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Abstract

This paper combines knowledge from soil science and economics to estimate economic determinants of soil capital. Explaining soil capital facilitates a better understanding of constraints and opportunities for increased agricultural production and reduced land degradation. This study builds on an unusually rich data set that combines data on soil capital (represented by chemical and physical properties) and economic data on household characteristics, labor supply, crop allocation, and conservation investments. The study yields both methodological and policy-relevant results.

On methodology, the analysis shows that soil capital is heterogeneous with soil properties widely distributed across the farms. Likewise, farmers' investment decisions and soil management vary widely across farms. Hence simplifications of soil capital, which are common in the economics literature, may have limited validity. On the other hand, soil science research, when limited to biological, physical, and chemical characteristics, fails to recognize that soil is capital that is owned and managed by farmers. Such research runs the risk of omitting important socio-economic determinants of soil capital. It also excludes the opportunity to explain some of the dynamics that are determined by soil's stock character.

For policy, this study shows that farmers' soil conservation investments, allocation of labor, manure and fertilizer inputs, and crop choice do indeed determine variation in farmers' soil capital. Particularly strong positive effects on key soil nutrients (nitrogen, phosphorus, and postassium) were observed for certain conservation technologies. Extension advice unexpectedly showed no significant effects on soil capital. The wide distribution of soil properties across farms reinforces the need to tailor technical extension advice to the specific circumstances in each farm, and to enhance the integration of farmers' knowledge and experiences, expert judgment, and scientific soil analysis at the farm level.

Key Words: Soil fertility, soil productivity, resource management

JEL Classification: Q12, Q20

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Introduction

Soil degradation and soil nutrient depletion are increasingly regarded as major constraints to food production in tropical environments of the world (Stoorvogel and Smaling 1998; Pimentel and Kounang 1998; Scherr 1999). These problems are primarily caused by soil erosion, which is particularly damaging in the tropical highlands (Lal 1987; 1995; Tengberg et al. 1998). The purpose of this paper is to estimate the economic determinants of soil capital to facilitate a better understanding of the constraints and opportunities facing agricultural production and sustainable land use (Shiferaw and Holden 1999, 2001; Nkonya et al. 2004).

In this paper, we argue that research on soil issues has been carried out by two disciplines—soil science and economics—and that these are insufficiently integrated. Research in soil science has advanced our knowledge of the functions and complexities of soil (for example, how soil is formed and changes over time). The traditional focus has been on physical, chemical, and biological determinants, and the integration of economic theory or economic factors has been limited. Soil-related research in economics has focused *inter alia* on the impact of soil properties on agricultural production (see, e.g., Berck and Helfand 1990; Berck et al. 2000). Research on explaining soil as such has, however, been limited, despite the fact that soil is a key factor in the world's crop production. As showed by soil science, soil is not a constant or homogenous factor. It varies across time and spatially, and its properties are unevenly distributed down the soil profile, with profound implications for crop production (Paul and Clark 1996; Sparks 1999).

Although economic research on optimal soil use (see, e.g., McConnell 1983; Barrett 1991, 1997; LaFrance 1992) has developed our understanding of soil from an economics perspective, a large share of the economics research featuring soil has tended to ignore or over-

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simplify natural capital, and soil in particular, in these analyses (Barrett 1991, Dasgupta and Mäler 1997). In many models, soil is presented as a homogeneous production factor represented by a single proxy, such as land area, soil depth, or some quality indicator. The important complexities explained by soil science are largely ignored. However, the different sets of knowledge accumulated in soil science and economics would benefit from enhanced integration. Specifically, increasing the understanding of economic determinants to soil capital would fill a gap in the field. It can also enhance policy making and policy decisions. For this paper, we combined knowledge from these two disciplines and studied the relationship between soil capital and farm management.

We address a number of questions in this paper. Do production inputs, such as labor supply to cultivation, inorganic fertilizer, and manure, explain the status of various soil properties? Do age, gender, and education of the household head help explain the status of various soil properties? To what extent do soil conservation investments explain differences in various soil properties? What role does technical extension advisory services play in determining soil capital? What impact does a farmer's choice regarding land allocation to various crops have on soil capital?

To help answer these questions, section 2 discusses some of the relevant literature on soil research. Section 3 presents the model to be estimated and section 4 describes the field study area, the data, and data collection. Section 5 has the statistical results and section 6 draws conclusions and sketches some pertinent policy implications.

1. Research on Soil

In order to identify the economic determinants to soil capital, we need a profound understanding of what soil is. The research on soil in the natural sciences is vast. Research in soil sciences (e.g., pedology, edaphology, geomorphology, agronomy, and ecology) has developed our understanding of what soil is and how it is formed. Soil is usually represented by a minimum set of biological, physical and chemical properties. Typical properties include primary macro-nutrients, such as nitrogen (N), phosphorus (P), potassium (K) and carbon (C); secondary macro-nutrients, such as calcium (Ca), magnesium (Mg), and sulphur; and micro-nutrients, such as iron

(Fe), copper (Cu); chemical properties, such as cation exchange capacity (CEC);[1] alkalinity/acidity (pH); structural properties;[2] and texture.[3] Jenny (1994) suggested that soil formation is a function of climate (*cl*), biota (*o*), topography (*r*), parent material (*p*), time (*t*), and other variables, (***Z***): $\boldsymbol{S} = f(cl, o, r, p, t, \boldsymbol{Z})$. Here, ***S*** is a vector of soil properties (or characteristics) and refers to the state of these properties at a point in time. Although the relationships between *cl, o, r, p,* and *t* are generally supported (see, e.g., Birkeland 1997; Bridges 1997; Gray and Murphy 2002), the relative importance of these different factors is still debated (Gray and Humphreys 2004).

1.1 Soil Quality

Soil scientists have addressed the issues of if and how the soils' complexities can be aggregated and properly represented in relation to its various functions.[4] Consequently, soil quality (SQ) has been developed as a concept to define soils' dynamic properties, to grade and assess soils' agricultural potential, and to assess soils' ecosystem functions (Andrews et al. 2004). Soil quality has been defined as "capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Allan et al. 1995). SQ is closely related to other concepts, such as soil fertility and soil productivity.[5] Identification and assessment of SQ are usually based on a minimum data set of biological, chemical, and physical

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[1] Cation exchange capacity (CEC) is the capacity of a soil for the exchange of positively charged ions between the soil and the soil solution. CEC is an essential soil property and is used to measure soil fertility and nutrient retention capacity. CEC is highest in clay soils.

[2] Soil structure is important because it determines the soil's porosity and air and water holding capacity.

[3] Texture represents grain-size distribution of clay, silt, and sand particles. It helps measure retention of water and nutrients. Clay has the highest capacity, but clayish soils are more erodible. Good plant growth usually favors more balanced soils, e.g., sandy loams (Sparks 1999).

[4] These function are production of food, fiber, and fuel; filtering and buffering wastes and water; nutrient storage; provision of gene reserves and raw materials; cultural heritage; and support for physical structures (Schjønning 2004).

[5] Soil productivity has been defined as "the overall productive status of a soil arising from all aspects of its quality and status, such as its physical and structural condition as well as its chemical content." Similarly, soil fertility is defined as "the soil's ability to produce and reproduce. It is the aggregate status of a soil consequent on its physical, chemical, and biological well-being" (Stocking and Murnaghan 2001, 146). Other concepts include, e.g., soil resilience, soil health, sustainable soil use, and soil degradation, including soil pollution (Coleman and Hendrix 2004).

properties, which are transformed into a weighted soil quality index (SQI).[6] Given the choice of soil properties and weights, the intended soil use and its objective(s), specific SQIs can be identified for various soils. Although some argue for the potentials of this approach (see, e.g., Karlen et al. 1997, 2003; Carter 2002), identification and use of SQ and SQIs have been criticized for being normative, use-dependent, and biased towards crop production and certain geographical regions, and for lacking consideration of the fact that crops have different soil requirements. The unlimited diversity in farming strategies (e.g., choice of physical inputs, management, and crops) implies an infinite number of unique SQ optima. The critics argue that the complexities of soil can or should not be reduced to one technical denominator, such as an index (Sojka and Upchurch 1999; Sojka et al. 2003; Letey et al. 2003; Schjønning 2004).

The soil sciences have developed our understanding of how soil is formed and how it changes as a result of natural phenomena. However, one perspective which is largely missing in the soil science literature is the contribution by economics—that soil is capital (McConnell 1983; Barrett 1997). All the observed soil properties can be, and often are, shaped by the hand of the farmer. Hence, the farmer's characteristics, skills, and choices may have roles in shaping the farmer's soil capital. For instance, Nkonya et al. (2004) showed that economic factors may contribute both positively and negatively to small-scale farmers' nutrient balances. They also showed that the annual cost of nutrient mining (losses of nitrogen, phosphorus, and potassium) in households subject to erosion and other forms of soil degradation amounts to around 20 percent of the farmers' income. By investing labor in soil conservation, farmers can increase their soil capital (build up soil productivity and soil fertility) and thus increase future harvests (Gachene and Kimaru 2003). Soil erosion and failure to maintain soil fertility imply capital depreciation.

Economists argue for the importance of treating soil conservation and erosion/nutrient depletion as dynamic processes in which a stock of *capital* is being built or depreciated (see, e.g., Barbier 1998). One of the fundamental insights from this concept is the long time lags and complicated dynamics involved in an investment in the past to an improved (but not readily visible) stock in the present and to tangible increases in crop yields in the future.

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6 For instance, Tiwari et al. (2006) suggested that $SQI = \sum_{i=1}^{n} W_i Q(X_i)$, where W_i is the weight factor associated with each soil quality factor $(Q(X_i))$.

1.2 Soil Research in Kenya

Compared to many other developing countries, Kenya is relatively well endowed with soil-related research. Relevant studies focusing on the highlands include Ovuka and Ekbom (2001), who investigated the relationships between farmers' wealth levels (capital assets and income) and soil properties. Smaling et al. (1993), Stoorvogel and Smaling (1998), van den Bosch et al. (1998), Hilhorst and Muchena (2000) and de Jager et al. (2001) identified soil nutrient balances of various farming systems. Ovuka (2000), Gachene (1995), Gachene et al. (1997) analyzed the impact of soil change (erosion) on individual soil properties. Gachene et al. (1998) and Kilewe (1987) analyzed the yield effects of soil erosion. Gicheru (1994) analyzed effects of residue mulch and tillage on soil moisture. Batjes (2004) projected changes in carbon stocks in relation to land use. Hartemink et al. (2000) investigated the nitrogen dynamics in fallows and maize production for different soil types. Gicheru (1994) analyzed the effects of mulch and tillage on soil moisture. Dunne (1979), Moore (1979), and Lewis (1985) estimated soil loss and sediment yields. Common to most of these studies and other similar research is the fundamental lack of integration of soil data and economic variables in order to identify determinants of soil capital.

2. The Empirical Model

We assumed that soil capital can be represented by a vector of individual soil properties[7], $\boldsymbol{S}=\{S_i\}$, i=1..n, and that each soil property can be explained by a set of independent variables:

$$\boldsymbol{S} = f(\boldsymbol{H}, \boldsymbol{I}, X, \boldsymbol{PF}, \boldsymbol{R}) \ . \qquad (1)$$

In equation (1), $\boldsymbol{H}$ represents a vector of household characteristics. $\boldsymbol{I}$ is a vector of variables representing soil conservation investment, $I \in \{I_1, I_2, I_3, ..., I_{11}\}$. X represents technical extension advice provided to farmers on soil and water conservation. $\boldsymbol{PF}$ is a vector of variables representing physical production factors used in the agriculture production. $\boldsymbol{R}$ is a vector representing variables on crop allocation. (These variables are explained in more detail in section 3.)

[7] It may be argued that soil capital would be better represented by some sort of index or a composite indicator. However, due to soils' inherent complexities and the arguments proposed by Sojka and Upchurch (1999), Sojka et al. (2003), Letey et al. (2003) above, we used a disaggregated representation of soil.

The rationale for the specification of equation (1) is based on our hypothesis that $\boldsymbol{Z}$ contains a sub-set of economic factors, where $\boldsymbol{Z} \in \{\boldsymbol{H}, \boldsymbol{I}, X, \boldsymbol{PF}, \boldsymbol{R}, E\}$, which may explain some of the variation in $\boldsymbol{S}$. If we observe large variation in the distribution of soil properties across farms, and can assume that the basic (inherent) soil-forming factors (climate, topography, bedrock, etc.) proposed by Jenny (1994) are identical or at least very similar for all farms, then it is reasonable to assume that economic factors have roles to play in explaining farmers' variations in soil capital. Besides our proposition that soil is a heterogeneous good, we also assumed that the farmers' decisions on soil management and (re)investment are made up of a set of heterogeneous decisions, which also vary across farms.

Ideally, identifying determinants of soil capital implies a study over a long time horizon since several soil properties are shaped or accumulated over significant time. It is generally true that soil capital is relatively inert and constant, particularly in sub-soil layers (B- and C-horizons), partly because several natural soil-forming factors are relatively stable over time (Coleman and Hendrix 2004). However, if the soil is subjected to erosion, drought, and inadequate farming practices, for example, the properties in the humus layer (O-horizon) and in the topsoil (A-horizon) can change rapidly, with negative effects on fertility and productivity (Gachene 1995; Tengberg et al. 1998; Stoorvogel and Smaling 1998). Hence, as an effect of the non-linear distribution of soil properties in the soil profile, even very deep soils (>200 cm) are at risk of quickly depreciating their economic value when subjected to erosion.

Since soil is capital, its development depends on the values of explanatory variables over a long time period. Consequently, the ideal data should cover the dependent and explanatory variables over many years, but such data are not available, and we are thus forced to try to glean evidence from a cross-section of farms over a limited number of years. Based on equation (1) and our data (which covers between 1 and 4 years for different variables), we performed a regression analysis in the hope that differences in behavior on farms were reasonably stable so that the data we have is representative for a longer period of time. Some of our variables—such as the quality of soil conservation measures—are themselves expert assessments of the accumulated effect of soil management over a fairly large number of years. In order to compare regression coefficients, all variable values were normalized around the statistical mean of the sample.

To prevent biased estimates caused by temporary events taking place during one growing season or a single year, our model includes field observations over eight consecutive growing seasons. Four years of data allowed for impacts caused by inputs and measures implemented in the most recent time periods. It can be argued that inputs and investments undertaken farther back than four years might also have significant impacts on current soil properties. To some extent, the assessment of farmers' soil conservation structures is used to compensate for our lack of historical data. In practice, the observations of soil conservation investments (I_1–I_{11}) represent the physical outcome today of farmers' labor allocation for soil conservation in the past. Regarding annual inputs, it can be argued that the impact of historical fertilizer and manure inputs on current soil capital diminishes rapidly as the nutrients are either taken up by plants, leached down the soil profile, volatilized, or washed away (van den Bosch et al. 1998; Hilhorst and Muchena 2000; Warren and Kihanda 2001).

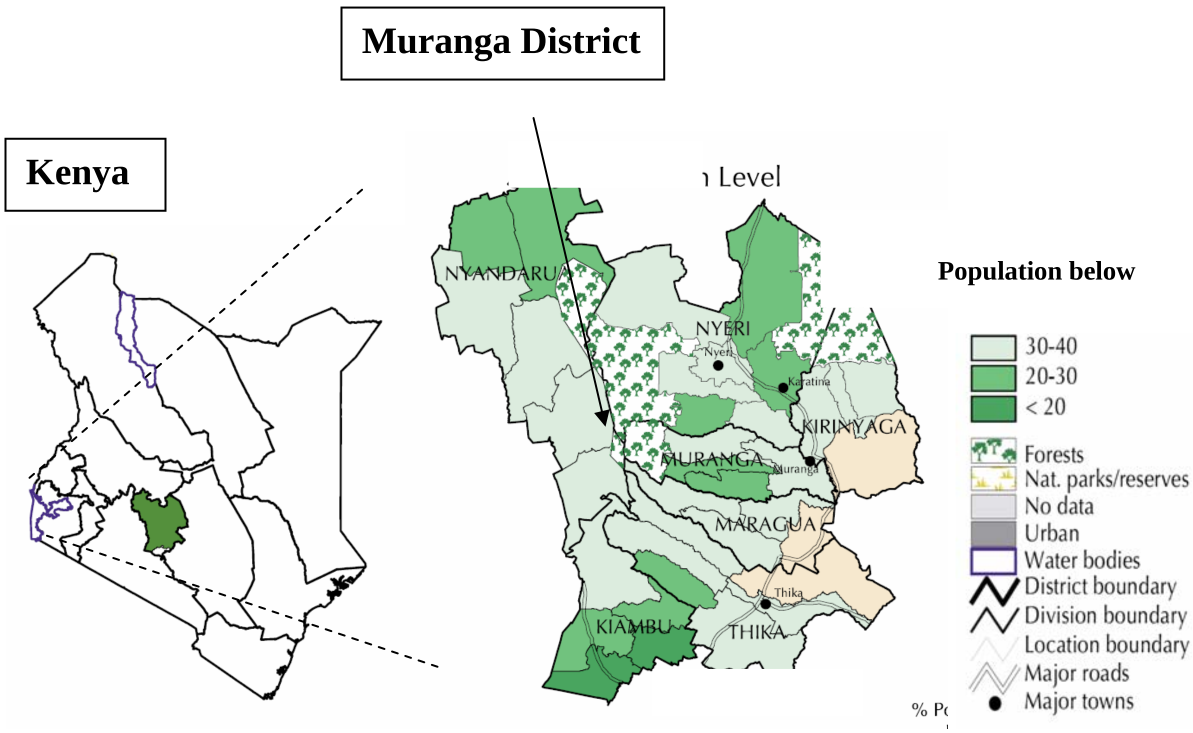
The proposition expressed by equation (1) warrants an explanation of how it should be understood. It does not represent a supply function of soil or a demand function of soil capital. Essentially, it describes an empirical metric for $\boldsymbol{S}$. Primarily we are trying to answer two questions: what can be a reasonable representation of $\boldsymbol{S}$ and what determines $\boldsymbol{S}$? It is true that one can see equation (1) as a reduced-form expression of a system in which there is both supply and demand. Defining whether equation (1) represents a supply *or* demand function of soil capital implies a non-separability problem since this is a complex household production with unobservable, interacting characteristics, some of which evolve slowly over time. Thus, all we have is the reduced form—influenced by both demand and supply factors.

The econometric estimation of model 1 implies regression of multiple equations based on the same data. This implies that the error terms may be contemporaneously correlated across the equations. In order to address this potential problem, we performed a joint estimation of the equations using SUR (seemingly unrelated regression), which is generally more efficient than separate estimation by ordinary least squares, or OLS (Zellner 1962; Mehta and Swamy 1976).

3. Field Study Area and Data

The study area is located in Muranga District, Kenya. It is located at 1,500 meters above sea level on the eastern slopes of the Nyandarua range in Kenya's central highlands, south of Mount Kenya and southeast of the Aberdares forest reserve. It consists of two adjacent watersheds. Muranga District covers 2,525 square kilometers and is part of the large drainage area of Kenya's central highlands. The climate is semi-humid (Sombroek et al. 1980), and the average annual precipitation is 1,560 mm, distributed over two rain seasons, March–May and October–December (Ovuka and Lindqvist 2000). The district thus has two growing seasons each year.

Map 1 Kenya and the Location of the Study Area



Source: World Resources Institute (2003)

The study area lies within the main coffee-producing zone. The main soil type is humic nitisol, distributed over volcanic foot ridges. The soils are dark reddish-brown, well-drained, and very deep (>200 cm). Undisturbed, they are classified as fertile with very good yield potential (Jaetzold and Schmidt 1983). However, erosion, strong leaching, continuous cropping, constant use of inorganic fertilizers, and other factors have severely reduced the soil fertility (Gachene and Kimaru 2003).

Land tenure in the field study area has historically been relatively secure (Dewees 1995). Traditionally, it was based on family and clan affiliation; and today, with some limitations,[8] most

[8] This is described in Kenya's draft land policy. See Republic of Kenya, "National Land Policy," draft (Nairobi, Kenya: Ministry of Lands, National Land Policy Secretariat, 2007), http://www.ardhi.go.ke/landpolicy.htm

farmers possess title deeds to surveyed, registered, and adjudicated plots, which implies that tenure security is relatively high, given a regional country comparison. The area shares many demographic, socioeconomic, and biophysical features with the rest of the central highlands, which hold the largest shares of Kenya's population and food production. Hence, the study of Muranga is important and relevant from a larger policy perspective.

The agricultural lands in Muranga District are subject to heavy population pressure. This is manifested by its high population density and increasing land fragmentation. At present, the average farm size in the district is around 3.1 acres (or 1.2 hectares). The average farm size in our specific study site is only 2.4 acres. The population of the district is young—children and teenagers make up more than 60 percent of the population. Given limited job opportunities outside of agriculture, erosive rains, erodible soils, and cultivation on steep slopes, the stress on the district's soil capital is severe and increasing. Identifying determinants of individual soil properties, therefore, has considerable policy relevance.

3.1 Data and Data Collection

The data used in our analysis was obtained from a household survey conducted over a four-year period (1995–98). The soil samples were collected and analyzed in 1998. Based on a random sample, 252 small-scale farm households were identified and interviewed once every year between June and August.

3.2 Dependent Variables

Collection and analysis of the soil samples followed this standard procedure: composite soil samples were taken in all farms at 0–15 cm depth from the topsoil, based on three replicates in each farm field (*shamba*) along its slope (slope crest, mid-slope, slope base). We avoided places where mulch, manure, and fertilizer were visible for soil sampling. The soil samples were air dried and analyzed at the Department of Soil Science, University of Nairobi. We determined the following soil properties: grain size distribution (sand, silt, and clay content); cation exchange capacity (CEC); rates of exchangeable potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), and phosphorus (P) in the soil; organic carbon (C); total nitrogen (N) concentration; and the pH-levels in water and calcium chloride ($CaCl_2$) solutions.[9]

The grain size distribution (texture) was determined by the hydrometer method. Grain size for sand, silt, and clay was 0.05-2mm, 0.002-0.05mm, and <0.002mm, respectively. CEC was analyzed by leaching the soil with potassium ammonium acetate at pH 7. Sodium and potassium were determined using the flame photometer while calcium and magnesium were determined using the atomic absorption spectrophotometer method. Available phosphorus was analyzed using the Mehlich method, and pH-level (H_2O) and pH-level ($CaCl_2$) were analyzed using soil-water ratio and soil-salt ratio 1:2.5, respectively. Total nitrogen was identified using the Kjeldahl digestion method and organic carbon using Walkley and Black's method. Further details of the standard analytical methods used at the DSS can be found in Okalebo et al. (1993), Ekbom and Ovuka (2001), and Ovuka (2000).

Summary statistics of the soil sample properties (table 1) show that the soils are clayish, although the local variation is significant (between 16–82 percent). Moreover, the soils are acidic with a minimum-maximum $pH_{(H_2O)}$–level distribution between 4.1 and 8.2.

Fertility, proxied by the cation exchange capacity, is low.[10] The summary statistics of the soil properties show two types of variation. First, there is large variation between farms. Second, there is large variation between the soil properties. This variation is captured by λ, which is the ratio between the standard deviation (σ) and the mean ($\bar{\mu}$) for each soil property. As indicated in table 1, λ ranges from 0.16 (clay content) to 1.37 (phosphorus).[11] Figures in appendix 1 (A1–A7) show that the distribution of individual soil properties across farms is considerable. The figures illustrate that soil capital is not a fixed homogeneous factor and that, even within a very small geographical area (such as our study area), the variation between farms can be very large. This insight has important implications for farmers' management strategies as well as the government's provision of agricultural extension advice.

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[9] The correlation coefficient between pH (H_2O) and pH (CaCl) is >0.95. Hence, we chose to use pH (H_2O) to represent pH in our empirical analysis. Due to the non-linear nature of pH and the associated difficulties of interpreting regression coefficients, the data on pH was converted by taking the absolute value of the difference between each farm's pH-value (pH_i) and neutrality $\left(|pH_i - 7|\right)$.

[10] Soils with a CEC of less than 16 m.eq./100g. soil are considered to be infertile (Gachene and Kimaru 2003).

[11] For acidity (pH), the variation coefficient is even lower, but the comparison is not appropriate since this is a logarithmic index.

Table 1 Summary Statistics of Soil Sample Properties

Soil property	Unit	Mean ($\overline{\mu}$)	Std. dev. (σ)	Min.	Max.	λ (= $\sigma / \overline{\mu}$)
pH $_{(H_2O)}$	-log H^+	5.63	0.66	4.1	8.2	0.12
pH $_{(CaCl)}$	-log H^+	4.72	0.62	3.1	7	0.13
Nitrogen (N)	%	0.18	0.05	0.08	0.32	0.28
Phosphorus (P)	ppm	17.90	24.60	1	195	1.37
Potassium (K)	m.eq./100 g.	2.36	1.72	0.15	11	0.73
Sodium (Na)	m.eq./100 g.	0.14	0.19	0.001	0.6	1.36
Calcium (Ca)	m.eq./100 g.	6.47	3.32	1.45	20	0.51
Magnesium (Mg)	m.eq./100 g.	5.28	2.83	0.02	17.42	0.54
Cation exchange capacity (CEC)	m.eq./100 g.	15.80	5.45	7.2	36.8	0.35
Organic carbon (C)	g per kg	1.52	0.48	0.16	4.1	0.32
Sand	%	16.41	6.84	5	50	0.42
Silt	%	20.45	5.61	8	40	0.27
Clay	%	63.15	10.33	28	82	0.16

3.3 Independent Variables

The household characteristics (***H***), believed to explain soil capital, include sex of household head (H_1), age of household head (H_2), number of household head's years of school education (H_3), and number of working adults in the household (H_4).

The farmers in the area carry out a large number of physical as well as biological soil conservation measures—soil conservation investments (***I***). Formally, the data on the soil conservation technologies (***I_i***) is based on a quality index assigned to a set of individual technologies: $\boldsymbol{I} \in \{I_1, I_2, ..., I_{11}\}$. The index is derived from a practical expert-assessment framework for evaluation of soil and water conservation investments (described in Thomas (1995) and Thomas et al. [1997]). Farm-specific ratings for individual soil conservation technologies are based on a rating scale of 0 to 10. A high rating implies that each soil conservation measure is characterized by high quality, based on the criteria presented below.

Physical conservation measures imply excavation of soil in various ways. Our data includes cut-off drains and terraces. The cut-off drain (COD) is a water retention ditch that infiltrates water into the soil in a controlled way. Position, length, depth, and width of the drain are critical factors in determining how effectively it traps water (Thomas et al. 1997). Quality criteria for rating CODs also include 1) discharge, 2) outlet and disposal of water; 3) vegetation cover and stability of the upper and lower embankment, and 4) the amount of sediment and weeds inside the COD.

Terraces assessed in our sample include bench terraces and built-up soil bunds. Coffee is mostly grown on bench terraces, which are usually covered by grass and are forward-sloping or level along the contour. Built-up soil bunds are developed either by throwing soil up the slope (*fanya juu*) or down the slope (*fanya chini*). Commonly, grasses of various types are cultivated on top of the terrace embankment to provide livestock fodder, stabilize the terrace edges, and reduce soil loss (Thomas et al. 1997). Eventually the soil bunds reduce the slope and develop into terraces. Criteria for quality rating include 1) spacing, 2) physical dimensions, 3) location, and 4) stability and vegetative cover on the embankments. These factors are critical to prevent the water from topping over the bund and from breaching the bund. Well-constructed terraces are level along the contour, perpendicular to the natural slope, reduce the natural slope, and show no signs of breach or surface run-off crossing the embankments. Poorly-constructed or -maintained structures are characterized by, e.g., signs of soil erosion, surface water run-off, breached embankments, and poor vegetative cover along the edges. Inadequate size and spacing[12] can easily break the structures and accelerate surface run-off and soil loss.

Biological conservation measures include conservation tillage, crop cover, integrated use of farmyard manure for conservation purpose, mulching, green manure, and agro-forestry. Fodder production and grazing areas can also be managed with soil conservation purposes. Conservation tillage implies seed-bed preparation, which facilitates adequate soil aeration, water absorption and retention, increased rooting depth, enhanced nutrient access, and establishment of ridges along the contour to prevent soil loss. Fodder management usually implies production of Napier grass on terrace structures which together with stalks and stovers are supplied to livestock as feed. Management of grazing lands is assumed to be a critical factor in determining soil capital. Crop cover pertains to the ground cover of the plants. Crop canopy and leaves reduce the velocity of raindrops and reduce splash erosion. Large crop cover is thus a critical factor for conserving the soil. Tree crops, like coffee and tea, create their own large ground cover, whereas onions, beans, potatoes, and pulses generally have low ground cover. Criteria in the quality

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[12] Adequate size and spacing for bunds are >10m for steep slopes; >15m for moderate slopes; >20m for gentle slopes.

assessment also include, e.g., area coverage of annual and perennial crops, inter-cropping, canopy cover, plant height and strength, and spacing between the plants.

Farmyard manure is used to conserve or enhance the soil capital by mixing excrements from livestock and poultry with grasses and litter from agriculture. Criteria for good management imply quick incorporation of the manure into the soil (to avoid leaching and volatilization) and application, which prevents physical loss of soil, and decline in soil fertility and moisture. Mulching is the application of dry, vegetative material in the field to cover the soil. It is stated to be an important factor in controlling erosion, reducing evaporation, improving soil structure, retaining existing soil nutrients and soil moisture, and promoting plants' uptake of additional nutrients from decomposed organic material (Ozara 1992; Gachene and Kimaru 2003). Factors determining the quality of residue mulching include, e.g., signs of (splash) erosion and pests, healthy crops, soil moisture, and the distribution of the vegetative material.

Green manure is a form of fallowing and implies planting fast-growing cover crops (legumes, grasses) to reduce soil erosion, maintain soil moisture, and improve soil fertility. Quality criteria include, e.g., ground cover and its distribution, soil moisture and structure, heat protection, weed abundance, interference with main crops, and signs of pests associated with the green manure legumes and grasses.

Agro-forestry implies planting trees or perennial bushes in the farm field (Nair 1997; Young 1997). Agro-forestry offers long-term benefits, such as 1) stabilizing the soil and preventing mass movement of soil (landslides, for example) with deep tree roots (Smith et al. 1999), 2) retaining soil moisture by providing a shade canopy from sunlight, 3) reducing the velocity of rain (and thus its erosivity) with the ground cover provided by the tree canopy and branches, 4) enhancing soil fertility by providing nutrients from decomposing (fallen) leaves, 5) increasing yields with the addition of fruit and/or nut crops, and 6) providing timber, fodder, and fuelwood. Crops from agro-forestry in the study area include coffee, mango, banana, avocado, lemon, papaya, and macadamia nut trees. Criteria for our quality assessment included tree choice, height, spacing, pruning and distribution of the trees, root exposure, ground cover, and signs of pests.

Although the numbers of livestock are decreasing in the central highlands, fodder production and management of grazing land are important components of farmers' soil management systems. Quality criteria for fodder production include plant choice, area allocation, location, and management of fodder crops (e.g., Napier grass). Good managers produce fodder crops on terrace embankments, in contour strips (which develop into terraces), in valley bottoms, or in strategically placed blocks or rows. They practice "cut-and-carry" in a zero-grazing system, which recycles the nutrients and biomass back into the soil (van den Bosch et al. 1998). Good management of grazing lands implies erosion control in pastures, appropriate number of livestock in relation to pasture capacity, rehabilitation of gullies, fencing or tethering, and grass planting on bare grounds. A low rating is given to denuded grazing land, which shows signs of erosion. Reseeding and gully reclamation are not practiced and land covered by woody bushes has a limited value from a soil-fertility or productivity perspective.

3.4 Extension Advice

The study area, like most agricultural areas in Kenya, has been subject to external soil conservation support over a number of years. Initially, this was implemented by the British during colonial rule. Since independence in 1963, soil conservation has been advocated by the government of Kenya. Due to the coercive measures practiced by the British, the farmers resisted soil conservation during the first decade of independence. Support by the government of Kenya took off in 1974, when a new public soil conservation project was launched. It has progressively developed into a national program, primarily built up by individual farm visits made by the Ministry of Agriculture's local soil and water conservation experts. They are technical extension agents (TAs), who provide on-site advice to individual households about soil and water conservation measures. Given the program's goals of conserving soil, enhancing soil fertility, and boosting food production, it interesting to identify the impact of this service on individual soil properties. To facilitate analysis within our framework, X represents the total number of times each household was visited over a four-year period by a technical extension agent and was given advice on soil and water conservation.

3.5 Physical Production Factors

Variables representing physical production factors (***PF***) used in the regression analysis include agricultural labor (L_Q), fertilizer (F), and manure (M). All variables are expressed in terms of input per unit area (acre). The variables represent an aggregation of the annual input for each production factor over a four-year period. Hence, fertilizer is an unweighted aggregation of fertilizer input over a four-year period ($F = \sum_{t=1}^{4} F_t$), which covers eight growing seasons.

3.6 Crop Allocation

Crop allocation (***R***) focuses on two crops: coffee (R_{coffee}) and maize (R_{maize}). They are expressed in terms of the area share allocated to them, respectively. Coffee and maize are two key crops, where coffee is cultivated mainly for cash income and maize for food. More than 75 percent of the farm area is allocated to coffee and maize. Remaining land is typically allocated to a small garden for fruits and vegetables, homestead, livestock grazing (*boma*), other food and cash crops (beans, potatoes, bananas), and a small woodlot. (Some farms also contain wastelands, such as gullies and rocky soil.) Each farmer pursues a certain farming strategy and the choice and area allocation of crops in the farm constitute crucial decisions. Apparently, farmers make very different choices. This does not only have an impact on cash income and food supply, but also on soil capital. Specifically, allocating a relatively large (or small) land area to coffee and maize, respectively, will yield different outcomes regarding profitability, food security, *and* soil properties.

The summary statistics (presented in table 2) indicate that as much as 30 percent of the households surveyed were reported as headed by females. This group consisted of divorced women, widows, and women with husbands who migrated (on a more or less permanent basis) to nearby towns and the capital to seek income. Most households were characterized by relatively old heads (the mean was greater than 55 years), little formal education, and few working adults. This was the result of a large emigration, which constrained labor availability during the agricultural peak-season (seed-bed preparation and harvesting). Labor was also relatively scarce during the time to construct or maintain physical soil conservation structures.

According to the quality rating of soil conservation investments, the area as a whole gets medium to low rates. Terraces rate highest (mean = 5.8), followed by crop cover (5.6), and fodder management (5.4). The relatively low rating of the soil conservation investments corroborated the substantial soil loss observed in the area.[13] Moreover, the coffee trees in the study area were relatively old (>20 years), although variation in the sample was considerable.

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[13] Although recent data is scarce, Lewis (1985) reported an average soil loss of 12 tons per hectare per year in the Muranga district. In some extreme cases, it exceeds 150 tons per hectare per year. Gachene (1995) and Gachene et al. (1997) identified equally large soil losses in Kenya's central highlands and associated depreciation of key soil quality properties and yield losses. Dunne (1979) estimated that the upper Tana River catchment in the central highlands yielded 4.8 million tons of soil sediment per year.

Table 2 Summary Statistics of the Independent Variables

Variable	Definition	Mean	Minimum	Maximum	Standard deviation
H_1	Sex of household head (1 = male; 0 = female)	0.71	0	1	0.45
H_2	Age of household head (years)	55.1	20	96	13.86
H_3	Education of household head (years)	5.7	0	20	4.42
H_4	Number of working adults	2.5	1	7	1.10
I_1	Cut-off drains	5.13	0	10	2.70
I_2	Crop cover	5.56	0	10	2.05
I_3	Tillage practices	4.94	0	10	2.55
I_4	Manure conservation	5.26	0	10	2.53
I_5	Mulching	2.20	0	9	2.69
I_6	Green manure	0.77	0	8	1.90
I_7	Agro-forestry	3.88	0	10	2.68
I_8	Fodder management	5.44	0	10	2.27
I_9	Grazing land management	2.00	0	10	2.92
I_{10}	Terrace quality	5.79	0	10	2.02
I_{11}	Coffee trees (years)	22.41	0	54	11.61
X	Number of TA visits	1.9	0	9	1.87
L_Q	Agric. labor/acre (hours)	3051	377	16224	1947.3
F	Fertilizer/acre (KSh)	5155	170	21320	3337.9
M	Manure/acre (KSh)	8001	0	54474	7319.4
R_{coffee}	Coffee area share (%)	34	0	80	17
R_{maize}	Maize area share (%)	42	0	100	20

Notes: When nothing else is stated, the variables are indices based on expert judgment.
KSh = Kenyan shilling; KSh 70 = US$ 1.

On average, each household was visited by a technical extension agent slightly less than two times during four years. Although this seems infrequent, each visit typically included a thorough evaluation of existing land husbandry practices and practical advice on how to enhance soil conservation, soil fertility, and crop productivity. It is thus difficult to say anything *a priori* about the effect of such a visit on the farmer's soil capital management. Given the government's comprehensive and long-standing financial extension support to farmers, it is of interest to assess the impact of the technical extension advice on their soil capital.

Due mainly to poverty, the level of commercial inputs is very low. Annual mean input of commercial fertilizer and farmyard manure is approximately 3300 KSh per acre (≈ US$ 48). The soil is only tilled with hand tools (hoes and machetes), and draft animals are not used for plowing. Instead, manual labor constitutes the largest production factor; the average farm supplies approximately 750 hours per acre per year.

Assuming that production factors have an impact on crop productivity *and* soil capital, it is worth examining the predictive relationship between farmers' production factors and soil conservation quality, and individual soil properties.

4. Statistical Results and Interpretations

The joint estimation of the multiple equations represented by model 1 above by seemingly unrelated regression (Greene 2000) yielded the results presented in tables 3–5 below.[14]

4.1 Carbon

In line with other research (see, e.g., Smaling and Braun 1996; Nandwa et al. 2000; Batjes 2004), soil conservation investments are generally positively associated with soil carbon. In particular, good ground cover from crops, conservation tillage, farmyard manure, and green manure significantly increase carbon concentrations in the soil stock. Similarly, cultivation of maize and coffee is associated with loss of organic carbon in the soil. Although the crop canopies provide some ground cover, relatively larger areas allocated to coffee and maize exposes the soil to erosion and loss of organic matter. The results suggest that selected erosion control measures and careful allocation of crops are effective means to build up organic matter, store carbon and prevent CO_2-emissions.

[14] General statistics were obtained from SUR: system-weighted mean squared error (MSE) = 1.00, degrees of freedom = 2465; system-weighted R-square = 0.31.

Table 3 Regression Results of Primary Macro-nutrients

		Dependent variables							
		Carbon		*Nitrogen*		*Phosphorus*		*Potassium*	
Indep. variable	**Definition**	***Coefficient***	***t-value***	***Coefficient***	***t-value***	***Coefficient***	***t-value***	***Coefficient***	***t-value***
α	Intercept	-0.517	-0.65	**-1.893**	**-2.38**	-0.429	-0.51	**0.669**	**2.19**
H_1	Sex of household head (1 = male; 0 = female)	**0.134**	**2.80**	0.028	0.60	0.040	0.83	0.002	0.11
H_2	Age of household head (years)	0.148	0.27	0.391	0.69	-0.054	-0.09	0.340	1.60
H_3	Education of household head (years)	-0.284	-0.95	0.307	1.07	0.411	1.35	**-0.232**	**-2.12**
H_4	Number of working adults	0.088	0.74	-0.052	-0.46	-0.075	-0.62	**0.081**	**1.81**
I_1	Cut-off drains	0.112	1.18	-0.007	-0.07	-0.082	-0.84	**0.164**	**4.48**
I_2	Crop cover	**0.123**	**1.76**	**0.129**	**1.92**	0.028	0.39	**0.223**	**7.31**
I_3	Tillage practices	**0.400**	**3.74**	-0.036	-0.35	**0.183**	**1.68**	**0.129**	**3.43**
I_4	Manure conservation	**0.263**	**2.06**	**0.441**	**3.61**	**0.570**	**4.37**	**0.185**	**4.01**
I_5	Mulching	0.025	0.60	**0.123**	**3.13**	0.023	0.55	**0.032**	**2.58**
I_6	Green manure	**0.144**	**2.12**	-0.008	-0.12	-0.021	-0.30	**0.061**	**2.72**
I_7	Agro-forestry	-0.041	-0.61	**0.310**	**4.85**	-0.060	-0.87	-0.003	-0.21
I_8	Fodder management	0.060	0.58	**-0.181**	**-1.86**	-0.095	-0.91	0.003	0.12
I_9	Grazing land management	0.194	0.65	**0.762**	**2.69**	0.371	1.23	0.047	0.42
I_{10}	Terrace quality	0.095	0.99	**0.355**	**3.86**	-0.002	-0.02	-0.013	-0.42
I_{11}	Coffee trees (years)	0.093	1.59	**0.180**	**3.22**	0.063	1.06	**0.046**	**2.16**
X	TA-visits (nr.)	0.030	0.24	-0.175	-1.49	-0.149	-1.19	-0.033	-0.85
L_Q	Ag. labor/acre (hours)	-0.011	-0.10	0.145	1.49	0.118	1.14	-0.032	-1.11
F	Fertilizer/acre (KSh)	0.119	0.73	0.142	0.91	0.174	1.04	-0.032	-0.62
M	Manure/acre (KSh)	0.051	0.32	**0.461**	**3.03**	0.146	0.90	0.011	0.29
R_{coffee}	Coffee area share	**-0.204**	**-1.94**	**-0.196**	**-1.96**	0.003	0.03	0.035	0.99
R_{maize}	Maize area share	**-0.124**	**-1.88**	-0.102	-1.62	-0.026	-0.38	-0.013	-0.61

Note: Bold figures imply statistical significance of at least 10%.

4.2 Nitrogen

Similar to carbon, investments in good soil conservation quality are associated with higher soil nitrogen content. This is particularly true for crop cover, integrated use of farmyard manure for conservation purposes, mulching, agro-forestry, appropriate grazing land management, terraces, and older coffee trees. Good ground cover physically prevents loss of nitrogen from rain; application of chicken manure and cow-dung replenishes soil with nitrogen; and mulching physically prevents loss of nitrogen from soil erosion and recycles it into the soil via decomposition of vegetative material (Hilhorst and Muchena 2000; van den Bosch et al. 1998; de Jager et al. 2001). Although agro-forestry trees consume nitrogen for their growth, they have a positive effect on soil nitrogen. There are many plausible explanations for this: the tree canopy prevents soil loss during the rain periods, deep roots capture leached nitrate from subsoil layers and recycles nitrogen into the soil via the decomposition of fallen leaves (Warren and Kihanda 2001). The roots stabilize the soil and prevent erosion together with leaves, which physically protects the soil. One negative sign in fodder production is a large loss of nitrogen associated with production of Napier grass.[15]

From a policy perspective, one should note that the largest positive effects on soil nitrogen come from good grazing land management, integrated use of manure, well-established terraces, and appropriate agro-forestry, in that order. Well-maintained grazing areas consist of perennial grass cover, which effectively prevents soil loss (Thomas 1997; Stocking and Murnaghan 2001). The positive impact of terraces is also well documented (see, e.g., Gachene 1995; Ovuka 2000).

There is a negative sign for cultivation of coffee and maize, which may be explained by the current farming practices associated with these crops. Despite some inflows of nitrogen from biological nitrogen fixation, organic and inorganic fertilizers, and atmospheric deposition, the reduction of soil nitrogen is considerable in a farming system like the one here. As an example, one study of coffee and maize production under similar conditions in Kenya's highlands showed a net annual loss of nitrogen corresponding to 31 kg/hectare and 88 kg/ hectare, respectively (van den Bosch et al. 1998). De Jager et al. (2001) found that maize production under similar farming

[15] Napier grass (*Pennisetum purpereum*) is the main fodder crop. It is grown to stabilize terrace embankments and harvested for milk and meat production. Van den Bosch et al. (1998) found that Napier production in a similar agricultural system in central Kenya reduced soil nitrogen by 126 kg/hectare per year.

practices and agro-ecological conditions reduced soil nitrogen concentrations with 44 kg/ hectare per year.

The losses of nitrogen have direct bio-physical causes, primarily leaching, volatilization, erosion, crop harvesting, and removal of crop residues. Due to the local soil type (humic nitisol) and inefficient fertilizer use, leaching of nitrogen from subsoils is substantial (Warren and Kihanda 2001). Loss of nitrogen in coffee production may also be a result of the abandonment in recent years of coffee trees; low farm coffee prices, high input prices, and eroding coffee cooperatives, in conjunction with each other, have reduced farmers' replenishment of soil nutrients in the coffee plantations, pruning, weed control and pest management. Low farm coffee prices have also reduced investments in the bench terraces on which coffee trees are grown. These factors have reduced farmers' profitability from coffee production which has further triggered disinvestment in the coffee production; besides lowered productivity some farmers have even uprooted their coffee trees and replaced them with other crops.

The statistical results also show that older coffee trees are associated with higher soil nitrogen concentrations. This might be explained by the fact that older trees have relatively deeper roots (compared to the younger ones), which can retrieve nitrogen from subsoil layers, and have relatively larger canopies (which prevents soil loss), more litter production (which supplies more nitrogen from the decomposed material), and better stabilization of the terrace structure than younger trees.

4.3 Phosphorus

Good tillage practices and manure conservation contribute to the soil's phosphorus content. As can be expected, turning over crop litter (stalks and stovers), cow dung, and other types of farmyard manure into the soil contributes to increase the soil's phosphorus concentration. The results are corroborated by de Jager et al. (2001), for example, who found positive phosphorus nutrient balances for manure-based cultivation in a similar agro-ecological setting. Interestingly, application of chemical fertilizer during a four-year period gives a positive but statistically insignificant effect on the soil's available phosphorus concentrations. This might be explained by losses from crop harvests and soil erosion, as well as quick fixation of inorganic phosphorus in acidic, strongly leached, and eroded soils (Gachene and Kimaru 2003). Application of farmyard manure increases the availability of phosphorus in at least two important ways. First, manure itself contains significant amounts of phosphorus; and second, fixation of phosphorus is inhibited since incorporation of farmyard manure into the soil reduces soil acidity.[16]

Table 4 Regressions Results of Ph, Texture, and Cation Exchange Capacity

		Dependent Variables							
		pH		*Clay*		*Silt*		*CEC*	
Indep. variable	Definition	*Coefficient*	*t-value*	*Coefficient*	*t-value*	*Coefficient*	*t-value*	*Coefficient*	*t-value*
α	Intercept	-0.835	-0.87	**1.320**	**5.74**	**1.430**	**1.67**	-0.407	-1.00
H_1	Sex of household head (1 = male; 0 = female)	0.077	1.37	0.019	1.43	**0.091**	**1.83**	0.050	1.45
H_2	Age of household head (years)	0.697	1.03	-0.261	-1.61	-0.911	-1.51	#	#
H_3	Education of household head (years)	-0.052	-0.15	**0.174**	**2.10**	**-0.572**	**-1.86**	0.274	1.26
H_4	Number of working adults	-0.105	-0.75	-0.043	-1.30	0.077	0.62	-0.009	-0.11
I_1	Cut-off drains	0.038	0.34	**0.097**	**3.69**	-0.034	-0.35	**0.128**	**1.88**
I_2	Crop cover	**0.156**	**1.89**	0.016	0.82	**0.170**	**2.34**	-0.004	-0.08
I_3	Tillage practices	**-0.259**	**-2.08**	0.048	1.62	0.088	0.80	**0.194**	**2.51**
I_4	Manure conservation	**0.368**	**2.46**	0.032	0.90	**0.598**	**4.53**	0.051	0.55
I_5	Mulching	**0.183**	**3.81**	-0.009	-0.75	**0.110**	**2.59**	-0.037	-1.26
I_6	Green manure	0.042	0.53	**-0.050**	**-2.65**	0.023	0.33	-0.010	-0.20
I_7	Agro-forestry	-0.066	-0.84	-0.004	-0.20	-0.029	-0.41	-0.011	-0.22
I_8	Fodder management	**-0.338**	**-2.84**	-0.006	-0.23	-0.088	-0.84	0.060	0.81
I_9	Grazing land management	**0.860**	**2.48**	0.037	0.45	0.131	0.43	0.329	1.53
I_{10}	Terrace quality	**0.353**	**3.14**	**-0.044**	**-1.66**	0.056	0.56	0.090	1.28
I_{11}	Coffee trees (years)	0.100	1.46	**-0.033**	**-2.05**	**0.120**	**1.98**	**0.077**	**1.81**
X	Number of TA visits	-0.043	-0.30	-0.017	-0.50	-0.012	-0.09	0.018	0.20
L_Q	Ag. labor/acre (hours)	-0.127	-1.06	0.005	0.18	-0.052	-0.50	0.018	0.24
F	Fertilizer/acre (KSh)	0.061	0.32	**0.166**	**3.66**	-0.265	-1.57	0.167	1.44

[16] Mean pH (H_2O) in farmyard manure typically ranges between neutral to mildly alkaline (pH = 7-7.8) in this farming system.

M	Manure/acre (KSh)	0.074	0.40	0.026	0.59	0.032	0.20	0.126	1.10
R_{coffee}	Coffee area share	-0.068	-0.56	**-0.290**	**-10.01**	-0.049	-0.46	0.066	0.87
R_{maize}	Maize area share	**-0.175**	**-2.27**	**-0.115**	**-6.30**	-0.111	-1.63	-0.045	-0.96

= omitted

Note: Bold figures imply statistical significance of at least 10%.

4.4 Potassium

Several soil conservation technologies have a positive and significant relationship with soil potassium, particularly cut-off drains, good crop cover, conservation tillage, integrated use of farmyard and green manure, and mulching. This finding is no surprise, since it has been demonstrated in several studies under similar conditions (Smaling et al. 1993; Gachene et al. 1997; Stoorvogel and Smaling 1998, van den Bosch et al. 1998; Hilhorst and Muchena 2000). For instance, van den Bosch et al. (1998) found that 29 percent of soil potassium originates from farmyard manure and crop residues. These findings are of some interest in view of the fact that the farmers in the area typically use inorganic fertilizers with low or no potassium content. Although insufficient, the lack of inorganic potassium replenishment is to some extent compensated by the use of potassium-promoting soil conservation measures and the relatively common use of farmyard manure to replenish potassium and other macro-nutrients.

Generally, one would expect a positive and statistically significant effect from inorganic fertilizers on the soils' potassium concentration. However, volatilization, leaching, erosion, and other nutrient-depleting processes strongly inhibit the increase of potassium in the soil under the present farming system (van den Bosch et al. 1998; Gachene and Kimaru 2003).

4.5 pH-Level

Depending on which technology is used, soil conservation investments yield mixed results with respect to the pH level. Good ground cover from the crops, manure conservation, mulching, good grazing-land management, and high-quality terraces are positively associated with the pH level. Conversely, conservation tillage and fodder management yield negative signs. The net effect of soil conservation on pH thus seems to be an empirical issue. Irrespectively, the largest (positive) effects are from manure conservation and management of grazing land and terraces. Increased area allocation for maize production is associated with lower pH. This result is important in view of the fact that the observed mean pH in the study area is already rather low (mean = 5.6) and that the optimal pH for production of many of the key crops produced in the area is typically higher (Thomas 1997; Gachene and Kimaru 2003). Since low pH (acidity) is a key constraint to increased production, the results call for selectivity in the choice of crops and conservation technologies.

Table 5 Regressions Results of Secondary Macro-nutrients

		Dependent Variables					
		Sodium		*Calcium*		*Magnesium*	
Indep. variable	**Definition**	***Coefficient***	***t-value***	***Coefficient***	***t-value***	***Coefficient***	***t-value***
α	Intercept	-0.055	-0.15	0.289	0.48	-0.027	-0.03
H_1	Sex of household head (1 = male; 0 = female)	-0.015	-0.71	0.019	0.55	-0.044	-0.85
H_2	Age of household head	-0.069	-0.27	0.122	0.29	0.493	0.78
H_3	Education of household head (years)	-0.031	-0.24	0.042	0.19	**0.592**	**1.85**
H_4	Number of working adults	0.023	0.44	0.021	0.24	-0.179	-1.40
I_1	Cut-off drains	**0.074**	**1.80**	0.094	1.38	0.132	1.29
I_2	Crop cover	0.004	0.15	-0.035	-0.70	**0.248**	**3.29**
I_3	Tillage practices	0.073	1.58	0.032	0.41	**0.281**	**2.45**
I_4	Manure conservation	-0.059	-1.08	-0.034	-0.37	-0.002	-0.01
I_5	Mulching	0.020	1.13	0.039	1.31	**0.103**	**2.33**
I_6	Green manure	-0.015	-0.51	-0.058	-1.20	-0.085	-1.17
I_7	Agro-forestry	0.034	1.20	0.015	0.31	0.065	0.91
I_8	Fodder management	-0.007	-0.15	-0.032	-0.44	0.042	0.38
I_9	Grazing land management	**0.718**	**5.62**	0.258	1.21	-0.239	-0.75
I_{10}	Terrace quality	0.053	1.28	0.042	0.60	-0.092	-0.89
I_{11}	Coffee trees (years)	0.036	1.43	**0.170**	**4.03**	-0.037	-0.59
X	Number of TA-visits	-0.046	-0.86	0.063	0.72	-0.140	-1.06
L_Q	Ag. labor/acre (hours)	0.065	1.48	-0.050	-0.69	-0.039	-0.36
F	Fertilizer/acre (KSh)	**0.344**	**4.89**	0.084	0.72	0.045	0.26
M	Manure/acre (KSh)	0.057	0.84	0.017	0.15	0.103	0.61
R_{coffee}	Coffee area share	**-0.093**	**-2.07**	-0.032	-0.43	0.024	0.21
R_{maize}	Maize area share	**-0.123**	**-4.32**	-0.069	-1.46	-0.058	-0.82

Note: Bold figures imply statistical significance of at least 10%.

4.6 Clay and Silt

Soil conservation investments have mixed effects with respect to the indicators of soil texture, clay and silt. The regression results showed a positive relationship between cut-off drains and clay content. Silt is trapped by good crop cover, manure conservation, mulching, and the larger root systems and broader canopies of older coffee trees. Interestingly, green manure, terraces, and coffee trees have small but negative effects on the soil's clay content. The effect of green manure may be explained by the fact that plowing legumes into the soil exposes the soil to erosion risks and loss of clay particles in particular (although more study is required). A similar effect of soil exposure may explain the strong negative relationship between the areas allocated to coffee and maize, respectively, and the soil's clay concentration. However, since crops have different requirements regarding texture (and other soil properties), and it is difficult, *a priori*, to recommend one conservation technology before another.

Further, fertilizer input is positively associated with clay content. Although causality is not determined, it seems plausible to believe that clay facilitates (relatively higher) nutrient uptake since soils with relatively more clay content have higher nutrient-retention capacity than soils with coarser texture (Sparks 1999).

4.7 Cation Exchange Capacity

The analysis of cation exchange capacity (CEC) shows that well established cut-off drains, good tillage practices, and mature coffee trees are positively associated with CEC. This result is important because CEC is an important indicator of soil fertility (nutrient retention capacity), and leads to the conclusion that investments in cut-off drains, appropriate conservation tillage, and long-term maintenance of coffee trees (with deeper root system, larger canopy) build up soil capital and soil fertility.

4.8 Secondary Macro-nutrients

The regression results indicate that all statistically significant effects of soil conservation investments are positively associated with sodium, calcium, and magnesium. The specific conservation technologies with positive effects include high-quality cut-off drains, crop cover, conservation tillage, mulching, and grazing land management. Older coffee trees are also positively correlated with soil calcium. This finding is arguably explained by the same factors (deeper roots, litter, larger canopy, etc.), which cause a positive relationship between mature coffee trees and carbon, nitrogen, phosphorus, and potassium, respectively. Significant positive effects on sodium are also observed for agricultural labor and inorganic fertilizer, whereas negative signs are observed between sodium and coffee and maize cultivation, respectively. This is probably explained by the current farming practices, where coffee and maize are cultivated with limited soil nutrient replenishment via fallows or organic and inorganic fertilizers, for example. Loss of micro-nutrients due to insufficient soil conservation and continuous cultivation is in accord with other studies (e.g., Gachene 1995; Gachene et al. 1997; Ovuka 2000) under similar conditions.

5. Conclusions and Policy Implications

Our study has both methodological and policy implications. For soil capital to be a relevant variable in economic analysis, one has to account for the fact that it is heterogeneous and consists of several properties which change over time and are unevenly distributed across farms and down the soil profile (Warren and Kihanda 2001). The diversity of $\boldsymbol{S}$ in reality implies that economic analyses of agricultural production in developing countries ought to pay more attention to the levels and relative proportions of key soil properties, their relationship to the diverse requirements for optimal growth of crops, *and* the roles played by traditional economic production factors, such as labor input. Hence, economic abstractions of $\boldsymbol{S}$, such as soil depth, need qualification since shallow soils may be fertile and deep soils may be quite infertile if eroded, leached, or subjected to other forms of degradation. Ideally, economic analyses that soil capital, should strive for more diversity and complexity in the way soil is represented.

In agronomic research, it is important to acknowledge soil as a form of capital. From this follows that soil, however important, is one asset among others in a farmer's portfolio. Soil capital depreciation may be an individually rational strategy if, for instance, reinvestment is too costly (van der Pol and Traore 1993; Nkonya et al. 2004) or if the soil capital is substituted for other capital which is more productive or yields a higher interest rate. As indicated by the wide distribution of S_i across farms, soil capital is shaped—both accumulated and depreciated—by the farmer, and not only by bio-physical factors, such as climate, geology, and topography. Farmers' characteristics and management strategies are heterogeneous across farms and have pervasive impacts not only on crop yield (the resource rent) but also on the formation of the capital stock over time. Failure to acknowledge the differing roles and preferences of farmers and their incentives, choices, constraints, and characteristics, introduces the risk of omitting crucial variables in the analysis of soil productivity and soil change.

There are also a number of interesting findings from the estimation results:

- ***The generally positive effects of soil conservation investments on soil properties.*** Farmers who have made considerable effort over time to establish and maintain high-quality conservation structures have been rewarded by higher macro-nutrient levels. It is, however, noticeable that some conservation investments show no significant effects on certain soil properties. Careful selection of conservation technology is crucial in the efforts to sustain soil capital. Moreover, there is no clear pattern indicating that physical and/or structural conservation measures dominate biological conservation measures, or vice versa, regarding their respective impact on soil properties.
- ***The negative effect of coffee and maize production on soil nutrients (carbon, nitrogen, sodium), clay concentration, and pH (maize).*** Given the farmers' large land allocation to maize and coffee production (>75 percent), it should be of policy interest to review the incentives for crop choice and the potential soil impacts of promoting other, more nutrient-efficient crop mixes. This is particularly important in view of the facts that crop choice matters a lot for soil structure, soil nutrient balance (coffee and maize production yields negative nutrient balances), and that some crops "mine" nutrients considerably more than others (van den Bosch et al. 1998; de Jager et al. 2001).
- ***Visual field assessment and laboratory soil sample analysis are useful complements***. The results of this study show that visual field assessment of soil conservation technologies can give a good indication of farmers' general soil quality. However, to ensure adequate knowledge about the links between conservation status and soil status, it is necessary to increase specific knowledge on individual soil properties. Hence, for farmers to optimize their production, visual field assessment based on expert judgment ought to be complemented with more frequent use of laboratory-based soil sample analysis.

Our results also have some important broader policy implications. The diversity in farmers' soil capital, production strategies, and general farming systems (including conservation investments) points to the value of internalizing these aspects in the formulation of the government's policies and extension advice on sustainable agriculture. Our findings reinforce the importance of providing extension advice and general farmer support, which is based on farmers' experiences and preferences and expert judgment, *as well as* site-specific information from scientific analysis (e.g., soil sample analysis). Such an approach would integrate farmers' knowledge and practice, extension services, and research to a larger extent than at present, and promote increased agricultural productivity *and* sustained soil capital.

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Appendices

Appendix 1 Distribution of Soil Properties

Figure A1.1 Distribution of pH (H_2O) and pH (CaCl)

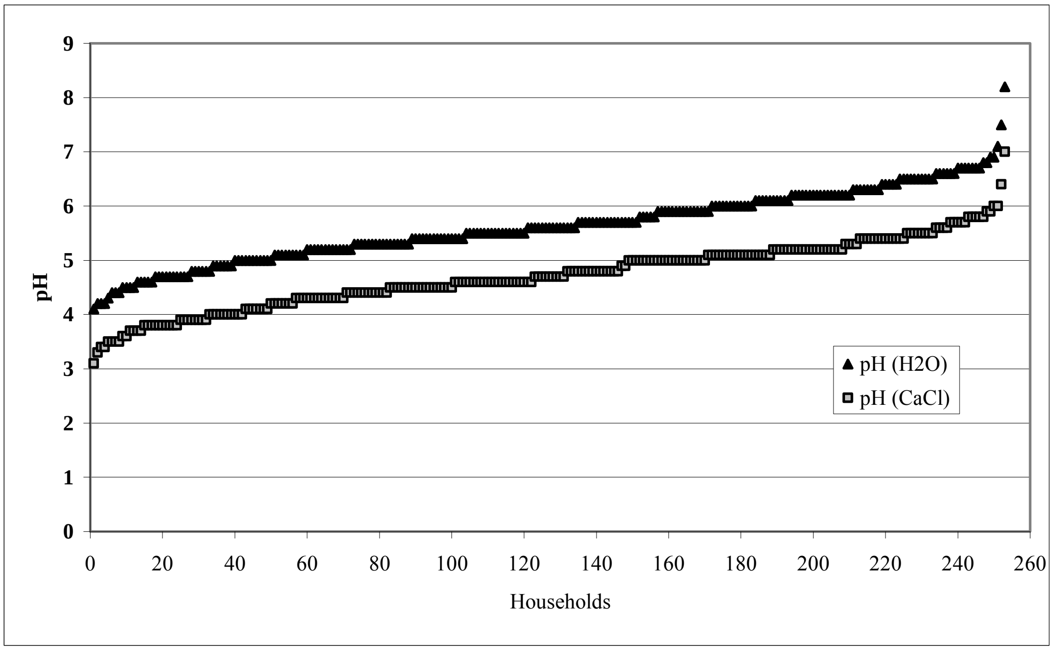


Figure A1.2 Distribution of Carbon (%)

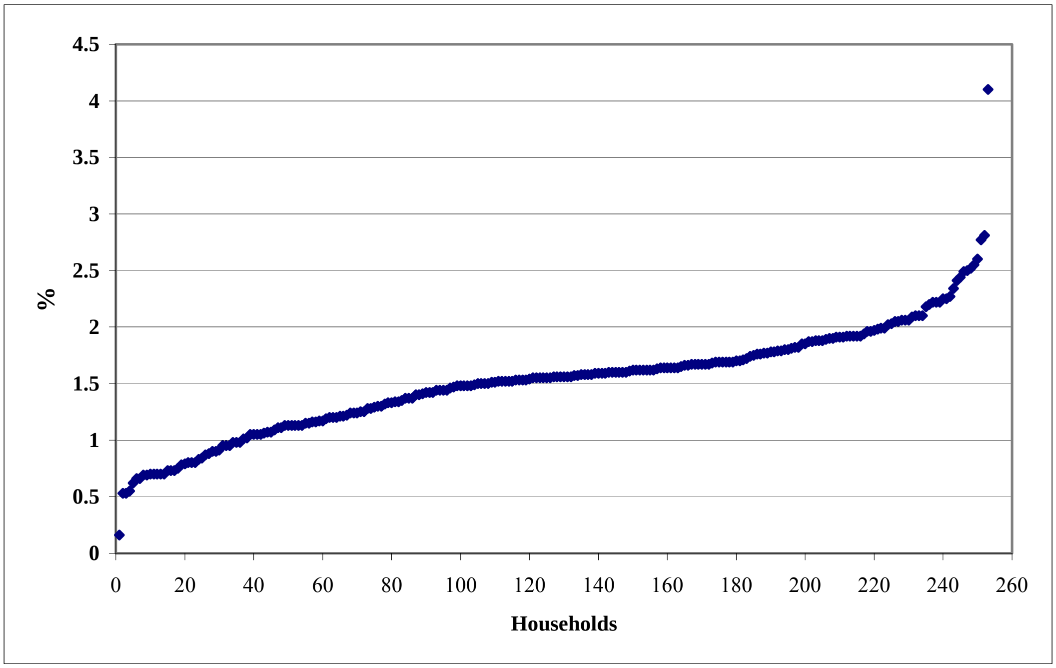


Figure A1.3 Distribution of Nitrogen (m.eq./100 g.)

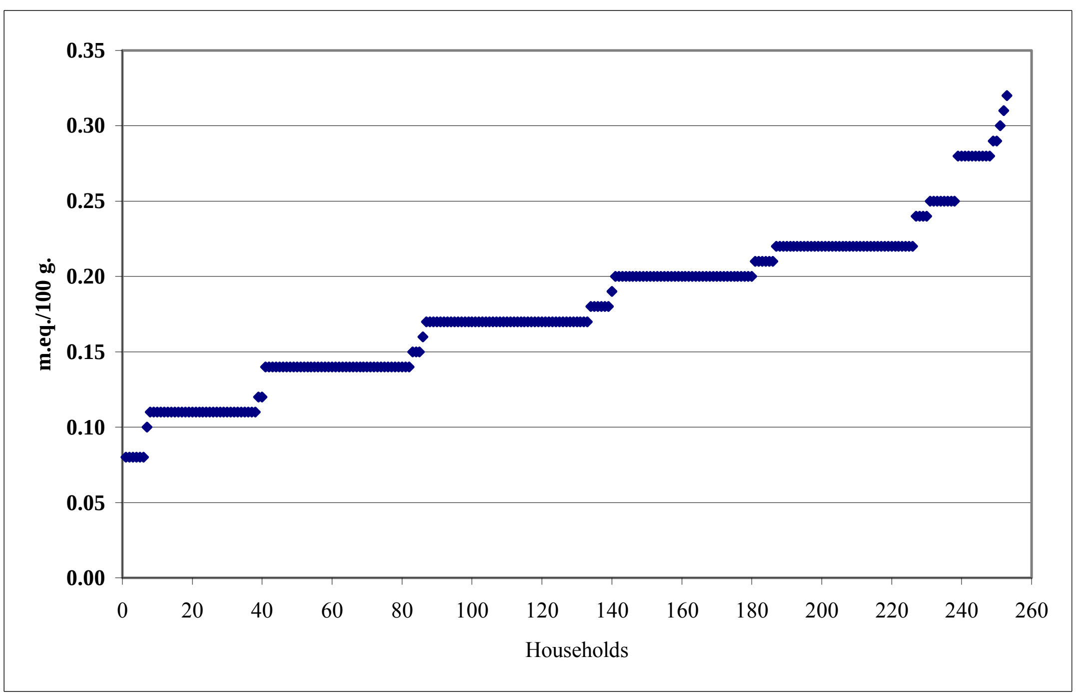


Figure A1.4 Distribution of Phosphorus (ppm)

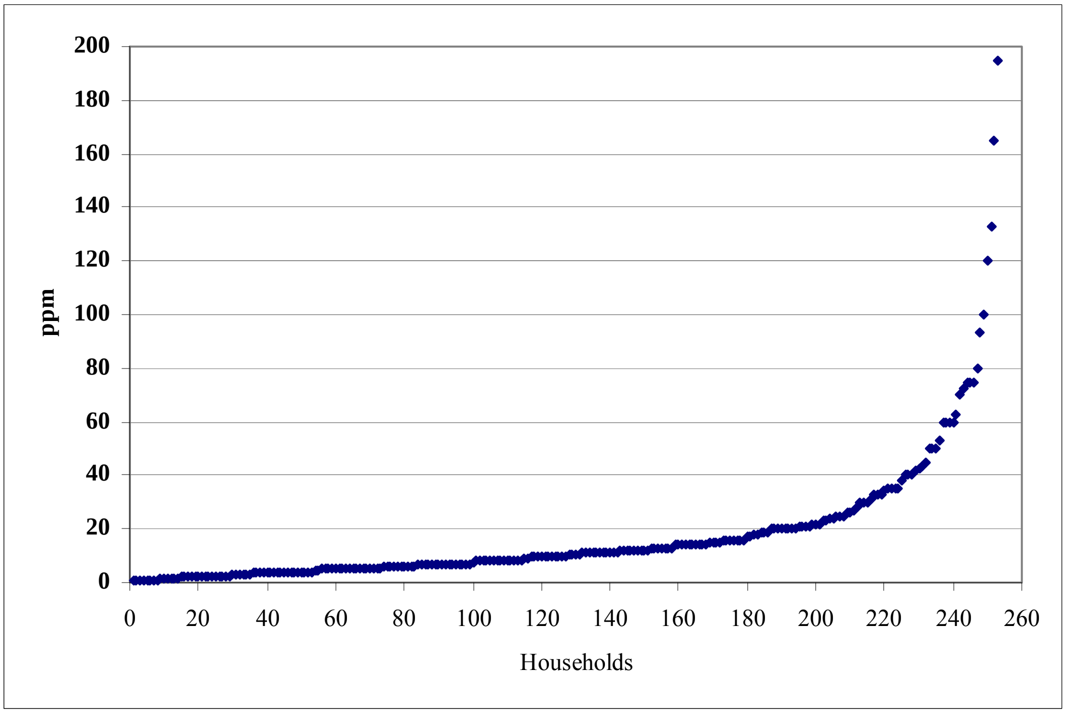


Figure A1.5 Distribution of Potassium, Calcium, Magnesium and Cation Exchange Capacity (m.eq/100 g.)

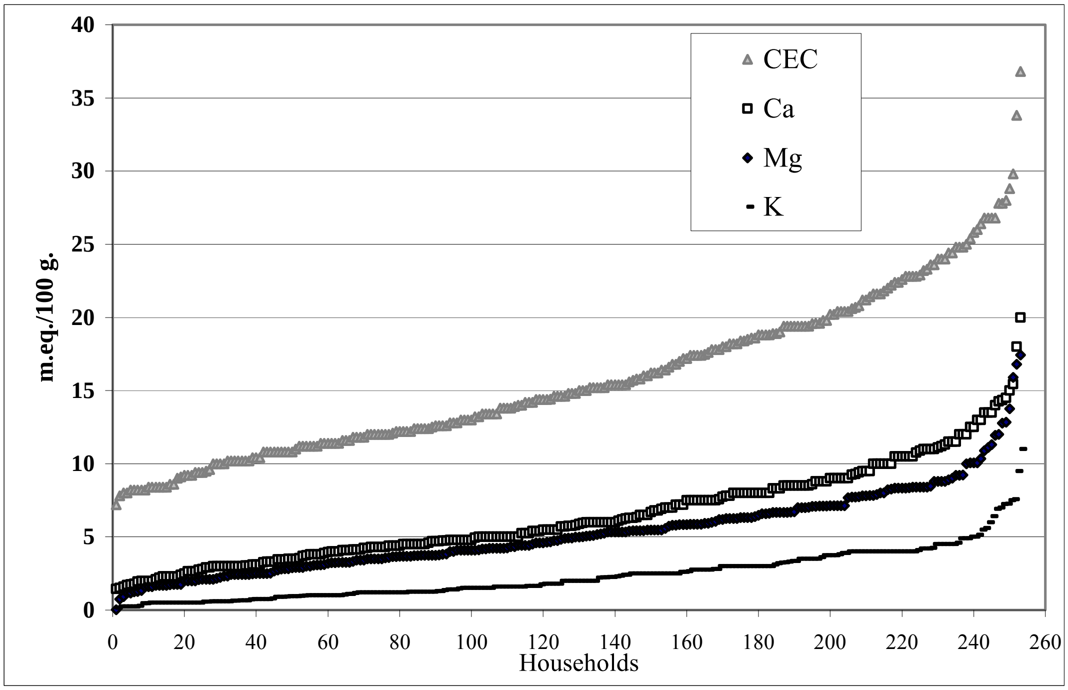


Figure A1.6 Distribution of Sodium (m.eq./100 g.)

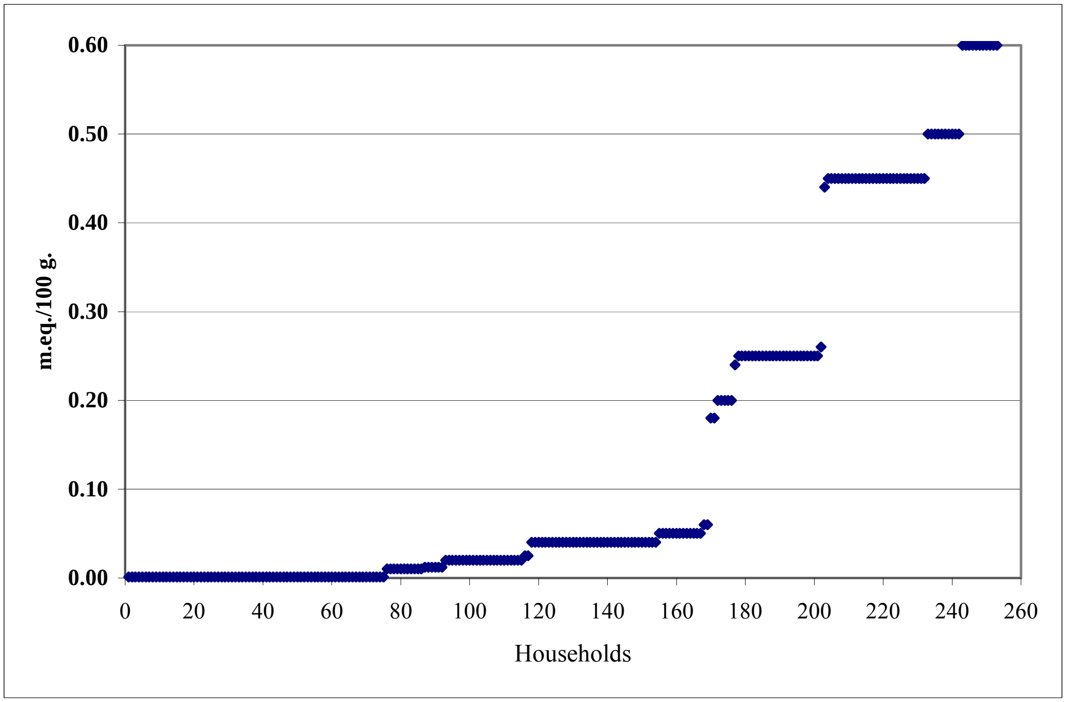
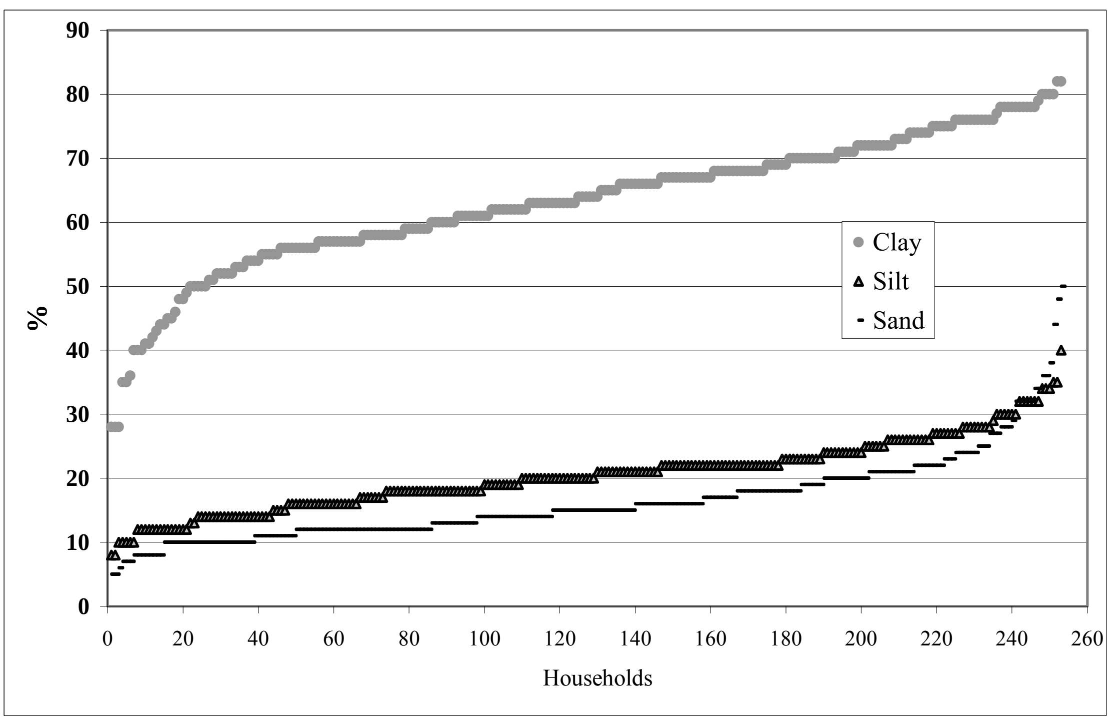


Figure A1.7 Distribution of Sand, Silt and Clay (%)



Appendix 2 Correlation Coefficients of Soil Properties

	pH[a]	pH[b]	C	N	K	Na	Ca	Mg	CEC	P	Sand	Silt	Clay
pH[a]	**1**	**0.95**	**-0.02**	**0.10**	**0.08**	**-0.20**	**0.53**	**0.57**	**0.59**	**0.36**	**-0.06**	**0.17**	**-0.05**
		<.0001	*0.717*	*0.108*	*0.200*	*0.001*	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*0.38*	*0.01*	*0.40*
pH[b]		**1**	**-0.07**	**0.10**	**0.06**	**-0.22**	**0.49**	**0.56**	**0.56**	**0.36**	**-0.10**	**0.12**	**0.00**
			0.250	*0.131*	*0.365*	*0.001*	*<.0001*	*<.0001*	*<.0001*	*<.0001*	*0.12*	*0.07*	*0.98*
Carbon (C)			**1**	**0.65**	**0.11**	**-0.01**	**-0.06**	**-0.17**	**-0.05**	**0.05**	**0.17**	**0.27**	**-0.26**
				<.0001	*0.09*	*0.87*	*0.37*	*0.01*	*0.40*	*0.40*	*0.01*	*<.0001*	*<.0001*
Nitrogen (N)				**1**	**0.10**	**-0.11**	**-0.01**	**-0.02**	**0.06**	**0.06**	**0.04**	**0.19**	**-0.13**
					0.12	*0.09*	*0.91*	*0.71*	*0.31*	*0.35*	*0.56*	*0.00*	*0.04*
Potassium (K)					**1**	**0.23**	**-0.02**	**-0.04**	**0.26**	**0.10**	**0.13**	**0.12**	**-0.15**
						0.00	*0.75*	*0.54*	*<.0001*	*0.10*	*0.05*	*0.06*	*0.02*
Sodium (Na)						**1**	**-0.14**	**-0.17**	**-0.10**	**-0.10**	**0.14**	**0.05**	**-0.12**
							0.03	*0.01*	*0.10*	*0.10*	*0.02*	*0.44*	*0.05*
Calcium (Ca)							**1**	**0.74**	**0.79**	**0.35**	**0.00**	**0.24**	**-0.13**
								<.0001	<.0001	<.0001	0.99	0.00	0.04
Magnesium (Mg)								**1**	**0.84**	**0.26**	**-0.07**	**0.22**	**-0.08**
									<.0001	<.0001	0.28	0.00	0.22
Cation Exchange Capacity (CEC)									**1**	**0.36**	**-0.01**	**0.27**	**-0.14**
										<.0001	*0.89*	*<.0001*	*0.02*
Phosphorus (P)										**1**	**0.07**	**0.10**	**-0.10**
											0.27	*0.11*	*0.11*
Sand content											**1**	**0.37**	**-0.86**
												<.0001	*<.0001*
Silt content												**1**	**-0.79**
													<.0001
Clay content													**1**

[a] measured in H_20-solution
[b] measured in CaCl-solution

Appendix 3 Cross Model Covariance and Correlation

Table A3.1 Cross Model Covariance

Variable	S_i	*pH*	*C*	*N*	*K*	*Na*	*Ca*	*Mg*	*CEC*	*P*	*Silt*	*Clay*
S_1	pH	1.20	0.29	0.10	0.16	0.01	0.02	0.25	0.15	0.14	-0.04	0.56
S_2	C		0.88	0.02	0.10	0.02	0.02	0.02	0.25	0.08	0.02	0.24
S_3	N			0.80	0.05	0.02	-0.01	0.13	0.03	0.25	0.06	0.10
S_4	K				0.27	0.03	0.02	0.04	0.09	0.03	0.01	0.15
S_5	Na					0.16	-0.01	0.05	0.01	0.03	0.00	0.01
S_6	Ca						0.45	0.01	0.07	0.08	0.02	0.03
S_7	Mg							1.01	0.08	0.24	0.00	0.10
S_8	CEC								0.46	0.09	0.03	0.09
S_9	P									0.91	0.03	0.04
S_{10}	Silt										0.07	-0.02
S_{11}	Clay											0.93

Table A3.2 Cross Model Correlation

Variable	S_i	*pH*	*C*	*N*	*K*	*Na*	*Ca*	*Mg*	*CEC*	*P*	*Silt*	*Clay*
S_1	pH	1.00	0.28	0.10	0.28	0.01	0.03	0.23	0.20	0.13	-0.14	0.53
S_2	C		1.00	0.03	0.20	0.04	0.03	0.02	0.39	0.09	0.09	0.26
S_3	N			1.00	0.11	0.05	-0.01	0.14	0.05	0.29	0.26	0.12
S_4	K				1.00	0.15	0.06	0.08	0.26	0.06	0.09	0.29
S_5	Na					1.00	-0.04	0.12	0.04	0.07	-0.02	0.01
S_6	Ca						1.00	0.02	0.16	0.12	0.10	0.05
S_7	Mg							1.00	0.12	0.25	0.00	0.11
S_8	CEC								1.00	0.15	0.15	0.14
S_9	P									1.00	0.13	0.04
S_{10}	Silt										1.00	-0.07
S_{11}	Clay											1.00

Appendix 4 Cross Model Inverse Correlation and Covariance

Table A4.1 Cross Model Inverse Correlation

Variable	S_i	*pH*	*C*	*N*	*K*	*Na*	*Ca*	*Mg*	*CEC*	*P*	*Silt*	*Clay*
S_1	pH	1.59	-0.21	-0.06	-0.18	0.07	0.02	-0.23	-0.08	-0.10	0.25	-0.67
S_2	C		1.30	0.07	-0.03	-0.04	0.07	0.10	-0.44	-0.05	-0.12	-0.19
S_3	N			1.20	-0.05	-0.03	0.09	-0.07	0.04	-0.29	-0.31	-0.12
S_4	K				1.21	-0.17	-0.02	0.02	-0.22	0.03	-0.10	-0.22
S_5	Na					1.05	0.05	-0.11	0.01	-0.05	0.06	0.03
S_6	Ca						1.06	0.02	-0.16	-0.13	-0.10	-0.07
S_7	Mg							1.14	-0.10	-0.23	0.02	0.00
S_8	CEC								1.30	-0.08	-0.12	0.05
S_9	P									1.19	-0.06	0.08
S_{10}	Silt										1.18	0.07
S_{11}	Clay											1.48

Table A4.2 Cross Model Inverse Covariance

Variable	S_i	*pH*	*C*	*N*	*K*	*Na*	*Ca*	*Mg*	*CEC*	*P*	*Silt*	*Clay*
S_1	pH	1.32	-0.21	-0.06	-0.32	0.16	0.02	-0.21	-0.11	-0.10	0.87	-0.63
S_2	C		1.48	0.08	-0.06	-0.10	0.11	0.11	-0.69	-0.06	-0.48	-0.21
S_3	N			1.50	-0.12	-0.07	0.14	-0.08	0.07	-0.34	-1.34	-0.14
S_4	K				4.51	-0.81	-0.07	0.04	-0.61	0.07	-0.75	-0.44
S_5	Na					6.45	0.18	-0.28	0.04	-0.12	0.53	0.07
S_6	Ca						2.33	0.03	-0.34	-0.21	-0.55	-0.10
S_7	Mg							1.13	-0.15	-0.24	0.07	0.00
S_8	CEC								2.83	-0.13	-0.70	0.07
S_9	P									1.31	-0.25	0.09
S_{10}	Silt										17.47	0.26
S_{11}	Clay											1.59