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Determinants of Soil Capital

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Determinants of Soil Capital[1]

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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. The 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, labour 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 limited to soils' biological, physical and chemical characteristics fail to recognize that soil is capital owned and managed by farmers. They thus run the risk of omitting important socio-economic determinants of soil capital. They also exclude the possibility to explain some of the dynamics that are determined by its stock character.

On policy, the study shows that farmers' soil conservation investments, allocation of labour, manure and fertilizer input, and crop choice indeed do determine variation in farmers' soil capital. Particularly strong positive effects on key soil nutrients (N,P,K) are observed for certain conservation technologies. Extension advice shows unexpectedly no significant effects on soil capital. The wide distribution of soil properties across farms reinforces the need to (i) tailor technical extension advice to the specific circumstances in each farm, and (ii) enhance the integration of farmers' knowledge and experiences, expert judgment and scientific soil analysis at the farm level.

Keywords: soil fertility, soil productivity, resource management;

JEL classification: Q12, Q20

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1. 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 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 e.g. how soil is formed and changes over time. The traditional focus has been on physical, chemical and biological determinants. 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 e.g. 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-simplify natural capital and soil in particular in the analysis (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 thus fill a gap in the field. It may also contribute to enhanced policy making. In this paper we seek to combine knowledge from the two disciplines and study the relationship between soil capital and farm management.

Questions we address in this paper include: do production inputs like labour supply to cultivation, inorganic fertilizer and manure explain the status of various soil properties? Do age, gender and education of the household head contribute to 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 is the impact on soil capital of farmers' choice regarding land allocation to various crops?

The paper is organized as follows. Section 2 of the paper presents and discusses some of the relevant literature on soil research. Section 3 presents the model to be estimated. Section 4 presents the field study area, the data and data collection. Section 5 presents the statistical results and section 6 presents conclusions and some policy implications.

2. 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 like pedology, edaphology, geomorphology, agronomy and ecology have 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)[3], alkalinity/acidity (pH) and structural properties[4] and texture[5]. Jenny (1994) suggests that soil formation is a function of climate (*cl*), biota (*o*), topography (*r*), parent material (*p*), time (*t*) and other variables ($\boldsymbol{Z}$): $\boldsymbol{S} = f(cl, o, r, p, t, \boldsymbol{Z})$. Here, $\boldsymbol{S}$ 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).

[3] Cation exchange capacity (CEC) is the capacity of a soil for ion exchange of positively charged ions between the soil and the soil solution. CEC is an important soil property which is used as a measure of soil fertility and nutrient retention capacity. CEC is largest in clay soils.
[4] Soil structure is important since it determines the soil's porosity and air and water holding capacity.
[5] Texture represents grain size distribution of clay, silt and sand particles. It is an important factor for retention of water and nutrients, where clay has the highest capacity. However, clayish soils are more erodible. Good plant growth is usually favoured by more balanced soils e.g. sandy loams (Sparks, 1999).

Soil scientists have addressed the issue if and how the soils' complexities can be aggregated and properly represented in relation to its various functions.[6] Consequently, soil quality (SQ) has been developed as a concept to define soils' dynamic properties, 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" p.7 (Allan *et al*., 1995). SQ is closely related to other concepts like soil fertility and soil productivity.[7] Identification and assessment of SQ are usually based on a minimum data set of biological, chemical and physical properties, which are transformed into a weighted Soil Quality Index (SQI)[8]. 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, biased towards crop production and certain geographical regions, and lack 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 critiques 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 are often shaped by the hand of the farmer. Hence, the farmer's characteristics, skills and choices may play a role for shaping the farmer's soil capital. For instance, Nkonya et al (2004) show that economic factors may contribute both positively and negatively to small-scale farmers' nutrient balances. They also show that the annual cost of nutrient mining (NPK-losses) among households subjected to erosion and other forms of soil degradation, amounts to around 20% of the farmers' income. By investing labour in soil conservation, farmers can

[6] Production of food, fibre 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).
[7] *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; p. 146). Other concepts include e.g. soil resilience, soil health, sustainable soil use, soil degradation including soil pollution (Coleman and Hendrix, 2004).
[8] For instance, Tiwari *et al*, 2006 suggest that $SQI = \sum_{i=1}^{n} W_i Q(X_i)$ where W_i is the weight factor associated with each soil quality factor $(Q(X_i))$.

increase their soil capital (build up soil productivity and soil fertility) and thus future harvests (Gachene and Kimaru, 2003). Soil erosion and failure to maintain soil fertility imply capital depreciation.

Economists argue for the importance of treating these 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 doing this is the long time lags and complicated dynamics involved from 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.

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 e.g. Ovuka and Ekbom (2001) who investigate 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) identify soil nutrient balances of various farming systems. Ovuka (2000), Gachene (1995), Gachene *et al.* (1997) analyse the impact of soil change (erosion) on individual soil properties. Gachene *et al.* (1998) and Kilewe (1987) analyse the yield effects of soil erosion. Gicheru (1994) analyses effects of residue mulch and tillage on soil moisture. Batjes (2004) projects changes in carbon stocks in relation to land use. Hartemink *et al.* (2000) investigates the nitrogen dynamics in fallows and maize production for different soil types. Gicheru (1994) analyses the effects of mulch and tillage on soil moisture. Dunne (1979), Moore (1979) and Lewis (1985) estimate soil loss and sediment yields. Common to most of these and other similar studies in this research area is the fundamental lack of integration of soil data and economic variables in order to identify determinants of soil capital.

3. The Empirical Model

We assume that soil capital can be represented by a vector of individual soil properties,[9] $\mathbf{S}=\{S_i\}$, i=1..n, and each soil property can be explained by a set of independent variables:

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

[9] 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 e.g. Sojka and Upchurch, 1999, Sojka et al, 2003, Letey et al, 2003 above, we use a disaggregated representation of soil.

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

The rationale for the specification of equation 1 is based on our hypothesis that ***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 ***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' variation in soil capital. Besides our proposition that soil is a heterogenous good, we also assume that farmers' decision on soil management and (re)investment is made up of a set of heterogenous decisions, which also vary across farms.

Ideally, identifying determinants of soil capital implies a study over a very long time horizon since several soil properties are shaped or accumulated over a long time. It is generally true that soil capital is relatively inert and constant, particularly in sub-soil layers (B- and C-horizon), partly because several natural soil-forming factors are relatively stable across time (Coleman and Hendrix, 2004). However, if the soil is subjected to e.g. erosion, drought and inadequate farming practices, the properties in the humus layer (O-horizon) and in the topsoil (A-horizon) can change very rapidly, with negative effects on fertility and productivity (Gachene, 1995; Tengberg *et al.*, 1998; Stoorvogel and Smaling, 1998). Hence, as an effect of soils' non-linear distribution of soil properties down the soil profile, even very deep soils (> 200cm) 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 one and 4 years for different variables) we perform regression analysis in the hope that differences in behaviour between farms are 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 judgments of the accumulated effect of soil management over a fairly large number of years. In order to compare regression coefficients, all variable values have been 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 year's data allow for impacts caused by inputs and measures implemented in the most recent time periods. It may be argued that inputs and investments undertaken longer back in time 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 the lack of historical data. In practice, the observations of soil conservation investments (I_I-I_{II}) represent the physical outcome today of farmers' labour allocation to soil conservation in the past. Regarding annual inputs, it can be argued that the impact on current soil capital of historical inputs of fertilizer and manure 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, nor does it represent a demand function for soil capital. Essentially, it describes an empirical metric for S. Primarily we are trying to answer the questions: what can be a reasonable representation of **S** and what determines **S**? It is true that one can see equation 1 as a reduced form-expression of a system in which you would have both demand and supply. Defining whether equation 1 represents a demand *or* supply function of soil capital implies a non-separability problem since this is complex household production with unobservable, interacting characteristics, some of which evolving very slowly over time; then 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 perform a joint estimation of the equations using Seemingly Unrelated Regression (SUR), which is generally more efficient than separate estimation by Ordinary Least Squares (Zellner, 1962; Mehta and Swamy, 1976).

4. Field Study Area and Data

The study area is located in Muranga district, Kenya. It is located at 1500 m a.s.l. (0º43' S, 37º07' E) on the eastern slopes of Nyandarua range in Kenya's central highlands, south of Mount Kenya and south-east of the Aberdares forest reserve. It consists of two adjacent hydrologically defined catchments. Muranga district covers 2525 square kilometres and is part of the large drainage area of Kenya's central highlands. The climate is semi-humid (Sombroek *et al.*, 1980); average annual precipitation is 1,560 mm distributed over two rain seasons, March to May and October to December (Ovuka and Lindqvist, 2000). This facilitates two growing seasons each year. The study area lies within the main coffee zone. The main soil type is humic nitisol, distributed over volcanic footridges. 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 and 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 is based on family and clan affiliation and today, with some limitations[10], most of the farmers possess title deeds to surveyed, registered and adjudicated plots, which implies that tenure security is relatively high in a regional country comparison. The area shares many demographic, socio-economic and bio-physical features with the rest of the central highlands, which is home to the largest share of Kenya's population and food production. Hence the study of Muranga is of importance and relevance from a larger policy perspective. The agricultural lands in Muranga district are subject to large population pressure. This is manifested by high population density and increasing land fragmentation. At present, 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, more than 60% of the population is constituted by children and teenagers. Given limited job opportunities besides agriculture, erosive rains, erodible soils and cultivation of steep slopes, the pressure on the district's soil capital is large and increasing. Identifying determinants of individual soil properties is therefore of considerable policy relevance.

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[10] described in e.g. Kenya's draft Land policy; Ref.: Republic of Kenya, 2007. *National Land Policy* (draft), Ministry of Lands, National Land Policy Secretariat, http://www.ardhi.go.ke/landpolicy.htm

Data and Data Collection

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

Dependent Variables: Collection and analysis of the soil samples followed the following 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). Places where mulch, manure and fertiliser were visible were avoided for soil sampling. The soil samples were air dried and analysed at the Department of Soil Science (DSS), University of Nairobi. The following soil properties were determined: grain size distribution (percentage 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-level in water solution and in a calcium chloride ($CaCl_2$) solution.[11]

The grain size distribution (texture) was determined by the hydrometer method. Grain size for sand, silt and clay is 0.05-2mm, 0.002-0.05mm and <0.002mm, respectively. CEC was analysed by leaching the soil with potassium ammonium acetate at pH 7. Na and K were determined using the flame photometer while Ca and Mg were determined using the atomic absorption spectrophotometer method. Available P was analysed using the Mehlich method, pH-level (H_2O) and pH-level ($CaCl_2$) were analysed using soil-water ratio and soil-salt ratio 1:2.5, respectively. Total N was identified using the Kjeldahl digestion method and organic C 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 e.g. that the soils are clayish although the local variation is significant (between 16-82%). Moreover, the soils are acidic with a min-max $pH_{(H_2O)}$-level distribution between 4.1 and 8.2.

[11] The correlation coefficient between pH (H_2O) and pH (CaCl) is >0.95. Hence we have chosen 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 has been converted by taking the absolute value of the difference between each farm's pH-value (pH_i) and neutrality $\left(|pH_i - 7|\right)$.

Table 1. Summary Statistics of Soil Sample Properties

Soil Property	Unit	Mean ($\bar{\mu}$)	St. Dev. (σ)	Min.	Max.	λ (= σ / $\bar{\mu}$)
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 Exch. Capacity	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

Fertility, proxied by the cation exchange capacity (CEC), is low[12]. 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 (P).[13] 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 homogenous 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.

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

*Soil conservation investments (**I**):* The farmers in the area carry out a large number of physical as well as biological soil conservation measures. 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

[12] Soils with a CEC <16 m.eq./100g. soil are considered not to be fertile (Gachene and Kimaru, 2003).
[13] For acidity (pH) the variation coefficient is even lower but the comparison is not appropriate since this is a logarithmic index.

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 ranging between 0 and 10. 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, with the purpose of infiltrating water into the soil in a controlled way. Position, length, depth and width of the drain are critical factors in determining the effectiveness to trap water (Thomas et al, 1997). Quality criteria for rating CODs also include: i) discharge, outlet and disposal of water; ii) vegetation cover and stability of the upper and lower embankment, (iii) and 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 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 spacing, physical dimensions, location, stability and vegetative cover on the embankments. These factors are critical to prevent over-topping of water and breakage. High quality terraces are level along the contour, perpendicular to the natural slope, reduce the natural slope, and show no signs of breakage 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, breakage of embankments, poor vegetative cover along edges, and inadequate size and spacing[14] can easily break the structures and accelerate surface run-off and soil loss.

Biological conservation measures include conservation tillage, crop cover, integrated use of farm-yard 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 and 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 are

[14] >10m for steep slopes; >15m for moderate slopes; >20m for gentle slopes.

assumed to be critical factors 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 have large ground cover, whereas onions, beans, potatoes and pulses generally have low ground cover. Criteria in the quality 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.

Farm-yard 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 implies 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* implies application of dry, vegetative material in the field to cover the soil. It is stated to be an important factor to control erosion, reduce evaporation, improve soil structure, retain existing soil nutrients and soil moisture, and promote plants' uptake of additional nutrients from decomposed organic material (Ozara, 1992; Gachene and Kimaru, 2003). Factors determining 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) aiming at reducing soil erosion, maintaining soil moisture and improving soil fertility. Quality criteria include e.g. distribution and ground cover, soil moisture and structure, heat protection, weed abundance, interference with main crops, and signs of pests associated with the green manure legume/grass.

Agro-forestry implies planting trees or perennial bushes in the farm field (Nair, 1997; Young, 1997). Agro-forestry is advocated to: (i) stabilize the soil and prevent mass-movements of soil such as landslides by the deep tree roots (Smith et al., 1999), (ii) retain soil moisture by providing shade from sunlight, (iii) reduce the velocity (erosivity) of rain due to the ground cover provided by the tree canopy and branches, (iv) enhance soil fertility by providing nutrients from decomposition of fallen leaves, and (v) increase yields from production of fruit crops, and provide timber, fodder and fuelwood. Crops from agro-forestry in the study area include coffee, mango, banana, avocado, lemon, papaya and macadamia nuts. Criteria for our quality assessment include e.g. choice, height, spacing, pruning and distribution of the trees, root exposure, ground cover, and signs of pests.

Although livestock numbers are decreasing in the central highlands, *fodder production* and *grazing land management* are important components of farmers' soil management systems. Quality criteria for fodder production include 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 re-cycles the nutrients and biomass back into the soil (van den Bosch *et al.*, 1998). Good management of grazing lands implies erosion control on pastures, appropriate supply of livestock in relation to pasture carrying capacity, rehabilitation of gullies, fencing or tethering, and grass planting on bare grounds. Low rating is given to denuded grazing land, which shows signs of erosion. Reseeding and gully reclamation are not practiced and the land is covered by woody bushes with a limited value from a soil fertility or productivity point of view.

Extension advice (X): 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 the colonial rule. Since Independence in 1963, soil conservation has been advocated by the Government of Kenya (GoK). Due to the coercive measures practiced by the British, soil conservation was resisted by the farmers during the first decade of independence. GoK's support took off in 1974 when a new public soil conservation project was launched. Progressively it has developed into a national program, and primarily built on individual farm visits provided by Ministry of Agriculture's local soil and water conservation experts. They are technical extension agents (TAs) providing on-site advice on soil and water conservation measures to individual households. Given the Program's goal to conserve soil, enhance soil fertility and boost food production, it is of interest 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 has been visited over a four year's period by a technical extension agent and been provided advice on soil and water conservation.

*Physical production factors (**PF**):* Variables representing physical production factors used in the regression analysis include agricultural labour (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's period. Hence, e.g. fertilizer is an un-weighted aggregation of fertilizer input over a four-year's period ($F = \sum_{t=1}^{4} F_t$), which covers eight growing seasons.

*Crop allocation (**R**):* Crop allocation 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 represent two key crops, where coffee is cultivated mainly for cash income and maize for food. Together, more than 75% of the farm area is allocated to coffee and maize. Remaining land is typically allocated to a small garden for cultivation of fruits and vegetables, homestead, livestock grazing (*boma*), other food and cash crops (beans, potatoes, bananas) and a small woodlot. Some farms are also occupied by wastelands (gullies, rocks). Arguably, each farmer pursues a certain farming strategy. Here, the choice and area allocation of crops in the farm constitute crucial decisions. Apparently, farms make very different choices. Arguably, this does not only 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 e.g. that as much as 30% of the households are reported to be headed by females. This group is represented by divorced women, widows and women with husbands who have migrated, at a more or less permanent basis, to nearby towns and the capital to seek an outcome. Most households are characterized by relatively old heads (mean>55 years), low formal education and few working adults. This is caused by large out-migration and puts a constraint on labour availability during the agricultural peak-season (seed-bed preparation and harvesting). Appropriate labour is also relatively scarce during the time for construction or maintenance of physical soil conservation structures.

Table 2. Summary Statistics of the Independent variables

Variable	**Definition**	**Mean**	**Min.**	**Max.**	**Std Dev**
H_1	Sex of Head (1=Male;0=Female)	0.71	0	1	0.45
H_2	Age of Head (years)	55.1	20	96	13.86
H_3	Education (years)	5.7	0	20	4.42
H_4	Working adults (nr)	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	TA-visits (nr.)	1.9	0	9	1.87
L_Q	Ag. Labour/acre (hrs)	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

When nothing else is stated the variables are indices based on expert judgement

According to the quality rating of soil conservation investments, the area as a whole acquires medium to low rates. Terraces rates highest (mean=5.8) followed by crop cover (5.6) and fodder management (5.4). The relatively low rating of the soil conservation investments corroborates the substantial soil loss observed in the area[15]. Moreover, the coffee trees in the study area are relatively old (>20 years), although variation in the sample is considerable.

On average, each household has been visited by a technical extension agent (TA) slightly less than two times during four years. Although this frequency seems little, each visit typically includes 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* on 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 farm-yard manure is approximately 3300 KSh per acre (≈50$US). The soil is only tilled with hand tools (hoe, machete). Draft animals are not used for ploughing. Instead, manual labour 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 of interest to investigate the predictive relationship between farmers' production factors and soil conservation quality, and individual soil properties.

[15] Although recent data is scarce, Lewis (1985) reports an average soil loss of 12 t/ha/yr in Muranga district. In some extreme cases it exceeds 150 t/ha/yr. Gachene (1995) and Gachene *et.al.* (1997) identify equally large soil losses in Kenya's Central Highlands and associated depreciation of key soil quality properties and yield losses. Dunne (1979) estimates that the Upper Tana river catchment in the Central Highlands, yields 4.8 million tons of soil sediment per year.

5. Statistical Results

Joint estimation of the multiple equations represented by model 1 above by Seemingly Unrelated Regression (Greene, 2000) yields the results presented in table 3-5 below.[16]

Table 3. Regression results of primary macro nutrients

		Dependent Variables							
Indep.		**Carbon**		**Nitrogen**		**Phosphorus**		**Potassium**	
variable	**Definition**	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
α	Intercept	-0.517	-0.65	**-1.893**	**-2.38**	-0.429	-0.51	**0.669**	**2.19**
H_1	Sex of Head 1=M;0=F	**0.134**	**2.80**	0.028	0.60	0.040	0.83	0.002	0.11
H_2	Age of Head	0.148	0.27	0.391	0.69	-0.054	-0.09	0.340	1.60
H_3	Years of education	-0.284	-0.95	0.307	1.07	0.411	1.35	**-0.232**	**-2.12**
H_4	Nr 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. Labour/acre (hrs)	-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

Interpretation of the statistical results

Carbon (C): 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, farm-yard manure and green manure significantly increase C concentrations in the soil stock. Similarly,

[16] General statistics obtained from SUR: System Weighted Mean Squared Error (MSE)=1.00, Degrees of Freedom=2465; System Weighted R-Square: 0.31.

cultivation of maize and coffee is associated with loss of soil organic C. 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.

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 farm-yard manure for conservation purposes, mulching, agro-forestry, appropriate grazing land management and terraces, and older coffee trees. Plausible explanations to these results are that: good ground cover physically prevents loss on N from rain; application of chicken manure and cow-dung replenishes soil with nitrogen; mulching physically prevents loss of N from soil erosion and re-circulates N 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 N for their growth, the results indicate a positive effect on soil nitrogen. There are many plausible explanations to this: the tree canopy prevents soil loss during the rain periods, deep roots capture leached nitrate from sub-soil layers and re-circulates N into the soil via decomposition of fallen leaves (Warren and Kihanda; 2001). The roots stabilize the soil and prevent erosion together with leaves, which physically protects the soil. The negative sign on fodder production is explained by the large loss of N associated with production of napier grass.[17]

From a policy perspective it is of interest to note that the largest positive effects on soil N concentration are obtained from good grazing land management, integrated us of manure, well established terraces structures, 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).

The negative sign of coffee and maize area may be explained by the current farming practices associated with these crops. Despite some inflows of N from biological N-fixation,

[17] 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) finds that napier production in a similar agricultural system in central Kenya reduces the soil N with 126 kg/ha per year.

(in)organic fertilizers and atmospheric deposition, the reduction of soil nitrogen are considerable in a farming system like the one we study. To exemplify, production of coffee and maize under similar conditions in Kenya's highlands causes a net annual loss of N corresponding to 31 kg/ha and 88 kg/ha, respectively (van den Bosch *et al.,* 1998). De Jager *et al.* (2001) find that maize production under similar farming practices and agro-ecological conditions reduces soil N concentrations with 44 kg/ha per year.

The losses of N are mainly due to leaching, volatilization, erosion, crop harvesting and removal of crop residues. Due to the local soil type (*nitisol*) and inefficient fertilizer use, leaching of N to sub-soils is substantial (Warren and Kihanda, 2001). Loss of N in coffee production may also be a result of recent-years' abandonment of coffee trees. Low farm-gate coffee prices, high input prices and eroding coffee cooperative societies have worked in conjunction to reduce investments in the bench terraces on which coffee is grown and in the coffee trees (soil nutrient replenishment, pruning, weed control, pest management etc.). Consequently, younger trees in particular are developing poorly, and some have even been subject to uprooting. Older trees, however, show higher soil N concentrations. This might be explained by deeper roots (which can retrieve N from sub-soil layers), larger canopies (which prevents soil loss), more litter production (which supplies more N from the decomposed material), and better stabilization of the terrace structure than younger trees.

Phosphorus (P): Good tillage practices and manure conservation contribute positively to the soil's P content. As can be expected, re-circulating crop litter (stalks and stovers), cow dung and other types of farm-yard manure into the soil contributes to increase the soil's P concentration. The results are corroborated by e.g. de Jager *et al.* (2001) who find positive P nutrient balances for manure-based cultivation in a similar agro-ecological setting. Interestingly, application of chemical fertilizer during a four-year's period gives a positive but statistically insignificant effect on the soil's available P 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 farm-yard manure (FYM) increases P availability in at least two important ways; first, manure it self contains significant amounts of phosphorus; second, fixation of P is inhibited since incorporation of FYM into the soil reduces soil acidity[18].

Potassium (K): Several soil conservation technologies have a positive and significant relationship with soil K, particularly cut-off drains, good crop cover, conservation tillage, integrated use of (farm-yard and green) manure and mulching. This finding is no surprise since it has been found 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) find that 29% of K inflows to the soil originate from farm-yard 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 K replenishment is to some extent compensated by the use of potassium promoting soil conservation measures and relatively large use of farm-yard manure for replenishment of K and other macro nutrients.

Generally, one would expect a positive and statistically significant effect of inorganic fertilizers on the soils' K concentration. However, volatilization, leaching, erosion and other nutrient depleting processes are strongly inhibiting factors to increasing the amount of K in the soil under the present farming system (van den Bosch et al., 1998; Gachene and Kimaru, 2003).

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

Table 4. Regressions results of pH, texture and cation exchange capacity

		Dependent Variables							
Indep.		**pH**		**Clay**		**Silt**		**CEC**	
variable	**Definition**	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
α	Intercept	-0.835	-0.87	**1.320**	**5.74**	**1.430**	**1.67**	-0.407	-1.00
H_1	Sex of Head 1=M;0=F	0.077	1.37	0.019	1.43	**0.091**	**1.83**	0.050	1.45
H_2	Age of Head	0.697	1.03	-0.261	-1.61	-0.911	-1.51	#	#
H_3	Years of education	-0.052	-0.15	**0.174**	**2.10**	**-0.572**	**-1.86**	0.274	1.26
H_4	Nr 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	TA-visits (nr.)	-0.043	-0.30	-0.017	-0.50	-0.012	-0.09	0.018	0.20
L_Q	Ag. Labour/acre (hrs)	-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
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

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 given by manure conservation, management of grazing land and terraces. Increased area allocation to 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 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.

Clay and silt: Soil conservation investments have mixed effects with respect the indicators of soil texture (clay, silt). The regression results show a positive relationship between cut-off drains and clay content. Silt is trapped by good crop cover, manure conservation, mulching and older coffee trees, which have bigger roots and larger canopies. Interestingly, green manure, terraces and coffee trees have small but negative effects on the soil's clay content. Determination of causes requires more study, but the effect of green manure may be explained by the fact that plowing of legumes into the soil exposes the soil to erosion risks, and loss of clay particles in particular. A similar effect of soil exposure may explain the strong negative relationship between area allocated to coffee and maize, respectively, and the soil's clay concentration. However, sine crops have different requirements regarding texture (and other soil properties), 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).

Cation Exchange Capacity (CEC): The analysis of 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 us to conclude 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.

Table 5. Regressions results of secondary macro nutrients

		Dependent Variables					
Indep.		**Sodium**		**Calcium**		**Magnesium**	
variable	**Definition**	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
α	Intercept	-0.055	-0.15	0.289	0.48	-0.027	-0.03
H_1	Sex of Head 1=M;0=F	-0.015	-0.71	0.019	0.55	-0.044	-0.85
H_2	Age of Head	-0.069	-0.27	0.122	0.29	0.493	0.78
H_3	Years of education	-0.031	-0.24	0.042	0.19	**0.592**	**1.85**
H_4	Nr 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	TA-visits (nr.)	-0.046	-0.86	0.063	0.72	-0.140	-1.06
L_Q	Ag. Labour/acre (hrs)	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

Secondary macro-nutrients: The regression results indicate that all statistically significant effects of soil conservation investments are positively associated with Na, Ca, and Mg. 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 Ca. 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 C, N, P and K, respectively. Significant positive effects on Na are also observed for agricultural labour and inorganic fertilizer, whereas negative signs are observed between Na 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 e.g. fallows or (in)organic fertilizers. 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.

6. Conclusions and Policy Implications

Our study has both methodological and policy implications. For soil capital to be a relevant variable in economic analysis, we have to account for the fact that it is heterogenous 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 ***S*** in reality implies e.g. 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 with crops' diverse requirements for optimal growth, *and* the roles played traditional economic production factors such as labour input. Hence, economic abstractions of ***S*** such as soil depth need qualification since shallow soils may be fertile while deep soils may be quite infertile if eroded, leached or subjected to other forms of degradation. Ideally, economic analyses, which include 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 (accumulated, depreciated) by the farmer and not only the outcome of bio-physical factors such as climate, geology and topography. Farmers' characteristics and management strategies are heterogenous 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 the farmer and his/her incentives, choices, constraints and characteristics, introduces the risk of omitting crucial variables in the analysis of soil productivity and soil change.

Interesting findings from the estimation results include:

(i) *the (generally) positive effects of soil conservation investments on soil properties;* farmers who have made considerable efforts over time to establish and maintain high-quality conservation structures have been rewarded by higher macro-nutrient levels; It is however, also noticeable that some conservation investments show no significant effects on certain soil properties. Careful selection of conservation technology is hence of great importance in the efforts to sustain soil capital. Moreover, there is no clear pattern indicating that physical/structural conservation measures dominate biological conservation measures, or vice versa, regarding their respective impact on soil properties.

(ii) *the negative effect of coffee and maize production on soil nutrients (C, N, Na), clay concentration and pH (maize)*. Given the farmers' large land allocation to maize and coffee production (>75%), 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).

(iii) *Visual field assessment and laboratory soil sample analysis are useful complements.* The results show that visual field assessment of soil conservation technologies can give a good indication of farmers' general soil quality. However, to ensure adequate knowledge on the links between conservation status and soil status it is necessary to increase their specific knowledge on individual soil properties. Hence, for farmers to optimize their production visual field assessment based on expert judgement 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) point at the importance of internalizing these aspects in the formulation 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, expert judgment *as well as* site-specific information based on and scientific analysis (e.g. soil sample analysis). Such an approach would integrate farmers' knowledge and practices, extension services and research to a larger extent than at present, and promote increased agricultural productivity *and* sustained soil capital.

Appendix 1: Distribution of Soil Properties

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

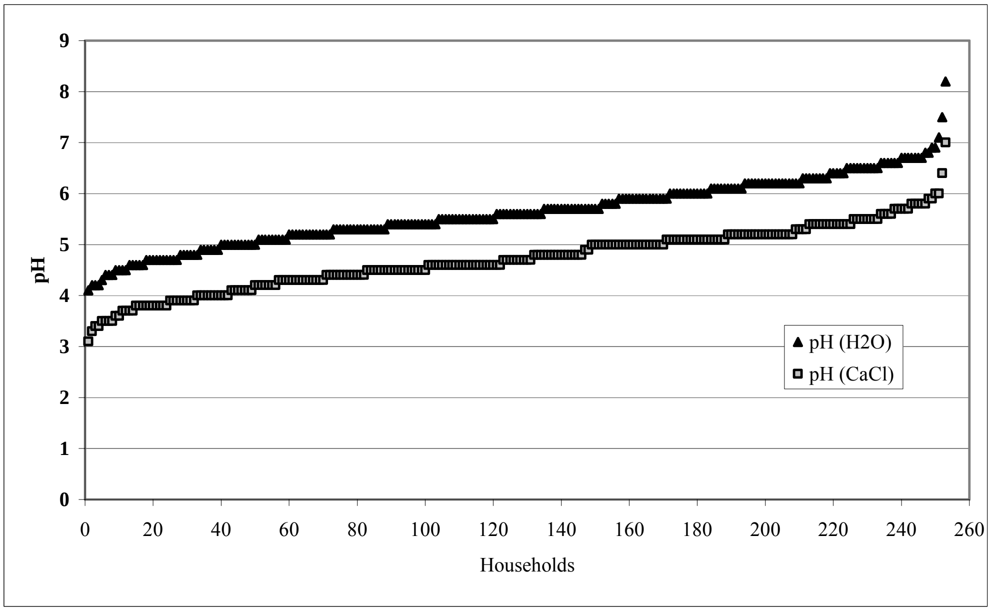


Figure A2. Distribution of Carbon (C) (%)

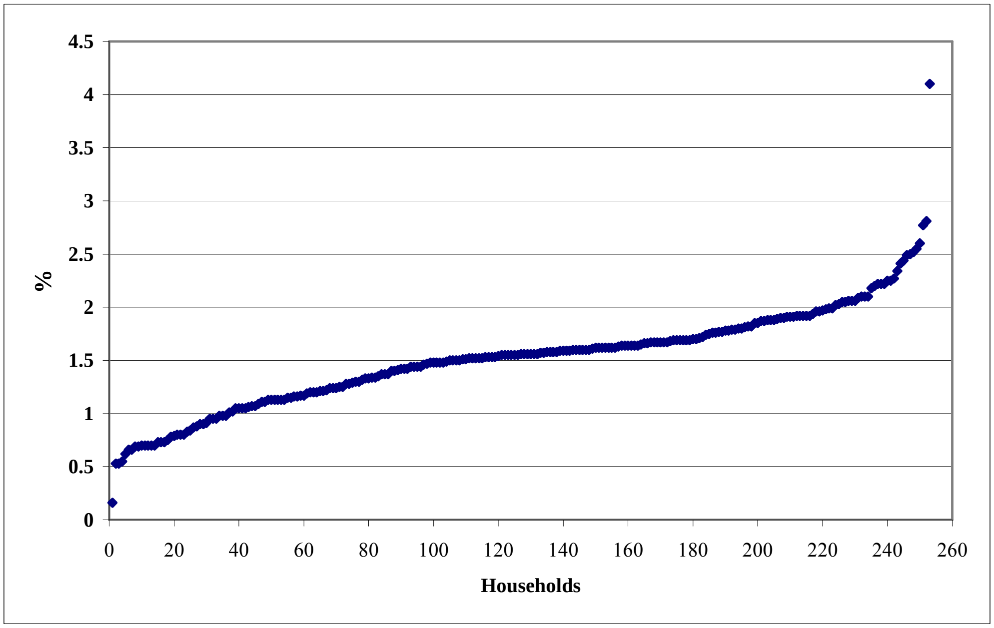


Figure A3. Distribution of Nitrogen (N) (m.eq./100 g.)

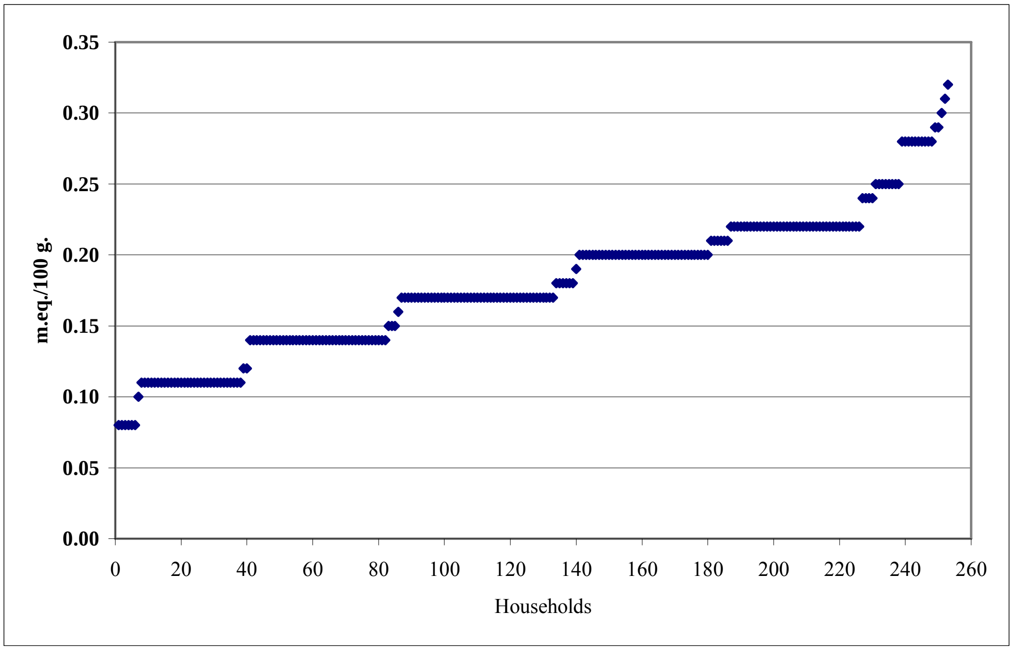


Figure A4. Distribution of Phosphorus (P) (ppm)

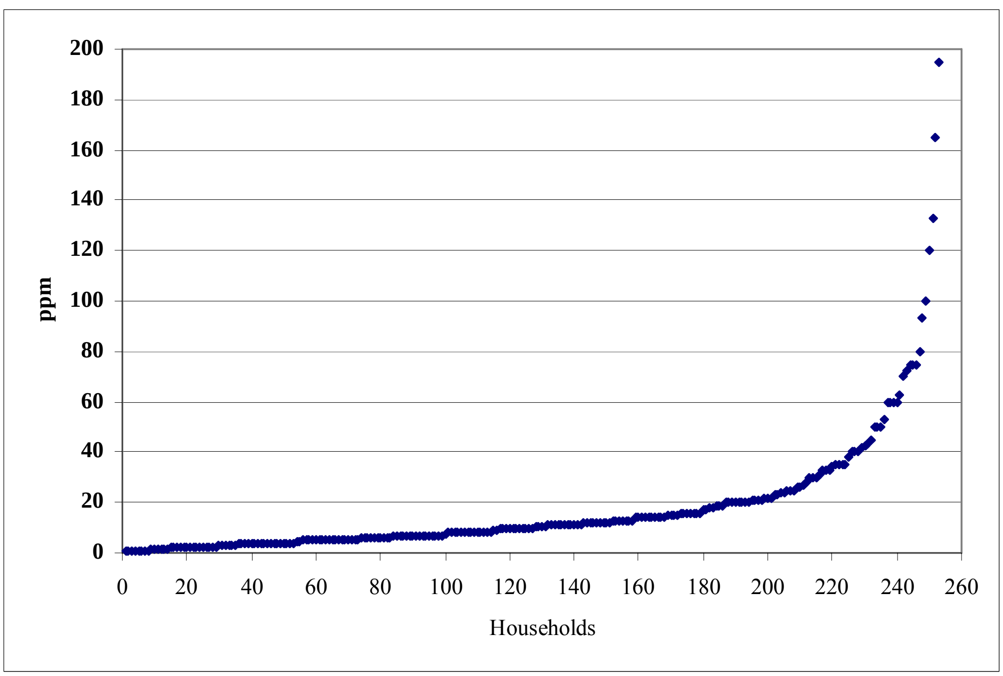


Figure A5. Distribution of Potassium (K), Calcium (Ca), Magnesium (Mg) and Cation Exchange Capacity (CEC) (m.eq/100 g.)

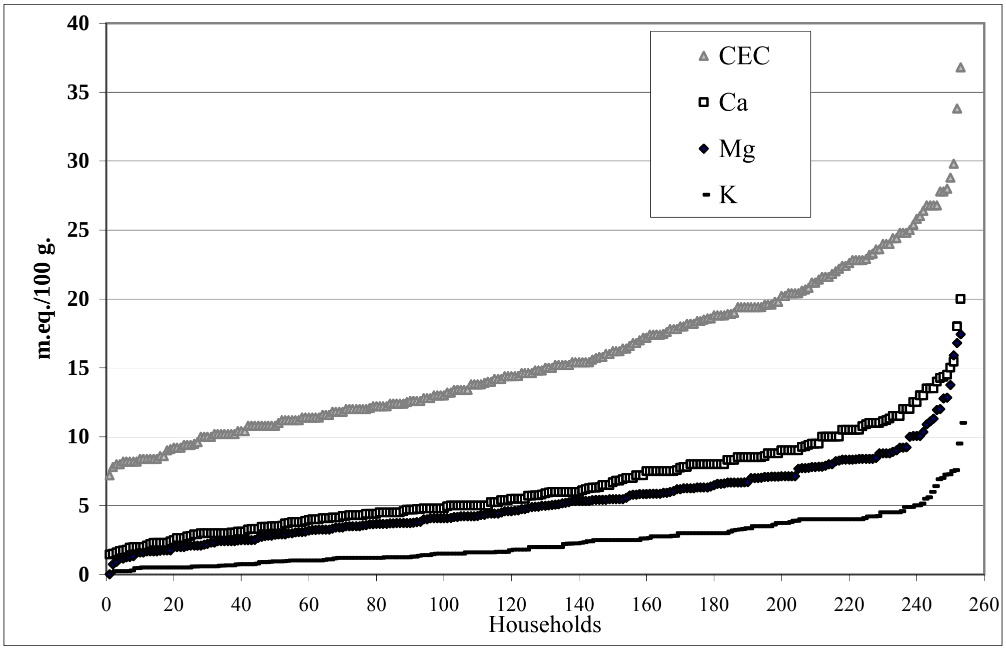


Figure A6. Distribution of Sodium (Na) (m.eq./100 g.)

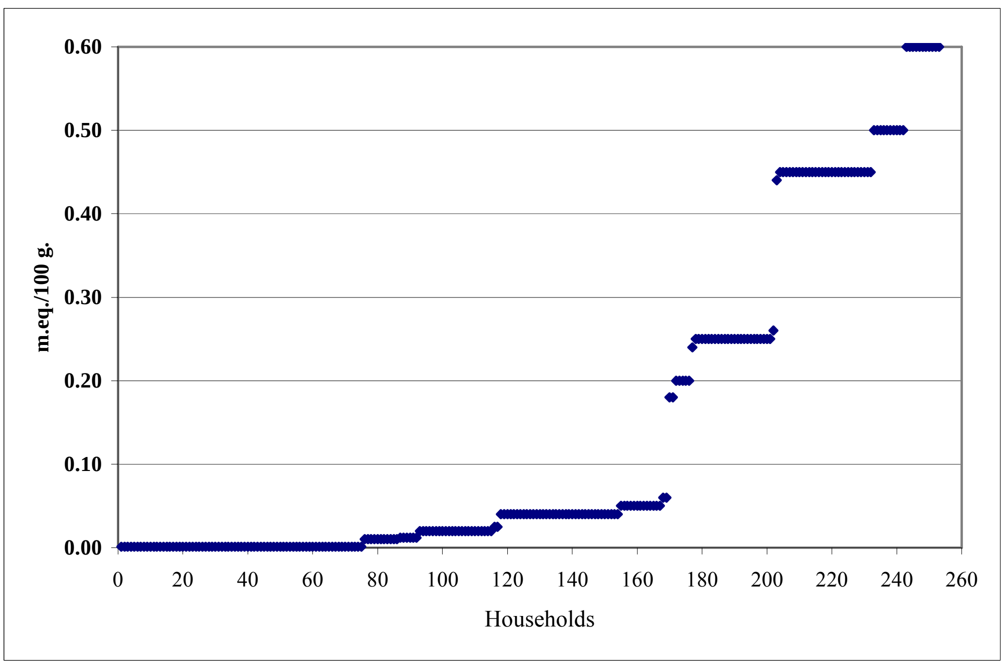
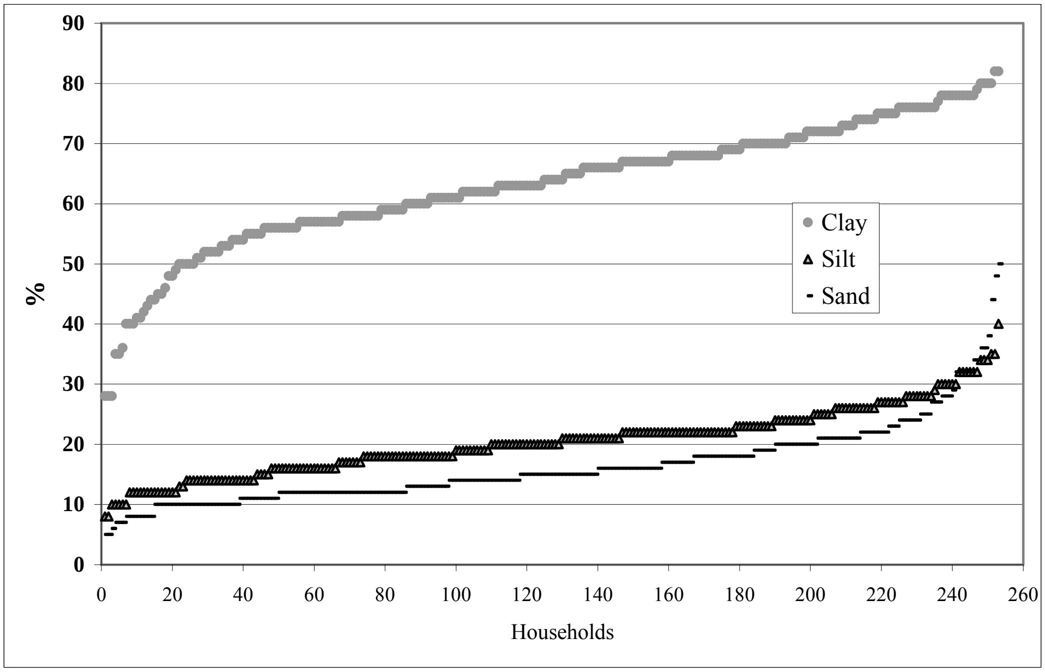


Figure A7. Distribution of Sand, Silt and Clay (%)


90
80
70
60
50
40
30
20
10
0
%
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Households
Clay
Silt
Sand

Appendix 2a. 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

		Cross Model Covariance										
Variable	$\mathbf{S_i}$	**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

		Cross Model Correlation										
Variable	$\mathbf{S_i}$	**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 5. Cross Model Inverse Correlation and Covariance

		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

		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

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