Allocation and valuation of non-marketed crop residues in smallholder agriculture: the case of maize residues in western Kenya*

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Abstract

Crop residues are used for animal feed and fuel, and are fundamental to maintaining fertility in tropical soils, depletion of which is considered to be one of the major biophysical causes of low per capita food production in Sub-Saharan Africa. Using data from a survey of over 300 households in western Kenya in 2011-2012, we investigate the contribution of maize residues to smallholders' agricultural production and estimate their shadow value to be 5.62 Kenyan shillings (US$0.07) per kilogram. Valuing the benefits of crop residues to farmers can help support local conservation efforts with global importance.

Keywords: natural resources, crop residues, sustainable agricultural practices, environmental benefits, western Kenya.

JEL Codes: O13, Q12, Q15, Q16, Q24, Q56.

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1 Introduction

With our increasing understanding of the role natural resources play in agricultural production and carbon sequestration, the land-use decisions of small-scale farmers in highly populated tropical regions have important implications for both farmers' welfare and for the global environment. The imperatives of reducing greenhouse gas emissions, increasing agricultural carbon sequestration, and enhancing farmers' resilience to climate change have fostered the promotion of many agricultural practices that rely on organic resources. Improved information about the scope of the contribution of natural resources to agricultural productivity will become even more important as population and economic pressures force many of the smallholders worldwide to intensify cultivation and adopt new sustainable technologies.

Crop residues[1] are one of the most important natural resources in smallholder agriculture. An estimated 60 percent of crop residues are produced in developing countries, and almost 45 percent in the tropics (Smil 1999; Lal 2005). They are an essential ingredient to maintaining and sustaining long-term soil fertility, and thereby contribute fundamentally to agricultural productivity. Crop residues also account for up to 50 percent of livestock diets in developing countries (Thornton, Herrero, and DeFries 2010), and they contribute to satisfying household energy needs for those who rely on solid biomass for cooking. This includes an estimated 730 million people in Sub-Saharan Africa (IEA 2014).

The multiple uses and competing applications of crop residues also create many challenges. The removal of crop residues for use as feed for domestic animals and fuel is, for example, a driving force behind the depletion of the soil organic matter pool in the tropics and subtropics, leading to soil degradation, a decline in soil structure, severe erosion, emission of greenhouse gases, and water pollution (Lal 2006). These soil fertility-depleting processes not only decrease agronomic productivity and reduce the soil carbon pool, but also reduce crop response to chemical fertilizer and other inputs. Moreover, depletion of soil fertility is considered to be one of the main biophysical causes of poor yields and low per capita food production in Sub-Saharan Africa (Sanchez 2002), contributing to widespread food insecurity and rural poverty.

Given the tradeoffs among alternative uses as well as the long lag in realizing the full agronomic

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[1] Crop residues are defined as all inedible phytomass of agricultural production (cereal and legume straws, leaves, stalks, and tops of vegetables, sugar, oil, and tuber crops, etc.).

benefits of leaving residues on the fields, the management and value of crop residues have important implications for current and future socio-economic and environmental outcomes. Yet quantifying crop residue production and accounting for its uses are rarely done even in developed countries (Smil 1999), where agronomic systems are better understood and data sources are typically more complete. There are also significant methodological challenges in valuing crop residues since organic resources are often non-marketed, entail multiple long-term benefits, and create environmental externalities (Shiferaw and Freeman 2003). Careful analysis of the allocation of crop residues to different uses, however, can improve our understanding of smallholder choices with respect to these resources. Moreover, deriving their monetary values as factors of production can help assess agricultural technology options (Magnan, Larson, and Taylor 2012) and measure the effects of technologies and policies on smallholder incomes and agricultural sustainability (Lopez 1997). Besides valuing the benefits of crop residues to farmers could help support local conservation efforts with global importance.

Understanding and quantifying the value of crop residues, for example, is important for promotion of mixed crop-livestock systems. With decline in grazing resources, farmers increasingly rely on crop residues for livestock feed. Intensification of livestock production, however, often results in reduced crop residue retention in the fields with long-term implications for soil health and soil carbon sequestration. Feeding residues to livestock does not necessarily break the nutrient and carbon cycling when these can be returned to the field in the form of manure. The labor costs of transporting bulky manure in necessary quantities, however, can be prohibitive (Duncan et al. 2016). And nutrient losses between manure production and its return to the fields can result in low nutrient cycling efficiencies (Castellanos-Navarrete et al. 2015). Therefore, given the inherent trade-offs in maintaining productive mixed crop-livestock systems, monetizing the value of crop residues will help create effective interventions aimed at improving crop and livestock productivity.

In this paper we study the allocation and value of crop residues in smallholder agriculture in the tropics. We estimate a household-level maize production function using detailed input and output data, including measurements of crop residues and household-specific environmental variables to calculate the shadow value of maize residues, using data from the highlands of western Kenya. In this densely populated rural part of the country, maize residues constitute one of the biggest sources of on-farm organic resources (Torres-Rojas et al. 2011) and have competing applications.

Our econometric estimates suggest that maize residues contribute about 30 percent to agricultural production, once this factor is measured at its shadow value. The shadow price of one kilogram of maize residues left on the fields is 5.62 Kenyan shillings or US$0.07, on average. Using this average shadow price, we show that maize cobs and stover make up around 37 percent of the total value of annual maize production and constitute about 22 percent of the median household income.

The following section briefly describes the links between soil organic matter management, soil fertility, and agricultural productivity, as well as the existing literature that analyzes the use of agricultural residues. Section 3 describes crop residue management in the western Kenya highlands and the data used. Section 4 presents our empirical strategy and section 5 discusses the estimation results, showing the economic importance of maize residues and comparing our estimates to other studies. Section 6 concludes the paper.

2 Value of Organic Resources in Smallholder Agriculture

Despite considerable progress in agricultural innovations and successes of the Green Revolution in other regions of the world, by the year 2013, cereal yields in Sub-Saharan Africa (SSA) remained at less than 1.5 metric ton per hectare, less than half the average yields in other developing country regions (FAOSTAT 2015). The reasons for this are many and complex but they include low levels of fertilizer use, the systematic removal of crop residues by farmers, and the region's widespread soil degradation and decline in soil fertility, among other factors (Sanchez 2002; Jayne and Rashid 2013). To address these challenges, research in agronomy, soil science, and farming systems ecology has widely called for initiatives promoting the sustainable intensification of SSA agriculture (see, for example, Lee and Barrett (2001) and Tilman et al. (2011)).

One of the most frequently cited priorities in increasing agricultural productivity in SSA — relieving soil fertility constraints — will require increased combined applications of chemical fertilizer and organic resources. Fertilizers and organic resources — which include traditional organic inputs such as crop residues and animal manures, as well as trees, shrubs, cover crops, and composts (Palm et al. 2001) — have different functions. While chemical fertilizers address short-term crop nutrient demands, organic inputs are fundamental for soil fertility management through their longer-term contribution to soil organic matter formation (Lal 2009). Moreover, both chemical fertilizers and organic resources are often not widely available or affordable in sufficient quantities, suggesting another practical reason for their combined application (Vanlauwe and Giller 2006). Fertilizer application rates are limited by high costs, restricted availability, and household liquidity constraints, while organic resources face numerous competing applications. Even if fertilizer use were to be widely expanded, chemical fertilizers alone are not capable of restoring soil fertility and increasing agricultural productivity across all soil types, and especially on "non-responsive" soils (Tittonell and Giller 2013).[2]

An adequate annual input of organic resources is crucial to maintaining soil fertility in developing countries, especially in coarse-textured soils (Chivenge, Vanlauwe, and Six 2011). Crop residues are the most readily available and accessible forms of organic resources for most smallholders. Most studies from developing countries show positive effects of crop residue retention on soil organic matter and carbon storage, nutrient cycling, decreased soil loss, and moisture retention, among many other benefits (Turmel et al. 2015). When crop residues are retained, they can either be left on the soil surface with conservation tillage or incorporated into the soil with conventional tillage practices. With poor access to herbicides, many farmers rely on tillage for weed control thus incorporating residues into the soil. These different tillage practices, as well as a range of agro-climatic and management factors, may have different impacts of residue retention on soil chemical, physical, and biological properties, and therefore yields.

In some environments, decomposition of cereal residues may lead to temporary nitrogen immobilization due to residues wide carbon to nitrogen ratio (Palm et al. 2001) and negatively affect crop performance. These negative impacts have been observed in cooler temperate climates, regions with high rainfall, and semi-arid systems (Turmel et al. 2015). These effects are, however, less common in mixed crop-livestock systems, with low crop and residues production volumes and where trade-offs on the use of residues are particularly strong.[3]

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[2] Discontinuous, limited or no fertilizer application, combined with continuous cultivation over time, leads to severe soil degradation through nutrient depletion and the loss of organic matter, thus rendering many soils "non-responsive" to the renewed application of nutrients or improved varieties (Tittonell and Giller 2013).

[3] The "continuous corn yield penalty" — declines in corn yields with continuous corn cultivation — has been linked with reduced mineralization of plant-available soil nitrogen due to residue retention (see, for example, Gentry, Ruffo, and Below (2013)). Many of the studies that find this link come from the United States, where observed maize yields are in the range of 5.5-12 tons/hectare (t/ha) and the weather patterns and management practices significantly differ from Sub-Saharan Africa. Baudron et al. (2014), for example, show that few farmers in East Africa retain more than one t/ha of cereal residues in their fields (36 percent in western Kenya and 3 percent in the Ethiopian Rift Valley) and significant increases in yields are observed with residue retention of up to one t/ha in Kenya and three t/ha in Ethiopia.

In recent years, organic resource management has also increasingly been viewed as contributing not just to agricultural productivity but also to wider environmental and economic goals. Increasing the soil carbon pool through recommended practices (mulching, retention of crop residues, use of manures, and biosolids) has the promise to sequester carbon, reverse soil degradation processes, improve soil quality, and increase food production, with a potentially strong impact on offsetting fossil fuel emissions (Lal 2006). These practices rely on organic resources and fall under the umbrella of "climate-smart" or "low emissions" agriculture with goals to reduce greenhouse gas emissions, increase carbon sequestration, and enhance farmers' resilience to climate change.

Despite the prominence of crop residues in the agronomic literature (see, for instance, recent work of Baudron et al. (2014) and Duncan et al. (2016)), they have been the subject of limited attention in economics research. Contrast this, for example, with the long recognized importance of chemical fertilizers and modern seed varieties to increasing crop yields and the constraints underlying their adoption and use in SSA and other developing countries (see, for example, recent work from Kenya by Marenya and Barrett (2009a); Suri (2011); Duflo, Kremer, and Robinson (2011)). One of the reasons for this neglect is the difficulties associated with quantifying organic resources. As a result, most studies that estimate crop response models rely on rough indicator variables for crop residues and animal manures. For instance, Gavian and Fafchamps (1996) and Sheahan, Black, and Jayne (2013) include indicator variables for manure use, while Marenya and Barrett (2009b) rely on the value of livestock as a control for unobserved manure application rates. Only a few studies include the quantities of animal manure in their estimation of production functions: Teklewold (2012) in his work in Ethiopia and Matsumoto and Yamano (2011) in their work in Kenya and Uganda.

The existing literature, though limited, nonetheless confirms important trade-offs among different uses of crop residues. Wealthy households in Kenya, for example, use chemical fertilizers, practice fallowing on a portion of their farm, or incorporate maize residues for soil fertility management to achieve higher crop yields, while poorer households obtain higher returns from using maize residues as fuel or livestock feed (Crowley and Carter 2000; Marenya and Barrett 2007). It is also often thought that agricultural residues are substitutes for fuelwood in consumption. The empirical evidence as to whether fuelwood and dung, or fuelwood and crop residues, are substitutes or complements, however, is mixed (Amacher, Hyde, and Joshee 1993; Mekonnen and Kohlin 2008;

Cooke, Kohlin, and Hyde 2008).

In order to demonstrate the value of organic resources in developing countries, the existing literature uses either a production or a substitution approach. The production approach establishes the value by calculating changes in overall farm profits or physical changes in production by including biomass as a production input (see, for example, Lopez (1997); Goldstein and Udry (2008); Klemick (2011)). Two recent studies use, alternatively, the substitution approach, deriving the value of biomass using the observed prices of agricultural inputs. Teklewold (2012) examines the role of returns to manure as energy and farming inputs in smallholder agriculture in Ethiopia, while Magnan, Larson, and Taylor (2012) analyze the value of cereal stubble in a mixed crop-livestock farming system in Morocco. Both of these 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). One of the strengths of the data set used here lies in the reliable estimates of quantities of both inputs and outputs and the market price of maize. Therefore, we use the production approach.

3 Research Area and Data

Western Kenya presents a compelling case study as a region of mixed rain-fed crop-livestock systems, high population density, small farm size, and multiple competing uses for natural resources in general and crop residues in particular. Despite the significant growth in fertilizer use and promotion policy in Kenya since the mid-1990s (Sheahan, Black, and Jayne 2013), for example, many farmers in the area still use low levels of chemical fertilizer, instead relying on on-farm residues to manage soil fertility. Expansion of arable land driven by population growth has also come at the expense of common pool resources — rangelands and pastures, so that farmers increasingly rely on crop residues for livestock feed (Baldyga et al. 2008; Duncan et al. 2016). And the crop residue demand for livestock feed is unlikely to decrease, as milk and meat consumption in mixed crop-livestock systems is projected to more than double over the next several decades (Herrero et al. 2010). As a consequence, reduced biomass production and retention in both cultivated and common areas has led to increased soil degradation and erosion, as well as potentially adverse changes to ecological and hydrological systems.

The research sites are five 10-kilometer blocks 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).[4] A socio-economic and household production survey of a sample of 309 households in 15 villages (three in each block) across the Nyanza, Rift Valley and Western counties was conducted in two rounds in 2011-2012 to account for the bi-modal annual precipitation pattern and associated two distinct cropping seasons. The survey covered a wide range of standard Living Standards Measurement Survey topics and, in addition, collected soil samples and detailed spatial and market data. Table 1 shows selected summary statistics for the sample households.

A typical household in the area has six members and owns 4.53 acres of land. The household head is on average 51 years old, has seven years of schooling, and for over 80 percent of households is male. Maize is the most popular grain crop in the area and is cultivated on almost half of the land owned. Maize established itself as the dominant food crop at the beginning of the 20th century due to its relatively higher yields per unit of land and the possibility of two crops per calendar year (Crowley and Carter 2000). The average maize plot in the sample is 0.61 acres (across 801 plots and two cropping seasons) and is rain-fed. Differences in geographic location and associated rainfall availability, maximum and minimum temperatures (proxied by altitude), and the possibility of two cropping seasons of varying length, as well as variations in farmer management practices together account for a high variance in maize grain yields, which average 670 kg/acre among sample farms.[5]

Dominant soil types in the Yala and Nyando river basins are acrisols, ferralsols and nitisols (Jaetzold and Schmidt 1982). Acrisols and ferralsols are strongly leached or weathered; indeed, farmers in the sample identified their soil fertility as mostly of moderate quality and the laboratory soil analysis[6] confirmed the poor soil fertility. We use two soil characteristics to capture fertility: soil carbon measured as percentage of soil organic carbon by mass (% by weight or % w/w) and cation exchange capacity (CEC) measured in milliequivalent of hydrogen per 100 grams of dry soil

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[4] The sites formed part of the original geographic coverage of the Western Kenya Integrated Ecosystem Management Project, implemented between 2005-2010 by the Kenya Agricultural Research Institute and the World Agroforestry Center and funded from the Global Environmental Facility of the World Bank.

[5] The farm and household characteristics are similar to those of the households in the representative panel data set from Kenya collected by the Tegemeo Institute of Agricultural Policy and Development at Egerton University and Michigan State University. See, for example, Mathenge, Smale, and Olwande (2014).

[6] Soil samples were collected during the first household visit in the end of the long rains season of 2011 from the largest maize plot on each farm. The laboratory analysis was carried out at the World Agroforestry Center's Soil-Plant Spectral Diagnostics Laboratory in Nairobi using mid-infrared spectroscopy (MIRS), a rapid nondestructive technique for examining the chemical composition of materials (Shepherd and Walsh 2002, 2007).

(meq/100g). Soil organic carbon or soil organic matter contents have been used in the literature to account for overall soil quality (Goldstein and Udry 2008; Marenya and Barrett 2009a). This measure, however, can be transient and influenced by management practices. Soil CEC, on the other hand, relates to soil texture and mineralogy, offering a more stable indicator for soil fertility (Sparks 1996).

Yield returns to organic resource addition are highly context specific, and their magnitude and direction is also dependent on resource quality, both in the short-term and long-term (Palm et al. 2001; Gentile et al. 2011). While additions of low quality crop residues can result in nitrogen immobilization in the short-term as discussed above, some soil scientists argue that since they build up the stocks of soil organic matter in the long-term, their application is the primary way to sustainably maintain and restore soil fertility in the tropics (Lal 2006). Recent work in the same research area of western Kenya by Guerena et al. (2016) demonstrates yield increases after the application of organic resources of contrasting quality (with and without fertilizer additions), with greater relative immediate impacts of high-quality and rapidly mineralizing resources and greater long-term residual effects of resources with greater carbon to nitrogen ratio. Similarly, a meta-analysis from of 57 studies from Sub-Saharan Africa reports positive maize yield responses after the applications of different quality organic resources, with and without additions of nitrogen fertilizer (Chivenge, Vanlauwe, and Six 2011). And the trials in Kakamega in western Kenya show the non-linear maize grain yield increase with the quantity of maize residues mulch applied, reaching the plateau in yields with a surface mulch of approximately one ton per hectare of maize stover (Baudron et al. 2014).

4 Production Function Estimation

The dependent variable in the production function is the log of maize harvest value. While most farmers rely on own maize production for food, many (about 40 percent) also sell at least some of their maize in the market. We use the median village maize prices to convert household-specific yields to maize value. Output is modeled as a function of land cultivated with maize, household and hired labor, fertilizer, and maize residues. Since maize grain is a market good, valuation of the non-market crop residues using a production function approach does not depend on detailed knowledge of the mechanisms at work (Maler 1990; Klemick 2011).

The choice of functional form for the estimation of the crop response function with respect to different inputs has received substantial attention in the agronomic and economic literature. We follow many studies that employ a household production model to calculate the shadow price of a non-market good using the Cobb-Douglas specification (see, for example, Magnan, Larson, and Taylor (2012); Arslan and Taylor (2009); Skoufias (1994); Jacoby (1993)). Farm i's maize revenue y_i can be represented as

$$\ln y_i = \alpha_0 + \sum_{j=1}^{m} \alpha_j \ln x_{ji} + \beta \mathbf{H_i} + \epsilon_i, \tag{1}$$

where x_i is a vector of production inputs (land, labor, fertilizer, and residues), H_i is a vector of controls for observable aspects of land quality and management practices and ability, including soil fertility, use of hybrid seeds, intercropping, manure applications, altitude, and number of formal extension services sources, α and β are parameters to be estimated, and ϵ_i represents the iid, mean zero, normally distributed error. Limiting the production function estimation to households that used only positive quantities of maize residues as a soil amendment could introduce selection bias into the estimates. In a smallholder setting such as ours, not all farmers use fertilizer and crop residues in positive quantities thus creating the "zero-observation" problem for estimation. To deal with this issue, we employ the approach outlined in Battese (1997) and recently used in Klemick (2011). We add two indicator variables for non-use of fertilizer and crop residues that function as different intercepts for farmers who do not use particular inputs.

Since the allocation of maize residues to different uses is a decision made at the farm 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. We aggregate output and inputs for all plots and across two seasons and disregard potential spatial and temporal variation in the use of one or more inputs. In this setting a smooth "aggregate" production function may be more appropriate (Berck and Helfand 1990). Since the agronomic literature argues for the existence of complementarities in input use (Chivenge, Vanlauwe, and Six 2011) and we are cautious to assume unitary elasticity of substitution necessary for the Cobb-Douglas estimation, we also estimate a generalized quadratic specification. The same functional form is used in some recent studies focusing on maize production across Sub-Saharan Africa (see, for example, Sheahan, Black, and Jayne (2013) and Harou et al. (2014)). The results are reported in the appendix.

Using the estimated coefficients of the production function, we can then calculate the household-specific shadow price of maize residues (in KES/kg) as follows:

$$\text{Shadow price}_i = \alpha_4 \frac{y_i}{x_{4i}}, \tag{2}$$

where y_i is farm i's maize revenue and x_{4i} is farm i's quantity of residues applied.

Table 1 reports the summary statistics of variables used in the estimation. Some variables deserve additional explanation. About 40 percent of households in the sample apply some chemical fertilizer. Di-ammonium phosphate (DAP) is commonly applied during planting, while urea and calcium ammonium nitrate (CAN) are applied as top dressing. To account for all types of chemical fertilizer applied and their different compositions without introducing too many variables, we create a "plant nutrient" measure, NPK, that aggregates the quantity of the active ingredients (rather than the total quantity of fertilizer), giving equal weight to the three most important plant nutrients: nitrogen (N), phosphorous (P), and potassium (K).[7] Application of 25.28 kg of NPK across all maize plots and two seasons, or 17.42 kg of NPK per acre, is the sample average. This represents a very low level of fertilizer usage. More than 8 in 10 (83 percent of) farmers in the sample left maize residues on their fields for soil fertility management, and 162 households (52 percent) used both chemical fertilizer and maize residues as organic soil amendments.

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). Ninety four percent of households keep farm animals with the average TLU in the sample being 2.38. Following Sahn and Stifel (2003), we create an asset index for each household derived from a factor analysis on household durables and housing quality. Household durables include assets such as radios, televisions, furniture, improved and gas/electric stoves, bicycles, motorcycles and cars; housing quality incorporates indicator variables for construction material (walls, roof, floor), source of drinking water, energy used for lighting, and toilet facilities.[8]

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[7] The NPK composition of the most common fertilizers used by farmers in the sample is the following: DAP (with N-P-K composition of 18-46-0), urea (46-0-0), CAN (26-0-0), TSP (0-46-0), NPK mixes (20-10-10, 23-23-0, 20-20-0).

[8] Scoring coefficients (weights) for asset index are reported in table A1 in the online appendix.

Allocation and amount of maize residues. Maize residues are used for multiple purposes, leaving none wasted. Nearly half (47 percent) of aboveground maize residues (both stover and cobs) in our sample are allocated to soil fertility management (left on the fields, mulched, or collected to be applied as organic soil amendments later on). Most livestock in smallholder systems in Kenya either graze on own or communal land, or are tethered, so that maize residues can constitute a significant portion of livestock diets — up to 24 percent of total livestock feed by dry weight (KARI 2008). Household energy sources are also predominantly from biomass, including wood and crop residues. The shares used for animal feed and household fuel are 25 percent and 22 percent, respectively (table 2). A minor amount of remaining residues are allocated to miscellaneous uses. Residue use also differs by household wealth (figure 3). Households in the first quartile of the asset index use the largest share of maize residues for soil fertility management (and the least fertilizer quantity), while households in the top two quartiles have more livestock and allocate more residues as animal feed.

While we collected yield, fertilizer and labor data at a plot level, no farmer in our sample could specify the quantity of residues left on a field for soil fertility at a plot level. The quantity of residues allocated to different uses is, therefore, reported in the survey at the household level for the twelve months preceding the survey visit. This includes two cropping seasons in the areas where maize is planted twice per year. In the absence of plot-level data on crop residue use over time, we assume that a large part of the residue allocation decision is persistent from year to year, given that the household needs for energy and livestock feed, on average, do not significantly change from year to year. As cooking activities display significant economies of scale, small changes in household size, for example, do not materially alter energy requirements. The survey included a household member roster during both visits; only six percent of households reported that the number of their family members either increased or decreased by more than one person.

Estimating plot-level amounts of maize residues is a challenging task. No nation tracks the production of crop residues the way they track food production or chemical fertilizer use; the most reliable estimates come indirectly from studies of the harvest index (the ratio of crop edible yield to the crop's total aboveground phytomass) or the straw-to-grain ratio on experimental plots (Smil 1999; Lal 2005). We instead rely on actual measurements of maize grain and residues from a different sample of 140 farmer plots in the same research sites in 2011-2012 (Torres-Rojas 2015). We first predict the within-sample plot-specific yields of maize grain and maize residues over the sample of 140 plots (see figure 2) and use this linear prediction (R^2=0.58) to generate plot-level residue quantities in our sample of 309 households. The total household-level residue quantities are then the sum of predicted plot-level quantities for each household, estimated across two cropping seasons of 2011 where appropriate.[9] This generated variable presents a couple econometric problems in the later estimations, one of which concerns the standard errors from a second-stage regression (Pagan 1984). We correct the biased standard errors caused by the generated regressor of maize residue quantities by bootstrapping techniques.

Endogeneity concerns: Particular concerns in the literature on the estimation of primal production functions in developing countries are the possibilities of measurement error, omitted variables (e.g., environmental production conditions), and/or simultaneity bias due to unobserved heterogeneity. The data set used in this study includes plot area measured with hand-held Global Positioning System (GPS) units, quantities of crop residues estimated using actual measurements, and household-specific measures of soil fertility and altitude to capture variation in maximum and minimum temperatures (as in Tittonell and Giller (2013)) — all variables which should attenuate potential measurement error and omitted variable bias.

Simultaneity bias, however, is still of concern: managerial ability (imperfectly captured by the number of formal extension services sources), for example, can lead to higher maize yields and higher residue retention. More importantly, given our data limitations, by construction the amount of crop residues applied is correlated with contemporaneous maize yield. Given that we only have cross-sectional data, we also estimate the production function with an indicator variable equal to one if more than one ton per hectare of residues applied over the course of a year. Quantities of residues below this threshold are found to be too low to have significant impact on maize yields in western Kenya (Baudron et al. 2014). While this indicator variable is also correlated with contemporaneous maize yield, it is a more coarse measure and is more likely to capture the time-invariant component of crop residues retention. The assumption of time invariance, however, deserves additional consideration that can be properly addressed only with panel data and is subject

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[9] We focus our analysis on the management of aboveground maize residues (stover and cobs) and do not consider maize root biomass. Since Kenyan farmers do not remove roots from soil after harvesting, there is no variation in use of maize roots among households. Moreover, maize roots are, on average, only about 10 percent of aboveground residues dry weight (Latshaw and Miller 1924).

to further research. In the absence of credible instruments, however, we rely on the estimation of the production function with the quantity of residues and with the indicator variable for high use, acknowledging the potential bias of our estimates.

5 Empirical Results

In order to elicit the shadow value of maize residues allocated to soil fertility management, we estimate a household-level production function for maize (equation 1). Output, the log of maize harvest value, is estimated as a function of land cultivated with maize, household and hired labor, fertilizer, and maize residues as soil amendments. Additional variables include a set of environmental variables to control for biophysical influences on production (soil carbon, soil CEC, altitude), other variables potentially influencing maize production (herd size in TLU as a proxy for unobserved manure application rates, the fraction of land planted with hybrid seeds and intercropped with legumes, and the number of formal extension services sources). The results of the estimation are reported in table 3.[10] Column (1) reports estimates with the quantity of maize residues, while column (2) shows estimates with the indicator variable for high use of maize residues.

Both specifications report consistent estimates and a satisfactory fit, as indicated by R^2 of 0.68-0.66. Land cultivated with maize, household and hired labor, fertilizer, and maize residues as soil amendments are all important factors of production in western Kenya, with statistically significant elasticities greater than zero. Notably, the elasticity of maize residues is high and similar across the two specifications (0.31 and 0.30), suggesting that retaining maize residues on the fields makes a substantial contribution to maize harvest revenue. This means that the contribution of crop residues to agricultural production is about 30 percent once this factor is measured at its shadow value. Given that we explicitly control for soil fertility status (soil carbon content and CEC), the estimated effect is unlikely due omitted variables like soil organic matter. And the similar and statistically significant elasticity on the indicator variable for high maize residue use that perhaps better captures the time-persistent component of residue retention also assures us of the validity of

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[10] We use altitude to capture variation in maximum and minimum temperatures. In our data set, altitude also serves as a geographic control — there is a strong correlation between household-specific altitudes within the same village. Addition of indicator variables for blocks, districts, or villages does not significantly change the estimation. A Wald test statistic of 4.88 and a P-value of 0.43 against the $\chi^2(5)$ distribution cannot reject the null hypothesis that the districts are, for example, statistically important.

this result.

The large magnitude of the maize residues elasticity estimate, which exceeds the NPK elasticity, is surprising. One explanation could be found in the relative quantities of residues and NPK applied. A median (average) household applies 1,192 (1,521) kg of residues and 6.4 (25.28) kg of NPK (table 1). When expressed as elasticity, the impact of residues seems high because a one percent change in residues represents a much bigger absolute change than a one percent change of fertilizer. The elasticity estimates are also high in other empirical studies. For example, Lopez (1997) finds the village-level biomass factor share, measured as total village area under fallow times the average vegetation density per acre, to vary between 0.15-0.18 and Klemick (2011) finds the elasticity of on-farm and upstream fallow in the range of 0.11-0.55.

The results of the estimation using a quadratic specification of the production function are reported in table A2 in the appendix. While we cannot reject the null hypothesis of the statistical insignificance of the second-order terms (with a Wald test statistic of 45.75 and a P-value of zero against the $\chi^2(10)$ distribution), individual coefficients on productive inputs and most of second-order terms are not statistically significant. We focus on the Cobb-Douglas specification, which presents a better fit, in our discussion that follows.

As discussed above, valuation of the non-market maize residues using a production function approach does not reveal the underlying mechanisms at work. Our estimates, however, demonstrate the valuable contribution of maize residue retention to agricultural yields. This contribution can be both short-term (contemporaneous) through the addition of nitrogen and long-term (residual) through building up the soil organic matter (Lal 2006; Chivenge, Vanlauwe, and Six 2011).

Some estimates from western Kenya show that nitrogen accounts for about 0.7 percent of maize residues (leaves, stems and cobs), as a percentage of dry weight (Gentile et al. 2011). The average (unconditional) retention of maize residues is 1,046 kg/acre in our sample, which corresponds to about 7 kg/acre of nitrogen (similar to the average application rate of nitrogen in chemical fertilizer of 7.61 kg/acre). Using 0.7 percent as the nitrogen content of maize residues and 350 KES as the mean price of one kilogram of nitrogen in the sample, the price of nitrogen in one kilogram of maize residues can thus be estimated at 2.45 KES or US$0.03. Moreover, the full value of using crop residues for soil fertility management is not only their marginal benefit in current period production, but also the discounted marginal value of having more crop residues in the future (as also demonstrated by our theoretical model discussed in the appendix). Chivenge, Vanlauwe, and Six (2011) show, for example, that the addition of organic resources in one season also has residual effects in the subsequent season with crop yield responses of 38 percent over the no-input control. Thus, the estimated value of 5.62 KES/kg is higher that the value of nitrogen and also includes the residual value of maize residue retention.

Economic importance of crop residues: Of the total of 309 sample households, not all households, however, left maize residues on the field — 17 percent of households used all of the residues for different purposes. The estimated average shadow value for households that used positive quantities of maize residues as inputs in maize production is shown in table 4 (equation 2). The average shadow value for maize residues left on the fields for soil fertility management is 5.62 KES/kg or 0.07 USD/kg. Using 5.62 KES/kg, table 4 also shows the values of maize residues per farm and per acre (per ha). Maize residues applied as a soil amendment are valued, on average, at 8,548 KES or US$102 per farm, which constitutes about 11 percent of the median annual household income in the sample (79,750 KES). Total maize residues per farm are valued at US$213 (22 percent of the median income). When these values are translated to per acre (per hectare) estimates, table 4 also shows that all maize residues constitute 37 percent of the total value of cereal production (both grain and residues) in western Kenya.

Although the estimated value of maize residues seems relatively high, they are indeed close to the previously estimated values of non-market crop stubble in Morocco and farmyard manure in Ethiopia. Magnan, Larson, and Taylor (2012) find the median and mean per hectare value of cereal crop stubble during two seasons of 2007 (drought year) and 2008 (normal rainfall year) to be US$221 and US$491, respectively. Our estimate, US$338 per hectare of maize residues produced, falls between these two values. The estimated average value of US$0.07/kg is also similar to the discounted marginal revenue product of farmyard manure in the Ethiopian study of Teklewold (2012).

With almost all households using at least some maize residues as fuel, the value of residues can also be inferred from their preferred market substitutes — fuelwood or charcoal. Over one-third of the households in the sample reported purchasing fuelwood in 2011. Based on the reported quantities and prices, the median and mean market price of 1 kilogram of mixed fuelwood is 5.85 and 8.94 KES/kg, respectively. The specific energy — energy per unit mass measured in megajoules per kilogram (MJ/kg), often used for fuel comparisons — of mixed fuel and maize stover and cobs in western Kenya is very similar (17.2 MJ/kg for mixed wood, 17.3 MJ/kg for maize stover and 16.9 MJ/kg for maize cobs) (Torres-Rojas et al. 2011). This market price gives another indication that our estimated shadow value of maize residues is within the realistic range. This comparison also allows us to assess whether the households in our sample allocate crop residues to equate the marginal value across allocations. For the 77 households who reported purchasing fuelwood and for whom we have the estimated shadow value, these two values are close. The mean (median) price of fuelwood is 8.97 (5.85) KES/kg and the mean (median) shadow value of residues is 7.05 (5.07).

While the estimated shadow value of maize residues is crop- and location-specific, these results point to the significant monetary value of using organic resources as a soil amendment. The agronomic research community largely agrees on the complementarity and necessity of using both chemical fertilizer and organic inputs for soil fertility management (Vanlauwe et al. 2002). In order to properly assess the value of organic inputs and their influence on crop yields, one also needs to account for organic resources in the estimation of production functions. Moreover, traditional practices in other regions of the world often include the burning of residues: about 25 percent of all residues are burnt in low-income countries (Smil 1999). This practice is often carried out to prepare fields for next planting and to destroy phytomass that may carry diseases or pests. Burning of residues, however, also contributes to substantial emissions from agriculture and has adverse respiratory health effects on nearby populations. Incorporating crop residues into soil instead can lead to substantial yield increases, as our findings suggest.

Differences in values across farming households: We also investigate the differences in the shadow value of maize residues across farming households. We regress the estimated household-specific value (KES/kg) on a set of household- and farm-level characteristics, such as household size, gender, age, and education of household head, asset index, herd size, total land area farmed, the share of land cultivated with maize, the number of formal extension services sources, and several farm-specific environmental characteristics capturing temperature variations and soil quality. We also include district fixed effects to account for unobserved characteristics common to a given district. The sample size is 257 households across fifteen villages and six districts — these are the households that used maize residues for soil fertility management (allowing us to estimate their shadow values). Since the left-hand size variable, the log of maize residues value (KES/kg), is estimated rather than observed, we bootstrap standard errors.

Table 5 shows the results, with the second column repeating the estimation with the district fixed effects. Overall the results suggest that, controlling for natural capital in the form of soil fertility, richer households — those with a higher asset index and more livestock — derive higher values per kilogram of maize residues. Since household with larger herds face a higher opportunity cost of leaving crop residues on the fields and higher feed demand, the shadow price is increasing in herd size. This finding is also consistent with previous qualitative work that shows that wealthier households obtain higher returns from using maize residues for livestock feed and can achieve higher crop yields by practicing fallowing, using chemical fertilizer, or animal manure; for poorer households, these options are more limited (Crowley and Carter 2000). Thus promotion of agricultural technologies centering on crop residues cannot presume their wide availability and similar cost across all households.

6 Conclusion

Together with land and labor, organic resources are already used to satisfy a variety of household needs and constitute critical productive resources for small-scale farmers in developing countries. Moreover, allocation patterns of organic resources form an essential element of the future economic and environmental sustainability of smallholder systems. Yet, our understanding of their availability, uses, and economic values is highly limited. Given the diversity of smallholder systems in Africa and elsewhere in the developing world, quantifying the economic benefits of organic resources as factors of production fills a gap in the literature in establishing realistic bounds on the monetary values. These values can inform the promotion of agricultural technologies and policies, as well as help support local conservation efforts such as investments in healthy soils and agricultural carbon sequestration that carry global importance.

The current research contributes to our understanding of the uses of maize residues in western Kenya and of farmers' decision-making with respect to their management. Our empirical findings show that maize residues contribute about 30 percent to agricultural production so that the shadow price of maize residues is significant. It is estimated at 5.62 Kenyan shillings per kilogram or US$0.7. This value is greater than the value of nitrogen in maize residues and likely includes many other contemporaneous and long-term benefits of leaving crop residues on the field. Maize stover and cobs make up around 37 percent of the total value of maize production on a typical farm in western Kenya, and constitute about 22 percent of the median household income.

The current socio-economic and policy environments of Kenya and most other nations do not fully support the adoption of sustainable agricultural practices such as retention of crop residues, use of manure and compost, no-till farming, agroforestry, and other practices that enhance soil fertility. It is important that, going forward, the sustainable management of soil resources becomes an integral component of national policies and practical actions (Powlson et al. 2011). These could include a combination of agricultural extension, information provision, economic incentives, and government regulations. Increasing overall agricultural productivity is fundamental to alleviating pressures on on-farm organic resources and widespread adoption of “climate-smart” or “low emissions” agricultural practices. Finding alternative sources for animal feed and household fuel is also important (Lal 2005). Further research is needed to precisely measure the monetary value of organic resources, identify location-specific alternatives to crop and animal residues, and design policies aimed at promoting soil fertility management. These actions are imperative to improve agricultural productivity and assure environmental sustainability and resilience to climate change, and hereby help achieve food security in Sub-Saharan Africa.

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Figures and Tables

Figure 1: Map of the research sites

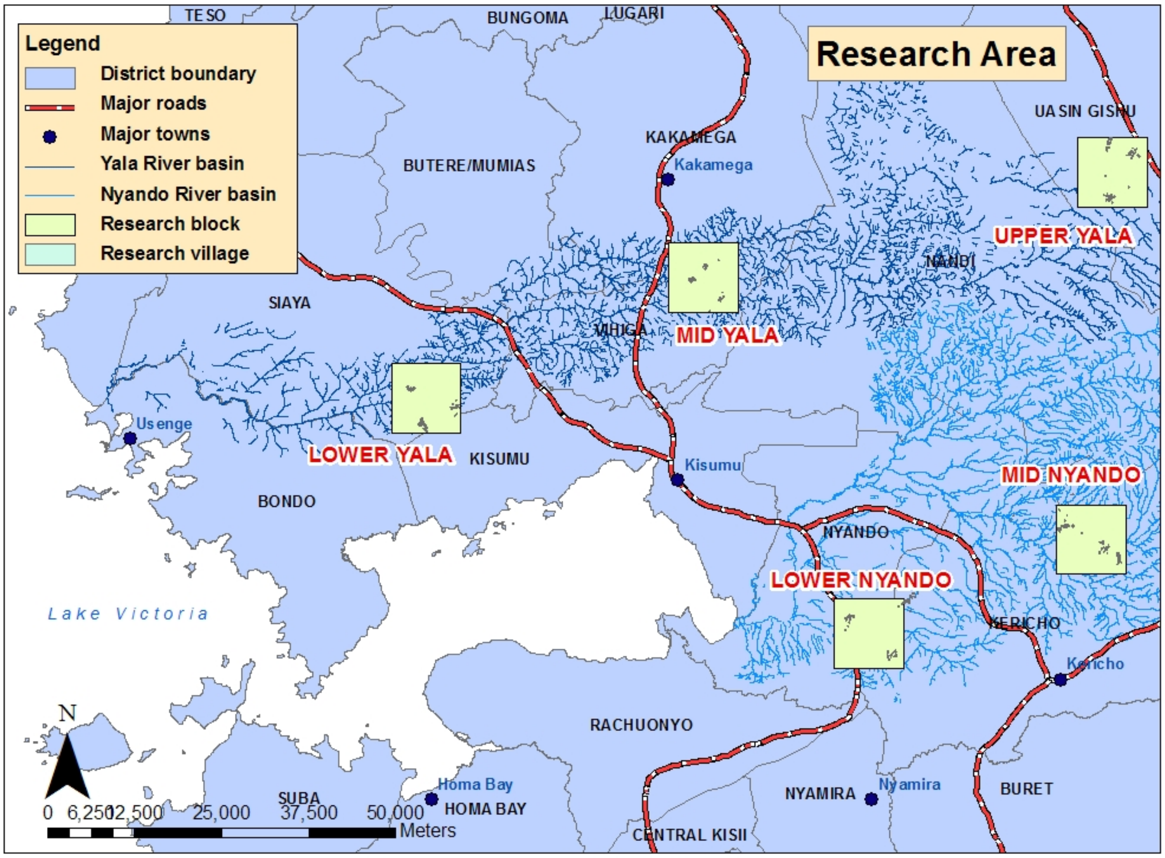

Figure 2: Maize grain vs. maize residues (kg/m^2), R^2=0.58

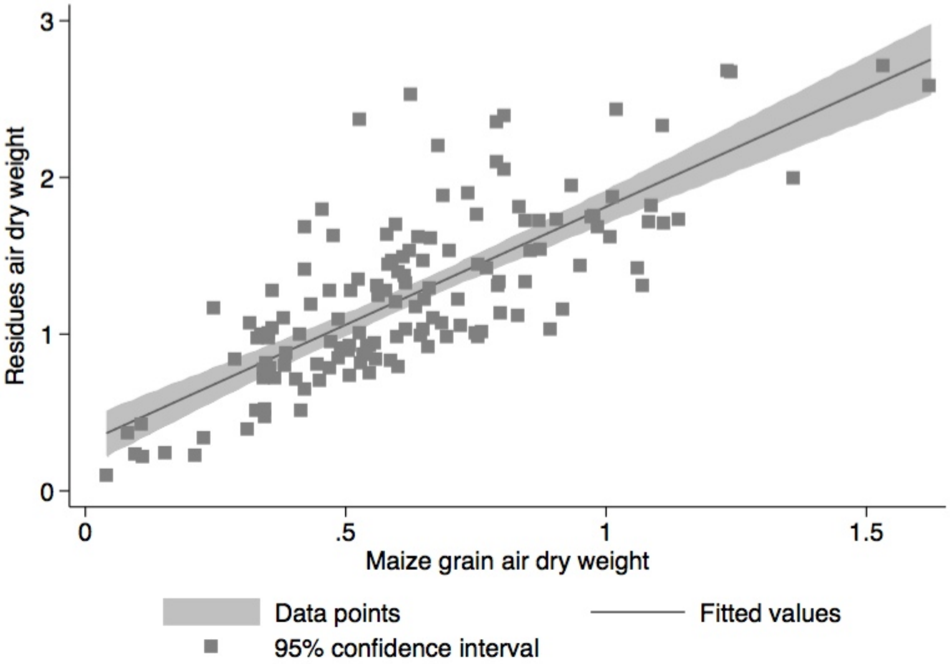

Figure 3: Maize residue use by asset index quartile

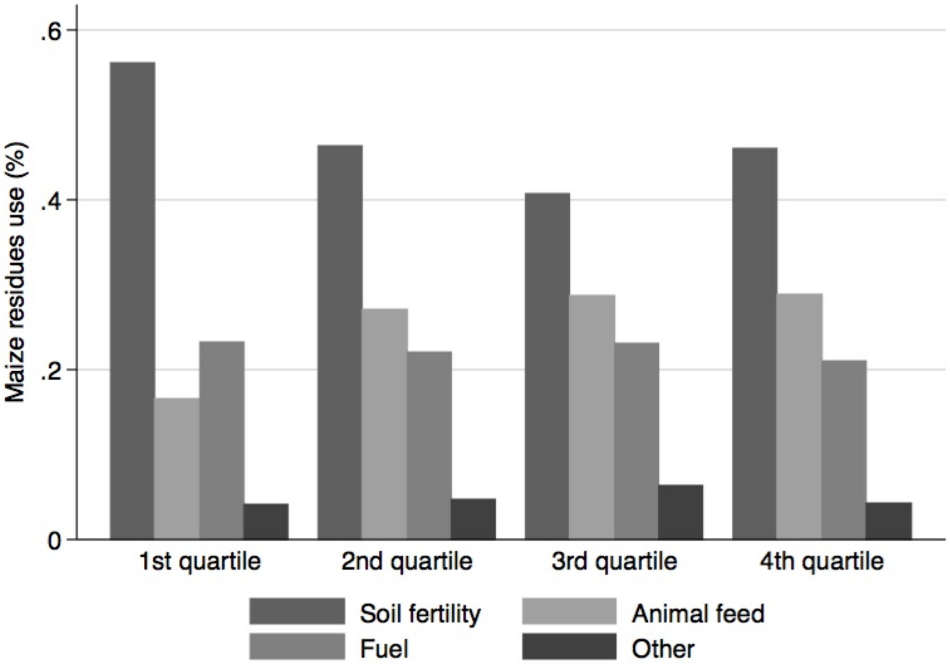

Table 1: Summary Statistics of Variables Used

Variable	Mean	Standard Deviation	Minimum Value	Maximum Value
Gender of household head: 1=male*	0.81			
Household head age	51.41	15.35	20.00	90.00
Household head years of education	6.75	4.53	0.00	18.00
Household size	6.06	2.46	1.00	13.00
Asset index	0.00	1.00	-1.00	5.95
Estimate of household annual income (KES)	146,610	262,733	0	3,674,650
Total land area farmed (acres)	4.53	9.82	0.05	110.00
Land in maize as share of total	0.42	0.27	0.01	1.00
Plot altitude (m)	1,606	330	1,205	2,258
Soil organic carbon (% w/w)	2.45	1.30	0.81	9.45
Soil CEC (meq/100g)	24.36	15.13	6.33	100.37
Own livestock*	0.94			
Herd size (TLU)	2.38	2.71	0.00	17.66
Number of formal extension services sources	1.12	1.34	0	7
Household-level, across two seasons				
Maize grain harvest (kg)	1,001.81	1,283.24	11.50	10,453.52
Maize land (acres)	1.58	1.22	0.08	7.14
Labor (person-days)	94.14	67.97	11.00	406.00
No chemical fertilizer applied*	0.36			
NPK (kg)	25.28	41.33	0.00	315.00
Fertilizer (kg)	48.26	81.32	0.00	700.00
N (kg)	10.79	18.71	0.00	154.00
No maize residues applied*	0.17			
Maize residues (kg)	1,521.08	1,579.88	0.00	9,561.73
Fraction of acres planted with hybrid maize	0.58	0.46	0.00	1.00
Fraction of acres intercropped with legumes	0.74	0.39	0.00	1.00

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

Table 2: Allocation of Maize Residues Across the Main Uses

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	0.27	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

Note: N=309 households.

Table 3: Household-level Maize Production Function

	Coefficient (std. error)	Coefficient (std. error)
Log maize land (acres)	0.468***	0.660***
	(0.0934)	(0.0743)
Log labor (days)	0.149*	0.179**
	(0.0858)	(0.0909)
Log NPK (kg)	0.0827*	0.0821*
	(0.0424)	(0.0440)
Log residues (kg)	0.307***	
	(0.0814)	
More than 1 t/ha residues applied (binary)		0.300***
		(0.0995)
Plot altitude (m)	0.000543***	0.000471**
	(0.000190)	(0.000199)
Soil organic carbon (% w/w)	0.215***	0.212***
	(0.0635)	(0.0656)
Soil CEC (meq/100g)	-0.0194***	-0.0186***
	(0.00545)	(0.00548)
Herd size (TLU)	0.0643***	0.0590***
	(0.0143)	(0.0135)
Fraction of acres intercropped with legumes	0.0769	0.0584
	(0.121)	(0.125)
Fraction of acres planted with hybrid maize	0.486***	0.552***
	(0.137)	(0.134)
Number of formal extension services sources	0.0864***	0.0972***
	(0.0250)	(0.0259)
No chemical fertilizer applied (binary)	-0.195	-0.187
	(0.121)	(0.123)
No maize residues applied (binary)	1.708***	
	(0.518)	
Constant	5.162***	7.011***
	(0.725)	(0.556)
Observations	309	309
R-squared	0.678	0.664

Note: Dependent variable = Log maize grain value (KES). Bootstrapped standard errors in parentheses (1,000 replications). *** p<0.01, ** p<0.05, * p<0.1.

Table 4: Economic Value of Maize Residues in Kenyan Shillings and US Dollars

Variable	Value in KES	Value in USD
Shadow value of maize residues per kilogram	5.62 (5.21)	0.07 (0.06)
Maize residues for soil fertility management per farm	8,548 (8,879)	102 (106)
All maize residues per farm	17,871 (19,988)	213 (238)
Value per acre		
Maize residues per acre	11,505 (6,722)	137 (80)
Maize grain per acre	19,426 (14,924)	231 (178)
Value per hectare		
Maize residues per hectare	28,417 (16,603)	338 (198)
Maize grain per hectare	47,982 (36,863)	571 (439)

Note: Values of total maize residues and grain are calculated using 5.62 KES as value of 1 kg of maize residues and 29 KES as price of 1 kg of maize grain. Standard deviations are in parentheses. N=309 households. 84 KES = 1 USD (average 2011-2012 exchange rate).

Table 5: Household- and Farm-level Determinants of the Shadow Value of Maize Residues

	Coefficient (std. error)	Coefficient (std. error)
Household size	0.0120	0.00475
	(0.0210)	(0.0205)
Household head is male: 1=yes	0.0164	-0.0381
	(0.146)	(0.152)
Household head age	-0.00424	-0.00142
	(0.00390)	(0.00390)
Household head years of education	-0.0348**	-0.0237*
	(0.0145)	(0.0143)
Number of formal extension services sources	0.0456	0.0644*
	(0.0315)	(0.0333)
Asset index from first PC	0.126**	0.135**
	(0.0548)	(0.0575)
Herd size (TLU)	0.0859***	0.0792***
	(0.0200)	(0.0232)
Total land area owned or cultivated in acres	-0.00920	-0.00948
	(0.00638)	(0.00662)
Land in maize as share of total	-0.155	-0.0860
	(0.205)	(0.199)
Plot altitude (m)	0.00106***	0.000875
	(0.000162)	(0.000634)
Soil organic carbon (% w/w)	0.157*	0.0699
	(0.0813)	(0.0864)
Soil CEC (meq/100g)	-0.0182***	-0.00842
	(0.00614)	(0.00763)
Constant	-0.0378	0.247
	(0.403)	(1.008)
District fixed effects		YES
Observations	257	257
R-squared	0.288	0.327

Note: Dependent variable = Log maize residues value (KES/kg). Bootstrapped standard errors in parentheses (1,000 replications). *** p<0.01, ** p<0.05, * p<0.1. Sample size is the households that used maize residues for soil fertility management.

Appendix

Conceptual Model

Since leaving crop residues for soil fertility is a long-term agricultural management strategy, it needs to be evaluated in an inter-temporal setting. Modifying the model of Magnan, Larson, and Taylor (2012) to account for the inter-temporal nature of residue management, we propose a simple two-period model to develop the intuition for a dynamic allocation problem.[11] The "full marginal value" of leaving crop residues on the field then includes their contribution to the current period production and its contribution to the increased yields and the amount of residues available in the following period. Our model also shows that the allocation of crop residues to soil fertility management depends on the value of alternative uses, as well as household-specific wealth, liquidity constraints, time preferences, and market interest rates. We infer the monetary value of crop residues from the household's shadow price — the household's internal price for nontradable residues, formed by household supply and demand (de Janvry, Fafchamps, and Sadoulet 1991).

A farming household maximizes net present value from two main household production activities: crop production (f) and all other household production activities (h) that include energy generation and livestock maintenance, using both market ($\mathbf{x}$) and non-market ($\mathbf{z}$) inputs. The net value from these two production activities represents the amount of profits the household could earn if all production activities resulted in marketable outputs. Given that crop residues in rural western Kenya are not typically traded, resource constraints are required to ensure that the amount of maize residues allocated to the two activities does not exceed the total residues produced during the previous season. And since liquidity constraints and transaction costs can introduce a wedge between market and shadow prices of inputs, we add a liquidity constraint.

To simplify the exposition, let each production activity be a function of one market input (x_{it}) such as chemical fertilizer or purchased animal feed or fuel and one non-market input (z_{it}) such as crop residues for $i = f, h$ and $t = 1, 2$. Then, the constrained maximization problem can be written as:

$$\begin{aligned} \max_{x_{it}, z_{it}} \; & p_f f(x_{f1}, z_{f1}) + p_h h(x_{h1}, z_{h1}) - w_f x_{f1} - w_h x_{h1} \\ & + \rho[p_f f(x_{f2}, z_{f2}) + p_h h(x_{h2}, z_{h2}) - w_f x_{f2} - w_h x_{h2}] \\ & \text{subject to} \\ & z_{f1} + z_{h1} \leq z_1^{max}, \\ & z_{f2} + z_{h2} \leq z_2^{max} \equiv \alpha f(x_{f1}, z_{f1}), \\ & w_f x_{f1} + w_h x_{h1} + \beta(w_f x_{f2} + w_h x_{h2}) \leq W, \end{aligned} \tag{3}$$

where p_f is the price of crops, p_h is the value of one unit of other production activities, w_f and w_h are

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[11] Potential market failures in rural Sub-Saharan Africa call for the use of a non-separable agricultural household model (de Janvry, Fafchamps, and Sadoulet 1991). To simplify our exposition, we specify a model focusing on the production behavior of agricultural households, but accounting for full income, income from producing both traded (crops) and non-traded (household energy) goods, and endogenous traded and non-traded inputs.

the prices of market inputs, ρ is the household's discount factor for the discount rate $\delta = 1/(1+\rho)$, β is the market discount factor for the market rate $r = 1/(1+\beta)$, z_t^{max} is the total amount of non-market input z_t available, and W is the household's two-period wealth available to spend on production inputs. Note that $z_2^{max} \equiv \alpha f(x_{f1}, z_{f1})$, where α is the product to grain ratio used to convert the amount of crops produced in period $t = 1$ to the amount of crop residues to allocate in period $t = 2$.

The Lagrangian is thus specified as:

$$\begin{aligned}\mathcal{L} = p_f f(x_{f1}, z_{f1}) + p_h h(x_{h1}, z_{h1}) - w_f x_{f1} - w_h x_{h1} \\ +\rho[p_f f(x_{f2}, z_{f2}) + p_h h(x_{h2}, z_{h2}) - w_f x_{f2} - w_h x_{h2}] \\ +\mu_1(z_1^{max} - z_{f1} - z_{h1}) + \rho\mu_2(\alpha f(x_{f1}, z_{f1}) - z_{f2} - z_{h2}) \\ +\lambda(W - (w_f x_{f1} + w_h x_{h1}) - \beta(w_f x_{f2} + w_h x_{h2})) \\ +\sum_{i=1}^{2}\sum_{t=1}^{2}\eta_{it}x_{it} + \sum_{i=1}^{2}\sum_{t=1}^{2}\zeta_{it}z_{it}.\end{aligned} \tag{4}$$

Here, μ_t is the shadow price of non-market input z_{it}, λ is the cost of liquidity, and η_{it} and ζ_{it} are multipliers on market and non-market inputs, for $i = f, h$ and $t = 1, 2$.

Assuming that all production activities are increasing in x_{it} and z_{it} and the farm household is liquidity constrained, the constraints will bind such that $z_1^{max} = z_{f1} + z_{h1}$, $z_2^{max} = z_{f2} + z_{h2}$, $W = w_f x_{f1} + w_h x_{h1} + \beta(w_f x_{f2} + w_h x_{h2})$, and $\mu_1 > 0$, $\mu_2 > 0$, and $\lambda > 0$. The Karush-Kuhn-Tucker (KKT) first order conditions (FOC) for Equation 4 with respect to x_{it} and z_{it} are the inverse demand functions for market and non-market inputs, respectively, and are as follows:

$$(p_f + \alpha\rho\mu_2)\frac{\partial f(x_{f1}, z_{f1})}{\partial x_{f1}} = w_f(1+\lambda) + \eta_{f1}, \tag{5a}$$

$$(p_f + \alpha\rho\mu_2)\frac{\partial f(x_{f1}, z_{f1})}{\partial z_{f1}} = \mu_1 + \zeta_{f1}, \tag{5b}$$

$$\rho p_f \frac{\partial f(x_{f2}, z_{f2})}{\partial x_{f2}} = w_f(\rho + \lambda\beta) + \eta_{f2}, \tag{5c}$$

$$\rho p_f \frac{\partial f(x_{f2}, z_{f2})}{\partial z_{f2}} = \rho\mu_2 + \zeta_{f2}, \tag{5d}$$

$$p_h \frac{\partial h(x_{h1}, z_{h1})}{\partial x_{h1}} = w_h(1+\lambda) + \eta_{h1}, \tag{5e}$$

$$p_h \frac{\partial f(x_{h1}, z_{h1})}{\partial z_{h1}} = \mu_1 + \zeta_{h1}, \tag{5f}$$

$$\rho p_h \frac{\partial h(x_{h2}, z_{h2})}{\partial x_{h2}} = w_h(\rho + \lambda\beta) + \eta_{h2}, \tag{5g}$$

$$\rho p_h \frac{\partial h(x_{h2}, z_{h2})}{\partial z_{h2}} = \rho\mu_2 + \zeta_{h2}, \tag{5h}$$

$$x_{it} \geq 0,\ \eta_{it} x_{it} = 0, \tag{5i}$$

$$z_{it} \geq 0,\ \zeta_{it} z_{it} = 0 \text{ for } i = f, h \text{ and } t = 1, 2. \tag{5j}$$

Several observations follow from the FOCs. FOCs 5a– 5h equate marginal value to marginal cost for market inputs x_{it} and non-market inputs z_{it}. However, since x_{f1} and z_{f1} not only contribute to higher yields in $t = 1$, but also increase the amount of crop residues available for allocation in period $t = 2$, "full marginal value" in 5a and 5b includes the term $\alpha\rho\mu_2$. Since $\mu_2 = p_f \frac{\partial f(x_{f2}, z_{f2})}{\partial z_{f2}}$ (from 5d), $\alpha\rho\mu_2$ is the discounted marginal value of having more crop residues in $t = 2$.

Marginal cost for x_{ft} includes the market price w_f, as well as the cost of liquidity λ in $t = 1$ and $\rho + \lambda\beta$, the discounted cost of liquidity, in $t = 2$. The shadow price of non-market input z_{ft} is μ_t. When in $t = 1$ crop residues are allocated to both production activities, f and h, so that z_{f1} and z_{h1} are non-zero (and $\zeta_{f1} = \zeta_{h1} = 0$), FOCs 5b and 5f imply $\mu_1 = (p_f + \alpha\rho\mu_2)\frac{\partial f(x_{f1}, z_{f1})}{\partial z_{f1}} = p_h \frac{\partial f(x_{h1}, z_{h1})}{\partial z_{h1}}$ and the household allocates crop residues to equate the marginal value across two uses, accounting for the fact that crop residues also contribute to crop production in $t = 2$.

The amount of the allocation in $t = 1$, however, depends not only on the shadow price of crop residues, but also the output value of the two production activities, the household-specific and market discount factors, and household wealth and cost of liquidity: $z^*_{i1} = z^*_{i1}(\mu_1, \mu_2, p_f, p_h, \rho, \beta, W, \lambda)$. These allocations thus necessarily reflect the trade-offs that households make among alternative uses of crop residues, household-specific liquidity constraints and time preferences, and existing market interest rates.

FOC 5b also gives us a way to estimate the value of crop residues in $t = 1$ empirically, when z_{f1} is non-zero (and $\zeta_{f1} = 0$). The shadow value μ_1 is simply the "full marginal value" of an additional unit of crop residues.

Estimation of the shadow price of a non-market good using a household production model requires the assumption of at least one well-functioning market (Jacoby 1993; Skoufias 1994; Le 2009).[12] Given the cross-sectional nature of our data set, unfortunately we cannot estimate the value of non-market inputs in different periods and we thus treat the amount of crop residues in any given year as exogenous. The problem collapses from dynamic to static and we can only estimate the contribution of crop residues in $t = 1$, thus likely underestimating the shadow price of crop residues.

At the same time, we believe that our theoretical framework is limited in predicting the optimal allocation quantities of crop residues to different uses for all households. The optimal allocation depends on the shadow price of crop residues, the output value of the production activities, household-specific and market discount factors, and household wealth and cost of liquidity. So it is household-specific and we cannot make recommendations for the optimal allocation rates across all households.

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[12] The assumption of well-functioning input markets is reasonable in the context of western Kenya. In the sample of households used in the empirical estimation, 84 percent of households engage in off-farm employment, 62 percent hire agricultural laborers, 60 percent purchase fertilizer, and about 15 percent participate in land markets, either renting in or renting out parcels of land for cultivation.

Table A1: Scoring Coefficients (Weights) for Asset Index

Variable	Weight
Durables: number of	
House	0.411
Radio	0.389
Telephone (mobile)	0.649
Fridge/freezer	0.620
Television	0.688
Electronic equipment	0.559
Air conditioning	0.339
Furniture	0.743
Kettle/iron	0.446
Mosquito net	0.602
Computer	0.529
Internet access	0.351
Electric/gas stove	0.526
Improved stove	0.217
Bicycle	0.332
Motorcycle	0.483
Car/truck	0.568
Bank account	0.699
Generator	0.291
Large battery	0.177
Solar panel	0.338
LPG	0.636
Characteristics: indicator for	
Brick/cement walls	0.700
Mabati (corrugated iron) roof	0.379
Cement/wood floor	0.666
Private piped water	0.447
Water from neighbor	-0.068
Borehole water	0.036
River/stream water	-0.184
No toilet	-0.279
Traditional toilet	-0.293
Improved toilet	0.703
Kerosene light	-0.717
Electricity light	0.763
Solar light	0.112
Observations	309

Quadratic Specification of Production Function

We repeat the estimation of the maize production function using the generalized quadratic specification:

$$y_i = \alpha_0 + \sum_{j=1}^{m} \alpha_j x_{ij} + \frac{1}{2} \sum_{j=1}^{m} \sum_{k=1}^{m} \alpha_{jk} x_{ij} x_{ik} + \epsilon_i, \tag{6}$$

where y_i is household-level annual maize production from all plots, x_{ij} is a vector of production inputs, α are parameters to be estimated, and ϵ_i represents the iid, mean zero, normally distribution error. In a small data set there is a trade-off between allowing for full flexibility of the quadratic function and degrees of freedom; the function is estimated allowing for all squared and interaction terms for the four inputs: land planted with maize, household and hired labor, chemical fertilizer, and maize residues as soil amendments. Additional variables include a set of environmental variables to control for biophysical influences on production (soil carbon, soil CEC, altitude), other variables potentially influencing maize production (herd size in TLU as a proxy for unobserved manure application rates, the fraction of land planted with hybrid seeds and intercropped with legumes, and the number of formal extension services sources).

The results are reported in table A2. We reject the null hypothesis of the statistical insignificance of the second-order terms with a Wald test statistic of 49.88 and a P-value of zero against the $\chi^2(10)$ distribution. Joint tests of the first- and second-order terms for the three productive inputs (land, fertilizer and crop residues) show that they are statistically significant determinants of production levels. The test of the significance of all coefficients for NPK, for example, is 29.48 with a P-value of zero. Individual coefficients on productive inputs and most of second-order terms, however, are not statistically significant (the interaction term between NPK and crop residues is positive as expected, yet statistically insignificant). Since we use the estimated coefficients from the production function to calculate the shadow value of residues left on the fields, we focus on the Cobb-Douglas specification, which provides statistically significant coefficients for the productive inputs.

Table A2: Household-level Maize Production Function: Quadratic Specification

	Coefficient (std. error)	Coefficient (std. error)
Maize land (acres)	4,252	8,059*
	(5,623)	(4,198)
Labor (days)	-41.54	-23.37
	(82.03)	(71.00)
NPK (kg)	-93.49	-66.90
	(172.4)	(145.4)
Residues (kg)	4.960	
	(3.211)	
1/2 Maize land sq.	6,360**	-396.8
	(2,701)	(2,373)
1/2 Labor sq.	-0.214	0.295
	(0.734)	(0.677)
1/2 NPK sq.	1.964	1.015
	(2.290)	(2.056)
1/2 Residues sq.	0.00354*	
	(0.00182)	
Interaction: Land * Labor	-9.470	-7.308
	(33.26)	(31.65)
Interaction: Land * NPK	13.22	104.7*
	(61.62)	(61.22)
Interaction: Land * Residues	-6.425***	
	(1.420)	
Interaction: Labor * NPK	1.497	0.440
	(1.307)	(1.113)
Interaction: Labor * Residues	0.0357	
	(0.0292)	
Interaction: NPK * Residues	0.0274	
	(0.0372)	
Plot altitude (m)	11.64***	9.771**
	(4.162)	(4.351)
Soil organic carbon (% w/w)	1,680	1,136
	(1,110)	(1,246)
Soil CEC (meq/100g)	-127.7	-106.6
	(111.7)	(121.9)
Herd size (TLU)	2,094***	2,131***
	(611.0)	(590.8)
Fraction of acres intercropped with legumes	-263.7	-382.1
	(2,494)	(2,998)
Fraction of acres planted with hybrid maize	737.2	4,089
	(2,840)	(3,464)
Number of formal extension services sources	1,516	1,953*
	(979.8)	(1,085)
More than 1 t/ha residues applied (binary)		2,823
		(2,565)
Constant	-16,720**	-17,034**
	(6,827)	(7,223)
Observations	309	309
R-squared	0.809	0.762
Wald tests	χ^2 (Prob> χ^2)	
Coefficients for land: $\alpha_1 = \alpha_{11} = \alpha_{12} = \alpha_{13} = \alpha_{14} = 0$	45.75 (0.00)	
Coefficients for labor: $\alpha_2 = \alpha_{12} = \alpha_{22} = \alpha_{23} = \alpha_{24} = 0$	3.82 (0.58)	
Coefficients for NPK: $\alpha_3 = \alpha_{13} = \alpha_{23} = \alpha_{33} = \alpha_{34} = 0$	29.48 (0.00)	
Coefficients for residues: $\alpha_4 = \alpha_{14} = \alpha_{24} = \alpha_{34} = \alpha_{44} = 0$	34.93 (0.00)	
All second-order terms: = 0	49.88 (0.00)	

Note: Dependent variable = Maize grain value (KES). Bootstrapped standard errors in parentheses (1,000 replications). *** p<0.01, ** p<0.05, * p<0.1.