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The Bioeconomics of Conservation Agriculture and Soil Carbon Sequestration in Developing Countries

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The Bioeconomics of Conservation Agriculture and Soil Carbon Sequestration in Developing Countries

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Abstract

Improving soil carbon through conservation agriculture in developing countries may generate some private benefits to farmers, as well as sequester carbon emissions, which is a positive externality to society. Leaving crop residue on the farm has become an important option in conservation agriculture practice. However, in developing countries, using crop residue for conservation agriculture has the opportunity cost of feed for livestock. In this paper, we model and develop an expression for an optimum economic incentive that is necessary to internalize the positive externality. A crude value of the tax is calculated using data from Kenya. We also empirically investigated the determinants of the crop residue left on the farm and found that it depends on the cation exchange capacity (CEC) of the soil, the prices of maize, whether extension officers visit the plot or not, household size, the level of education of the household head, and alternative cost of soil conservation.

Key Words: conservation agriculture, soil carbon, climate change, bioeconomics, Kenya

JEL Classification: C61, Q18, Q24, Q54, Q56

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The Bioeconomics of Conservation Agriculture and Soil Carbon Sequestration in Developing Countries

Wisdom Akpalu and Anders Ekbom*

Introduction

Carbon dioxide (CO_2) is the primary greenhouse gas that contributes to climate change. Reducing CO_2 emissions is necessary to prevent the projected negative impacts of climate change (IPCC 2007a,b; Stern et al. 2006). An important area of mitigation is soil carbon sequestration. Agricultural soils are among the planet's largest reservoirs of carbon—roughly twice the amount that is stored in all terrestrial plants—and hold potential for expanded carbon sequestration. Decreasing carbon stocks in the biosphere, including agricultural soils, have historically been a net source of CO_2 emissions to the atmosphere (Marland et al. 2007).

Currently, agriculture and other forms of land use contribute 32 percent to the world's greenhouse gas (GHG) emissions (IPCC 2007a,b). Moreover, each ton of carbon lost from soil adds approximately 3.7 tons of CO_2 to the atmosphere. Conversely, every ton increase in soil organic carbon represents 3.7 tons of CO_2 sequestered from the atmosphere. Therefore, integrated crop residue management (ICRM) promotes carbon sequestration and has a huge potential to reverse the net carbon flows from the atmosphere to the biosphere (Dick et al. 1998; Marland et al. 2007). As noted in the literature, best-practice organic agriculture emits less greenhouse gas than conventional agriculture, and the carbon sequestration from increasing soil organic matter leads to a net reduction in greenhouse gases (Drinkwater et al. 1998; Mäder et al. 2002; Pimentel 2005; Reganold et al. 2001).

Soil carbon is one of the most important factors promoting soil fertility, pest control, soil-water moisture, and farm productivity. Specifically, soil carbon is a key component of soil organic matter, which consists of living microorganisms, partially decomposed residue, and well-decomposed organic matter (humus). It improves the physical properties of soil, increases its

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capacity to hold water, and contributes to improved soil structure. In addition, soil organic matter contains large shares of the soil nutrients and other soil properties that are important for healthy plant growth, prevention of nutrient leaching, and buffering of soil from adverse pH changes (Hobbs 2007). The management of crop residue may improve crop yields and land resilience against drought and other hazards, while at the same time protecting and stimulating the biological functions of the soil (Unger et al. 1988). As a result, increasing soil carbon concentrations through conservation agriculture generates private benefit, as well as the public benefit of mitigating GHG emissions.

Sub-Saharan Africa's contribution to GHG emissions through agriculture is just about 6 percent of the global total. Nevertheless, this figure is expected to rise with increasing demand for agricultural products and changing food preferences. Because land degradation is accelerating as a serious problem, maintaining or enhancing farmers' soil capital has increasingly become a prime focus for sustainable agriculture and increased food production. Yet, most African farmers face great difficulties achieving this. To a large extent, this is because farmers collect the crop or plant residue to feed livestock (livestock even graze freely on crop residue) and households use the residue as an energy/fuel source. This removal of crop residue, combined with low levels of fertilizer application, depletes soil fertility and contributes to the deepening poverty in many developing countries (Triomphe et al. 2007).

Although resource-saving agricultural crop production is desirable, farmers are not likely to internalize benefits from environmental preservation (e.g., carbon sequestration) unless they are given adequate incentives. In this paper, we model a cropland management practice in Kenya, where farmers optimally allocate crop residue between reintegrating it directly into the soil (which improves soil quality, sequesters carbon, and therefore reduces net atmospheric carbon) and using it as fodder to feed livestock. Naturally, this poses a real trade-off for the farmer, because reintegrating crop residue into the soil, inter alia, reduces the amount of fodder available to feed livestock.

We derived an expression for the optimum amount of residue that the farmer will leave on the farm and the corresponding optimum incentive (i.e., subsidy) necessary to internalize the externality if the residue allotted for livestock is used as private fodder or a common pooled resource. We found that the optimal subsidy should decrease in the marginal net benefit of the off-farm activity and wage rate, but increase in total biomass of crop residue generated. Furthermore, if the residue is used as a common pooled resource, then the subsidy should increase with the number of users. In addition, an empirical model that relates the optimal residue left on the farm and some socioeconomic determinants has been estimated. Using the estimated value of the residue left on the farm plus some parameter values from the literature, we computed a rough estimate of the subsidy.

To put our research in context, it is worth noting that several biophysical and socioeconomic studies have been done on soil carbon sequestration and the linkage among conservation agriculture, increased productivity, and poverty reduction (see e.g., Antle et al. 2007; Pimentel 2005; Antle and Diagana 2003; Mäder et al. 2002). However, the literature on bioeconomic models on the optimum allocation of crop residue is scarce. The closest to our study are Hartel (2004), Graff-Zivin and Lipper (2008), and Antle and Stoorvogel (2008). The common feature of these studies is that the benefit that accrues to the farmer for practicing conservation agriculture is in situ, or increased farm yield. Moreover, these studies seek the optimum incentive that should be given to the farmer for generating positive externality through soil carbon sequestration. While our study, like the others, seeks to determine the optimum incentive or subsidy, we have extended the existing models by considering conservation agriculture as a resource allocation problem, which is very common in developing countries. As a result, the magnitude of the incentive would determine the optimal allocation decision (i.e., the quantity of the residue to be left on the farm).

The rest of the paper is organized as follows. The model and propositions are presented in section 1 followed by an empirical computation of incentive for the residue left on farms in Kenya (section 2). Section 3 estimates the subsidy rates and section 4 contains an estimation of the determinants of the crop residue left on farms. Section 5 summarizes our finding.

1. The Model

Suppose a farmer cultivates a crop that generates some residue after harvest (e.g., corn stovers). Let $\overline{R}_i$ be the biomass of stovers generated on plot i in the preceding farming season, which could be considered exogenous. If the farmer practices integrated crop residue management, then the biomass $\overline{R}_i - R_i$ is deposited on the field to improve soil quality and sequester carbon (a positive externality to society). Incorporating crop residue in the soil is costly, so we assume that the cost is linear in the biomass of residue deposited on the farm (i.e., $\sigma\left(\overline{R}_i - R_i\right)$, where σ is cost per unit of the residue incorporated in the soil).

The rest R_i is used to feed livestock (i.e., an alternative agricultural activity). Thus, R_i is a control variable. Let the marginal net benefit from this alternative agricultural activity be ρ, so that the total benefit is ρR_i. The yield function of the crop ($q = q\left(s, L\right)$) depends on soil quality s (a stock variable) and labor input L. The farmer does not internalize the positive externality of carbon sequestration; the farmer therefore maximizes a value or utility function, which consists of the surplus from cultivation of the crop ($q(s,L) - wL - \sigma(\overline{R}_i - R_i)$) and the alternative activity (ρR_i), given by equation (1) and subject to a soil-quality evolution equation (equation [2]). Note that labor usage depletes soil quality. From the soil dynamic equation, $\alpha, \beta > 0$, implying that labor usage depletes soil quality and the crop residue left on the farm improves the quality of the soil. In addition, the price per unit of the yield has been normalized to 1, so that all other prices are relative prices of yield.

$$V = \int_0^{\infty} \left(q(s,L) + \rho R_i - wL - \sigma(\overline{R}_i - R_i) \right) e^{-rt} dt \quad , \tag{1}$$

such that:

$$\dot{s} = \alpha + \beta(\overline{R}_i - R_i) - L \quad , \tag{2}$$

where the following partial derivatives hold: $q_s > 0$, $q_{ss} \leq 0$, $q_L > 0$, $q_{LL} \leq 0$, and $q_{sL} = q_{Ls} > 0$. The price of q is normalized to 1. The corresponding current value Hamiltonian of the farmer's objective function, expressed in equations (1) and (2), is:

$$\mathrm{H} = q(s,L) + \rho R_i - wL - \sigma(\overline{R}_i - R_i) + \mu\left(\alpha + \beta(\overline{R}_i - R_i) - L\right) \ . \tag{3}$$

The first order conditions, with respect to L and R_i, are equations (4) and (5), respectively, and the costate equation is equation (6):

$$\frac{\partial H}{\partial L} : q_L - w = \mu \quad ; \tag{4}$$

$$\frac{\partial H}{\partial R_i} : \rho + \sigma - \beta\mu \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0 \Rightarrow \begin{pmatrix} R_i = R_{\max} \\ R_i = R^* \\ R_i = R_{\min} \end{pmatrix} \text{; and} \tag{5}$$

$$\dot{\mu} - r\mu = -\frac{\partial H}{\partial s} = -q_s \ . \tag{6}$$

Equation (4) indicates that in equilibrium the value of the marginal productivity of labor (q_L) equals the marginal cost of labor, which is the sum of the wage rate (w) and shadow value of the soil capital (μ). Since R_i is not an argument in equation (5), the optimum solution could be at a maximum value of R_i ($R_i = R_{\max}$) or minimum value ($R_i = R_{\min}$). Suppose an interior solution exists. Then, the equation indicates that in equilibrium the marginal benefit from leaving the residue on the farm ($\beta\mu$) should equal the marginal opportunity cost to the farmer ($\rho+\sigma$). From the costate equation, in inter-temporal equilibrium, the marginal benefit from depleting an additional unit of the soil capital today ($r\mu$) must reflect the opportunity cost, which is the sum of the soil capital gain ($\dot{\mu}$) and some output effect (q_s). In a steady state, $\dot{s} = \dot{\lambda} = \dot{\mu} = 0$ and $R_i^* = R_i(\Phi)$, where Φ is a function of all the parameters in the Hamiltonian. Using a Cobb-Douglas specification of the production function of the form $q = AL^{\varepsilon}S^{v}$ with $(\varepsilon + v) \in (0,1)$, the optimal R_i (i.e., $R_i^* = \left(\bar{R} + \frac{\alpha}{\beta}\right) - \frac{\left(\varepsilon A v^{-1}\right)^{v}}{\beta}\left(\frac{\delta(\rho+\sigma)}{\beta}\right)^{v}\left(w + \frac{(\rho+\sigma)}{\beta}\right)^{(1-v)}$) is decreasing in the wage rate ($\frac{\partial R_i^*}{\partial w} = -\frac{(1-v)}{\beta}\left(w + \frac{\rho}{\beta}\right)^{-v} < 0$), the marginal net benefit of the non-farmer activity ($\frac{\partial R_i^*}{\partial \rho} < 0$), and the marginal cost of incorporating the crop residue in the soil ($\frac{\partial R_i^*}{\partial \sigma} < 0$), but increasing in $\bar{R}_i$ ($\frac{\partial R_i^*}{\partial \bar{R}_i} > 0$).

1.1 The Social Planner's Problem

Suppose a social planner wants to design an optimum economic incentive that could encourage the farmer to internalize the positive externality generated through carbon sequestration. Following Panayotou et al. (2002), who specified the damage from GHG as quadratic, let the term $\gamma(\bar{R}_i - R_i)^2$ define the external benefit from the leftover residue, and τ be the marginal incentive to the farmer to internalize the externality. The quadratic specification indicates that the marginal external benefit is increasing in the residue. The corresponding current value Hamiltonian is:

$$\mathrm{H} = (1+\tau)q(s,L) + \rho R_i - wL - \sigma\left(\bar{R}_i - R_i\right) + \lambda\left(\alpha + \beta\left(\bar{R}_i - R_i\right) - L\right) + \gamma(\bar{R}_i - R_i)^2 \qquad (7)$$

From the maximum principle, the first order conditions are

$$\frac{\partial H}{\partial L} : (1+\tau)q_L - w = \lambda \text{ ; and} \qquad (8)$$

$$\frac{\partial H}{\partial R_i} : (\rho+\sigma) - 2\gamma(\bar{R}_i - R_i) - \beta\lambda = 0 \text{ .} \qquad (9)$$

The costate equation is:

$$\dot{\lambda} - r\lambda = -\frac{\partial H}{\partial s} = -q_s \ . \tag{10}$$

With the economic incentive, equation (8) indicates that in equilibrium the subsidized value of the marginal productivity of labor equals the marginal cost of labor. Also, equation (9) indicates that the marginal benefit from leaving the residue on the farm ($\beta\lambda$) must equate the marginal opportunity cost to the farmer (i.e., $\rho + \sigma - 2\gamma(\overline{R}_i - R_i)$).

1.2 Economic Incentive (Subsidy)

Proposition 1

If conservation agriculture increases soil carbon sequestration, which is a positive externality, but decreases private benefits from an alternative agricultural use (e.g., livestock feed), the optimal subsidy necessary to internalize the externality is:

$$\tau^* = 2\gamma(\overline{R}_i - R_i^*) \big/ \left(w\beta + \rho + \sigma\right).$$

***Proof*:** Following Akpalu and Parks (2007), we equate equation (4) to equation (8) and derive the expression for the subsidy (i.e., τ). The expression is thus:

$$\tau = \frac{u - \lambda}{q_L} \tag{11}$$

But, we know from equations (1) and (2) that $q_L = \left(w\beta + \rho - \sigma\right)\beta^{-1}$, and from equations (5) and (9) that $\mu = \left(\rho + \sigma\right)\beta^{-1}$ and $\lambda = \left(\rho + \sigma - 2\gamma(\overline{R}_i - R_i)\right)\beta^{-1}$. In addition, since $R_i = R_i(\Phi) = R_i^*$ in steady state, equation (11) can be rewritten as:

$$\tau^* = \frac{2\gamma(\overline{R}_i - R_i^*)}{\left(w\beta + \rho + \sigma\right)} \tag{12}$$

Proposition 2

The optimal subsidy necessary to internalize the positive externality from conservation agriculture should be decreasing in the marginal net benefit of the off-farm activity and wage rate, but increasing in total biomass of crop residue generated.

Proof: The proof for this proposition requires taking the derivative of equation (12) with respect to ρ, σ, w, and γ, and investigating the signs. The comparative statics are:

$$\frac{\partial \tau^*}{\partial \rho} = -\left(\left(\frac{2\gamma(\bar{R}_i - R_i^*)}{(w\beta+\rho+\sigma)^2}\right) + \left(\frac{2\gamma\beta}{w\beta+\rho+\sigma}\right)\frac{\partial R_i^*}{\partial \rho}\right) < 0 \text{, since } \frac{\partial R_i^*}{\partial \rho} > 0 \tag{13}$$

$$\frac{\partial \tau^*}{\partial \sigma} = -\left(\left(\frac{2\gamma(\bar{R}_i - R_i^*)}{(w\beta+\rho+\sigma)^2}\right) + \left(\frac{2\gamma\beta}{w\beta+\rho+\sigma}\right)\frac{\partial R_i^*}{\partial \sigma}\right) < 0 \text{, since } \frac{\partial R_i^*}{\partial \sigma} > 0 \tag{14}$$

$$\frac{\partial \tau^*}{\partial w} = -\left(\left(\frac{2\gamma\beta(\bar{R}_i - R_i^*)}{(w\beta+\rho+\sigma)^2}\right) + \left(\frac{2\gamma\beta}{w\beta+\rho+\sigma}\right)\frac{\partial R_i^*}{\partial w}\right) < 0 \text{, since } \frac{\partial R_i^*}{\partial w} > 0 \tag{15}$$

$$\frac{\partial \tau^*}{\partial \gamma} = \frac{2(\bar{R}_i - R_i^*)}{(w\beta+\rho+\sigma)} > 0 \ . \tag{16}$$

From the comparative static analyses, the subsidy should decrease if the wage rate increases. This is because an increase in the wage rate, all other things being equal, makes it more profitable to substitute soil quality for labor. As a result, the soil carbon subsidy to farmers should decrease. Secondly, an increase in ρ, all other things being equal, makes it profitable for the farmer to feed livestock with the residue. Since the community is better off keeping livestock, the farmer should be given less incentive to leave the residue on the farm. Furthermore, if the cost of incorporating the residue in the soil increases, all other things including the marginal benefit from carbon sequestration remaining constant, the subsidy to the farmer should decrease. However, if the marginal benefit from carbon sequestration increases, then the subsidy should increase.

1.3 Residue Removed as a Common Pooled Resource (Herds Feed Together)

Farmers tend to collect residue or allow livestock herds to graze freely on crop residue. This may be an individual decision or, by way of insurance, the result of agreements and traditions regulating the relationships between farmers. Suppose the livestock within a community feed on common pastures, where the residue removed is stored. Let $M(R)$ define the total benefit to all the farmers within the community, where $R = \sum_{i=1}^{n} R_i$ and $\bar{R} = \sum_{i=1}^{n} \bar{R}_i$, so that $\frac{R_i}{R}$ is the individual i's share in the benefit. The current value Hamiltonian defining the farmer's problem is:

$$\mathrm{H} = q\left(s,L\right) - wL - \sigma\left(\overline{R}_i - R_i\right) + \mu\left(\alpha + \beta\left(\overline{R}_i - R_i\right) - L\right) + \frac{R_i}{R} M(R) \ . \tag{17}$$

From the maximum principle, the first order conditions (using $R = nR_i$) are:

$$\frac{\partial H}{\partial L} : q_L - w = \mu \ \text{; and} \tag{18}$$

$$\frac{\partial H}{\partial R} : \sigma + \frac{1}{n} M_R + \left(1 - \frac{1}{n}\right)\frac{M(R)}{R} - \beta\mu = 0 \ . \tag{19}$$

The costate equation is:

$$\dot{\mu} - r\mu = -q_s \ . \tag{20}$$

Equation (19) stipulates that if the collected residue is used as a common pooled resource, the shadow value of the soil quality is some weighted value of the average and the marginal benefit from the alternative activity and the marginal opportunity cost of incorporating the residue in the soil. Note that, if $n = 1$, we have an equilibrium condition for a private use of the resource, where the marginal benefit equals marginal opportunity cost. On the other hand, if $n \to \infty$, then we have an open access condition, where the average benefit equals the marginal opportunity cost. As a result, the marginal benefit from the common property management of the residue lies between that of the private property and the open access, if $M(R)$ is nonlinear. However, for simplicity, suppose that $M(R) = \rho R$, so that equation (19) can be redefined as:

$$\frac{\partial H}{\partial R} : \sigma + \frac{1}{n}\rho + \left(1 - \frac{1}{n}\right)\rho - \beta\mu = 0 \ \text{; and} \tag{21}$$

$$\frac{\partial H}{\partial R} : \rho + \sigma - \beta\mu = 0 \ . \tag{22}$$

1.4 Optimum Subsidy to Foster Social Optimum Conservation

The policymaker may want to design an optimum subsidy that will internalize the positive externality, assuming that the livestock is raised collectively by the farmers (as opposed to one farmer keeping all the livestock):

$$H = (1+\tau)nq\left(s,L\right) + \gamma n^2(\overline{R}_i - R_i)^2 - wnL - \sigma n\left(\overline{R}_i - R_i\right) + \omega\left(\alpha + \beta n\left(\overline{R}_i - R_i\right) - nL\right) + M\left(nR_i\right) \tag{23}$$

The first order conditions are:

$$\frac{\partial H}{\partial L}:\left(1+\tau\right)q_L - w = \omega \text{ ; and} \tag{24}$$

$$\frac{\partial H}{\partial R}: n\left(\rho+\sigma\right) - 2\gamma n^2(\overline{R}_i - R_i) - \beta n\omega = 0 \text{ .} \tag{25}$$

The costate equation is:

$$\dot{\omega} - r\omega = -nq_s \text{ .} \tag{26}$$

Proposition 3

If conservation agriculture increases soil carbon sequestration which generates crop residue that is used as a common pool resource, the optimal subsidy necessary to guarantee a socially optimal level of conservation is:

$$\tau^* = \frac{2\gamma n(\overline{R}_i - R_i^*)}{\left(w\beta+\rho+\sigma\right)} \text{ .}$$

Proof: From equation (25), we derive the following expression for the shadow value:

$$\omega = \frac{\left(\rho+\sigma\right) - 2\gamma n(\overline{R}_i - R_i)}{\beta} \text{ .} \tag{27}$$

Also, from equations (18) and (24), the following expression is derived for the optimum subsidy:

$$\tau^* = \frac{\omega-\mu}{q_L} \text{ .} \tag{28}$$

Combining equations (19) and (23) gives:

$$q_L = \left(\frac{w\beta+\rho+\sigma}{\beta}\right) \text{ .} \tag{29}$$

Therefore, using equation (29), (27), and $\mu = \frac{\rho+\sigma}{\beta}$ in (28) gives:

$$\tau^* = \frac{2\gamma n(\overline{R}_i - R_i^*)}{\left(w\beta + \rho + \sigma\right)} \ . \tag{30}$$

Proposition 4

If the crop residue collected is used as a common pooled resource to feed the livestock, the optimal subsidy necessary to internalize the positive externality from conservation agriculture will increase the number of users of the residue.

Proof: The proof of this preceding proposition requires taking the derivative of equation (29), with respect to n:

$$\frac{\partial \tau^*}{\partial n} = \frac{2\gamma(\overline{R}_i - R_i^*)}{\left(w\beta + \rho + \sigma\right)} > 0 \ . \tag{31}$$

Thus, as the number of the residue users increases, the opportunity cost of the residue usage, which depends on the number of the users, increases. As a result, a greater per unit subsidy is needed to encourage the farmers to practice integrated crop management.

2. Computing the Crop Residue Left on Plots

In an attempt to obtain a crude estimate of the economic incentive necessary to internalize the positive externality of soil carbon sequestration, we begin by computing $\left(\overline{R}_i - R_i\right)$ in this section. As noted in the literature, it is quite difficult to obtain data on the quantity of crop cover left on a plot. However, it has been estimated that the ratio of residue to maize yield is approximately 2:1 (see, e.g., Said 1982). Using this ratio, we computed the data for the maize residue generated. The crop cover left on the farm was then computed using a rating scale of 0:10 (i.e., 10 percentage point increments from 0–100 percent). The rating, which is measured by field technical assistants, is derived from a practical expert assessment framework for evaluating soil conservation technologies as described in Thomas (1997).

The data for the empirical analysis includes quality rating data for stover-deposits carefully collected in Muranga District in the central highlands of Kenya in 1998. Although the data is fairly old, farming practices in Kenya and many developing countries have remained unchanged over several decades. Moreover, this type of biophysical data is time independent. A random sample of 252 farms was identified. The sample constituted of 20 percent of the small-scale farms within the study area. Unlike other countries (e.g., Ethiopia), the households in the area cultivate only one plot. Hence, a "farm" constitutes *one* plot. The mean area allocated to farming in our sample is 2.4 acres,[1] indicating a relatively high land scarcity and fragmentation.

A typical farm in the area is distributed in a narrow strip, sloping downwards from a sharp ridge. The farm stretches from the ridge crest some 100–150 meters down to the slope base at the valley bottom, until it reaches a stream or a river. The slopes are steep, with mean farm-gradients ranging between 20–60 percent. Mean revenue from agricultural output of each household in the sample is about KSH 38,000 (≈ US$ 550).[2] Maize (*Zea mays*) is grown on a larger proportion of the planted area, as both a cash crop and a food crop. The study area is classified as very fertile and has two rainy seasons with a mean annual precipitation of 1,560 millimeters (Ovuka and Lindqvist 2000). Like other developing countries in sub-Saharan Africa, the farmers in Kenya are poor and live on less than $ 2 per capita per day. Despite the fertile soils, yields are low and there is chronic food insecurity. The farmers use simple technologies (mainly hoes, machetes [*panga*], and spades) to till the land, establish and maintain soil conservation structures, and harvest crops.

Based on the data, we computed the average stover residue generated (i.e., mean of $\overline{R}$) to be 1,269, and the mean residue deposited on the farm to be approximately 54 percent of the total (i.e., 695).

3. Estimating the Subsidy Rate

To provide a rough estimate of the optimum subsidy, we relied on some parameter values from the literature. First, an experiment conducted in Malawi showed that if livestock (cattle) feeds on the maize stover ad libitum, the average daily weight gain and consumption are 0.36 kilogramand 3.6 kilogram, respectively (Munthali 1987). With 1 kilogram of beef currently selling at approximately US$ 2.50 in Kenya, 0.36 kg of maize will sell at $0.90 (i.e., $\rho = \frac{0.9}{\theta}$, where $\theta = 0.44$ is the price per kilogram of bag of maize in U.S. dollars). Second, the average daily rural wage in Kenya is $1.25 (i.e., $w = \frac{1.25}{0.44}$). For simplicity, we assume that the cost per unit of incorporating the residue equals the wage rate (i.e., $w = \sigma$). Third, Shafi et al. (2007)

[1] The total farm size is on average 2.8 acres; some land is allocated to homesteading, grazing, or woodlots, or is classified as wasteland.

[2] KSH = Kenya shillings; US$ 1 ≈ KSH 70.

found from an experiment that soil N fertility was improved by 29.2 percent due to crop residue retention. As a result, we assume that $\beta = 0.292$. Fourth, since a one-ton increase in soil organic carbon could sequester about 3.7 tons of CO_2 from the atmosphere (holding many factors constant), the marginal environmental benefit from the crop cover is $\gamma = \frac{0.00185}{0.44}$ per kilogram. Bringing all these figures together, in addition to $\left(\overline{R_i} - R_i\right) = 695$, the mean ad valorem subsidy rate from equation (12) is computed as $\tau^* = 1.02$, or 102 percent of the price of maize. Thus, given the current biomass of stover deposits, each farmer should be given a subsidy equivalent of the price per kilogram of maize harvested. Note that this tax, all other things being equal, will increase with the number of herders, if the collected stover is managed as a common pooled resource.

4. Determinants of Crop Residue Left on Plots

This section contains an empirical analysis of determinants of Kenyan farmers' crop residue left on their farms. The dependent variables are soil characteristics, prices, and socioeconomic characteristics of the farmers (denoted Ω). Thus, our equation of interest is:

$$E\left(\overline{R_i} - R_i\right) = R_i(prices, soil\ charateristics, \Omega) \ . \quad (32)$$

In addition to the soil characteristics, a household survey was conducted during the same period to collect data on socioeconomic characteristics. Table 1 presents the descriptive characteristics of the variations used for the regression.

Table 1. Descriptive Statistics

Variable	Observations	Mean	SD
Residue left on the farm (per hectare)	233	713.06	1367.525
pH in water	243	5.618	0.669
Extension officers visit farm (=1, 0 otherwise)	246	0.236	0.425
Household size	246	4.183	2.227
Education (in years)	244	5.652	4.436
Cost of alternative soil conservation (in 1000sh)	243	0.240	0.599
Age of household head	246	55.187	13.782
Cation exchange capacity (CEC)	243	15.723	5.417
Price of maize (in 1000sh)	236	0.042	0.059

The summary statistics in table 1 indicates that the mean residue left on each plot is approximately 713 kilograms, with very high variance of 1269 kilograms.[3] The data on soil capital was obtained from physical soil samples collected during the same period from all the farms. The soil samples were taken from the topsoil at depths of 0–15 centimeters, based on three replicates in each farm field (*shamba*). Places where mulch, manure, and chemical fertilizer were visible were avoided for soil sampling. The soil samples were air dried and analyzed at the Department of Soil Science (DSS), University of Nairobi.

Based on geographical comparisons and laboratory analysis (Thomas 1997), the soil samples statistics indicated that the soils in the study area are generally acidic, moderate in carbon and organic matter, and have a low mean cation exchange capacity (CEC) of 15.72. The CEC is a value on a soil analysis report to indicate its capacity to hold cation nutrients. Generally, the more clay and organic matter present in the soil, the higher its value. The pH in water was also measured and a mean value of 5.618 was obtained.

Of the total sample of 246 farmers who practice conservation agriculture, agricultural extension officers visited only 24 percent of the plots. Furthermore, the mean price of maize was KSH 42, and the average cost of alternative methods of conservation per hectare was KSH 240. In addition, the average household size was 4 people, and the head of the household had an average of 5.7 years of education. Finally, the mean age of the household head was 55 years.

To obtain the estimated value of the residue left on each plot, we estimated an ordinary least square (OLS) regression with robust standard errors. The R-squared indicates that the line is a fairly good fit to about 27 percent of the variation in the residue deposited on the plots explained by the explanatory variables. From the regression results, plots with relatively high cation exchange capacity (CEC), on the average, have low crop-residue deposits, with the highest elasticity coefficient of 0.63. Second, households that sell maize at relatively higher prices left more residue on the farm soil. The corresponding elasticity indicates that a 10 percent increase in the price of maize could increase the quantity of deposits deposited on the plots by 1.8 percent. Third, plots that were visited by extension officers had more residue left on the farm and farmers who could manage the relative high alternative cost of conservation, all other things being equal, deposited more residues on the farm.

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[3] Thorne et al. (2002) noted that in Kiambu, Kenya, average amount of maize stovers per hectare was 1116 kilograms, which is close to our estimate.

The policy implications are that extending extension services to plots could improve conservation agriculture. Furthermore, household size and the level of education of the head of the household are positively related to the quantity of residue deposited on the plots. Incorporating residue in soil is labor intensive. As a result, a big household size indicates that the farmer could afford the labor needed for conservation agriculture. In addition, a better educated farmer is likely to understand the benefit of conservation agriculture.

Table 2. OLS Regressions of the Determinants of Crop Cover Deposited on Plots

Variable	Coefficient	Elasticity	t-stats
pH in water	0.138	0.770	1.26
Extension officers visit farm (= 1; 0 otherwise)	0.626	0.146***	3.84
Household size	0.069	0.288**	2.35
Education (in years)	0.063	0.357***	3.70
Cost of alternative soil conservation	0.423	0.103***	4.28
Age of household head	0.005	0.249	0.87
Cation exchange capacity (CEC)	-0.041	-0.634 **	-2.13
Price of maize (in 1000sh)	4.196	0.184***	4.29
Constant	4.278		6.70
R-Squared	0.27		
Observations	227		

* significant at 10%; ** significant at 5%; *** significant at 1%.
Robust and absolute values of t-statistics are in parentheses.

5. Conclusions

Agriculture and land use are two of the largest contributors to the world's greenhouse gas emissions (32 percent). Agricultural soils are among the planet's largest reservoirs of carbon and hold—given changed practices—huge potential for increased carbon sequestration. Conservation agriculture is a somewhat different cultivation practice and includes conservation tillage and integrated crop residue management, for example. It may be a desirable option to maintain or improve soil fertility and crop yields of farms (by replenishing essential nutrients, such as soil carbon), and increase land resilience against drought and other hazards.

Providing soil cover by leaving crop residue on the soil also has other private benefits, such as preventing or reducing soil loss and maintaining soil moisture on farms. However, in developing countries, leaving crop residue on a plot has alternative beneficial uses, such as fodder for livestock or fuel for homes. In addition, crop residue reintegrated into the soil sequesters carbon (offsets CO_2 emissions), which generates positive externalities to society that are not typically internalized by the farmer.

We modeled this trade-off and developed an expression for an optimum economic incentive that is necessary to internalize the positive externality. We considered two situations that represent the practice in Kenya: whether the harvested residue is privately used as fodder or as a common pooled resource. The results indicate that the subsidy should be higher if it is used as a common pooled resource than as a private resource. A rough estimation based on an estimated value of the residue deposited on plots and other parameter values adopted from the literature gives an ad valorem subsidy of approximately 102 percent on the price of maize. Furthermore, we investigated the determinants of the residue left on the plot and found that plots with relatively high cation exchange capacity (CEC) have low crop residue deposits. On the other hand, households that sell maize at relatively higher prices, plots that were visited by extension officers, relatively larger household size, the level of education of the head of the household, and farmers who could manage the relatively high alternative cost of conservation left more residue on the farm land. As a result, policies that target any of these variables, for example, extending extension services to plots, could impact conservation agriculture within that farming area in Kenya.

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