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

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Abstract

Organic resources play a dominant role in smallholders' production and livelihood objectives. They are used for animal feed, fuel, and fiber. They are also fundamental to maintaining soil 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. This paper addresses the use, management and value of one source of on-farm organic resources – maize residues in western Kenya. Using data from a survey of 309 households in 2011-2012, the analysis shows that the allocation of maize residues to soil fertility management among Kenyan farmers is traded off against the competing uses: household energy and livestock feed. To understand the economic and environmental benefits of crop residues in smallholder systems one must first value the resource. Given the absence of markets for crop residues, we estimate the shadow value of maize residues using the coefficients from a household-level maize production function and household-specific fertilizer prices to find that maize cobs and stover make up around 37 percent of the total value of maize production among western Kenyan smallholders. The estimated value of one kilogram of maize residues left on the fields as a soil amendment is 4.88-9.26 Kenyan shillings or US$0.06-0.11, reflecting not only the value of macronutrients in maize residues but also the value of other environmental benefits that extend beyond fertilizer substitution and impact agronomic productivity and sustainability of tropical soils.

Keywords: crop residues, maize production, sustainable agricultural practices, value of natural resources, western Kenya. **JEL Codes:** O13, Q12, Q15, Q16, Q24, Q56.

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Introduction

Despite considerable progress in agricultural innovations and successes of the Green Revolution in other regions of the world, by the year 2000, only four percent of the crop area in Sub-Saharan Africa (SSA) was irrigated, less than a quarter of the planted area in cereals used modern seed varieties, and each hectare of arable land received, on average, less than 13 kilograms of nutrients (WB 2007). As a result, cereal yields in Africa have remained at around one ton per hectare, less than half the average yields in other developing country regions. The reasons for this are many and complex. They include increasing land pressure; the rainfed nature of African agriculture (about 96 percent of cultivated land in Africa is rainfed as compared to 45 percent in South Asia); 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 others (Sanchez 2002; Jayne and Rashid 2013). To address insufficient total food production 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), Tilman et al. (2011)).

One of the most frequently cited priorities – relieving soil fertility constraints – will require combined applications of chemical fertilizer and organic resources. Fertilizers and organic resources that 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 and/or lack of external inputs, while organic resources face numerous competing applications. Despite low energy content and their bulkiness, residues constitute an important source of energy in rural Africa and Asia. Crop residues are fed to domestic animals, either chopped and added to feed mixes, and left in the fields for stubble-grazing. Residues are also used as sources of fiber, building materials, and burnt to become pest control additives and preservatives, among many other uses.

In addition to their importance in smallholders' production and livelihood objectives, the sheer volume and importance of organic resources also motivate our attention. Estimates put the amount of total annual harvests of crop residues, for example, at 3.8 Gt (3.8×10^6 ton), of which 74 percent are from cereals, over 60 percent are produced in developing countries, and almost 45 percent are produced in the tropics (Smil 1999; Lal 2005). In recent years, organic resource management has increasingly been viewed as contributing to wider environmental goals as well. Reducing greenhouse gas emissions, increasing agricultural carbon sequestration, and enhancing farmers' resilience to climate change have become imperatives for the promotion of many agricultural practices ("climate-smart" agriculture) that rely on organic resources. The soil carbon pool is estimated at 2,500 Gt (up to a 2-m depth), about three times the quantity of carbon currently in atmospheric CO_2 (WB 2012), and is viewed both as a threat and an opportunity in the context of climate change (Powlson et al. 2011). Current land-use practices and land-change processes, such as deforestation, soil erosion, residue removal, and biomass burning are estimated to reduce soil carbon by 0.7-2.1 Gt per year (WB 2012). Increasing the soil carbon pool through recommended practices (mulching, retention of crop residues, use of manures and biosolids), on the other hand, 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). In addition, organic resources have been seen as a feedstock for biofuel production, as many nations seek alternatives to fossil fuel-based energy sources (Lal 2009). For example, the Kenyan government is developing a national biofuels policy to promote the development of sustainable biofuels (USDA 2011). Prospective bioenergy uses effectively raise the stakes in resolving the tradeoffs between food and energy in many developing countries.

Given the importance of organic resources to farming systems worldwide, there has been surprisingly little economic attention to on-farm organic resources, in general, and the valuation of crop and animal residues, in particular. To begin, there is limited understanding of fundamental ecosystem processes and their interactions with human activities. Quantifying crop residue production and accounting for its uses, for example, is rarely done even in developed countries (Smil 1999), where agronomic systems are better understood and data sources are typically more complete. And there are significant methodological challenges in valuation arising from the complexity of ecosystem processes and the fact that organic resources are often non-marketed, entail multiple benefits, and create environmental externalities and extended benefits that accrue over time (Shiferaw and Freeman 2003). Notwithstanding their multiple benefits – including improved yields and yield stability, and carbon sequestration – applications of organic resources for soil fertility management are often not adopted due to labor or land constraints (Place et al. 2003), or unless their profitability is greater than pay-offs from alternative uses. Valuing crop residues is, therefore, critical for understanding the importance of organic resources in smallholder agricultural systems, estimating the value of the environmental benefits they provide, and assessing the cost of introducing new technologies that rely on crop residues.

Our paper addresses this gap by examining the use, management and valuation of one source of on-farm organic resources – maize crop residues in western Kenya. This study complements from an economic perspective numerous biophysical and agronomic studies of organic resources. We extend the analysis of Magnan, Larson, and Taylor (2012) who estimate the value of cereal stubble as animal feed in the mixed farming systems in Morocco. We analyze the value of maize residues as an organic soil amendment, taking into account their allocation among three competing uses: for soil fertility management, as animal feed, and as residential energy. We estimate a household-level maize production function using detailed production input and output data, including measurements of crop residues and household-specific environmental variables to calculate the shadow value of maize residues among western Kenyan farmers. Our econometric estimates suggest that one kilogram of maize residues left on the fields is valued at 4.88-9.26 Kenyan shillings which correspond to US$0.06-0.11, on average. This value extends beyond fertilizer substitution and includes the value of the environmental services that crop residues provide. Maize cobs and stover account for around 37 percent of the total value of annual maize production. Our results provide valuable evidence regarding the importance of on-farm organic resource management, with implications for advancing food security in smallholder agriculture, while increasing its sustainability and resilience to climate change.

Organic Resources in Smallholder Agriculture

The addition of mineral fertilizer and the use of modern seed varieties have long been recognized as fundamental to increasing crop yields. Their limited adoption and use by smallholders in SSA and other developing countries is attributed both to market and non-market forces: poorly developed input and output markets, credit constraints, taste preferences, differences in agroecological conditions (Marenya and Barrett 2009a), heterogeneous returns (Suri 2011), fixed costs associated with learning (Conley and Udry 2010), and farmers' behavioral biases (Duflo, Kremer, and Robinson 2011), among others.

Discontinuous, limited or no fertilizer application, combined with continuous cultivation over time, leads to severe soil degradation through nutrient depletion and loss of organic matter, thus rendering many soils "non-responsive" to the renewed application of nutrients or improved varieties (Tittonell and Giller 2013). Even if fertilizer use were to be widely expanded, mineral fertilizers alone are not capable of restoring soil fertility and increasing agricultural productivity across all soil types. Soil organic matter management through the use of organic resources must be a critical component to soil fertility restoration (Sanchez 2002; Lal 2006; Vanlauwe and Giller 2006). Crop residues constitute a critical portion of the available organic resources for many smallholders. They are generally defined as all inedible phytomass of agricultural production: cereal and legume straws; leaves, stalks, and tops of vegetables, sugar, oil, and tuber crops; and the litter and prunings of nut and fruit trees. Returning these crop residues to the soil is essential for multiple reasons. These include the recycling of plant nutrients (both macronutrients such as nitrogen, phosphorous and potassium, and micronutrients), sequestering soil carbon, improving soil physical, mechanical and hydrological properties, erosion control, and sustaining agronomic productivity of soils by decreasing losses and increasing use efficiency of other inputs (Lal 2009).

Despite the long-demonstrated importance of crop residues in the agronomic literature, few economic studies include organic resources as inputs in the estimation of crop response models. Given the many difficulties associated with quantifying crop and animal residues, most studies rely on rough indicator variables. For example, 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. We are not aware of any economic study that uses quantities of crop residues in estimating production relationships.

The existing literature also confirms the existence of important trade-offs among different uses of crop residues. Production and utilization patterns for crop residues 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-Rojas et al. (2011) demonstrate 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 in Kenya. Also in Kenya, wealthy households 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 (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).

When it comes to the estimation of the value of organic resources in developing countries, the existing literature uses either a production or a substitution approach. The production approach estimates the value by calculating changes in overall farm profits or physical changes in production by including biomass as a production input. For example, Lopez (1997) studies village-level stocks of biomass in Ghana, Goldstein and Udry (2008) demonstrate the importance of fallows for on-farm soil quality and profits also in Ghana, and Klemick (2011) examines the value of forest fallow ecosystem services in the Brazilian Amazon. Two recent studies – Teklewold (2012) and Magnan, Larson, and Taylor (2012) – use the substitution approach, deriving the value of biomass using the observed prices of agricultural inputs. 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). Teklewold (2012) models a system of allocation equations for farmyard manure to examine the role of returns to manure as energy and farming inputs in smallholder agriculture in Ethiopia. Magnan, Larson, and Taylor (2012) analyze the value of cereal stubble in a mixed crop-livestock farming system in Morocco, and, similar to Le (2009), use the price of a market input, purchased feed, to derive the shadow price of cereal stubble. One of the strengths of the data set used here lies in the reliable estimates of quantities of both inputs and outputs, which dictates our choice of the substitution approach.

Conceptual Framework and Empirical Strategy

Given the long lag in realizing the agronomic benefits of leaving crop residues in their fields, farmers often 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 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. Our survey results from sample farm households show that almost half of maize residues (stover and cobs) – the largest source of crop residues on western Kenya farms – is left on the fields as an organic soil amendment, while the rest is roughly split between animal feed and cooking fuel.[1]

To model these trade-offs and estimate the value of crop residues, we specify a sequential problem. In period $(t-1)$ farming households produce crop residues, and in period t they maximize profits by allocating crop residues as an input into three main household production activities: crop production, energy generation, and livestock maintenance. The profits from these three production activities represent the amount of profits the household could earn if all production activities resulted in marketable output. In addition, since crop residues in western Kenya are non-tradable, a resource constraint is required to ensure that the amount of maize residues allocated to these uses does not exceed the total residues produced during the previous season. To simplify the analysis, we assume that households do not face liquidity constraints and that markets for land, labor and fertilizer are present and are competitive.[2]

More generally, following de Janvry, Fafchamps, and Sadoulet (1991), Jacoby (1993) and Magnan, Larson, and Taylor (2012), the second-stage constrained maximization problem can be written as the sum of profits from the three production activities and a combination of market and non-market inputs:

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[1] The allocation shares to three different uses vary between households in our study sites; they can also be different in other locations in Kenya.

[2] Magnan, Larson, and Taylor (2012) note that to estimate the shadow price of a non-market good using a household production model one needs to assume at least one well-functioning market. If liquidity or credit constraints were to exist, this approach would likely underestimate the true value. 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.

$$\max_{\mathbf{x},\mathbf{z}} \pi(\mathbf{x},\mathbf{z}) = p_f f(\mathbf{x},\mathbf{z}) + p_g g(\mathbf{x},\mathbf{z}) + p_h h(\mathbf{x},\mathbf{z}) - \mathbf{wx}$$
$$\text{subject to} \tag{1}$$
$$z_{jf} + z_{jg} + z_{jh} \leq z_j^{max} \text{ for } j = 1, ..., N,$$

where π, the profit function, is the sum of profits from the three production activities: crop production (f), energy generation (g), and livestock maintenance (h); $\mathbf{x}$ for $i = 1, .., M$ are market inputs such as purchased fertilizer, wood, livestock feed, hired labor, etc.; $\mathbf{z}$ for $j = 1, .., N$ are non-market inputs such as crop residues, with z_{jf}, z_{jg} and z_{jh} being the amount of non-market input j allocated to crop production (f), energy generation (g), and livestock maintenance (h), respectively; z_j^{max} is the total amount of non-market input j available; p_f is the price of crops, p_g is the value to the farmer of generating an additional unit of energy, p_h is the value of maintaining an additional unit of livestock; and $\mathbf{w}$ are the prices of market inputs.

Let z_1 be the non-market crop residue input, and x_1 be the purchased chemical fertilizer used in crop production only (all other inputs such as land, labor, etc. are contained in $(\mathbf{x},\mathbf{z})$). In addition, let $z_{1f} + z_{1g} + z_{1h} \leq z_1^{max}$ reflect the trade-offs between using crop residues for different production activities: z_{1f} is the amount of crop residues allocated to soil fertility management, z_{1g} is the amount allocated to energy generation, and z_{1h} is the amount fed to livestock. While the allocation of crop residues to different uses must be non-negative, the amounts allocated may be zero.

The Lagrangian function is thus specified as:

$$\begin{aligned} \mathcal{L} = {} & p_f f(x_1, z_{1f}, \mathbf{x}, \mathbf{z}) + p_g g(z_{1g}, \mathbf{x}, \mathbf{z}) + p_h h(z_{1h}, \mathbf{x}, \mathbf{z}) - w_1 x_1 - \sum_{i=2}^{M} w_i x_i \\ & + \rho_1 (z_1^{max} - z_{1f} - z_{1g} - z_{1h}) + \sum_{j=2}^{N} \rho_j (z_j^{max} - z_{jf} - z_{jg} - z_{jh}) + \mu_f z_{1f} + \mu_g z_{1g} + \mu_h z_{1h}. \end{aligned} \tag{2}$$

Here, ρ_j is the shadow price of non-market inputs for $j = 1, ..., N$ with ρ_1 being the shadow price of crop residues; μ_f, μ_h and μ_g are the multipliers on the non-negativity constraints. Assuming that all production activities are increasing in allocable z_1, the availability constraint will bind such that $z_1^{max} = z_{1f} + z_{1g} + z_{1h}$ and $\rho_1 > 0$. The Karush-Kuhn-Tucker (KKT) first order conditions

(FOC) for Equation 2 with respect to **x** and **z** are the inverse demand functions for market and non-market inputs, respectively, and are as follows (with respect to x_1, z_{1f}, z_{1g}, and z_{1h}):

$$p_f \frac{\partial f(\cdot)}{\partial x_1} - w_1 = 0, \tag{3a}$$

$$p_f \frac{\partial f(\cdot)}{\partial z_{1f}} - \rho_1 + \mu_f = 0, \tag{3b}$$

$$p_g \frac{\partial g(\cdot)}{\partial z_{1g}} - \rho_1 + \mu_g = 0, \tag{3c}$$

$$p_h \frac{\partial h(\cdot)}{\partial z_{1h}} - \rho_1 + \mu_h = 0, \tag{3d}$$

$$z_{1f} \geq 0,\ \mu_f z_{1f} = 0,\ z_{1g} \geq 0,\ \mu_g z_{1g} = 0,\ z_{1h} \geq 0,\ \mu_h z_{1h} = 0. \tag{3e}$$

FOCs 3b - 3d imply that, when the farm household allocates crop residues to all three production activities, the marginal values of the respective allocations are equated, such that the shadow price of crop residues can be inferred from any production activity:

$$\rho_1 = p_f \frac{\partial f(\cdot)}{\partial z_{1f}} + \mu_f = p_g \frac{\partial g(\cdot)}{\partial z_{1g}} + \mu_g = p_h \frac{\partial h(\cdot)}{\partial z_{1h}} + \mu_h. \tag{4}$$

Since the allocations to different production activities may be zero, there are several cases to be considered, each of which corresponds to observed farm household practices, as discussed below:

Case 1: Suppose crop residues are used *for soil fertility management only.* It then must be the case that the farm household does not use crop residues in energy generation and livestock maintenance, for the marginal factor cost of crop residues in these two production activities exceeds their marginal value. Mathematically, we have $z_{1f} > 0$, $\mu_f = 0$, $z_{1g} = 0$, $\mu_g > 0$, $z_{1h} = 0$, $\mu_h > 0$, and $z_1^{max} = z_{1f}$. Then, analogously to Magnan, Larson, and Taylor (2012), the shadow value of crop residues, $\hat{\rho}_1$, can be found from FOC 3a and 3b:

$$\hat{\rho}_1 = w_1 \frac{\partial f(\cdot)}{\partial z_{1f}} \Big/ \frac{\partial f(\cdot)}{\partial x_1}, \tag{5}$$

that is, the amount of fertilizer required to compensate for the loss of one unit of crop residues times the market price of fertilizer. Empirically, the shadow price then can be calculated given the price of chemical fertilizer and the estimated coefficients of the household-level maize production function for those households that used both chemical fertilizer and crop residues as inputs.

Case 2: Now suppose that crop residues are used as inputs in *two production activities* – crop production and energy generation – such that $z_{1f} > 0$, $\mu_f = 0$, $z_{1g} > 0$, $\mu_g = 0$, $z_{1h} = 0$, $\mu_h > 0$, and $z_1^{max} = z_{1f} + z_{1g}$. Equation 4 implies that the marginal value of the two uses should be equated, and that the shadow value of crop residues could be estimated either from the crop production or energy generation functions. Further, substituting $z_{1g} = z_1^{max} - z_{1f}$ in the Lagrangian (Equation 2), the shadow value in **Case 2**, $\bar{\rho}_1$, should be less than the shadow value in **Case 1**:

$$\bar{\rho}_1 = p_f \frac{\partial f(\cdot)}{\partial z_{1f}} - p_g \frac{\partial g(\cdot)}{\partial z_{1f}} \ < \ \hat{\rho}_1 = p_f \frac{\partial f(\cdot)}{\partial z_{1f}}. \tag{6}$$

The opportunity cost (per unit) associated with crop residues is now lower – the scarce crop residues are used in two production activities. The alternative case in which crop residues are allocated to crop production and livestock maintenance ($z_{1f} > 0$, $\mu_f = 0$, $z_{1g} = 0$, $\mu_g > 0$, $z_{1h} > 0$, $\mu_h = 0$, and $z_1^{max} = z_{1f} + z_{1h}$) will have similar implications.

Case 3 considers the positive allocation of crop residues to *all three production activities*: $z_{1f} > 0$, $\mu_f = 0$, $z_{1g} > 0$, $\mu_g = 0$, $z_{1h} > 0$, $\mu_h = 0$, and $z_1^{max} = z_{1f} + z_{1g} + z_{1h}$ (interior solution). The shadow value, $\check{\rho}_1$, is now equated among the marginal value productivities in crop production, energy generation, and livestock maintenance, and is lower than in **Case 2**, $\bar{\rho}_1$, or **Case 1**, $\hat{\rho}_1$:

$$\check{\rho}_1 = p_f \frac{\partial f(\cdot)}{\partial z_{1f}} - p_g \frac{\partial g(\cdot)}{\partial z_{1f}} - p_h \frac{\partial h}{\partial z_{1f}} \ < \ \bar{\rho}_1 \ < \ \hat{\rho}_1. \tag{7}$$

Equation 7 suggests the ordering of shadow values of crop residues according to the number of uses. The marginal value (and hence, the shadow value) is highest if a household allocates all crop residues to soil fertility management only, followed by the shadow value of two allocations (soil fertility management and energy generation, or soil fertility management and animal feed), and then by the shadow value corresponding to three allocations.[3] We test this ordering empirically.

Simultaneous solution of the FOCs will yield unconditional factor demand equations for crop residues as functions of the shadow price of crop residues and the output prices from all three

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[3] All other cases are omitted since their predictions are similar to the cases considered.

production activities, reflecting the trade-offs that households make among alternative uses:

$$z^*_{1f} = z^*_{1f}(\rho_1, p_f, p_g, p_h), \tag{8a}$$

$$z^*_{1g} = z^*_{1g}(\rho_1, p_f, p_g, p_h), \tag{8b}$$

$$z^*_{1h} = z^*_{1h}(\rho_1, p_f, p_g, p_h). \tag{8c}$$

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. Since we focus on household-level maize production disregarding potential spatial and temporal variation in the use of one or more inputs (across plots and seasons), a smooth "aggregate" production function is appropriate (Berck and Helfand 1990). We employ a generalized quadratic specification as a second-order local approximation of the unknown true maize production function similar to some recent studies focusing on maize production across Sub-Saharan Africa (see, for example, Sheahan, Black, and Jayne (2013) and Harou et al. (2014)). Moreover, this specification allows us to derive estimates of the marginal physical productivities of fertilizer and maize residues applied as soil amendments and to calculate the shadow values:

$$y_i = \alpha_0 + \sum_{i=1}^{m} \alpha_i x_i + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \alpha_{ij} x_i x_j + \epsilon_i, \tag{9}$$

where y_i is household-level maize yield from all plots, x_i is a vector of production inputs, α are parameters to be estimated, and ϵ_i represents the iid, mean zero, normally distribution error.

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 (e.g., in managerial ability). In this case, the error term in the production equation may capture not only white noise but also measurement errors, agroecological conditions, farmers' skills and status, and other factors not accounted for in the data. Despite the dependence of smallholder agricultural production on largely exogenous environmental conditions, however, few studies directly control for them (Sherlund, Barrett, and Adesina 2002).

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, household-specific measures of soil quality and altitude as proxies for 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 of concern with the use of several inputs. Higher application rates of crop residues for soil fertility management, for example, 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. A common approach to address endogeneity of inputs – estimating the dual cost or profit function to instrument for input quantities and/or output prices – carries its own concerns. Output and input prices appropriately adjusted for household-specific transactions costs are rarely available in developing country data, introducing similar endogeneity concerns to the estimation of dual functions (Barrett, Sherlund, and Adesina 2008). In the absence of credible instruments, we rely on the estimation of the primal production function and use bootstrap methods to focus our attention on the importance of on-farm organic resources in smallholder agriculture in developing countries.

Research Area and Data

The research sites are five 10-kilometer 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.[4] A socio-economic and household production survey of a sample of 309 households in 15 villages (three in each block) 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, tailored to the goals of the project and local conditions. In addition, spatial and biophysical as well as village- and market-level data were collected.

Table 1 shows selected summary statistics for the sample households. A typical household has six members.[5] The head of household, the main income earner and decision-maker of the household,

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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 (ICRAF) and funded from the Global Environmental Facility of the World Bank.

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

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

A typical farm in the sample is 4.53 acres.[6] Survey farms are often highly 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 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. Although most sample households are subsistence farmers and cultivate their own land, more than half of households also hire agricultural labor for planting, weeding or harvesting. Differences in geographic location and associated rainfall availability, 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 669.87 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 of moderate quality. 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 spectroscopy (NIRS), a rapid nondestructive technique for analyzing the chemical composition of materials, following protocols developed by Shepherd and Walsh (2002) and Cozzolino and Moron (2003).[7] The analysis explained 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.[8] While the average C,

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head and sharing a common source of food and/or income.

[6] As reported by households. 1 acre = 4,047 square meters = 0.405 hectares.

[7] Soil samples were collected during the first household visit in the end of the long rains season of 2011. Top soil (0-20 cm) was collected from four randomly chosen spots within the largest maize plot using a soil auger. The four samples were thoroughly mixed, then air dried at the ICRAF field office in Kisumu, and passed through a 2-mm sieve before laboratory analysis.

[8] 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 2010).

P and K contents of analyzed samples were classified as "good," the average nitrogen content and soil pH received "very low" and "low" values, respectively. Nitrogen is a critical macronutrient for plant growth and yield; nitrogen content seems to be very low across the sample – 0.16 percent by weight. 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.[9]

Overall soil quality – nitrogen content, in particular – appears to be poor across the sample. This can be partly explained by continuous cropping and the limited use of chemical fertilizers and organic resources. 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).[10] 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.[11] At the same time, 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.

Nearly all households (94 percent) 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.[12] Eighty percent of households keep livestock with the average TLU in the sample being 2.38. 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), we create an asset index for each household derived from a

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[9] Soil organic carbon or soil organic matter content have been used in the literature to account for overall soil quality (Marenya and Barrett 2009a; Goldstein and Udry 2008). In the sample of farms considered, it is the nitrogen content and soil pH that seem to be limiting factors. Moreover, the correlation between organic carbon and nitrogen content is very high, with the correlation coefficient of 0.96, and both serve as indicators of overall soil fertility.

[10] 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).

[11] Use of total quantity of chemical fertilizer or of nitrogen quantity only across different fertilizer types does not substantially alter the estimated shadow values. See Table A3 in the Appendix.

[12] This is equivalent to 0.7 cattle or 0.1 sheep/goat or 0.2 pigs or 0.01 chicken or 0.5 donkey.

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.[13]

Allocation and amount of maize residues. Most crop residues are used for multiple purposes, leaving none wasted. Feeding own animals (either collecting crop residues or grazing animals on the fields after harvest), fuel for the kitchen or household, and soil fertility management (leaving crop residues in the fields, mulching, or collecting biomass to apply as organic soil amendments later on) are the main uses of biomass. Nearly half (47 percent) of maize residues (both stover and cobs) are allocated to soil fertility management, while the shares used for animal feed and household fuel are 25 percent and 22 percent, respectively (Table 2). The minor amount of remaining residues are allocated to miscellaneous uses – left on the fields for grazing others' animals, collected for building materials, burned, etc. Of the total of 309 sample households, 143 households reported allocating positive amounts of maize residues to all three main uses.

The quantity of residues allocated to different uses is 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.[14] 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 inorganic 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). Instead of using harvest index estimates from the literature, we rely on actual

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[13] Scoring coefficients (weights) for asset index are reported in Table A1 in the Appendix.

[14] The assumption of time invariance in the use of crop residues deserves additional consideration that can be properly addressed only with panel data.

measurements of maize grain and residues from 140 farmer plots in the same research sites in 2011-2012 (Torres 2014). We use the weight of air-dried maize grain, stover and cobs, from several 2×2 meter sub-plots on each of the 140 farmer maize plots, to reflect actual farming conditions.[15]

Based on actual measurements we predict the within-sample plot-specific quantity of maize grain and maize residues (stover and cobs) in kilograms per square meter 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 the full 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. This generated variable comes with several 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.

Empirical Results

In order to elicit the shadow value of maize residues allocated to soil fertility management, we estimate a household-level quadratic production function for maize for the whole sample. 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. Limiting the production function estimation to households that used only positive quantities of maize residues as a soil amendment would necessarily introduce selection bias into the estimates. 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 pH, soil nitrogen content, altitude), other variables potentially influencing maize production (herd size in TLU as a proxy for unobserved manure application rates, the fraction of

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[15] We do not consider maize root biomass since Kenyan farmers do not remove roots from soil after harvesting, so there is no variation in use of maize roots among households. Moreover, maize roots are, on average, only about 20 percent of grain dry weight (Latshaw and Miller 1924).

land planted with hybrid seeds and intercropped with legumes), and controls (characteristics of the household head such as gender, age, and years of education).

The total sample size is 309 households. Not all households in the sample, however, left maize residues on the field – 17 percent of households used all of the residues for different purposes (animal feed or fuel) – and not all households used chemical fertilizer, only 64 percent did. Just over half (52 percent, or 162 households) used both inputs in positive quantities. The non-essential inputs do not pose a problem for the estimation of a quadratic production function. Moreover, the flexible nature of the quadratic function allows for interaction effects between different inputs. This is additionally important given agronomic evidence that the combined application of organic resources and chemical fertilizer offers greater yield benefits mainly due to the direct interactions between the two inputs (Chivenge, Vanlauwe, and Six 2011).

The results of the estimation are reported in Table 3. 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 interaction term between NPK and crop residues is positive as expected, yet statistically insignificant. Average plot altitude and herd size are also statistically important determinants of output in maize systems of western Kenya. While hybrid maize seeds are usually associated with increased yield when used together with nitrogen fertilizer and when rainfall stress is limited (Sheahan, Black, and Jayne 2013), their use in western Kenya does not guarantee increased returns. There have been reports of "recycled" hybrid seeds – seeds replanted from previous year's harvest (Matsumoto and Yamano 2011; Suri 2011), and only 60 percent of our sample reported using either both hybrid seeds and chemical fertilizer or neither. This may help explain the statistically insignificant value of the estimated coefficient for the fraction of land planted with hybrid maize. We reject the null hypothesis of the unitary elasticity of substitution between inputs (the nested Cobb-Douglas production technology) with a Wald test statistic of 61.06 and a P-value of zero against the $\chi^2(10)$ distribution.[16]

Table 4 shows the estimated marginal physical productivities (MPP) for land, labor, NPK and

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[16] Addition of geographic controls – indicator variables for blocks/districts or villages – does not significantly change the estimation. The results are reported in Table A2 in the Appendix. A Wald test statistic of 2.28/5.32 and a P-value of 0.81/0.26 against the $\chi^2(5/4)$ distribution cannot reject the null hypothesis that the blocks/districts are, for example, statistically important. Moreover, due to close correlation, the measure of altitude loses its significance and decreases in value with the addition of geographic controls. The results of the estimation using a generalized translog specification of the production technology are reported in Table A4 in the Appendix.

maize residues, as well as their marginal value productivities (MVP) and benefit/cost ratios, based on the sample average maize price of 29 Kenyan shillings per one kilogram (KES/kg) and prices of inputs.[17] The resulting estimates have the expected signs and are generally consistent with previous findings. Marginal physical productivity estimates show that an additional acre of land increases output by 103 kg on average, showing no evidence of an inverse land holding size-productivity relationship. The estimated MPP of labor is positive, yet low and has high variance. Marenya and Barrett (2009b) note that measuring labor employed in tropical agriculture poses specific difficulties for empirical estimation, such as measurement error associated with variable effort and absorption of under-employed or unemployed household members.

Both chemical fertilizer and maize residues also positively influence output: for an additional kilogram of N, P, K nutrients and maize residues, maize grain harvest increases by 7.03 kg and 0.17 kg, respectively.[18] The estimated mean MPP of NPK is comparable to the estimated returns in existing studies. Jayne and Rashid (2013), for example, find the recent estimates across Sub-Saharan Africa to be around 8-24 kilograms of maize grain per 1 kilogram of nitrogen applied, with the most estimates concentrated in the lower 8-15 kg range. Specifically for Kenya, the MPP of nitrogen from chemical fertilizer is found to be 17.6 kg in the western highlands by Marenya and Barrett (2009b), 11.1-19.8 kg in central and western regions by Matsumoto and Yamano (2011), and 17 kg across the country by Sheahan, Black, and Jayne (2013). The estimated MPP of 7.03 kg maize/kg of NPK is lower than the MPP of nitrogen alone in the referenced studies as the composite NPK measure aggregates the benefits of two other nutrients (phosphorous and potassium), the content of which in the soils of the region is not limiting. The estimated marginal benefit/cost ration for NPK of 1.40 suggests the profitability of chemical fertilizer for households in the sample and is exactly the same as the estimated ratio for western Kenya highlands in Sheahan, Black, and Jayne (2013).

In order to estimate the household-specific shadow value of 1 kg of maize residues as a soil

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[17] We use the 2011-2012 average exchange rate of 84 Kenyan Shillings (KES) per US Dollar.

[18] The MPP estimate of NPK is positive for all observations, while the MPP of maize residues is positive for 86 percent of the sample. Other studies relying on the estimated coefficients of the production function, for example, Jacoby (1993) and Skoufias (1994), also find negative marginal revenue productivities. While they drop those observations or set their value equal to one, we keep the observations not to introduce unknown bias. The average MPP of maize residues for the observations with positive values only is, as expected, higher – 0.24 kg of maize/kg of maize residues, while the estimated marginal benefit/cost ratio is 1.14 suggesting the profitability of leaving crop residues for soil fertility management.

amendment using Equation 5, a price of 1 kg of NPK is needed. Assuming that all the value in chemical fertilizer is derived from the three essential nutrients for plant growth (N, P and K), a household-specific price of NPK is calculated as the total reported expenditure on chemical fertilizer across two cropping seasons divided by the quantity of NPK in kg. This price, however, does not account for household-specific transport and transaction costs that have been found to be significant for rural households in developing countries (de Janvry, Fafchamps, and Sadoulet 1991). While availability and access to chemical fertilizer in rural Kenya have been improving over time leading to considerable reduction in real transport costs (Sheahan, Black, and Jayne 2013), they are still significant. We include an estimated transport cost to be added to the price of purchased fertilizer by calculating the shortest distance from the household to a fertilizer seller in the nearest commercial center, using the household and center GPS coordinates. The average distance is 3 km in the sample. Given this household-specific distance (rounded up to the nearest 0.5 km) and the median cost of travel observed in the village surveys, we calculate the cost of a round trip (made twice if households cultivate maize during two seasons in 2011) to purchase fertilizer. The cost of transport adds about 9 KES, or 6 percent, to the price of 1 kg of NPK as reported by households.[19]

Since the estimates of the shadow price rely on input ratios, which can be large if one input is used in very small quantities, we also calculate the shadow price excluding the top and bottom tails (5 percent of the distribution).[20] Descriptive statistics on the estimated shadow values overall and for the various subsamples of households that used positive quantities of both chemical fertilizer and maize residues as inputs in maize production are shown in Table 5. The top panel shows the shadow values using the household-specific price of 1 kg of NPK, while the bottom panel uses this price adjusted for travel costs as described above. The average shadow values for maize residues left on the fields for soil fertility management are in the range of 4.88-9.26 KES/kg which correspond to US\$0.06-0.11/kg. Using the estimated average value of maize residues (6 KES), Table 4 shows that the average benefit/cost ratio for maize residues is 0.82. For about 50 percent of the households, however, it is profitable to leave maize residues as soil amendments (the ratio is greater than one).

The empirical results also confirm the ordering of shadow values of crop residues according to

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[19] Since the distance is calculated "as crow flies," this cost likely underestimates true distance, yet allows for household-specific estimates.

[20] Alternatively, we calculate the shadow price replacing the top and bottom tails with the 95th and 5th-percentile values, respectively (top- and bottom-coding). The results do not significantly change.

the number of uses among farming households, as predicted by Equation 7. Figure 3 shows the distribution of shadow values for households that allocated maize residues either only to one use – soil fertility management, two uses – soil fertility management and energy generation or soil fertility management and livestock feed, or all three uses – soil fertility management, energy generation, and livestock feed. The average estimated value is highest, 8.95-9.26 KES/kg, for the households that used maize residues as a soil amendment only. As expected, the average value of maize residues as a soil amendment decreases once households start allocating residues to alternative uses as well: the average value is 6.35-7.15 KES/kg for households with two uses and 4.88-5.30 KES/kg for households with three uses.

Economic importance of crop residues

Using 5.49 KES as the estimate of the shadow value of 1 kg of maize residues allocated to soil fertility management, Table 6 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 8,351 KES or US$99 per farm, which constitutes about 10 percent of the median annual household income in the sample. Using 5.49 KES as a proxy for the shadow value of all maize residues produced, total maize residues per farm are thus valued at US$208 (22 percent of the median income). When these values are translated to per acre estimates, Table 6 also shows that 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 surprisingly close to the previously estimated value of non-market crop stubble in Morocco and farm-yard 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$330 per hectare of maize residues produced, falls between these two values. The estimated average value of US$0.06/kg is also the same as the discounted marginal revenue product of farm-yard 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 one kilogram of mixed fuelwood are 5.85 and 8.94 KES/kg, respectively. Given that 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.

Crop residues are not substitutes for mineral fertilizers as both inputs fulfill different purposes. Mineral fertilizers provide crops with nutrients, while organic resources help preserve and grow the soil organic matter pool that maintains the physical and physicochemical components of soils, contributing to long-term soil fertility (Vanlauwe and Giller 2006). It is interesting, however, to look at the value of N, P and K found in dry maize residues in order to disaggregate their estimated values. Some estimates for the United States maize show that NPK accounts for about 2.5 percent of maize residues (leaves, stems and cobs), as a percentage of weight on the dry basis (Latshaw and Miller 1924). Similar estimates for nitrogen in western Kenya point to slightly lower values (for example, 0.7 percent of nitrogen (Gentile et al. 2011)). Using 2.5 percent as the highest possible NPK content of maize residues and 138 KES as the mean price of one kilogram of nutrients (NPK) in the sample, the price of NPK in one kilogram of maize residues can thus be estimated at 3.46 KES or US$0.04. Our estimates of the shadow value of one kilogram of maize residues left on the fields are higher – 4.88-9.26 KES or US$0.06-0.11.

This shadow price reflects not only the value of nutrients 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 physical, mechanical and hydrological properties, erosion control, etc. Moreover, maize residues, like other organic resources, are high in carbon (over 40 percent by content), which 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 percent over the no-input control. Thus, the estimated value of 4.88-9.26 KES/kg also likely includes the residual value of maize residue applications.

While the estimated shadow value of maize residues is crop- and location-specific, these results point to the significant economic value of using organic resources. The agronomic research community largely agrees on the complementarity and necessity of using both mineral 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

Following Magnan, Larson, and Taylor (2012), we 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 gender of household head, asset index, herd size and herd size squared, household size, total land area farmed, the share of land cultivated with maize, and several farm-specific environmental characteristics capturing temperature variations and soil quality. We include village fixed effects to account for unobserved characteristics common to a given village. The sample size is 162 households across fifteen villages – these are the households that used both chemical fertilizer and maize residues for soil fertility management in positive quantities (allowing us to estimate their shadow values). Since the left-hand size variable is estimated rather than observed, we bootstrap standard errors.

Table 7 shows the results, with the second column repeating the estimation but excluding the households with shadow values in the top and bottom tails (5 percent of the distribution). Overall the results suggest that, controlling for natural capital in the form of soil quality, poorer households – those with a lower asset index, fewer livestock and a lower share of land in maize – derive higher values per kilogram of maize residues. This finding is consistent with previous work that shows that wealthier households can achieve higher crop yields by practicing fallowing, using inorganic fertilizer or animal manure; for poorer households, these options are more limited (Crowley and

Carter 2000). This fact is of importance for policy-makers and development practitioners who promote agricultural technologies centering on crop residues, presuming their wide availability and no or low cost.

Conclusions

Together with land and labor, organic resources are used to satisfy a variety of household needs and constitute critical productive resources for small farmers in developing countries. Yet, our understanding of their availability, uses and economic value is highly limited. Given the diversity of smallholder systems in Africa and elsewhere in the developing world, economic analysis of organic resources and their uses in different agroecosystems is needed to establish realistic bounds on their economic value. 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 theoretical framework highlights important trade-offs when it comes to crop residue management: farm households allocate crop residues to the three major production activities – crop production, energy generation, and livestock maintenance – so as to equate the marginal values of the respective allocations. When the marginal value of crop residues is highest in maize production, a farm household allocates all crop residues to soil fertility management only. The marginal value decreases with two and then three allocations amongst the available options. Our empirical findings show that the shadow value of maize residues is significant, while confirming the theoretical ordering according to the number of uses. The value of maize residues left on the fields for soil fertility management is estimated at 4.88-9.26 Kenyan shillings per kilogram, which correspond to US$0.06-0.11/kg. This price includes not only the value of macronutrients in maize residues but also the value of other environmental benefits that extend beyond fertilizer substitution. Maize stover and cobs make up around 37 percent of the total value of maize production on an average farm in western Kenya, and constitute about 22 percent of the median household income. The high shadow value of maize residues left on the fields as an organic soil amendment highlights the many environmental benefits of crop residues and their recognition by smallholder farmers in Kenya.

Crop residues are an important resource in smallholder agriculture, providing numerous ecosystem services essential to enhancing, maintaining and sustaining long-term soil quality and agricultural productivity. They have, however, multiple competing applications. The removal of crop residues for use as feed for domestic animals and the use of residues for fuel are the driving forces responsible for depletion of the soil organic 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 degrading processes decrease agronomic productivity, reduce crop response to chemical fertilizer and other inputs, and require additional labor for plowing. Recently, emerging uses which compete for the scarce organic resources, such as the use of crop residues for biofuel production, will only exacerbate the soil degrading processes on agricultural lands.

The current socio-economic and policy environments of Kenya and most other nations do not support the full 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. Finding alternative sources for animal feed, household fuel and biofuel production, such as establishing biofuel plantations on degraded lands (not currently used for food production), are also important (Lal 2005). Further research is needed to precisely measure the 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 hereby help achieve food security in Sub-Saharan Africa, and to help address climate change.

References

Amacher, G., W. Hyde, and B. Joshee. 1993. “Joint production and consumption in traditional households: Fuelwood and crop residues in two districts in Nepal.” *Journal of Development Studies* 30:206–225.

Barrett, C.B., S.M. Sherlund, and A.A. Adesina. 2008. “Shadow wages, allocative inefficiency, and labor supply in smallholder agriculture.” *Agricultural Economics* 38:21–34.

Berazneva, J. 2014. “Audio Recording of Household Interviews to Ensure Data Quality.” *Journal of International Development* 26:290–296.

Berck, P., and G. Helfand. 1990. “Reconciling the von Liebig and differentiable crop production functions.” *American Journal of Agricultural Economics* 72:985–996.

Chivenge, P., B. Vanlauwe, and J. Six. 2011. “Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis.” *Plant and Soil* 342:1–30.

Conley, T.G., and C.R. Udry. 2010. “Learning about a New Technology: Pineapple in Ghana.” *American Economic Review* 100:35–69.

Cooke, P., G. Kohlin, and W. Hyde. 2008. “Fuelwood, Forests and Community Management? Evidence from Household Studies.” *Environment and Development Economics* 13:103–135.

Cozzolino, D., and A. Moron. 2003. “The potential of near-infrared reflectance spectroscopy to analyse soil chemical and physical characteristics.” *The Journal of Agricultural Science* 140:65–71.

Crowley, E., and S. Carter. 2000. “Agrarian Change and the Changing Relationships Between Toil and Soil in Maragoli, Western Kenya (1900–1994).” *Human Ecology* 28:383–414.

de Janvry, A., M. Fafchamps, and E. Sadoulet. 1991. “Peasant Household Behaviour with Missing Markets: Some Paradoxes Explained.” *Economic Journal* 101:1400–1417.

Duflo, E., M. Kremer, and J. Robinson. 2011. “Nudging Farmers to Use Fertilizer: Theory and Experimental Evidence from Kenya.” *American Economic Review* 101:2350–2390.

Gavian, S., and M. Fafchamps. 1996. “Land tenure and allocative efficiency in Niger.” *American Journal of Agricultural Economics* 78:460–471.

Gentile, R., B. Vanlauwe, P. Chivenge, and J. Six. 2011. “Trade-offs between the short- and long-term effects of residue quality on soil C and N dynamics.” *Plant and Soil* 338:159–169.

Goldstein, M., and C. Udry. 2008. “The Profits of Power: Land Rights and Agricultural Investment in Ghana.” *Journal of Political Economy* 116:981–1022.

Harou, A., Y. Liu, C.B. Barrett, and L. You. 2014. “Spatiotemporally Heterogeneous Expected Returns to Fertilzer and Poverty Rates in Malawi.” Working paper, Cornell University, Ithaca, NY.

Jacoby, H.G. 1993. “Shadow Wages and Peasant Family Labour Supply: An Econometric Application to the Peruvian Sierra.” *Review of Economic Studies* 60:903–921.

Jaetzold, R., and H. Schmidt. 1982. *Farm Management Handbook of Kenya. Vol. II. Natural Conditions and Farm Management Information*. Nairobi, Kenya: Ministry of Agriculture.

Jayne, T., and S. Rashid. 2013. “Input subsidy programs in sub-Saharan Africa: a synthesis of recent evidence.” *Agricultural Economics* 44:547–562.

KARI. 2008. “Growing maize for food and fodder.” Information Brochures No. I, Kenya Agricultural Research Institute (KARI), Nairobi, Kenya.

Klemick, H. 2011. “Shifting cultivation, forest fallow, and externalities in ecosystem services: Evidence from the Eastern Amazon.” *Journal of Environmental Economics and Management* 61(1):95–106.

Lal, R. 2006. “Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands.” *Land Degradation & Development* 17:197–209.

—. 2009. “Soil quality impacts of residue removal for bioethanol production.” *Soil and Tillage Research* 102:233–241.

—. 2005. “World crop residues production and implications of its use as a biofuel.” *Environment International* 31:575–584.

Latshaw, W., and E. Miller. 1924. “Elemental Composition of the Corn Plant.” *Journal of Agricultural Research* XXVII:845–860.

Le, K.T. 2009. “Shadow Wages and Shadow Income in Farmers’ Labor Supply Functions.” *American Journal of Agricultural Economics* 91:685–696.

Lee, D., and C. Barrett, eds. 2001. *Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment*. Wallingford, U.K.: CABI Press.

Lopez, R. 1997. “Environmental externalities in traditional agriculture and the impact of trade liberalization: the case of Ghana.” *Journal of Development Economics* 53:17–39.

Magnan, N., D.M. Larson, and J.E. Taylor. 2012. “Stuck on Stubble? The Non-market Value of Agricultural Byproducts for Diversified Farmers in Morocco.” *American Journal of Agricultural Economics* 94:1055–1069.

Marenya, P., and C. Barrett. 2007. “Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya.” *Food Policy* 32:515–536.

—. 2009a. “Soil quality and fertilizer use rates among smallholder farmers in western Kenya.” *Agricultural Economics* 40:561–572.

—. 2009b. “State-conditional Fertilizer Yield Response on Western Kenyan Farms.” *American Journal of Agricultural Economics* 91:991–1006.

Matsumoto, T., and T. Yamano. 2011. “Optimal Fertilizer Use on Maize Production in East Africa.” In T. Yamano, K. Otsuka, and F. Place, eds. *Emerging Development of Agriculture in East Africa*. Springer Netherlands, pp. 117–132.

Mekonnen, A., and G. Kohlin. 2008. “Biomass Fuel Consumption and Dung Use as Manure: Evidence from Rural Households in the Amhara Region of Ethiopia.” EfD Discussion Paper No. 08-17, Environment for Development Initiative and Resources for the Future, Washington, D.C.

Moebius-Clune, B.N. 2010. “Applications of integrative soil quality assessment in research, extension, and education.” PhD dissertation, Cornell University, Ithaca, New York.

Mukhwana, E., and J. Odera. 2009. “Best-bet comparison of soil fertility management recommendations in western Kenya: independent testing by NGOs.” 10th KARI biennial scientific conference volume i, Kenya Agricultural Research Institute (KARI), Nairobi, Kenya.

Pagan, A. 1984. “Econometric Issues in the Analysis of Regressions with Generated Regressors.” *International Economic Review* 25:221–247.

Palm, C., C. Gachengo, R. Delve, G. Cadisch, and K. Giller. 2001. “Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database.” *Agriculture, Ecosystems and Environment* 83:27–42.

Place, F., C.B. Barrett, H. Freeman, J.J. Ramisch, and B. Vanlauwe. 2003. “Prospects for integrated soil fertility management using organic and inorganic inputs: evidence from smallholder African agricultural systems.” *Food Policy* 28:365–378.

Powlson, D.S., P.J. Gregory, W.R. Whalley, J.N. Quinton, D.W. Hopkins, A.P. Whitmore, P.R. Hirsch, and K.W.T. Goulding. 2011. “Soil management in relation to sustainable agriculture and ecosystem services.” *Food Policy* 36, Supplement 1:S72–S87.

Sahn, D.E., and D. Stifel. 2003. “Exploring Alternative Measures of Welfare in the Absence of Expenditure Data.” *Review of Income and Wealth* 49:463–489.

Sanchez, P. 2002. “Soil fertility and hunger in Africa.” *Science* 295:2019–2020.

Sheahan, M., R. Black, and T. Jayne. 2013. “Are Kenyan farmers under-utilizing fertilizer? Implications for input intensification strategies and research.” *Food Policy* 41:39–52.

Shepherd, K., and M. Walsh. 2002. “Development of Reflectance Spectral Libraries for Characterization of Soil Properties.” *Soil Science Society of America Journal* 66:988–998.

Sherlund, S.M., C.B. Barrett, and A.A. Adesina. 2002. “Smallholder technical efficiency controlling for environmental production conditions.” *Journal of Development Economics* 69:85–101.

Shiferaw, B., and H. Freeman, eds. 2003. *Methods for assessing the impacts of natural resource management research*. A summary of the proceedings of an International Workshop, 6-7 December 2002, Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Skoufias, E. 1994. “Using shadow wages to estimate labor supply of agricultural households.” *American Journal of Agricultural Economics* 76:215–227.

Smil, V. 1999. “Crop Residues: Agriculture’s Largest Harvest.” *BioScience* 49:299–308.

Suri, T. 2011. “Selection and Comparative Advantage in Technology Adoption.” *Econometrica* 79:159–209.

Teklewold, H. 2012. “The impact of shadow prices and farmers’ impatience on the allocation of a multipurpose renewable resource in Ethiopia.” *Environment and Development Economics* 17:479–505.

Tilman, D., C. Balzer, J. Hill, and B. Befort. 2011. “Global food demand and the sustainable intensification of agriculture.” *Proceedings of the National Academy of Sciences* 108:20260–20264.

Tittonell, P., and K. Giller. 2013. “When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture.” *Field Crops Research* 143:76–90.

Torres, D. 2014. “Biomass Resource Inventory and Selection for Biochar Production using Manual and Object Based Image Analysis.” PhD dissertation, Cornell University, Ithaca, New York.

Torres-Rojas, D., J. Lehmann, P. Hobbs, S. Joseph, and H. Neufeldt. 2011. “Biomass availability, energy consumption and biochar production in rural households of Western Kenya.” *Biomass and Bioenergy* 35:3537–3546.

USDA. 2011. “Kenya’s Draft National Biofuel Policy.” GAIN Report on Bio-Fuels No. Prepared by Souleymane Diaby, USDA Foreign Agricultural Service.

Vanlauwe, B., J. Diels, N. Sanginga, and R. Merckx. 2002. *Integrated plant nutrient management in Sub-Saharan Africa: from concept to practice*. Wallingford, Oxon, UK; New York, NY, USA: CABI.

Vanlauwe, B., and K. Giller. 2006. “Popular myths around soil fertility management in sub-Saharan Africa.” *Agriculture, Ecosystems & Environment* 116:34–46.

WB. 2012. *Carbon Sequestration in Agricultural Soils*. 67395-GLB, Washington, D.C.: The World Bank (WB).

—. 2007. *World Development Report 2008: Agriculture for Development*. Washington, D.C.: The World Bank (WB).

Figures and Tables

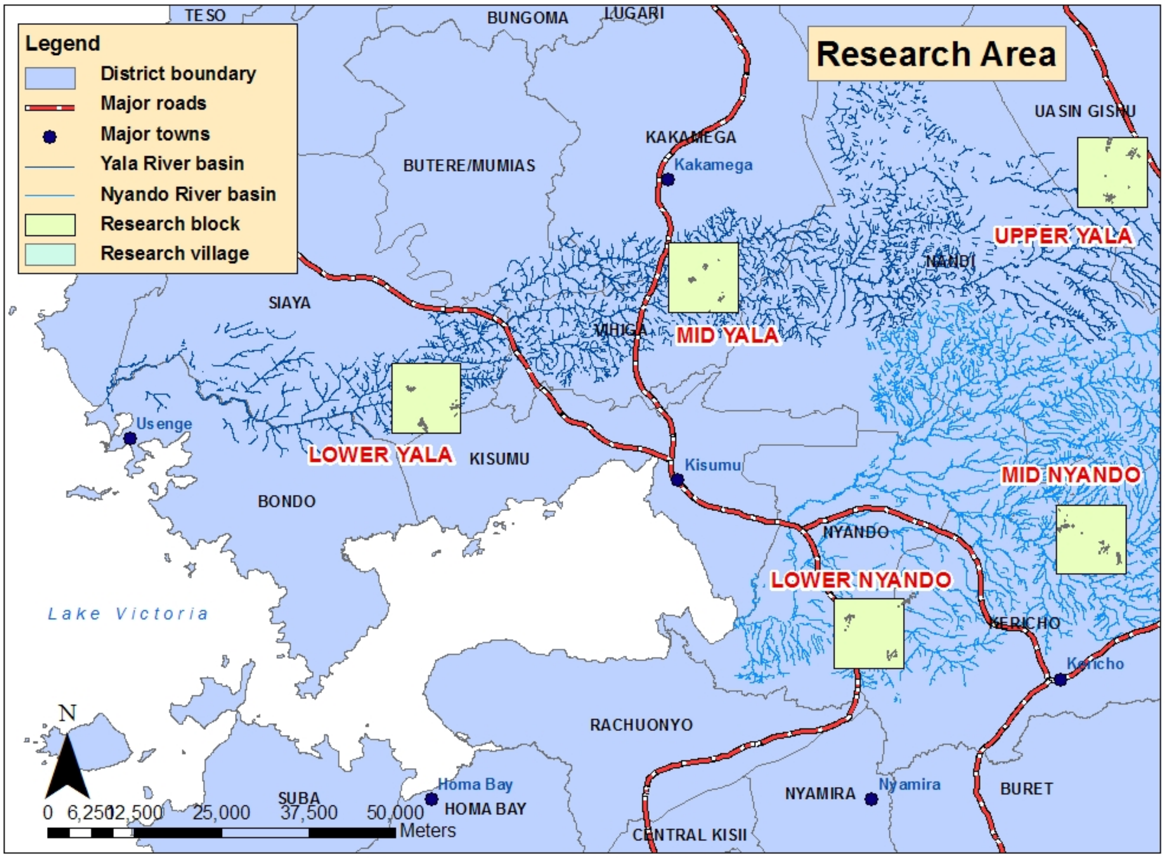

Figure 1: Map of the research sites.

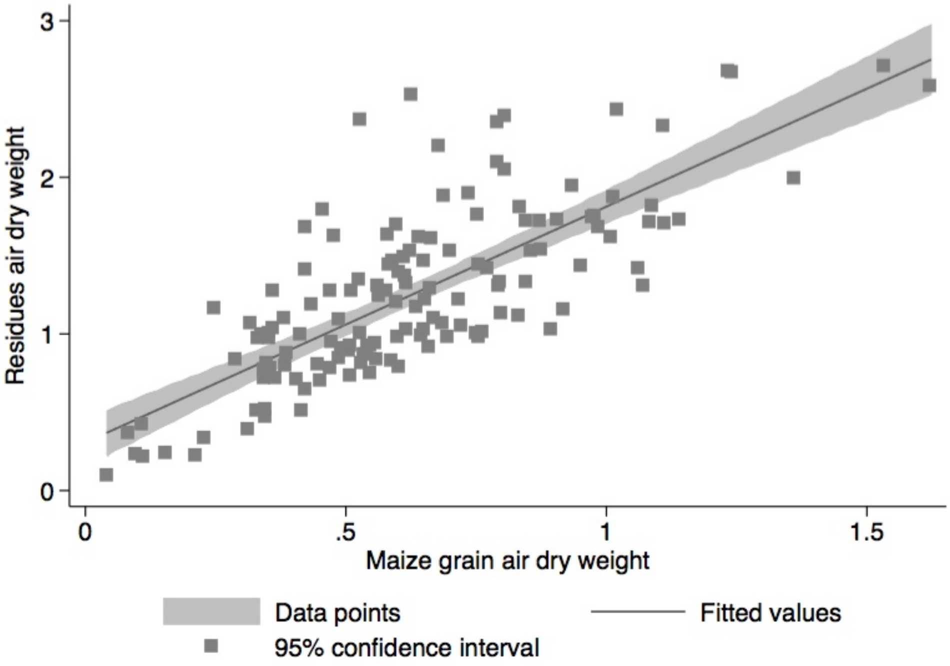

Figure 2: Estimating maize residues: maize residues vs. maize grain (kg/m^2). R^2=0.58.

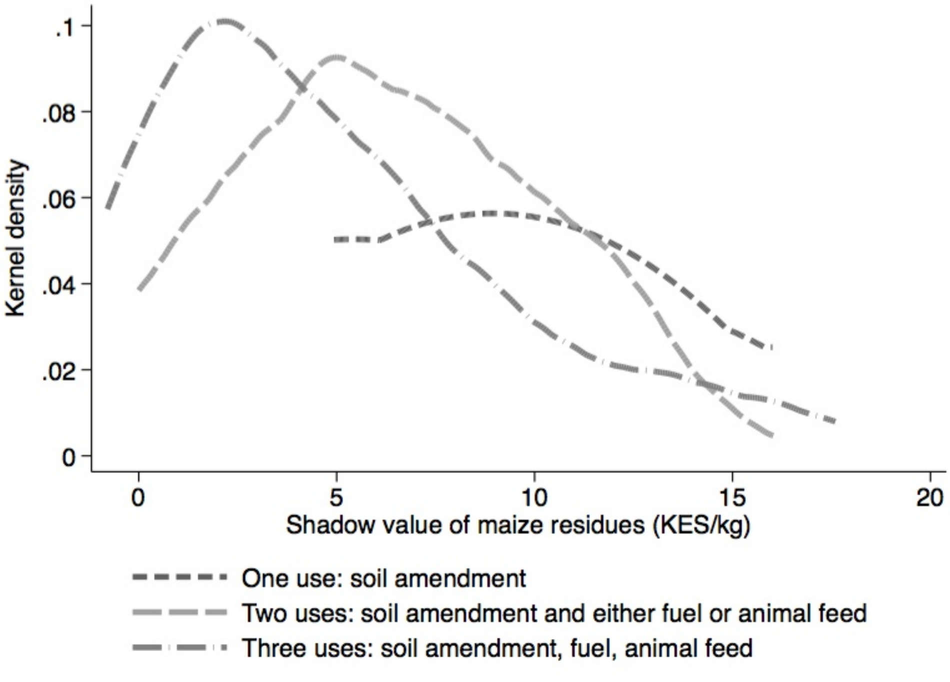

Figure 3: Estimated shadow values across main uses.

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
No chemical fertilizer applied*	0.36			
No maize residues applied*	0.17			
Soil pH	5.82 (Low)	0.52	4.35	7.13
Soil nitrogen (% by weight)	0.16 (Very low)	0.09	0.06	0.87
Average plot altitude (m)	1,606	330	1,205	2,258
Herd size (TLU)	2.38	2.71	0.00	17.66
Own livestock*	0.94			
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
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
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

N=309 households.

Table 3: Household-level maize quadratic production function.

Maize grain (kg)	(1)
Maize land (acres)	65.79
	(182.7)
Labor days	-0.251
	(2.509)
NPK (kg)	0.659
	(4.751)
Residues (kg)	0.217**
	(0.102)
1/2 Maize land sq.	252.6**
	(100.1)
1/2 Labor days sq.	-0.0125
	(0.0233)
1/2 NPK sq.	0.0823
	(0.0685)
1/2 Residues sq.	0.000133**
	(5.27e-05)
Interaction: Land * Labor	-0.135
	(1.132)
Interaction: Land * NPK	1.177
	(2.006)
Interaction: Land * Residues	-0.250***
	(0.0503)
Interaction: Labor * NPK	0.00997
	(0.0367)
Interaction: Labor * Residues	0.00127
	(0.000856)
Interaction: NPK * Residues	0.000979
	(0.00110)
Average plot altitude (m)	0.649***
	(0.150)
Soil pH	92.72
	(67.85)
Soil nitrogen (% by weight)	125.5
	(307.1)
Herd size (TLU)	66.31***
	(19.39)
Fraction of acres intercropped with legumes	-26.62
	(90.32)
Fraction of acres planted with hybrid maize	-105.9
	(87.55)
Gender of household head: 1=male	-79.48
	(75.93)
Household head age	-1.464
	(2.072)
Household head years of education	1.574
	(6.802)
Constant	-1,285**
	(540.3)
Observations	309
R-squared	0.852

Note: Bootstrapped standard errors in parentheses (1,000 replications). *** p<0.01, ** p<0.05, * p<0.1.

Table 4: Household-level marginal physical productivities (MPP), marginal value productivities (MVP), and benefit/cost estimates.

Variable	MPP (kg maize/ unit input)	MVP (KES)	Input price (KES)	Marginal benefit/cost (MVP/input price)
Maize land (acres)	103.36 (335.03)	2,997.44 (9,715.87)	2,110	1.42 (4.60)
Labor (person-days)	0.54 (1.91)	15.74 (55.31)	138	0.01 (0.40)
NPK (kg)	7.03 (5.34)	203.94 (154.92)	146	1.40 (1.06)
Maize residues (kg)	0.17 (0.22)	4.90 (6.34)	6	0.82 (1.06)

Standard errors are in parentheses. N=309 households. Input prices are based on the mean reported prices from the household survey (price of land is the sample average rental price of 1 acre of land, price of labor is the sample average price of 1 person-day of hired labor, and price of NPK is the household-level sample average price of 1 kilogram of NPK (expenditure on chemical fertilizer divided by the quantity of N, P, K in kg). Price of 1 kg of maize residues is based on the estimation of the paper.

84 KES = 1 USD (average 2011-2012 exchange rate).

Table 5: Shadow price of maize residues across main uses (KES/kg).

Variable	Mean	St. Dev.	N
Using market price of NPK			
Value for full sample	6.29	7.43	162
Value for full sample, excluding top and bottom 5%	5.49	4.34	144
Value for households with one use only (soil fertility management)	8.95	6.13	3
Value for households with two uses (soil fertility, and energy or animal feed)	6.35	3.90	51
Value for households with three uses (soil fertility, energy, animal feed)	4.88	4.44	90
Using market price of NPK adjusted for travel cost			
Value for full sample	6.90	9.07	162
Value for full sample, excluding top and bottom 5%	6.05	5.06	144
Value for households with one use only (soil fertility management)	9.26	6.41	3
Value for households with two uses (soil fertility, and energy or animal feed)	7.15	4.82	51
Value for households with three uses (soil fertility, energy, animal feed)	5.30	5.06	90

Calculated using household-specific price of 1 kg of NPK.

84 KES = 1 USD (average 2011-2012 exchange rate).

Table 6: Economic value of maize residues in Kenyan shillings and US dollars.

Variable	Value in KES	Value in USD
Maize residues for soil fertility management per farm	8,351 (8,674)	99 (103)
All maize residues per farm	17,458 (19,526)	208 (232)
Value per acre		
Maize residues per acre	11,239 (6,567)	134 (78)
Maize grain per acre	19,426 (14,924)	231 (178)
Value per hectare		
Maize residues per acre	27,760 (16,219)	330 (193)
Maize grain per acre	47,982 (36,863)	571 (439)

Calculated using 5.49 KES as value of 1 kg of maize residues and 29 KES as price of 1 kg of maize grain. Standard errors are in parentheses. N=309 households.

84 KES = 1 USD (average 2011-2012 exchange rate).

Table 7: Household- and farm-level determinants of the shadow value of maize residues.

Value of crop residues (KES/kg)	(1)	(2)
Gender of household head: 1=male	2.717*	0.520
	(1.535)	(1.027)
Asset index from first PC	-1.191*	-1.158***
	(0.638)	(0.394)
Herd size (TLU)	-1.146**	-0.204
	(0.501)	(0.312)
Herd size squared	0.0799	0.0122
	(0.0556)	(0.0323)
Household size	-0.611**	-0.222
	(0.293)	(0.186)
Total land area farmed (acres)	-0.0904	-0.0685
	(0.225)	(0.150)
Land in maize as share of total	-6.663***	-3.220*
	(2.187)	(1.690)
Average plot altitude (m)	0.0762**	0.0298**
	(0.0379)	(0.0129)
Soil nitrogen (% by weight)	15.55	1.194
	(14.22)	(7.392)
Soil pH	3.463*	1.522
	(1.800)	(1.043)
Constant	-115.3**	-42.39**
	(57.80)	(21.01)
Observations	162	149
Village fixed effects	YES	YES
R-squared	0.359	0.384

Note: Bootstrapped standard errors in parentheses (1,000 replications). *** p<0.01, ** p<0.05, * p<0.1. Sample size is the households that used both chemical fertilizer and maize residues for soil fertility management in positive quantities. Column (2) excludes the households with the shadow value in the top and bottom tails (5 percent of the distribution).

Appendix: Additional Tables

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

Table A2: Specifications of the household maize production function.

Maize grain (kg)	(1) Parsimonious	(2) Quadratic	(3) Environ. vars	(4) All controls	(5) Block dummies	(6) Village dummies
Maize land (acres)	318.8***	176.9	80.63	65.79	75.70	45.51
	(95.02)	(195.2)	(184.2)	(190.5)	(189.7)	(191.5)
Labor days	-0.922	-2.031	-0.0931	-0.251	-0.508	0.0175
	(0.888)	(2.797)	(2.542)	(2.533)	(2.644)	(2.537)
NPK (kg)	19.98***	4.761	0.309	0.659	0.292	0.723
	(2.299)	(5.147)	(4.563)	(4.663)	(4.753)	(4.560)
Residues (kg)	0.0538	0.186*	0.203**	0.217**	0.221**	0.220**
	(0.0676)	(0.109)	(0.0938)	(0.0978)	(0.103)	(0.104)
1/2 Maize land sq.		225.1**	243.7**	252.6**	255.7**	267.1**
		(114.3)	(97.78)	(99.56)	(99.53)	(104.5)
1/2 Labor days sq.		-0.00586	-0.0129	-0.0125	-0.0106	-0.0131
		(0.0248)	(0.0237)	(0.0239)	(0.0243)	(0.0226)
1/2 NPK sq.		0.1000	0.0859	0.0823	0.0811	0.0806
		(0.0721)	(0.0649)	(0.0687)	(0.0682)	(0.0684)
1/2 Residues sq. / 1,000		0.151***	0.133***	0.133***	0.131**	0.136***
		(0.0537)	(0.0513)	(0.0501)	(0.0521)	(0.0507)
Interaction: Land * Labor		-0.0326	-0.109	-0.135	-0.239	-0.257
		(1.216)	(1.149)	(1.159)	(1.128)	(1.085)
Interaction: Land * NPK		0.416	1.210	1.177	1.085	1.121
		(2.240)	(1.956)	(2.004)	(1.946)	(2.046)
Interaction: Land * Residues / 1,000		-253.3***	-246.6***	-249.6***	-244.6***	-243.3***
		(55.71)	(48.50)	(48.35)	(49.44)	(51.94)
Interaction: Labor * NPK		0.0162	0.00875	0.00997	0.0142	0.0110
		(0.0397)	(0.0345)	(0.0356)	(0.0390)	(0.0359)
Interaction: Labor * Residues / 1,000		1.150	1.281	1.273	1.211	1.139
		(0.916)	(0.833)	(0.825)	(0.832)	(0.818)
Interaction: NPK * Residues / 1,000		0.588	0.976	0.979	0.972	0.893
		(1.191)	(1.051)	(1.113)	(1.058)	(1.131)
Average plot altitude (m)			0.601***	0.649***	0.385	-0.120
			(0.141)	(0.158)	(0.333)	(0.555)
Soil pH			85.88	92.72	149.1	245.1*
			(60.60)	(68.09)	(111.8)	(136.4)
Soil nitrogen (% by weight)			95.07	125.5	203.5	269.6
			(309.2)	(302.1)	(339.3)	(349.6)
Herd size (TLU)			59.96***	66.31***	68.90***	66.12***
			(17.99)	(19.15)	(19.28)	(20.14)
Fraction of acres intercropped with legumes				-26.62	-67.30	-90.71
				(92.18)	(98.79)	(95.46)
Fraction of acres planted with hybrid maize				-105.9	-76.11	-179.5
				(95.16)	(111.6)	(125.6)
Gender of household head: 1=male				-79.48	-86.98	-74.84
				(76.87)	(76.52)	(85.96)
Household head age				-1.464	-2.014	-2.425
				(2.085)	(2.077)	(2.463)
Household head years of education				1.574	-0.658	1.613
				(7.121)	(6.838)	(8.012)
Constant	-3.355	216.2**	-1,366***	-1,285**	-1,339	-1,202
	(73.59)	(108.9)	(495.6)	(541.7)	(1,071)	(1,129)
R-squared	0.722	0.826	0.850	0.852	0.854	0.863

Note: Bootstrapped standard errors in parentheses (1,000 replications). *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A3: Quadratic maize production function, using NPK, N and Total fertilizer (kg).

Maize grain (kg)	(1) NPK	(2) N	(3) Fertilizer
Maize land (acres)	65.79	129.8	78.40
	(188.1)	(193.2)	(187.9)
Labor days	-0.251	-0.364	-0.448
	(2.603)	(2.183)	(2.404)
NPK/N/Fertilizer (kg)	0.659	2.004	0.766
	(4.808)	(8.407)	(2.424)
Residues (kg)	0.217**	0.199**	0.202**
	(0.102)	(0.0919)	(0.0938)
1/2 Maize land sq.	252.6***	385.2***	286.4***
	(97.62)	(103.3)	(95.16)
1/2 Labor days sq.	-0.0125	0.0154	-0.00299
	(0.0234)	(0.0204)	(0.0214)
1/2 NPK/N/Fertilizer sq.	0.0823	0.645**	0.0163
	(0.0666)	(0.320)	(0.0154)
1/2 Residues sq. / 1,000	0.133***	0.181***	0.158***
	(0.0489)	(0.0445)	(0.0464)
Interaction: Land * Labor	-0.135	-1.749*	-0.542
	(1.132)	(1.027)	(1.097)
Interaction: Land * NPK/N/Fertilizer	1.177	-2.737	0.664
	(1.953)	(5.181)	(0.977)
Interaction: Land * Residues / 1,000	-249.6***	-281.4***	-258.5***
	(48.75)	(53.38)	(44.76)
Interaction: Labor * NPK/N/Fertilizer	0.00997	0.00442	0.00416
	(0.0364)	(0.0495)	(0.0176)
Interaction: Labor * Residues / 1,000	1.273	0.885	1.037
	(0.840)	(0.584)	(0.740)
Interaction: NPK/N/Fertilizer * Residues / 1,000	0.979	2.911	0.398
	(1.007)	(2.379)	(0.543)
Average plot altitude (m)	0.649***	0.783***	0.654***
	(0.157)	(0.153)	(0.149)
Soil pH	92.72	63.10	87.96
	(68.46)	(64.62)	(68.81)
Soil nitrogen (% by weight)	125.5	210.4	225.3
	(313.0)	(299.5)	(309.4)
Herd size (TLU)	66.31***	53.25***	62.47***
	(19.45)	(15.31)	(16.89)
Fraction of acres intercropped with legumes	-26.62	-46.76	-14.12
	(87.73)	(90.78)	(92.45)
Fraction of acres planted with hybrid maize	-105.9	-61.70	-110.7
	(92.07)	(81.47)	(85.57)
Gender of household head: 1=male	-79.48	-71.18	-87.21
	(76.55)	(74.16)	(75.49)
Household head age	-1.464	-0.262	-1.489
	(2.083)	(2.028)	(2.170)
Household head years of education	1.574	4.787	2.704
	(7.052)	(7.107)	(7.485)
Constant	-1,285**	-1,450***	-1,281**
	(550.0)	(520.9)	(527.5)
R-squared	0.852	0.861	0.858
Shadow price of residues (KES/kg)	6.29 (7.43)	9.74 (17.50)	5.28 (5.43)
Shadow price of residues (KES/kg), excl. top and bottom 5%	5.49 (4.34)	8.81 (8.33)	5.00 (3.74)

Note: Bootstrapped standard errors in parentheses (1,000 replications). *** p<0.01, ** p<0.05, * p<0.1. Column (1) is the same as Table 3. Column (2) repeats the estimation with N (kg) instead of NPK (kg); shadow price is calculated using household-specific price of nitrogen (depending on the fertilizer type). Column (3) repeats the estimation with Total fertilizer (kg) instead of NPK (kg); household-specific price of fertilizer is calculated as price of fertilizer divided by fertilizer amount in kg.

Table A4: Translog maize production function, with and without indicator variables for no use of NPK and maize residues.

LN(Maize grain (kg))	(1) Translog	(2) Translog with dummies for no use
LN(Maize land (acres))	1.379**	1.521**
	(0.702)	(0.756)
LN(Labor days)	-0.698	-0.720
	(0.978)	(1.022)
LN(NPK (kg))	0.176	-0.0513
	(0.274)	(0.337)
LN(Residues (kg))	-0.633***	-0.622
	(0.153)	(0.646)
1/2 Maize land sq.	0.149	0.156
	(0.152)	(0.159)
1/2 Labor days sq.	0.163	0.158
	(0.216)	(0.222)
1/2 NPK sq.	0.0351	0.0963
	(0.0450)	(0.0740)
1/2 Residues sq.	0.149***	0.145
	(0.0279)	(0.0889)
Interaction: Land * Labor	-0.115	-0.110
	(0.150)	(0.158)
Interaction: Land * NPK	0.0430	0.0459
	(0.0478)	(0.0633)
Interaction: Land * Residues	-0.126***	-0.152***
	(0.0256)	(0.0299)
Interaction: Labor * NPK	-0.0290	-0.0266
	(0.0543)	(0.0688)
Interaction: Labor * Residues	0.0360	0.0415
	(0.0254)	(0.0281)
Interaction: NPK * Residues	-0.00382	-0.00194
	(0.00899)	(0.0129)
Average plot altitude (m)	0.000650***	0.000642***
	(0.000186)	(0.000185)
Soil pH	-0.154*	-0.135
	(0.0910)	(0.0898)
Soil nitrogen (% by weight)	0.453	0.521
	(0.548)	(0.547)
Herd size (TLU)	0.0707***	0.0709***
	(0.0152)	(0.0152)
Fraction of acres intercropped with legumes	0.0717	0.0673
	(0.115)	(0.114)
Fraction of acres planted with hybrid maize	0.202*	0.183
	(0.123)	(0.121)
Gender of household head: 1=male	-0.0151	-0.0290
	(0.112)	(0.114)
Household head age	-0.00175	-0.00190
	(0.00280)	(0.00279)
Household head years of education	0.00147	0.00143
	(0.0112)	(0.0102)
No chemical fertilizer applied: =1		-0.234
		(0.152)
No maize residue applied: =1		0.518
		(1.584)
Constant	6.776***	7.022**
	(2.470)	(3.438)
R-squared	0.712	0.715
Shadow price of residues (KES/kg)	14.25 (19.03)	4.77 (166.31)
Shadow price of residues (KES/kg), excl. top and bottom 5%	11.31 (7.97)	8.27 (15.86)

Note: Bootstrapped standard errors in parentheses (1,000 replications). *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Column (1) is the translog specification with maize grain harvest, land, labor, NPK and residues are in log forms. LN(NPK (g)) = LN(NPK (kg)*1,000 + 1) and LN(Residues (g))=LN(Residues (kg)*1,000 + 1) (Conversion to grams is to minimize the effect of introducing 1 before taking logs). Column (3) adds the indicator variables for no use of NPK and residues. Here, LN(NPK (g)) = LN(NPK (kg)*1,000 if NPK>0), =1 otherwise and LN(Residues (g))=LN(Residues (kg)*1,000 if Residues>0), =1 otherwise.