mixed (Cooke, Kohlin, and Hyde 2008). For example, using data from two districts in east-central Nepal, Amacher, Hyde, and Joshee (1993) find that fuelwood and crop residues are substitutes in one district and complements in another, and crop residues are more important substitutes for low income households across both districts. Mekonnen and Kohlin (2008) find evidence that dung and woody biomass are considered complements by rural households in Ethiopia, and demonstrate that the decision to use dung as fuel is influenced by household assets and characteristics. Similarly, the empirical evidence on whether household use of an improved stove reduces fuelwood use is also mixed (e.g. Heltberg, Arndt, and Sekhar (2000), Edmonds (2002), Amacher et al. (2004)).

Empirical studies also do not find an immediate decline in crop production as crop residues and dung are diverted from their use as soil amendments to fuel use in response to fuelwood scarcity (Cooke, Kohlin, and Hyde 2008). Households alter their practices in order to minimize the impact of fuelwood scarcity on crop production, for example, either by spending more time collecting firewood without reducing the time spent on crop production (Cooke 1998), or by avoiding using dung as fuel when it is needed for farming (van 't Veld et al. 2006).

# Conceptual Framework and Empirical Strategy

The analytical foundation of this study lies in the agricultural household model that integrates the consumption and production behavior of agricultural households (Singh, Squire, and Strauss 1986) with the treatment of non-tradable commodities, reflecting market failure (de Janvry, Fafchamps, and Sadoulet 1991). The model is modified to account for the allocation of non-tradable maize residues produced during the previous agricultural season as an input into three main household production activities: crop production, livestock maintenance, and energy generation. An additional resource constraint is added to ensure that the amount of maize residues allocated to these uses does not exceed the total residues produced. Households derive utility from agricultural and purchased goods, energy, and leisure and they maximize their utility subject to three constraints: production (maize, livestock, fuel), resources (labor, maize residues), and full-income. The first order conditions taken with respect to the shares of residues allocated to the three different uses show that, at the optimum, households will allocate maize residues across alternative uses so as to equate the marginal values of different allocations.

Some empirical evidence also suggests trade-offs among different uses of crop residues. Previous research shows that biomass production and utilization patterns vary according to the agricultural season, farm size, land use practices, soil fertility, household size and socio-economic characteristics, and prevailing cultural practices. For example, Torres (2011) demonstrates that higher productivity of maize crops on more fertile soils or on farms more recently converted from forest leads to higher productivity (per hectare) of maize residues. Also in Kenya, wealthy households may use inorganic fertilizers, practice fallowing on a portion of their farm or incorporate maize stover for soil management to achieve higher crop yields, while poorer households obtain higher returns from using maize residues as fuel or livestock feed (e.g. Crowley and Carter (2000), Marenya and Barrett (2007)).

Given a potential long lag and annual compounding in the realization of the agronomic benefits of leaving crop residues in the field, farmers may choose to satisfy their more immediate needs first – food for their livestock and cooking fuel for the home. Most livestock in smallholder systems in Kenya are either grazed on own or communal land, or tethered, so that maize residues constitute a significant portion in livestock diets – up to 24% of total livestock feed (KARI 2008). Energy sources are also predominantly from biomass, including on- and off-farm wood and crop residues. Below, I test whether the share of maize residues left in the fields to improve soil fertility is influenced not only by maize production inputs, but also by allocations to other uses – as inputs in livestock maintenance and fuel collection. Since the data are in proportions, I estimate the factors contributing to the share of maize residues allocated to soil fertility management using OLS, Tobit and the Papke and Wooldridge (1996) techniques.

Similar to the model described in Magnan, Larson, and Taylor (2012), farmers' crop production activities can be analyzed as a constrained profit maximization problem: farmers grow maize with market inputs (chemical fertilizers) and non-market inputs (maize residues from the previous season left as organic soil amendments) to maximize yields, with the amount of non-market inputs applied limited by their availability. Then, the first order conditions with respect to two inputs in maize production – the quantity of chemical fertilizer and the quantity of maize residues – can be used to calculate the endogenous price of maize residues for each household. I estimate a household-level maize production function in logarithmic form (Cobb-Douglas):

$$ln(Q) = \beta_q ln(B^q) + \beta_v ln(V) + \sum_k \beta_k ln(X_k) + \epsilon \tag{1}$$

where $Q$ is the amount of maize produced, $B^q$ is the amount of maize residues from the previous season left on the fields as organic soil amendment, $V$ is the amount of chemical fertilizer applied, $X_k$ is a vector of farm and household characteristics, $\beta_q$, $\beta_v$, and $\beta_k$ are the respective coefficients to be estimated, and $\epsilon$ is the error term. Since both chemical fertilizer and maize residues, as well as another purchased input (hybrid maize seeds) are potentially endogenous, I also estimate maize production with instrumental variables, using the generalized method of moments (GMM) to combine several instruments (IV-GMM). These potential endogenous variables are identified with variables representing farm and household characteristics: bio-physical and geographic measurements (soil quality, altitude, distance to plots), as well as inputs in livestock maintenance and fuel collection. Following the estimation of the maize production function, I use the estimated coefficients for chemical fertilizer and maize residues to calculate the shadow price of maize residues left on the fields, $\rho$:

$$\rho = p_v \frac{\partial Q}{\partial B^q} / \frac{\partial Q}{\partial V} = p_v \frac{\hat{\beta}_q}{\hat{\beta}_v} \frac{V}{B^q}, \tag{2}$$

where $p_v$ is the price of marketed chemical fertilizer. That is, the shadow price of non-market maize residues is the amount of chemical fertilizer required to compensate for the loss of one unit of maize residues times the market price of fertilizer (equal to the marginal rate of technical substitution between maize residues and chemical fertilizer times the market price of fertilizer).

## Research Area and Data

The research sites are five 10x10 km quadrants located in the Nyando and Yala river basins of western Kenya, two of the major seven rivers feeding the Kenyan side of Lake Victoria (see Figure 1). These sites are identified as follows: Lower-Nyando, Mid-Nyando, Lower-Yala, Mid-Yala, and Upper-Yala.[1] A socio-economic and household production survey of a sample of 317 households in 15 villages (three in each block) was conducted in 2011-2012 in two rounds to account for the bi-modal precipitation pattern and associated two distinct cropping seasons. The survey covered a wide range of standard Living Standards Measurement Survey topics, tailored to the goals of the project and local conditions. Household-level data were supplemented with our own bio-physical measurements (spatial data, tree identification, count and measures of diameter at breast height, and soil sampling), as well as village and market surveys.

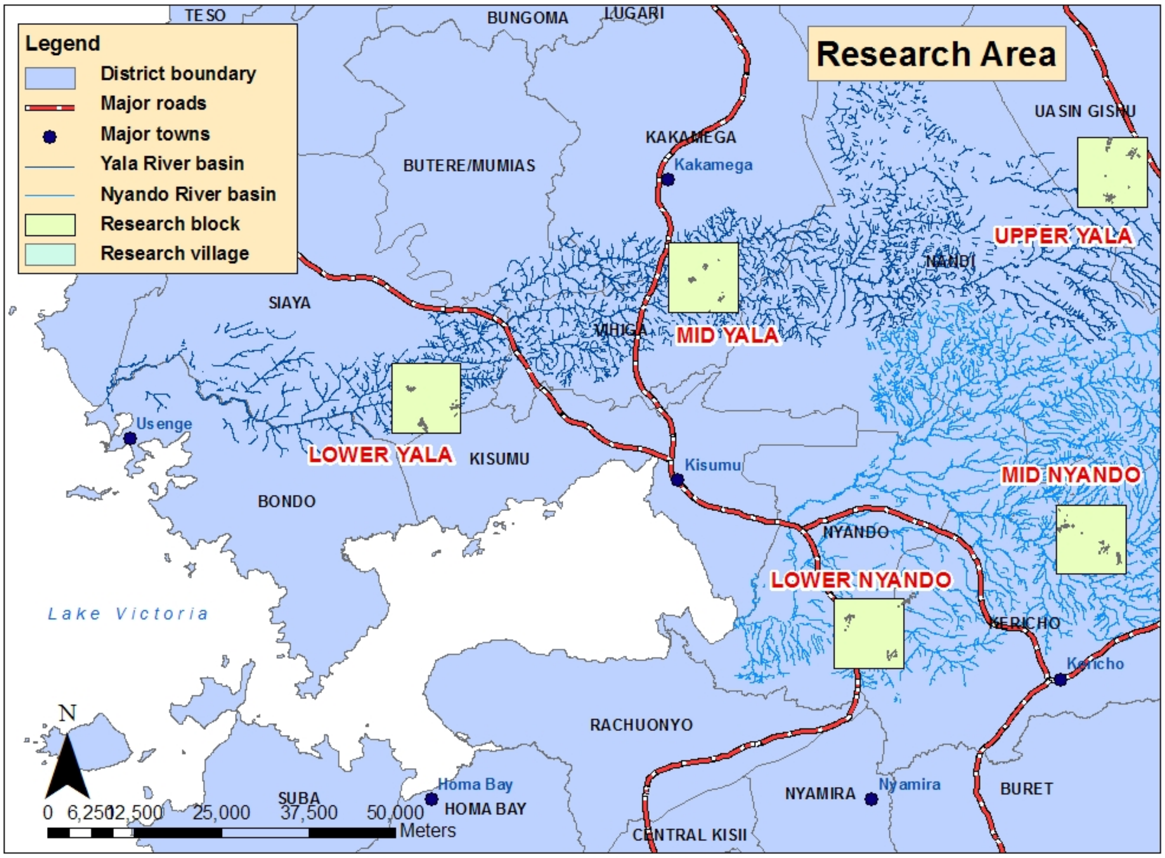

Figure 1: Map of the research sites.

Table 1 shows the summary statistics for the households in the sample.[2] A typical household has 6 household members.[3] The head of household, the main income earner and decision maker for the household,

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[1] These sites formed part of the original geographic coverage of the Western Kenya Integrated Ecosystem Management Project (WKIEMP), implemented between 2005-2010 by the Kenya Agricultural Research Institute (KARI) and the World Agroforestry Center (ICRAF) and funded from the Global Environmental Facility (GEF) of the World Bank.

[2] The sample size used in estimation is 310 households. Several households drop out from the estimation as they did not grow maize in 2011.

[3] A household is defined as a person or a group of people living in the same compound, answerable to the same head and

| Variable | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|
| Household head is male* | 0.81 | 0.39 | 0 | 1 |
| Household head's age | 51.35 | 15.36 | 20 | 90 |
| Household head years of education | 6.76 | 4.53 | 0 | 18 |
| Household size | 6.05 | 2.46 | 1 | 13 |
| Asset index | 0.01 | 1.00 | -1.15 | 5.55 |
| Number of formal extension services sources | 1.13 | 1.34 | 0 | 7 |
| Total land area owned or cultivated in acres | 4.52 | 9.8 | 0.05 | 110 |
| Total maize grain yield in kg | 1,003.97 | 1,281.73 | 11.5 | 10,453.52 |
| Total farm land under maize in acres | 1.58 | 1.22 | 0.08 | 7.14 |
| Average maize grain yield kg/acre | 673.10 | 516.94 | 19.26 | 3,207.63 |
| Total labor used on maize plots in labor-days | 93.88 | 68.02 | 11 | 406 |
| Total N, P, K used on maize plots in kg | 25.45 | 41.37 | 0 | 315 |
| No chemical fertilizer used* | 0.36 | 0.48 | 0 | 1 |
| Total maize residues left on maize plots in kg | 1,283.60 | 1,520.45 | 0 | 11,369.68 |
| No maize residues left* | 0.17 | 0.38 | 0 | 1 |
| Hybrid seed used* | 0.57 | 0.46 | 0 | 1 |
| Soil pH - value | 5.82 | 0.52 | 4.35 | 7.13 |
| Total soil nitrogen | 0.16 | 0.09 | 0.06 | 0.87 |
| Average distance to maize plots in m** | 156.49 | 434.18 | 5.45 | 6,292.36 |
| Average maize plots altitude in m** | 1,605.94 | 330.30 | 1,204.66 | 2,257.79 |
| Livestock ownership* | 0.80 | 0.40 | 0 | 1 |
| Herd size in TLU | 2.27 | 2.67 | 0 | 17.6 |
| Grazing livestock on others' land* | 0.46 | 0.50 | 0 | 1 |
| Purchasing feed for livestock* | 0.12 | 0.32 | 0 | 1 |
| Number of on-farm trees with DBH>5cm | 64.67 | 74.64 | 0 | 503 |
| Cultivation of woodlot* | 0.16 | 0.37 | 0 | 1 |
| Improved stove* | 0.46 | 0.50 | 0 | 1 |
| Fuelwood collection* | 0.43 | 0.50 | 0 | 1 |
| Fuelwood purchase* | 0.34 | 0.50 | 0 | 1 |

*Note: * indicates binary variable. **N=309 households.*

Table 1: Summary statistics (N = 310 households).

is on average 51 years old, and for over 80% households in the sample is male. On average, the household head has about 7 years of schooling, which corresponds to partial completion of primary school (in Kenya, primary school is currently 8 years).

A typical farm in western Kenya is about 2.5-5 acres in size (Tittonell et al. 2005); in our sample, the average is 4.52 acres.[4] Survey farms are often very diversified: households grow annual crops for home consumption, perennial cash crops for sale, and trees to satisfy residential energy needs. Maize is the most popular grain crop in the area, having quickly established itself as a dominant food crop at the beginning of the 20th century due to its relatively higher yields per unit of land and two crops per calendar year in many villages (Crowley and Carter 2000). The average maize plot in the sample is 0.62 acres (across 787 plots and two cropping seasons) and is rain-fed. Although most sample households are subsistence farmers

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sharing a common source of food and/or income.

[4] 1 acre = 4,047 square meters = 0.405 hectares.

and cultivate their own land, more than half of households also hire agricultural labor for planting, weeding or harvesting. Differences in geographical location and associated rainfall availability, altitude, and the possibility of two cropping seasons and their length, as well as variations in farmer management practices, account for a high variance in maize grain yields, which average 673.10 kg/acre among sample farms.

Dominant soil types in the Yala and Nynado river basins are acrisols, ferralsols and nitisols (Jaetzold and Schmidt 1982). While nitisols can be of high fertility, acrisols and ferralsols are strongly leached or weathered. Farmers in the sample identified their soil fertility as mostly moderate. Soil samples were taken from the largest maize plot on each farm, and were analyzed at the World Agroforestry Center's Soil-Plant Spectral Diagnostics Laboratory in Nairobi using near infrared (NIR) spectroscopy, a rapid nondestructive technique for analyzing the chemical composition of materials. The analysis predicted some key soil properties such as organic carbon (C), nitrogen content (N), extractable phosphorous (P) and potassium (K), and soil pH, which were later used for a three-tiered soil fertility classification scheme.[5] While analyzed samples were classified as "good" based on carbon, phosphorous and potassium contents, the average nitrogen content and soil pH received "very low" and "low" values, respectively. Soil nitrogen is a critical nutrient for plant growth and yield; nitrogen content seems to be very low across the sample – 0.16% by volume. Soil pH measures the degree of soil acidity or alkalinity (from 0 to 14); neutral pH is 7 and optimum pH for plant growth is 6.5. The average pH in the sample is lower than optimal – 5.82.

Soil quality – nitrogen content, in particular – appears to be poor across the sample. This can be partly explained by the limited use of chemical fertilizers and organic resources. About 40% of households in the sample apply some chemical fertilizer. Di-ammonium phosphate is commonly applied during planting, and urea and calcium ammonium nitrate are applied as top dressing. To account for all types of chemical fertilizer applied and its different composition, I create a 'plant nutrient' measure that aggregates the weight of the active ingredients (rather than the total weight of fertilizer), giving equal weight to the three most important plant nutrients: nitrogen (N), phosphorous (P) and potassium (K). Application of 25.45 kg of N, P, K across all maize plots on each farm, or 17.62 kg of N, P, K per acre, is the sample average. The Kenya Agricultural Research Institute (KARI) recommends the following rates of N, P, K application: 24, 24, 16 kg/acre, respectively (Kanyanjua and Ayaga 2006). Clearly, there is a substantial gap between actual and recommended fertilizer application rates.

Nearly all households (93.38%) in the sample keep farm animals. Each household has, on average, two local cows (Zebu breeds), one improved dairy cow and eleven chickens. Herd size is measured in Tropical Livestock Units (TLU), where 1 TLU is equivalent to 250 kg of animal body mass (0.7 cattle or 0.1 sheep/goat

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[5] The three tiers used were "good," "low," and "very low," and were created based on thresholds and recommendations for soils in the area from the Kenya Agricultural Research Institute (Mukhwana and Odera 2009) and from the Cornell Soil Health Test (Moebius-Clune et al. 2011).

or 0.2 pigs or 0.01 chicken or 0.5 donkey). Poultry is excluded from the estimation of TLU, since chickens are usually kept around homesteads and find food in kitchen scraps. Eighty percent of households keep livestock with the average TLU in the sample being 2.27. Almost all households that own livestock reported that the primary source of animal feed is either grazing on own land, or cutting and carrying from their own land.

Following Sahn and Stifel (2003), I create an asset index for each household derived from a factor analysis on household durables, farm implements and housing quality. The household durables include assets such as radios, televisions, furniture, improved and gas/electric stoves, bicycles, motorcycles and cars; farm implements include the number of hand tools as well as farm buildings, ploughs, and machinery (tractors, trailers, etc.); while housing quality incorporates indicator variables for construction material (walls, roof, floor), source of drinking water, energy used for lighting, and toilet facilities.

**Allocation of maize residues.** Most of the crop residues are used for several different purposes, leaving no biomass wasted. Feeding own animals (either collecting crop residues or grazing animals on the fields after harvest), kitchen or household fuel, and soil fertility management (leaving crop residues in the fields as fertilizer, mulching or collecting biomass to apply as organic soil amendments later on) are the main uses of biomass. Seventy seven percent of the sample households leave maize stover in the field as a soil amendment, 33% collect it for feeding their animals, and 27% leave it in the field for grazing their animals.[6] At the same time, 96% of households use maize cobs as cooking fuel, while some households also leave cobs in the fields or collect them for soil fertility management (12% and 4%, respectively).

| Variable | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|
| Share of maize residues to soil fertility management | 0.47 | 0.31 | 0 | 1 |
| Share of maize residues to animal feed | 0.25 | 0.28 | 0 | 0.9 |
| Share of maize residues to residential fuel | 0.22 | 0.15 | 0 | 1 |
| Share of maize residues to other uses | 0.05 | 0.17 | 0 | 0.8 |

Table 2: Allocation of maize residues across main uses (N = 310 households).

When weighted by the share of maize residues allocated to the main uses, 47% of maize residues (both stover and cobs) is allocated to soil fertility management, 25% is fed to livestock, 22% is used as kitchen fuel, and the remaining residues are allocated to miscellaneous uses – left on the fields for grazing others' animals, collected for building materials, burned, etc. (see Table 2). Of the total of 310 sample households, 143 households reported allocating positive amounts of maize residues to all three main uses: soil fertility management, animal feed and fuel.

**Quantifying maize residues.** Estimating plot-level amounts of maize residues is a challenging task.[7] No nation tracks the production of crop residues as they do other crops and inputs; the most reliable

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[6] The uses are not exclusive.

[7] Measuring the amount of residues on all of the 787 plots across 310 farms would be infeasible.

estimates come indirectly from studies of the harvest index (the ratio of crop edible yield to the crop's total aboveground phytomass) on experimental plots (Smil 1999). Instead of using harvest index estimates from the literature, I rely on actual measurements of maize grain and residues from 115 farmer plots, chosen using stratified unaligned random sampling in the same research sites in 2011-2012.[8] I use the average air-dried weight of grain, stover and cobs, not accounting for missing plants or cobs, to reflect farming conditions.

Based on actual measurements and available information in both data sets – maize seed type (hybrid or open-pollinated), grain weight, and research block – I predict the plot-specific quantity of maize grain and maize residues (stover and cobs) in kg per square meter from the 115 plots (see Figure 2) and use the linear prediction ($R^2$=0.52) to generate plot-level amounts of residues in the sample of 310 households.[9]

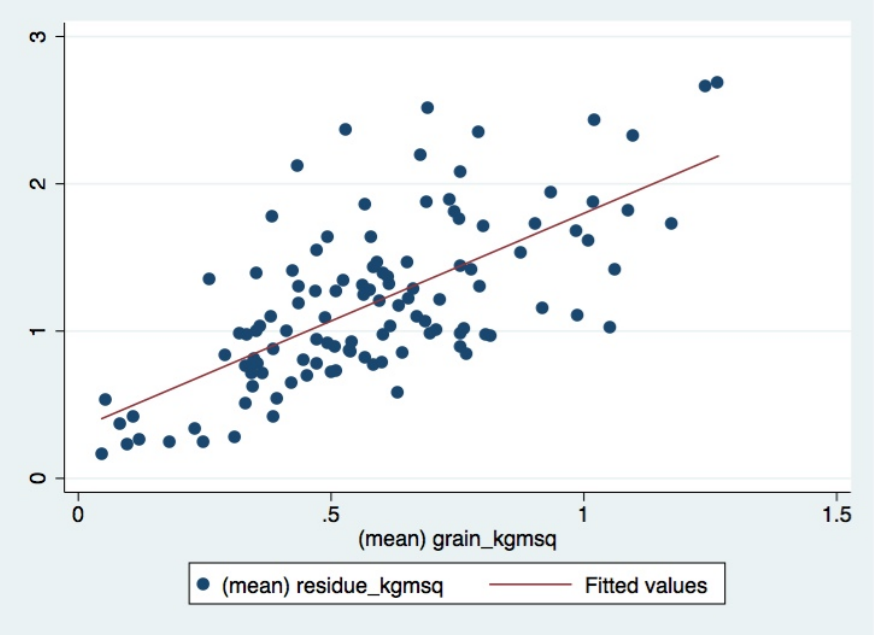

Figure 2: Maize residues vs. maize grain kg/sq.m.

The quantity of residues allocated to different uses is reported in the survey at the household level for the 12 months preceding the survey visit. Given that the numbers of family members and livestock were stable in the sampling period, I assume that the recorded quantity of residues allocated to different uses approximates the quantity of residues produced during both seasons of 2011.

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[8] Dorisel Torres, Department of Crop and Soil Sciences, Cornell University, unpublished.

[9] At a later stage, this prediction will be improved as the data on altitude, soil characteristics and the exact geographic coordinates of each sub-plot become available.

# Empirical Results

## Allocation of maize residues

Table 3 shows the estimation of the share of maize residues allocated to soil fertility management, using OLS regression (first two columns) and censored normal regression (Tobit), since the shares contain zeroes and ones (last two columns). The results in Columns 1 and 3 show the influence of maize production outputs and inputs on the share of maize residues allocated to soil fertility management – average maize grain yield (kg/acre), total N, P, K and labor (both hired and household) used on maize plots, soil characteristics (pH and total soil nitrogen (% by volume)) – as well as the number of formal extension services sources, controlling for total farm area, farmer characteristics (gender, age, and asset index), and geographic location. The expected influences of these variables on the allocation of maize residues is discussed further below. The results reported in Columns 2 and 4 test the hypothesis that the allocation of maize residues to soil fertility management is traded off against the allocations to other uses, that is, the share of maize residues allocated as a soil amendment is also influenced by inputs and outputs associated with livestock maintenance and household fuel collection activities. The additional variables include livestock ownership, herd size in TLU, an indicator variable for grazing livestock off-farm, household size, number of farm trees, cultivation of trees on a woodlot, the ownership of improved stove, fuelwood collection off-farm and time spent collecting 1 kg of firewood, fuelwood purchase and cost of 1 kg of firewood bought. Standard errors are clustered at the block level.

The coefficients from both the OLS and Tobit estimation are roughly similar in magnitudes and statistical significance. Higher maize grain yields (kg/acre), as well as larger land area owned or cultivated (acres) both translate to higher production of maize residues. More maize residues available means that households can allocate larger shares to soil fertility management, as other needs are satisfied. The negative sign on the variable capturing total N, P, K used on maize plots points to the potential substitutability between chemical and organic fertilizer from the farmer's perspective. However, the very low value of the coefficient suggests a weak substitutability of the two – for each kg of plant nutrients from chemical fertilizer, the share of maize residues allocated to organic fertilizer decreases only by 0.08-0.09%. The influence of soil quality, as captured by soil pH and total soil nitrogen, becomes significant in the Tobit specification. As soil quality improves (higher pH value and higher nitrogen content), less crop residues are allocated as soil amendments. Since a unit increase in pH or nitrogen content value would be quite significant, the magnitude of the coefficients is also large.

The indicator variables for livestock ownership and fuelwood purchase have negative coefficients, significant at least at the 10% level. The share of maize residues allocated to organic fertilizer decreases if households use the maize residues to feed their livestock or need to buy firewood. Similarly, Marenya and Barrett (2007) find that farmers in western Kenya are less likely to use stover for soil fertility management when crop residues are more valuable as livestock feed and there is empirical evidence that crop residues and firewood are considered to be substitutes by some households (Amacher, Hyde, and Joshee 1993). Other variables that determine the share of maize residues allocated to other uses – herd size, household size, and number of trees, among others – have insignificant coefficients, yet with expected signs. Perhaps, given a wide range of substitutes for maize residues as livestock feed (e.g. grazing on communal land) and fuel (e.g. twigs/branches collected on-farm), the variables included in the estimation do not sufficiently capture the trade-offs between the alternative uses. Their influences (and the influences of other variables not included) deserve further investigation.

As the observed allocation shares are fractional response data which are strictly bounded (not feasible outside the [0,1] interval) but are not censored, both OLS and Tobit may not be an appropriate estimation strategy. Table 4 shows the same estimation using the Papke and Wooldridge (1996) method suggested to handle fractional response data with values of zeros and ones. The estimation procedure is based on maximizing the Bernoulli log-likelihood function of a logistic functional form that ensures that the predicted responses lie between zero and one. In the data set, 53 households did not allocate any maize residues as a soil amendment while three households allocated all of their residues to soil fertility management. The coefficient signs and their significance for all variables are the same as with the OLS and Tobit estimations. The second and fourth columns of Table 4 report the average marginal effects after the estimation: the magnitudes of the effects of each variable (value of coefficients) are similar to those in Table 3.

Table 5 repeats the OLS estimation using the quantity (rather than the share) of maize residues (in kg) allocated to soil fertility management. For the most part the signs and significance of coefficients are similar to those in Table 3 and Table 4. There are, however, some differences. The coefficient on N, P, K in Table 5 switches in sign from negative to positive, suggesting that as the amount of chemical fertilizer applied increases, so does the quantity of residues produced. For each additional kilogram of N, P, K, the amount of maize residues allocated to soil fertility management increases by about 12 kg. In addition, the coefficients on household size and number of on-farm trees become significant (Column 2). For each additional household member, the quantity of maize residues left on the field increases by 60 kg. More household members able to collect firewood both on-farm and off-farm lowers the value of maize residues as fuel. The negative sign on the number of on-farm trees points to a potential cost to maize production in terms of foregone land required to grow trees.

### Value of maize residues left on the field

I estimate a Cobb-Douglas maize production function to elicit the shadow value of maize residues left on the field. The results of the estimation are reported in Table 6. Since the allocation of maize residues to different uses is a decision made by farmers at a household level, maize production is estimated at the household level from all maize plots cultivated during two seasons: the long rains and the short rains of 2011.

The total sample size is 309 households.[10] However, not all households in the sample left maize residues on the field – 17% of households used all of the residues for different purposes (animal feed or fuel) – and not all households used chemical fertilizer, only 64% did. Since the use of the log-linear Cobb-Douglas specification requires all inputs of positive quantity, the usual strategy is to add a small shifter to the inputs before taking logs. However, parameter estimates can be sensitive to the value of the shifter. Klemick (2011) follows the approach outlined in Battese (1997): adding dummy variables to indicate non-use of each input which serve as intercept shifters for the respective groups of farmers who do not use a particular input. I use the same approach. This allows estimation of household-level maize production using the entire sample of 309 households (first two columns of Table 6). As a robustness check, I repeat the estimation using only households that used positive quantities of both maize residues and chemical fertilizer (last two columns of Table 6).

A particular concern in the literature on the estimation of primal production functions in developing countries is the possibility of measurement error, omitted variables (e.g., environmental production conditions), and/or simultaneity bias due to unobserved heterogeneity (e.g., in managerial ability). While managerial ability may be partly captured by farmers' characteristics (years of education) and access to information, unobserved plot characteristics are likely to inform the use of purchased inputs such as chemical fertilizer and hybrid seeds, as well as applications of organic soil amendments. The significant and positive coefficients for the indicator variables for no use of chemical fertilizer and no use of maize residues in Column 1 reinforce the endogeneity concerns because of unobserved differences across plot and farmer characteristics. Simultaneity bias is also of concern with the use of maize residues as a soil amendment. Higher application rates can lead to higher maize yields; at the same time higher maize yields lead to higher maize residue output, thereby increasing the amount of organic soil amendments applied. In this case, the error term in the production equation will capture not only white noise but also measurement errors, agroecological conditions, farmers' skills and status, and other factors not accounted for in the data (Klemick 2011).

A common approach to deal with the issue of endogeneity in the estimation of primal production functions is to instrument for potentially endogenous regressors (e.g., Jacoby (1993), Skoufias (1994), Gavian and

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[10] One household is lost due to missing geographic variables.

Fafchamps (1996), Teklewold (2012)). I use bio-physical and geographic measurements (soil quality, altitude, distance to plots), as well as inputs in livestock maintenance and fuel collection – the variables from the estimation of the share of maize residues allocated to soil fertility management – as well as farmer age variables, as instruments for purchased inputs (chemical fertilizer and hybrid seeds) and maize residues used. The specific instruments used are the following: soil pH and nitrogen content, log of total farm area, livestock ownership, herd size in TLU, indicator variable for grazing livestock off-farm, household size, number of farm trees and cultivation of trees on a woodlot, the ownership of improved stove, fuelwood collection off-farm and time spent collecting 1 kg of firewood, fuelwood purchase and cost of 1 kg of firewood bought, farmer's age and age squared, average distance to plots in meters, and altitude.

Columns 2 and 4 of Table 6 show the elasticity estimates from the instrumental variables estimation (IV-GMM).[11] The instruments' correlation with the endogenous variables can be partly assessed by examining the explanatory power of the instruments in the first-stage regressions: the F-statistic for all the potentially endogenous variables are jointly significant at least at the 5% level. The Hanson J test, the overidentification test of all instruments, also confirms the validity of the instruments used (the estimated J-statistic is 9.03 with a $\chi^2(13)$ p-value of 0.77 in Column 2 and the J-statistic is 21.67 with a $\chi^2(15)$ p-value of 0.12 in Column 4).

The signs of coefficients for all the variables remain the same across the OLS and IV-GMM estimations and across the two samples examined, while some changes are observed for the variables suspected of causing endogeneity. The coefficients on the indicator variables for no use of chemical fertilizer and no use of maize residues lose their significance in Column 2. The elasticity estimates for the variables in question also increase in magnitude: the coefficient on *LN(Nutrient (N, P, K) content in grams)* increases from 0.16 to 0.31, the coefficient on *LN(Amount of maize residue applied in grams)* increases from 0.28 to 0.29, and the coefficient on *Seed used: 1=hybrid* increases from 0.39 to 0.89 in Column 2. Chemical fertilizer and labor inputs provide the most substantial contributions to output, with an elasticity of 0.31 – i.e., a one percent increase in the amount of chemical fertilizer or labor applied yields a 0.31% increase in maize grain output with all other inputs held fixed. Land and maize residue application variables are also important, with elasticities of 0.30 and 0.29, respectively. The use of hybrid seeds, as expected, positively influences maize yields.

As the sample changes from 309 to 162 households, the estimated coefficients change their magnitude, though for the most part preserve their signs and significance. The estimated IV-GMM coefficients for the two variables of particular interest – *LN(Nutrient (N, P, K) content in grams)* and *LN(Amount of maize residue applied in grams)* – in Column 4 are very similar to those estimated using the full sample (Column 2): 0.35 and 0.26 as compared to 0.31 and 0.29, respectively.

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[11] I use the GMM estimator as it is more efficient in the presence of heteroskedasticity.

Based on the estimated coefficients in Table 6, I calculate $\rho$, the shadow price of 1 kg of maize residues as a soil amendment, using Equation 2 and household-specific fertilizer prices. Since the estimates of the shadow price rely on input ratios which can be large if one input is used in very small quantities, I also calculate the shadow price excluding the top and bottom tails (5%) of the distribution. The shadow price estimates are reported in Table 6 for each of the estimated regressions. They range from 2.38 to 12 KES ($0.028-0.14).[12]

Using 3.11 KES as the estimate of the shadow value of 1 kg of maize residues allocated to soil fertility management (based on the estimated coefficients in Column 2 of Table 6), Table 7 shows the estimated values of maize residues per farm and per acre. The average quantity of maize residues produced on the sample farms in 2011 is valued at 9,902.24 KES or $117.88 per farm, while the average quantity of maize residues applied as a soil amendment is valued at 3,993.24 KES or $47.53. The estimated value of maize residues per acre is about $76, which is slightly lower than the estimated shadow value of cereal stubble in a good harvest year (2008) in Morocco. Magnan, Larson, and Taylor (2012) estimate the median (mean) shadow price of crop stubble per acre at $97 ($198). Table 7 also shows that maize residues constitute about 25% of the total value of cereal production (both grain and residues) in western Kenya.

Given that the maize residues in Kenya, on average, contain 0.7% of nitrogen (Gentile et al. 2011) and the mean (median) price of 1 kg of nutrients (N, P, K) in the sample is 142 (130) KES, the price of nitrogen in 1 kg of maize residues is then 0.99 (0.91) KES. My estimate of the shadow value of 1 kg of maize residues left on the fields is higher – 3.11 KES, the shadow price that reflects not only the value of nitrogen but also the value of other environmental benefits that extend beyond fertilizer substitution, such as the provision of other micro- and macro-nutrients, improvements in soil moisture status, reduction of soil borne pests and diseases, etc. (Place et al. 2003). Organic inputs contain carbon that drives most of soil processes and recharges the soil organic matter pool, thus enhancing long-term soil fertility (Vanlauwe and Giller 2006). A meta-analysis from 57 studies across Sub-Saharan Africa by Chivenge, Vanlauwe, and Six (2011) shows that the addition of organic resources in one season also have residual effects in the subsequent season with crop yield responses of 38% over the no input control. Thus, the estimated 3.11 KES also likely includes the residual value of maize residue applications.

# Conclusion

Together with land and labor, biological resources are used to satisfy many household production needs and constitute critical productive resources in developing country agriculture. Yet, our understanding of biomass

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[12] 100 KES = $1.19.

availability, its uses and its value in smallholder agriculture is limited. Given the high diversity of smallholder systems in Africa and elsewhere in the developing world, economic analysis of different agroecosystems is needed to establish realistic bounds on the economic value of biomass. The current research contributes to our understanding of the uses of maize residues in the East African Highlands and of farmers' decision-making with respect to their management. The decision to allocate maize residues to soil fertility management and the levels of such allocations among Kenyan farmers is influenced by the quantity of maize residues produced, as well as conventional inputs into production such as labor and chemical fertilizers and soil quality. Such decisions are also influenced by livestock ownership and the purchase of firewood – competing uses for maize residues. The value of maize residues left on the fields is estimated at 3.11 Kenyan shillings or $0.04 per 1 kg, a price that includes not only the value of nitrogen in maize residues but also the value of other environmental benefits that extend beyond fertilizer substitution.

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|  | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| VARIABLES | OLS I | OLS II | Tobit I model | Tobit II model |
| Average maize grain yield kg/acre | 7.44e-05** | 7.42e-05** | 9.50e-05*** | 9.16e-05*** |
|  | (2.15e-05) | (2.24e-05) | (2.45e-05) | (2.68e-05) |
| Total N, P, K used on maize plots in kg | -0.000850** | -0.000812** | -0.000921*** | -0.000901*** |
|  | (0.000287) | (0.000266) | (0.000294) | (0.000272) |
| Total labor used on maize plots in labor-days | 6.17e-05 | 0.000172 | 0.000100 | 0.000204 |
|  | (0.000258) | (0.000227) | (0.000315) | (0.000269) |
| Soil pH - value | -0.0877 | -0.0763* | -0.122** | -0.109*** |
|  | (0.0450) | (0.0352) | (0.0493) | (0.0386) |
| Total soil nitrogen | -0.305 | -0.340* | -0.408** | -0.452** |
|  | (0.148) | (0.157) | (0.180) | (0.187) |
| Number of formal extension services sources | 0.0199 | 0.0238 | 0.0214 | 0.0249 |
|  | (0.0107) | (0.0128) | (0.0134) | (0.0157) |
| Livestock ownership: 1=yes |  | -0.111* |  | -0.117* |
|  |  | (0.0517) |  | (0.0638) |
| Herd size in TLU (no chickens) |  | -0.0149 |  | -0.0142 |
|  |  | (0.0125) |  | (0.0136) |
| Feed source: 1=grazing on others' land |  | 0.0328 |  | 0.0447 |
|  |  | (0.0244) |  | (0.0326) |
| Household size |  | 0.000738 |  | 0.000850 |
|  |  | (0.00162) |  | (0.00144) |
| Number of large and medium trees |  | 0.000105 |  | 0.000176 |
|  |  | (0.000131) |  | (0.000135) |
| Woodlot: 1=yes |  | 0.0641 |  | 0.0886* |
|  |  | (0.0448) |  | (0.0529) |
| Improved stove: 1=yes |  | 0.0227 |  | 0.0188 |
|  |  | (0.0480) |  | (0.0581) |
| Fuelwood collection off-farm: 1=yes |  | 0.0195 |  | 0.0230 |
|  |  | (0.0484) |  | (0.0495) |
| Time spent collecting 1 kg of firewood |  | 0.0776 |  | 0.0709 |
|  |  | (0.135) |  | (0.155) |
| Fuelwood purchase: 1=yes |  | -0.0810* |  | -0.0916** |
|  |  | (0.0364) |  | (0.0449) |
| Cost of 1 kg of firewood purchased |  | 0.000477 |  | -0.000257 |
|  |  | (0.00232) |  | (0.00348) |
| Total land area owned or cultivated in acres | 0.00270** | 0.00366*** | 0.00294*** | 0.00380*** |
|  | (0.000606) | (0.000664) | (0.000743) | (0.000696) |
| Household head is male: 1=yes | 0.0392 | 0.0617 | 0.0537 | 0.0719 |
|  | (0.0382) | (0.0362) | (0.0519) | (0.0460) |
| Household head years of education | 0.00817* | 0.00648* | 0.00966*** | 0.00822*** |
|  | (0.00295) | (0.00262) | (0.00334) | (0.00315) |
| Asset index | -0.0651** | -0.0455* | -0.0767*** | -0.0597** |
|  | (0.0154) | (0.0205) | (0.0191) | (0.0251) |
| Constant | 0.927** | 0.953*** | 1.085*** | 1.110*** |
|  | (0.258) | (0.200) | (0.280) | (0.215) |
| Observations | 310 | 310 | 310 | 310 |
| R-squared | 0.230 | 0.278 |  |  |
| Block Dummies | YES | YES | YES | YES |
| Pseudo R2 | 0.194 | 0.214 | 0.227 | 0.276 |

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 3: Share of maize residues as organic fertilizer: OLS and Tobit.

| VARIABLES | (1)<br>P.W.I | (2)<br>P.W.I AME | (3)<br>P.W.II | (4)<br>P.W.II AME |
|---|---|---|---|---|
| Average maize grain yield kg/acre | 0.0003*** | 0.0001*** | 0.0003*** | 0.0001*** |
| | (0.0001) | (0.0000) | (0.0001) | (0.0000) |
| Total N, P, K used on maize plots in kg | -0.0044*** | -0.0010*** | -0.0041*** | -0.0009*** |
| | (0.0014) | (0.0003) | (0.0012) | (0.0003) |
| Total labor used on maize plots in labor-days | 0.0003 | 0.0001 | 0.0007 | 0.0002 |
| | (0.0010) | (0.0002) | (0.0009) | (0.0002) |
| Soil pH - value | -0.4066** | -0.0923** | -0.3533** | -0.0786** |
| | (0.1824) | (0.0408) | (0.1411) | (0.0307) |
| Total soil nitrogen | -1.4186** | -0.3219** | -1.6407*** | -0.3648*** |
| | (0.6243) | (0.1401) | (0.6240) | (0.1384) |
| Number of formal extension services sources | 0.0889** | 0.0202** | 0.1085** | 0.0241** |
| | (0.0442) | (0.0099) | (0.0523) | (0.0116) |
| Livestock ownership: 1=yes | | | -0.4909** | -0.1103** |
| | | | (0.2134) | (0.0476) |
| Herd size in TLU (no chickens) | | | -0.0659 | -0.0146 |
| | | | (0.0520) | (0.0116) |
| Feed source: 1=grazing on others' land | | | 0.1493 | 0.0331 |
| | | | (0.1123) | (0.0249) |
| Household size | | | 0.0024 | 0.0005 |
| | | | (0.0068) | (0.0015) |
| Number of large and medium trees | | | 0.0005 | 0.0001 |
| | | | (0.0006) | (0.0001) |
| Woodlot: 1=yes | | | 0.2948 | 0.0653 |
| | | | (0.1949) | (0.0430) |
| Improved stove: 1=yes | | | 0.0943 | 0.0209 |
| | | | (0.1932) | (0.0426) |
| Fuelwood collection off-farm: 1=yes | | | 0.0928 | 0.0207 |
| | | | (0.2062) | (0.0461) |
| Time spent collecting 1 kg of firewood | | | 0.3383 | 0.0752 |
| | | | (0.5781) | (0.1279) |
| Fuelwood purchase: 1=yes | | | -0.3538** | -0.0798** |
| | | | (0.1605) | (0.0362) |
| Cost of 1 kg of firewood purchased | | | 0.0020 | 0.0005 |
| | | | (0.0125) | (0.0028) |
| Total land area owned or cultivated in acres | 0.0119*** | 0.0027*** | 0.0166*** | 0.0037*** |
| | (0.0030) | (0.0007) | (0.0025) | (0.0006) |
| Household head is male: 1=yes | 0.1695 | 0.0384 | 0.2788* | 0.0618* |
| | (0.1719) | (0.0387) | (0.1539) | (0.0336) |
| Household head years of education | 0.0357*** | 0.0081*** | 0.0282** | 0.0063** |
| | (0.0135) | (0.0031) | (0.0127) | (0.0028) |
| Asset index | -0.2822*** | -0.0640*** | -0.1993** | -0.0443** |
| | (0.0599) | (0.0132) | (0.0860) | (0.0190) |
| Constant | 2.0412** | | 2.1312*** | |
| | (1.0396) | | (0.7865) | |
| Observations | 310 | 310 | 310 | 310 |
| Block Dummies | YES | YES | YES | YES |

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Share of maize residues as organic fertilizer: the Papke and Wooldridge estimator.

| VARIABLES | (1)<br>OLS I | (2)<br>OLS II |
|---|---|---|
| Average maize grain yield kg/acre | 0.538** | 0.456* |
| | (0.191) | (0.168) |
| Total N, P, K used on maize plots in kg | 12.17*** | 12.14*** |
| | (1.827) | (2.195) |
| Total labor used on maize plots in labor-days | 3.923** | 3.138 |
| | (1.407) | (1.578) |
| Soil pH - value | -497.4** | -371.5* |
| | (122.6) | (151.2) |
| Total soil nitrogen | -1,194 | -1,325 |
| | (563.2) | (700.8) |
| Number of formal extension services sources | 26.27 | 14.26 |
| | (70.19) | (65.17) |
| Livestock ownership: 1=yes | | 115.1 |
| | | (172.6) |
| Herd size in TLU (no chickens) | | 16.20 |
| | | (85.64) |
| Feed source: 1=grazing on others' land | | 23.09 |
| | | (95.12) |
| Household size | | 60.16*** |
| | | (11.56) |
| Number of large and medium trees | | -1.838** |
| | | (0.590) |
| Woodlot: 1=yes | | 353.3 |
| | | (225.9) |
| Improved stove: 1=yes | | 133.7 |
| | | (140.1) |
| Fuelwood collection off-farm: 1=yes | | -21.03 |
| | | (100.2) |
| Time spent collecting 1 kg of firewood | | -307.8 |
| | | (493.7) |
| Fuelwood purchase: 1=yes | | -390.0*** |
| | | (37.44) |
| Cost of 1 kg of firewood purchased | | -8.370 |
| | | (6.999) |
| Total land area owned or cultivated in acres | 26.98*** | 22.39** |
| | (2.260) | (6.444) |
| Household head is male: 1=yes | 145.8 | -41.87 |
| | (158.6) | (113.2) |
| Household head years of education | 52.57* | 53.17* |
| | (20.32) | (19.79) |
| Asset index | -89.39 | -104.2 |
| | (73.00) | (127.6) |
| Constant | 3,536** | 2,663** |
| | (791.5) | (885.0) |
| Observations | 310 | 310 |
| R-squared | 0.290 | 0.326 |
| Block Dummies | YES | YES |
| Pseudo R2 | 0.256 | 0.266 |

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5: Amount of maize residues as organic fertilizer: OLS.

|  | All households |  | Interior households |  |
|---|---|---|---|---|
|  | (1) | (2) | (3) | (4) |
| VARIABLES | OLS | IV-GMM | OLS | IV-GMM |
| LN(Maize plot area planted with maize in acres) | 0.501*** | 0.295** | 0.351*** | 0.222* |
|  | (0.0890) | (0.135) | (0.0955) | (0.132) |
| LN(Labor in person-days: household and hired) | 0.111 | 0.306*** | 0.0104 | 0.189* |
|  | (0.0859) | (0.0925) | (0.0938) | (0.100) |
| LN(Nutrient (N, P, K) content in grams) | 0.161*** | 0.305** | 0.151*** | 0.353*** |
|  | (0.0402) | (0.136) | (0.0501) | (0.0734) |
| No chemical fertilizer applied: =1 | 0.885** | 1.995 |  |  |
|  | (0.362) | (1.291) |  |  |
| LN(Amount of maize residue applied in grams) | 0.279*** | 0.288* | 0.412*** | 0.255* |
|  | (0.0703) | (0.159) | (0.0784) | (0.132) |
| No maize residue applied: =1 | 3.413*** | 3.202 |  |  |
|  | (0.923) | (2.252) |  |  |
| Seed used: 1=hybrid | 0.389*** | 0.887*** | 0.0185 | 0.466** |
|  | (0.123) | (0.229) | (0.131) | (0.206) |
| Number of formal extension services sources | 0.0599** | 0.0453 | 0.0102 | 0.0235 |
|  | (0.0275) | (0.0339) | (0.0287) | (0.0273) |
| Household head is male: 1=yes | 0.0721 | -0.0330 | -0.0635 | -0.0103 |
|  | (0.115) | (0.132) | (0.148) | (0.128) |
| Household head years of education | -0.00708 | -0.0125 | -0.0125 | -0.0165 |
|  | (0.0119) | (0.0129) | (0.0136) | (0.0131) |
| Asset index | 0.0828* | 0.0539 | 0.139*** | 0.0246 |
|  | (0.0430) | (0.0575) | (0.0491) | (0.0529) |
| Constant | 0.256 | -2.121 | -0.628 | -1.495 |
|  | (1.062) | (2.179) | (1.122) | (1.833) |
| Observations | 309 | 309 | 162 | 162 |
| R-squared | 0.644 | 0.571 | 0.703 | 0.638 |
| F test of excluded instruments F(18,284) or F(18,137): |  |  |  |  |
| lnnutrientg |  | 20.11*** |  | 4.45*** |
| nonutrient |  | 17.10*** |  |  |
| lnmresappliedg |  | 1.78** |  | 3.44*** |
| noresidue |  | 1.65** |  |  |
| mhybrid |  | 18.15*** |  | 7.08*** |
| Overidentification test of all instruments: |  |  |  |  |
| Hansen J Statistic $\chi^2(13)$ or $\chi^2(15)$ |  | 9.03 |  | 21.67 |
| $\chi^2$ p-value |  | 0.77 |  | 0.12 |
| Residues shadow price (per 1 kg) | 7.66 KES | 4.16 KES | 12 KES | 3.19 KES |
| Residues shadow price excl. top and bottom 5% | 5.74 KES | 3.11 KES | 8.98 KES | 2.38 KES |

Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
**Instrumented variables:** lnnutrientg, nonutrient, lnmresappliedg, noresidue, mhybrid.
**Instruments:** soilphv, totnitrogenv, lnlandareaA, livestock, herdsize2, otherslandfeed, hhsize, lmtreenum, woodlot, imprstove, fuelcollect, fuelcollecthrskg, fuelbuy, fuelbuykeskg, age, agesq, distvin_m, altitude.

Table 6: Household-level maize production: OLS and IV-GMM.

| Variable | Value (KES) | Value (USD) |
|---|---|---|
| All maize residues per farm | 9,902.24 | 117.88 |
| Maize residues left on the fields per farm | 3,993.24 | 47.53 |
| Maize residues per acre | 6,391.05 | 76.08 |
| Maize grain per acre | 19,519.90 | 232.38 |

Table 7: Shadow value of maize residues in KES and USD.