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An Econometric Investigation of Impacts of Sustainable Land Management Practices on Soil Carbon and Yield Risk

A Potential for Climate Change Mitigation

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ABSTRACT

We investigate the impacts of sustainable land management practices on soil carbon stocks and also impacts of soil carbon on the mean and variance of crop production using econometric tools. Using a cross-sectional plot-level dataset collected from three agroecological zones of Uganda with soil carbon measured at a depth of 0 to 15 centimeters, our results have robustly shown that irrigation, fertilizers, improved fallow, crop residues, mulching, and trash lines are positively and significantly associated with higher soil carbon, corroborating results from agronomic experiments. However, we found crop rotation associated with lower soil carbon, which has also been observed in some agronomic experiments. Soil carbon has shown a significant nonlinear effect on crop production with the threshold occurring at 29.96 milligrams of carbon per hectare, above which farmers start to see significant positive effects on crop production. Furthermore, we found soil carbon to be associated with lower variance of crop production; hence, soil carbon is an indicator of crop yield loss risk (soil carbon has a risk-reducing effect). These empirical results have demonstrated strong evidence for developing countries of the potential of sustainable land management practices to enhance carbon sequestration and also the potential of soil carbon to reduce production risk. The results have implications for the role that soil carbon can play in adaptation to climate change and provision of ecosystem services.

Keywords: land management, climate change, soil carbon, Uganda, production risk, carbon sequestration, Just and Pope stochastic production function

1. INTRODUCTION

Increase in the emission of greenhouse gases such as carbon dioxide is a major concern due to its effect on global warming and climate change (Rastogi, Singh, and Pathak 2002). Current carbon credit markets are part of the global response to this challenge. Unfortunately, agricultural carbon is not included in the major carbon credit market despite the facts that soil is a major source of and sink for atmospheric carbon dioxide (Jensen et al. 1996; Jassal et al. 2005) and that soil contains twice as much carbon as the atmosphere (Mielnick and Duga 1999; Maier and Kress 2000). Soil temperature and moisture content are the main characteristics that affect carbon dioxide efflux from soils (Jabro et al. 2008). Land management practices can influence soil temperature and moisture content (Curtin et al. 2000; Al-Kaisi and Yin 2005; Kravchenko and Thelen 2007), which directly affect carbon dioxide fluxes from the soil surface (Bajracharya, Lal, and Kimble 2000; Parkin and Kaspar 2003; Amos, Arkebauer, and Doran 2005), hence affecting soil carbon levels. Land management practices, such as tillage, cropping system, cover crop, and nitrogen fertilization, influence the stock of and changes in soil organic carbon (Campbell et al. 1989; Cambardella and Elliott 1992; Chan 1997; Bayer et al. 2001; Sainju et al. 2006; Sainju et al. 2008). Carbon sequestration, using long-term improved soil and crop management practices, is needed not only to increase soil carbon storage for carbon trading and to mitigate greenhouse gas emissions from the soil profile but also to improve soil quality and increase economic crop production (Sainju et al. 2008).

There is ample evidence from experimental studies on the effect of land management practices in developing countries (Bayer et al. 2001; Sainju et al. 2006; Sainju et al. 2008). However, there is little evidence of the effects of farmers' land management practices in developing countries on soil carbon (Conant, Paustian, and Elliott 2001; Smith et al. 2006; Jobro et al. 2008). Therefore policymakers, development practitioners, and scientists have little information about which land management practices should be part of development themes to encourage carbon sequestration in developing countries. This study fills this gap by sharing robust empirical evidence on the carbon stock potential of various land management practices in Uganda, which could be part of carbon sequestration schemes promoted in similar agroecological conditions in Sub-Saharan Africa. Soil carbon sequestration has an important strategic role due to its low cost and potential for early deployment within a portfolio of technologies to mitigate climate change (Edmonds, Dooley, and Wise 1997; Rosenberg and Izaurralde 2001). Unlike previous studies from developing countries, which have investigated these relationships using long- and short-term experiments, we have used an econometrically based, multivariate analysis that controls for many potential confounders as well as farmers' constraints, which has the advantage of controlling for the effects of the unobservables while also allowing for interaction effects between Soil and Water conservation technologies SWC technologies.

2. THEORETICAL AND EMPIRICAL CONCEPTUAL FRAMEWORK

Impacts of Land Management on Soil Carbon and Production Risk

Soil organic carbon (SOC) is two-thirds of the total terrestrial carbon pool (Trumbore, Charwick, and Amundson 1996) and is one of the key indicators of soil quality (Seybold et al. 1997; Six et al. 2002). Soils play a role in the global carbon cycle, acting as a sink and a source of atmospheric carbon dioxide; hence, they have potential to influence global climate change (Paustian et al. 1998, 2000). Changes in SOC can be attributed to crop species grown, cropping systems (including rotations), residue management practices, fertilizer applications, tillage practices, and other management factors (Unger 1968; Bauer and Black 1981; Anderson, Gantzer, and Brown 1990; Havlin et al. 1990; Bremer, Janzen, and Johnson 1994; Campbell et al. 1995).

Experiments have shown nitrogen fertilizer to increase organic matter content (Power and Legg 1978; Blevins et al. 1983; Stevenson 1986; Tate 1987), but mostly in monoculture systems. Rasmussen and Rohde (1988) reported linear increases in SOC when nitrogen fertilizer was applied and noted that crop residue had a positive impact on SOC. Rasmussen and Parton (1994) reported that the rate of SOC change was directly related to carbon input from crop residues and amendments. Manure, crop residues, and compost have also been found to increase carbon sequestration, with implications for global climate change (Dersch and Bohm 2001; Iazurralde et al. 2001; Eghball 2002). Many of these practices that favor carbon storage appear to interact synergistically with each other, so that increases in SOC under one practice are greater when combined with other practices (Grant et al. 2001). Although conventional tillage without cover crop and without nitrogen fertilization reduces the soil organic matter level by enhancing carbon mineralization and limiting carbon inputs (Dalal and Mayer 1986; Balesdent, Mariotti, and Boisgontier 1990; Cambardella and Elliott 1993), conservation tillage with cover cropping and nitrogen fertilization can increase carbon storage and active carbon fractions in the surface soil (Jastrow 1996; Allmaras et al. 2000; Sainju et al. 2002, 2006). Studies suggest that conversion of conventional till to no-till can sequester atmospheric carbon dioxide by 0.1 percent per hectare at a depth of 0 to 5 centimeters every year, or by a total of 10 tons in 25 to 30 years (Lal and Kimble 1997; Paustian et al. 1997). However, SOC deeper than 7.5 centimeters can be higher in tilled areas, depending on the soil texture, due to residue incorporation at greater depths (Jastrow 1996; Clapp et al. 2000). Similarly, cover cropping and nitrogen fertilization can increase carbon fractions in tilled and non-tilled soils by increasing the amount of crop residue returned to the soil (Kuo, Sainju, and Jellum 1997; Omay et al. 1997; Sainju et al. 2002, 2006). The impact of tillage on soil carbon fractions can interact with cover cropping and nitrogen fertilization rate (Gregorich et al. 1996; Wanniarachchi et al. 1999; Sainju et al. 2002), soil texture and sampling depth (Ellert and Bettany 1995), and time since treatments were initiated (Liang et al. 1998).

Use of agroforestry practices enhances carbon uptake by lengthening the growing season, expanding the niches from which water and soil nutrients are drawn, and in the case of nitrogen-fixing species, enhancing soil fertility (Nair, Kumar, and Nair 2009). The result is that when agroforestry systems are introduced in suitable locations, carbon is sequestered in the tree biomass and tends to be sequestered in the soil as well (Jose 2009). Improved management in existing agroforestry systems could sequester 0.012 teragrams of carbon per year while conversion of 630 million hectares of unproductive or degraded croplands and grasslands to agroforestry could sequester as much as 0.59 teragrams of carbon annually by 2040 (IPCC 2000). Other practices that enhance production, such as supplying adequate moisture through irrigation and nutrients, also result in greater carbon uptake, ecosystem carbon stocks, and forage production (Conant, Paustian, and Elliott 2001). As for production risk, surface cover, mulch, and soil organic matter all contribute to a decrease in interannual variation in yields (Lal et al. 2007), and practices that diversify cropping systems, such as grass and forage crops in rotation, sequester carbon and enhance yield consistency.

Conceptual Framework

The effects of land management practices on soil carbon were assessed through ordinary least squares (OLS) and instrumental variables (IV) structural regressions, while the impacts of soil carbon on the mean and variance of yield was done using the Just and Pope stochastic production framework (1978, 1979).

The Just and Pope parametric approach allows yield-enhancing inputs to have either a negative or a positive effect on the variance of yield by relating the variance of output to explanatory variables in a multiplicative heteroskedastic regression model. The stochastic production function is $y = f(\boldsymbol{X},\boldsymbol{S},\boldsymbol{\varepsilon})$, where y is the output; $\boldsymbol{S}$ is a vector of soil carbon and SWC inputs; $\boldsymbol{X}$ is a vector of other inputs; and $\boldsymbol{\varepsilon}$ represents the climate risks that are unknown at planting time. Just and Pope (1978) decomposed the production function into deterministic and stochastic elements as $f(\boldsymbol{X},\boldsymbol{S},\varepsilon) = g(\boldsymbol{X},\boldsymbol{S}) + [h(\boldsymbol{X},\boldsymbol{S})]^{1/2}\, e(\varepsilon)$, where $h(\boldsymbol{X},\boldsymbol{S}) > 0$, and $e(\varepsilon)$ is a random variable with mean zero and variance $h(\boldsymbol{X},\boldsymbol{S})$. This implies that $g(\boldsymbol{X},\boldsymbol{S})$ represents the mean production function and $h(\boldsymbol{X},\boldsymbol{S})$ is the variance of output, where $E(y) = g(\boldsymbol{X},\boldsymbol{S})$ and $Var(y) = Var(\varepsilon)\, h(\boldsymbol{X},\boldsymbol{S}) = h(\boldsymbol{X},\boldsymbol{S})$. Given $\partial Var(y)/\partial \boldsymbol{S} = \partial h/\partial \boldsymbol{S}$, it follows that $\partial h/\partial \boldsymbol{S} > 0$ implies that $\boldsymbol{S}$ is a risk-increasing input, and $\partial h/\partial \boldsymbol{S} < 0$ implies that $\boldsymbol{S}$ is a risk-decreasing input. This reflects the fact that the Just–Pope specification corresponds to a regression model with a heteroskedastic error term. After choosing a parametric form for $g(\boldsymbol{X},\boldsymbol{S})$ and $h(\boldsymbol{X},\boldsymbol{S})$, Just and Pope proposed estimating the model either by using a three-stage feasible generalized least squares (FGLS, also called *three steps*) or by full information maximum likelihood (FIML) estimating the $g(\boldsymbol{X},\boldsymbol{S})$ and $h(\boldsymbol{X},\boldsymbol{S})$ functions simultaneously, with the latter estimator being more efficient than the FGLS.

The Just and Pope framework has been widely used in previous studies (Smale et al. 1998; Widawsky and Rozelle 1998; Di Falco and Perrings 2005). It is applied in this study to investigate the effect of soil carbon at the plot level on the mean and variance of crop production. To account for market imperfections in the study sites, we included plot and household characteristics in the specification, capturing them as part of vector $\boldsymbol{X}$. Our choice of explanatory variables is guided by economic theory and earlier empirical studies on adoption of farm technologies (Feder, Just, and Zilberman 1985; Feder and Umali 1993), analyses on agricultural production and intensification (Vosti and Reardon 1997; Lee and Barrett 2001; Barrett, Place, and Aboud 2002; Benin 2006; Nkonya et al. 2008; Pender and Gebremedheni 2008), and analyses on the determinants of farm income (Hill 2000; López and Valdés 2000; Ruben and Clemens 2000).

3. STUDY AREA

This study in Uganda was part of a cross-country comprehensive study undertaken by the World Bank's TerrAfrica component and implemented by the International Food Policy Research Institute (IFPRI), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and the World Agroforestry Centre in the four Sub-Saharan African countries of Nigeria, Uganda, Kenya, and Niger to identify sustainable land management (SLM) approaches and practices that are suited to improve food security and economic prospects while reducing climate-related risks and greenhouse gas emissions. Selection of the four case study countries was done so as to represent the pattern of climate change in the Sub-Saharan Africa region. Transboundary case studies were selected to capture the impact of policies on response of farmers to climate change. The selection ensured that the transboundary sites had comparable biophysical and livelihood characteristics and that the major difference between the sites across the border was the policies in each country. A five-step site selection procedure was used:

1. Determination of climatologically similar areas: Monthly rainfall data from the Climatic Research Unit (CRU) (1981 to 2001) and NASA (2002 to 2007) for the four countries were used to compute the mean and standard error of annual rainfall, annual trend, and year squared trend coefficients for each pixel (0.5 degree pixel for CRU data and 1 degree pixel for NASA). Shift due to data sources was controlled in regression models with inclusion of month dummy variables and a dummy for the period from 2002 to 2007. T-statistics of the coefficients revealed a linear trend since the coefficients on the quadratic terms were not significant and were therefore excluded from the estimation. Hence the subsequent steps use only the linear trend model.
2. Pixel matching: This was done using the nearest-neighbor matching procedure (Abadie and Imbens 2006. Pixels from Niger and Nigeria in western Africa and Kenya and Uganda in eastern Africa were matched to demarcate areas having similar mean annual rainfall, standard error of annual rainfall, rainfall trend coefficient, and standard error of the coefficient. The matches with minimum percentage difference in these statistics between the matching pixels were kept. In western Africa, a minimum cutoff point of 10 percent difference was set to ensure that only matches that are close were included in the matched sample. In eastern Africa the matching pairs were fewer, and therefore the cutoff point was 20 percent.
3. Elevation: In the case of eastern Africa, elevation was also included in the matching characteristics to take into account terrain differences.
4. Market access and presence of sustainable land and water management (SLWM) projects: To determine the impact of access to market and technical support on farmer response to climate change, the matching pairs were further grouped according to market access and presence of SLWM projects.
5. Administrative division: The selected pixels were overlaid on boundaries of administrative units (districts in Kenya and Uganda, communes in Niger, local government areas [LGAs] in Nigeria), and the pixel that best represented the administrative division was selected.

In eastern Africa, three different agroecological zones (AEZ) were selected: (1) the semi-arid zone with pastoral communities, which represents 18 percent of the land area in Sub-Saharan Africa, (2) the matching site of Samburu district in Kenya, and (3) another matching site of Moroto district in Uganda. In the two latter districts, rainfall and population density are low and the major livelihood is transhumance even though subsistence crop production is an emerging livelihood undertaken as a diversification strategy to adapt to climate change.

4. METHODS

Dependent and Explanatory Variables

We implemented our analysis at plot level because soil carbon and SWC technologies, which are the focus of this study, were measured at plot and our dependent variable was also measured at the same level. This level of analysis is advantageous because it captures more spatial heterogeneity and also helps to control for plot-level covariates that condition crop production; hence it helps to minimize the omitted-variable bias that would confound household-level analysis.

The dependent variable for our Cobb–Douglas specification was expressed as value of crop production per hectare, which is a better representation than yield because most plots had intercropping with more than one crop, making estimation of single-crop production functions difficult. This approach of aggregating all crops on a plot into a single measure of value of crop production per hectare rather than using individual crop yields has been used in many previous plot-level microeconometric studies in Uganda and in other places in Sub-Saharan Africa (Pender et al. 2001, 2004; Nkonya et al. 2004, 2005, 2008; Benin 2006; Jansen et al. 2006; Pender and Gebremedhin 2008). We used village-level average crop prices to estimate the value of each crop and then generated an aggregate value of crop production per hectare for each plot.

Although the focus of this study is the effects of soil carbon and SWC technologies, we also controlled for a number of other explanatory variables that would be correlated with the observed plot-level crop outputs. The explanatory variables ($\boldsymbol{X}$) we controlled for included both plot-level and household-level covariates. The plot-level covariates included plot area and plot land tenure, plot biophysical characteristics (for example, soil type, soil fertility status, and soil erosion status), inputs used on the plot (such as draft power, fertilizers, purchased seeds, own seeds, family labor, and hired labor), land management practices used on the plot (for example, mulching, crop residues, manure, compost, and fertilizers), and land investments on the plot (for example, grass strips, improved fallows, trees, and irrigation). Household-level covariates included human capital factors (sex, age, education, and livelihood strategies), physical capital factors (value of equipment, livestock, farm area, female labor, and male labor), social capital factors (membership in production, saving, marketing, religious, and economic groups), and access to services (extension and market access). We also included district fixed effects to control for unobserved time-invariant characteristics that might be correlated with the dependent variable, which also mitigates the omitted-variable bias problem.

Functional Form and Econometric Diagnostics

Double logarithmic functional form of the Cobb–Douglas specification in the Just and Pope framework was used to improve normality of the residuals, thus reducing problems of nonlinearity, heteroskedasticity, and sensitivity to outliers (Mukherjee, White, and Wuyts 1998). All functional forms impose some restrictions, and even when enough is known to specify them adequately, greater flexibility is achieved with losses in degrees of freedom and increased colinearity as in the case of the translog functional form (Griffin, Montgomery, and Rister 1987). The Breusch–Pagan test in the OLS model and the Pagan–Hall test in the IV–two-stage least squares (IV-2SLS) model and the IV–generalized method of moments (IV-GMM) model were used to check for heteroskedasticity. In all cases, the null hypothesis of homoskedasticity was rejected at the 1 percent level of significance and we therefore applied the White heteroskedasticity-robust covariance matrix (White 1980), which is robust to heteroskedasticity of unknown form, as a correction. Due to the many explanatory variables used in the models, colinearity is a likely concern, which would affect inference. The variance inflation factors (VIF) and pair-wise correlations were used to test for multicollinearity. However, multicollinearity was not a serious problem: The VIFs were less than 6.0 and the pair-wise correlations were less than 0.4, indicating that the standard errors were not being affected by collinearity problems.

Estimation Procedure

We tried to estimate the Just and Pope production function using the more efficient full-information maximum likelihood procedure, but we failed to achieve convergence. To circumvent this, we used the three-stage FGLS procedure outlined by Judge and others (1982, 416–423). Following this procedure, the first step estimates the mean function $g(\boldsymbol{X},\boldsymbol{S})$ using ordinary least squares (OLS), the second step predicts the residuals and then constructs squared residuals, and the third step uses the squared residuals as the dependent variable for the variance function estimation $h(\boldsymbol{X},\boldsymbol{S})$ using OLS. The third-stage OLS estimates of the variance function are the main point of interest. A positive coefficient implies risk-increasing effects and, conversely, a negative coefficient implies a risk-decreasing effect of soil carbon on crop output.

Endogeneity and Robustness

Use of land management practices as explanatory variables in determination of soil carbon regressions and also as explanatory variables in the Just and Pope framework could cause a bias problem arising from the endogeneity of households choosing practices at the same time they make production decisions; hence these variables could be correlated with the error term. Because of this, the two-step, efficient GMM estimator was used for comparison and to check the robustness of the results. Traditional instrumental variables (2SLS) and ordinary least squares (OLS) results are also reported. GMM is more efficient than 2SLS and robust to heteroskedasticity of unknown form as well as to arbitrary intracluster correlations (Wooldridge 2002). To the extent that the instruments are weak, it is important to offer the OLS estimates for comparison (Bound, Jaeger, and Baker 1995). Because results may be influenced by outliers, the results of the robust regression, which is a more efficient estimator in the presence of outliers because it gives little weight to outlying observations, were also reported.

The validity of the overidentifying restrictions in the GMM model is tested using the Hansen J-test. The relevance of the excluded instrumental variables as predictors of the potentially endogenous explanatory variables is also tested, indicating that the chosen instruments are good predicators of the potentially endogenous explanatory variables. The results of these tests are reported with the regression results. In all cases, the results support the validity of the overidentifying restrictions of the instruments in the regression models. The Hausman exogeneity tests reject the null hypothesis, suggesting that the land management practices are endogenous. However, the results appear qualitatively the same with or without correcting for endogeneity. Most of the results appear quite robust across the different estimators of robust regression: OLS, IV-GMM, and IV-2SLS.

5. EMPIRICAL RESULTS

The econometric empirical results are reported in Tables 1 and 2; we report only results on soil carbon and SWC technologies, which are the main focus of this study. To avoid overwhelming the reader with too many results, we do not report the results of other factors that were controlled in the estimations; these other factors are not the key interest of this paper but were included to avoid the omitted-variable bias problem and ensure proper identification of the effects of carbon and SWC technologies.

Effects of Sustainable Land Management Practices on Soil Carbon

The econometric results of the effects of SLM practices on soil carbon at 0 to 15 centimeters are shown in Table 1. In both least squares and IV econometric estimations, the results robustly show that irrigation, agroforestry, fertilizer, improved fallow, crop residues, mulching, and trash lines are positively and significantly associated with higher soil carbon stocks measured at the soil depth of 0 to 15 centimeters. Surprisingly, we find crop rotation and interactions between mulching and either manure or residues associated with lower carbon stocks.

Table 1. Effects of land management practices on soil carbon (0–15 centimeters depth)

Variable	Least squares		IV	
Explanatory variables	Robust regression	OLS	IV-GMM	IV-2SLS
Mulch x manure	-0.436***	-0.329**	-0.329***	0.049
Mulch x crop residue	-0.303***	-0.194*	-0.194**	-1.428**
Agroforestry	0.153***	0.111**	0.111**	0.479
Irrigation	-0.017	0.302**	0.302***	1.392**
Fertilizer	0.194**	0.239***	0.239***	0.029
Improved fallow	0.335***	0.233*	0.233**	0.68
Crop rotation	-0.107***	-0.059	-0.059	-0.361*
Manure	0.041	-0.106	-0.106	-0.525
Deep tillage	0.066	0.058	0.058	-0.223
Strip cropping	-0.109*	-0.019	-0.019	0.519
Fanya chini	-0.128	-0.039	-0.039	-0.236
Crop residue	0.123***	0.026	0.026	0.941***
Mulching	0.155**	0.121	0.121*	0.357
Trash lines	0.211***	0.125	0.125*	0.073
_constant	3.395***	3.770***	3.770***	3.604***
N	349	349	349	349
Relevancy test of excluded instruments (p-value)				
Mulch x manure			0.004***	
Mulch x residue			0.000***	
Agroforestry			0.008***	
Irrigation			0.000***	
Fertilizer			0.000***	
Improved fallow			0.000***	

Table 1. Continued

Variable	Least squares		IV	
Explanatory variables	Robust regression	OLS	IV-GMM	IV-2SLS
Crop rotation			0.000***	
Manure			0.001***	
Deep tillage			0.000***	
Grass strips			0.000***	
Fanya chini			0.000***	
Crop residue			0.000***	
Mulching			0.000***	
Trash lines			0.000***	
Hansen j-statistic				
(Overidentification test of all instruments) (p-value)			0.160	
Exogeneity tests				
Wu–Hausman f-test (p-value)			0.000***	
Durbin–Wu–Hausman chi-square test (p-value)			0.000***	

Source: Authors Survey and soil Data.
Note: To avoid overcrowding the results, other explanatory variables used in the estimation are not reported since they are not the focus of this study.
***significance at 1% level; ** significance at 5% level;* significance at 10% level.

These empirical results have robustly demonstrated that sustainable land management practices involving use of irrigation, fertilizers, agroforestry, mulching, crop residues, and trash lines have the potential to increase soil carbon, which is consistent with most carbon sequestration literature (Follet, Kimble, and Lal 2001; Conant, Paustian, and Elliott 2001; Lal et al. 2007; Jose 2009; Nair, Kumar, and Nair 2009; Woodfine 2009). However, our findings that crop rotation is associated with lower carbon stocks is inconsistent with West and Post (2002), who found higher carbon stocks in rotations involving grasses and hay. In the present study, the rotations involved crops rather than grasses, but our finding is consistent with a study in the Philippines (Witt et al. 2000), which found higher soil carbon in fields that were continuously cropped with rice than in fields with a maize–rice rotation. The explanation for the latter observation was that replacement of rice with maize caused reduction in soil carbon and nitrogen sequestration due to mineralized carbon and less nitrogen input from biological nitrogen fixation during the maize crop (Witt et al. 2000).

This study therefore has provided more empirical support that sustainable land management practices have potential to sequester soil carbon and hence provide resilience to climate variation and climate change (Vallis et al. 1996; Pan et al. 2006). This demonstrates win–win outcomes of using land management practices to control soil and water conservation while also increasing carbon stocks that have a mitigative effect on climate change.

Effect of Soil Carbon on Crop Production and Production Risk

The econometric results showing the effects of soil carbon on the mean and variance of crop production are shown in Table 2 below. On the mean effects, the results are very robust across all the estimators used (OLS, robust regression, and IV), showing that crop production is significantly lower at lower carbon levels and significantly higher with higher soil carbon levels. From the regression estimates, the nonlinear relationship between soil carbon and crop production suggests that soil carbon levels have to exceed a threshold of 29.96 milligrams per hectare for farmers to start realizing a significant positive response on crop yields. According to the data, 43 percent of the plots sampled were below this carbon stock threshold, and they were associated with low manure use (3 percent), low compost use (0.6 percent), and nonuse of fertilizer; however, they had disproportionately higher use of crop rotation (50 percent) and crop residues (31 percent).

Table 2. Effects of soil carbon on the mean and variance (risk) of crop production

	Mean Function				Variance Function	
Variable	OLS	Robust regression	IV-GMM	IV-2SLS	OLS	Robust regression
Log (carbon)	-25.702**	-17.483**	-24.007***	-29.074**	4.174	50.525*
Log (carbon) squared	3.646**	2.512***	3.402***	4.205**	-0.569	-6.653*
Mulch x crop residue	-1.458	-1.572**	-1.446	-2.232	-3.385***	3.87
Agroforestry	0.521	0.600*	0.45	-0.528	0.076	-1.614
Irrigation	0.104	-4.209**	0.779	-3.374	0.394	-2.468
Fertilizer	-1.186	-2.117***	-1.152	-0.184	-0.313	-0.29
Improved fallow	0.642	2.258***	0.543	3.592	-2.168*	-4.848
Crop rotation	0.448	0.403	0.501	-0.968	-0.901*	-1.695
Manure	-0.075	0.512	-0.284	0.741	0.449	1.465
Deep tillage	0.266	0.027	0.187	0.195	0.109	-0.035
Grass strips	-0.412	-0.611	-0.423	-0.189	0.392	-0.347
Fanya chini	0.544	-0.283	0.547	2.042	-4.024***	-2.358
Crop residue	0.2	-0.216	0.099	1.268*	-1.167**	-0.704
Mulch	0.067	0.518	0.121	0.941	3.597***	0.161
Trash lines	0.914	0.553	0.874	-1.055	1.443**	-1.097
_consant	56.118***	43.371***	53.432***	62.456**	-4.186	-89.305*
					162	162
N	158	158	162	162		

Source: __Authors survey data and soil data.
Note: To avoid overcrowding the results, other explanatory variables used in the estimation are not reported since they are not the focus of this study.
***significance at 1% level; ** significance at 5% level;* significance at 10% level.

Conversely, the nonlinear relationship between soil carbon and variance of crop production shows that higher carbon levels are associated with lower variability in crop yields, indicating that soil carbon reduces production risk. This empirical finding further provides evidence that enhancing and increasing soil carbon stocks has the potential to mitigate the effects of climate change on crop production in a developing country like Uganda.

6. CONCLUSIONS AND IMPLICATIONS

In this study we have investigated the effects of land management practices on soil carbon as well as the effects of soil carbon stocks on crop production and production risk after controlling for other potential confounders. Using multivariate analysis methods, we find very robust evidence that the use of irrigation, agroforestry, fertilizer, improved fallow, mulching, crop residues, and trash lines are significantly associated with higher soil carbon stocks, while use of crop rotation and interactions between mulch and either manure or crop residues is associated with lower soil carbon stocks in Uganda. The results further show that higher soil carbon stocks are associated with higher crop production and lower variance in crop production; hence carbon stocks reduce risk, which is a beneficial effect for risk-averse farmers faced with climate change and climate variability. Our results have also shown soil carbon to have a nonlinear effect on crop production and variance, with the threshold being 29.96 milligrams of carbon per hectare, above which farmers start to realize significant positive effects on yields.

These empirical findings have useful implications. First, programs that focus on enhancing carbon sequestration in developing countries should also consider promoting sustainable land management practices because they have win–win outcomes of controlling soil erosion as well as facilitating carbon sequestration. Second, as interventions are being sought for protecting farmers against adverse effects of future climate change in Sub-Saharan Africa, an effort to increase soil carbon stocks is a very promising intervention, since it has been empirically shown in our analysis to significantly reduce production variance (risk), indicating that soil carbon has the potential to mitigate the effects of climate on crop production. These findings and implications have relevance to other places with similar farming systems and agroecological conditions to those in Uganda, and therefore the evidence from this study can be used to outscale such interventions in those environments.

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