EFFECT OF LAND USE SYSTEM ON SOIL CARBON AND SELECTED SOIL PROPERTIES IN MT. ELGON ECOSYSTEM, KENYA

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DECLARATION

This thesis is my original work and has not been presented for award of a degree in any other University.

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DEDICATION

To my parents, my mother Mrs. Evelyne Nanga Okwuosa, my siblings Ikuni, Ufeli, Olisa, Eddah and Damarise, my grandmother Mrs Flora Ilavutsa Otsyula. You inspire me in your own unique way.

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ABBREVIATIONS AND SYMBOLS

BD	Bulk Density
ES	Environmental Services
FAO	Food and Agriculture Organisation
IPCC	Intergovermental Panel on Climate Change
KEFRI	Kenya Forest Research Institute
KFS	Kenya Forest Service
KWS	Kenya Wildlife Services
PES	Payment for Environmental Services
GT	Giga tonnes
REDD	Reduced Emissions from Deforestation and Degradation
SOC	Soil Organic Carbon
Tg	Tera gram
UNFCCC	United Nations Framework Convention on Climate Change.

ABSTRACT

The aim of this study was to systematically quantify differences in soil organic carbon and key related soil properties in different land-use systems in Mt. Elgon Ecosystem, Kenya. Results show that soil organic carbon stocks varied significantly with depth ($P<.001$) and among land use systems ($P<.001$) with primary and secondary forests having higher soil organic carbon storage. Mean values for soil organic carbon stocks in primary forests were 61.5 t ha^{-1}, 48.67 t ha^{-1} and 34.34 tha^{-1} in the 0-10, 10- 20 and 20-30 cm depths, respectively while for plantation forests were 43.23 t ha^{-1}, 38.72 t ha^{-1} and 26.4 t ha^{-1} in the same depths. Carbon concentrations in 0-10 cm soil depths in areas under by tea (49.05 t ha^{-1}) were similar to those in areas under plantation forest. Areas with a maize crop had low soil organic carbon stock, viz., namely 25.06 t ha^{-1}, 37.30 t ha^{-1} and 39.75 t ha^{-1} in the three respective soil depths. The estimated depth -wise distribution of soil organic carbon stocks up to 30 cm soil depth in the Mt. Elgon study sites was 41, 36 and 32% in the 0-10, 10-20 and 20-30 cm soil depths respectively. The total soil organic carbon stock in the soil up to 30 cm depth was estimated to be 6,688.4 Gt of carbon distributed at 59, 19, 11, and 10 % in natural forests, bamboo, plantation forests and tea plantations respectively. Land-use and soil depth had a significant effect ($P<.001$) on the total nitrogen levels in the order of primary forests> secondary forest> cultivated land-uses. Primary forests had 0.6, 0.4 and 0.3 % N in the 0-10, 10- 20 and 20-30 cm soil depths, respectively. Cultivated land had the lowest amounts of nitrogen compared to forest land-uses. The study concludes that natural and plantation forests have higher potential for carbon storage when compared to cultivated land-use systems.

Keywords: Land use system, Soil Organic Carbon, Soil properties

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND INFORMATION

Soils as carbon sink is proposed in recent years as a strategy to mitigating the effects of elevated atmospheric carbon dioxide (CO_2) concentration (Lal, 2002, 2005, 2009) contributed by burning of fossil fuels and land use change (Swift, 2001). In order to determine the potential of soil to absorb carbon, estimation of soil organic carbon (SOC) content under different land use and management practices needs to be assessed through estimation of C stocks in existing land uses (IPCC, 2007). Globally soil bound carbon is estimated at 3300 GT (Gt =Gigaton) (Essington.,2003; Swift., 2001) and constitutes approximately two-thirds of the carbon in terrestrial ecosystems (Eswaran *et al.*, 2000).

Soil carbon is regulated by land management practices (Powlson *et al.*, 2011), and show variability according to land use and soil depth with the 30 cm soil depth estimated to have 684-724 GT globally (Batjes, 1996). Land use effect on soil carbon has been demonstrated locally by various studies focusing on tillage (Mochoge and Mwonga, 1992; Miriti, 2010), which leads to loss of organic matter which is a huge reservoir of organic carbon. Tropical forest systems play a big role given their vast size and distribution which make them significant carbon reservoir (Schimel, 1995). Land use, soil erosion, and re-afforestation are significant in controlling the soil carbon cycle. Soil through accumulation of soil organic carbon (SOC) is therefore seen as potential viable sink for atmospheric carbon dioxide contributing significantly to mitigating global climate change. This however is achievable if there is a clear indication of an increase in SOC.

1.2 STATEMENT OF THE PROBLEM

The Mt. Elgon Ecosystem is undergoing major changes in land use and forest degradation and destruction has continued unabated despite government's efforts to manage and re-afforestate. A high population growth in Mt. Elgon and Kwanza districts is rapidly changing land use patterns and land cover (Mt Elgon Management Plan, 2007; Jaetzold *et al.*, 2008). Vegetation cover has decreased since the 1960s with 8.98% of land previously under natural forest converted to current agricultural and settlement uses (Mt Elgon Management Plan, 2007). The land use changes are having an effect on soil leading to increased soil erosion and nutrient loss, a decline in organic matter, and biodiversity (Jaetzold *et al.*, 2008). Soil carbon loss is also affected by the land use change activities in the ecosystem. A global estimate of soil carbon loss due to land conversion is between 42 and 78 GT of the original carbon stored in soil (Lal and Follet, 2009).

1.3 JUSTIFICATION

Soils can be a source or sink of atmospheric C depending on land use and management practices (Lal, 2002). Soils are believed to have the capacity to store additional carbon 0.4-1.2 GT C/year with judicious land management practices (Lal, 2004). Estimates of carbon changes under different land use and management practices are needed to make soil C sequestration projections within the ecosystem. The vegetation changes and the carbon depletion occurring with the land use changes within the Mt. Elgon ecosystem offers an opportunity to study the soil carbon dynamics. Given its vast area, Mt. Elgon ecosystem is a potential carbon sink capable of contributing to terrestrial carbon stock in the East African region. Insights into its potential for soil carbon sequestration are essential in developing carbon offset products for the ecosystem. A limited number of studies on non –agricultural land uses have systematically quantified the carbon stocks of soils in Mt. Elgon ecosystem to evaluate their carbon storage potential and document associated changes in other key soil properties. There is need for information therefore that reflects current soil conditions and the likely direction of change due to land management effects. This information is required to inform development and implementation of land management practise that maintain and improve soil resources and also guide the development of carbon offset programs.

1.4. OBJECTIVES

1.4.1 Broad Objectives

This study aimed at quantifying the differences in soil carbon and related soil properties (Bulk density, pH, Nitrogen, Magnesium and Potassium) under dominant land use systems in the Mt Elgon ecosystem.

1.4.2 Specific objectives

1. To determine the effects of land use systems on soil organic carbon content.
2. To determine the soil organic carbon stored in a humid tropical ecosystem of Kenya.
3. To assess the effects of land use systems on selected soil properties.

1.4.3 Research question

- How do different land-use systems impact on soil organic carbon?
- What is the soil organic carbon stock of Mt Elgon ecosystem?
- How do different land-use systems impact on selected soil properties?

CHAPTER TWO

LITERATURE REVIEW

2.1. Carbon Cycle and Climate Change

Carbon cycling involves the transformation of C through biomass accumulation and decomposition with the release of CO_2 (Brady and Weil, 2002). Carbon enters the terrestrial ecosystem through photosynthesis and is transferred through plant residues, wastes and manures into the soil (Schulze *et al.*, 2006). Microbial activities and soil processes through decomposition and respiration breakdown residues into complex organic substances and release CO_2 which escapes to the atmosphere (Nair and Nair, 2003). Human activities such as land clearing release additional CO_2 into the atmosphere (IPCC, 2001). Approximately three-quarters of present-day anthropogenic CO_2 emissions are due to fossil-fuel combustion. Land-use change accounts for the remaining quarter. Atmospheric concentrations of these greenhouse gases can only be curbed by simultaneously reducing emissions and storing carbon in available sinks in the terrestrial and aquatic ecosystems (IPCC, 2007).

2.2 Carbon Sequestration

Carbon sequestration potential revolves around the fundamental biological/ecological processes of photosynthesis, respiration, and decomposition (Nair and Nair, 2003). According to the Intergovernmental Panel on Climate Change (IPCC), "Carbon Sequestration is a process of increasing the carbon content of a carbon pool other than the atmosphere" (IPCC, 2000). Carbon sequestration contributes to climate change if there is a net transfer of carbon from atmospheric CO_2 to terrestrial carbon pools slowing increase in atmospheric concentration of CO_2 (Powlson *et al.,2008;* 2011). Ecosystem carbon storage is controlled by a balance between biomass production and decomposition (De Deyn *et al*, 2008). Soil can be source or sink of atmospheric C depending on land use, cropping system, and management practices (Lal, 2002). Soils have up to 80% of terrestrial C making them significant in C cycling (IPCC 2007). Plant litter decomposition, root exudates and decaying roots contribute organic residues which form a major part of the soil organic carbon making soils a major carbon sink worldwide. Globally soil carbon sequestration potential is estimated to be 1–2 Gt C/year (IPCC, 2000). Forest soils are identified as being useful in carbon sequestration.

2.3. Global Carbon Pools

A Carbon pool is defined as "a reservoir of carbon", a system which has the capacity to accumulate or release carbon (IPCC, 2000). Major global carbon pools are (i) carbon in oceans, (ii) geologic pool (iii) atmospheric carbon (CO_2), (iv) biotic carbon (vegetation) and (v) soil carbon. Janzen (2004) in an analysis of global literature found amounts of carbon in predominant pools as 38000-39000 GT C in ocean, 4000-5000 GT C in geologic pool (IPCC, 2001), 785 GT C in the atmosphere (Janzen, 2004), 466-835 GT C in biotic pools (Janzen, 2004; Sombroek *et al*, 1993) and 2000-2500

GT C as total soil carbon within one meter soil depth (Janzen, 2004.; Eswaran *et al.*, 2000). Of the total soil carbon 1220-1550 GT C is estimated to be SOC pool (Batjes, 1996; Eswaran *et al.*, 1993, 1995; Post and Kwon, 2000) and 750-950 GT C as soil inorganic carbon (Lal and Kimble, 2000).

2.3.1 Soil Carbon

Carbon in soils can be found in two fractions, (a) organically bound, i.e. as soil organic matter (SOM), and (b) in its inorganic form as carbonate minerals (calcite or dolomite). It is commonly assumed that Soil Organic Carbon (SOC) constitutes 58% of the mass of soil organic matter (Nelson and Sommers, 1982). Soil organic carbon pools are partitioned based on "turn overtime" (Parton *et al.*, 1987), and/or organic compounds (Essington, 2003). Three major pools of soil organic carbon are (i) carbon in living organism in the soil (biomass), (ii) carbon in the undecayed and partially decayed plant and animal tissues (organic residues) and (iii) soil organic matter (humus).

2.3.2 Soil Carbon Stocks

Carbon stock is the absolute quantity of carbon held within a pool at a specified time (IPCC, 2007). Soil is the largest terrestrial C sink, and contains two thirds of the world's terrestrial C (Amundson, 2001; Batjes, 1996;) with approximately 1500 Pg C in the top 100cm (Batjes 1996; Eswaran *et al.*, 1993). According to Bowen (1979) and Helmke (2000), median carbon content of soil is 2000 mg kg^{-1} but does not exceed 60g kg^{-1} in mineral soil (Essington, 2003). Batjes (2004) estimated the national SOC amount within 100 cm soil depth to range from 3452 to 3797 Tg C in Kenyan soils.

2.4 Factors Influencing Soil Carbon Stocks

Soil organic carbon stocks are largely controlled by environmental factors, inherent soil properties and historical and current land management and vegetation inputs with global C gradients largely following that of plant biomass production (Wong *et al.*, 2010).

2.4.1 Soil texture

Soil organic carbon is associated with different soil particle size fractions (Six *et al.*, 2002). Soil texture has an acknowledged effect on soil organic carbon stocks, with coarse sandy soils having lower carbon stocks than fine textured soils such as loams or clayey soils (Magdoff, 1996; Oades, 1995). Soils with a fine texture provide mineral surfaces where soil organic matter and organic compounds chemically form aggregates (Weil and Magdoff, 2004). Aggregation prevents organic matter from being decomposed by microbs. The main mechanisms involved are physical-chemical stabilization through adsorption to fine soil particles and formation of complexes, aggregates and physical encapsulation of soil organic matter protecting it from microbial attack (Krull *et al.*, 2003). Soil aggregation is therefore enhanced by soil organic matter accumulation, soil texture, clay mineralogy (Weil and Magdoff,

2004) and Fe and Al oxides (Six *et al.*, 2000a) in some highly weathered soils. Studies have shown a positive correlation between clay content and soil organic carbon content (Hassink, 1997). Texture of the soil is a useful indicator which moderates quantity of carbon in the soil and the likely amount emitted as CO_2 upon conversion (Kettler *et al.*, 2001). Soil particle size fractions can be used to better understand C dynamics and other ecosystem processes and mechanisms under different land use practice

2.4.2 Land-use System

Land-use system is a key factor for determining the equilibrium level of carbon stock in the soil (Paul *et al.*, 2002; Post and Kwon, 2000). Land management practices act as powerful drivers of terrestrial carbon sinks and sources hence the carbon stocks. Some of the common activities that affect soil organic carbon are shifts in land use and cultivation systems. The shift in land use is manifested through the influence in the amount of plant residue input and therefore soil organic matter. Historic and current land-use changes and resource management practices impact on the overall carbon cycle. Better land management practices like reduced tillage leads to higher soil organic matter favouring formation and stabilization of soil aggregates and protects the soil organic carbon in these aggregates from rapid decomposition (Six *et al.*, 2000b). However, changes in land use and management such as clearing forests and grasslands and intensive tillage and harvest practices release CO_2 to the atmosphere (IPCC, 2007). Elevated CO_2 leads to a rapid rate of climate change, and may outpace the ability of ecosystems to adapt resulting in steep declines in biodiversity and ecosystem resilience (IPCC, 2007).

Different tree species and their set up (forest structure) can impact differently on soil carbon dynamics (Paul *et al.*, 2002; Glenday, 2006; Russell *et al.*, 2007). Glenday (2006) in a tropical undisturbed indigenous forest in Kenya noted carbon stocks of 356 t C ha^{-1} compared to 94 and 108 t C ha^{-1} in a 10-year *Eucalyptus saligna* and 30-year *Cupressus lusitanica* plantations respectively. In tea plantations in Kenya, Kamau *et al.* (2008) reported that biomass carbon ranged from 43 to 72 t C ha^{-1} which compared with carbon stored in tree plantations of 30 years old.

Land uses effects on soil organic carbon is well documented. Guo *et al.* (2002) in a meta analysis from 75 publications found a 10% and 59% decline when land under pasture was converted to plantation and crop, 13% and 42% decline when native forest was converted to plantation and crops respectively, and an increase of 8% (forest to pasture), 19% (crop to pasture), 18% (crop to plantations), 53% and (crop to secondary forest).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in the Mt. Elgon ecosystem which is bisected by the border between Kenya and Uganda (Figure 1). In Kenya the ecosystem covers an area of 107,821 ha (Forest Department, 2000) and falls within Trans Nzoia and Bungoma counties.

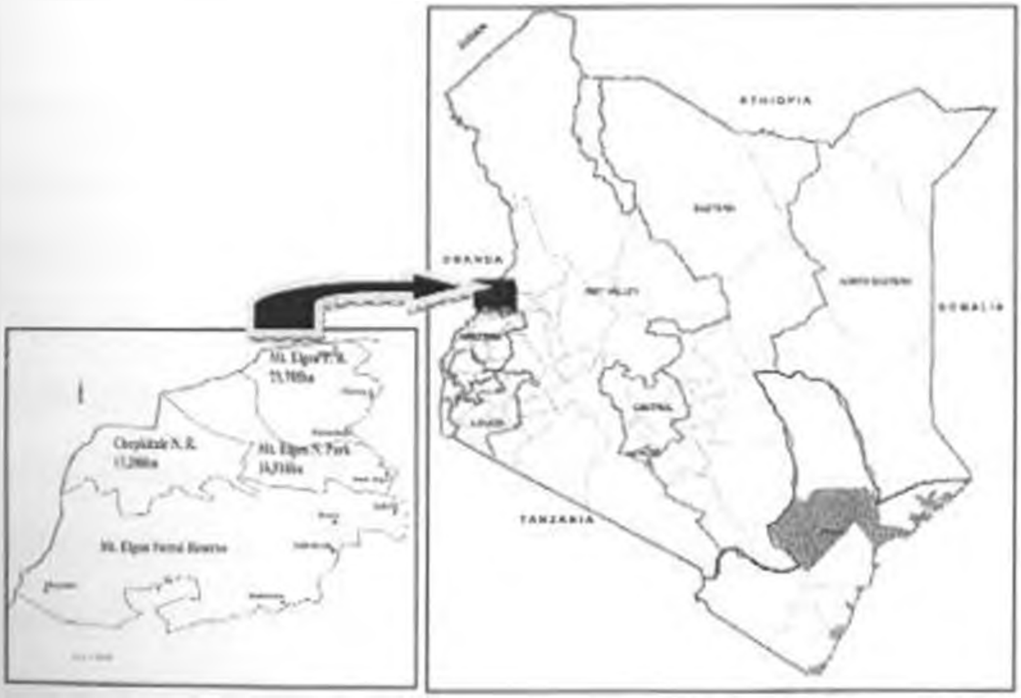

Figure 1: Map showing location of Mt. Elgon study sites, Kenya.

The site lies between latitude 25' S and 15° N and longitude 32' and 35' E and has altitudes of up to 4250 metres above sea level. Pre-dominant soil types within the ecosystem are Nitisols, Cambisols, Leptosols and Ferralsols

Minor soil types include Gleysols, Regosols and Acrisols according to the FAO classification system (FAO, 1994).

The Ecosystem can be divided into natural undisturbed and plantation forest (62%), cultivation (22%) and grazing (5%) land uses. The ecosystem is made up of settlements and protected areas which include a forest reserve with indigenous/natural and plantation forests, a national park and a game reserve which are under the jurisdiction of the Kenya Forest Service, Kenya Wildlife Service and the local county councils respectively.

Vegetation in natural forests include *Diosporos abyssinica, Croton macrostachys* Hochst. ex A. Rich, *Podocarpus* g., *Arundinaria alpine* (Bamboo). The common tress species in plantation forests within Mt. Elgon were *Juneperous procera* (cider), *Olea europea var africana,* (brown olive), *Pinus patula* (pine), *Gravillea robusta* (silk oak) *and Eucalyptus grandis.* A buffer strip of tea plantations separate the forest and settlements on the slopes of the mountain. Coffee (*Coffea canephora var robusta*) is mainly planted by farmers adjacent to the forest. Dominant crops on the slopes of Mt. Elgon are coffee maize, and horticultural crops. Farmers in the region intercrop legumes with coffee and maize.

3.2. Sampling design

A stratified sampling design was used to classify the ecosystem vegetation/use and identify sampling sites. Remote sensing and Geographic information systems techniques were used to stratify the ecosystem as described bt Mwasi *et al*, (2010). Sites were randomly selected to represent each stratum and each measured one hectare (100×100m). Sites was selected to represent naturally occurring primary forests, secondary forests of mixed or pure stand forest plantations, tea plantations coffee and maize subsistence farms. A reference site was included which comprised of a natural primary mixed forest over 100-200 years old. Sites were located in the field with the aid of a global position system. Description of each sampled strata are summarized in Table 1.

Table 1: Description of land uses sampled in Mt. Elgon study sites, Kenya

Land use	**Dorminant Vegetation**	**Age (years)**	**Other vegetation**
primary forests (Natural forest)	*Prunus africana*	100-200	*Croton macrostachys*
	Croton macrostachys	100	*Diasporus abyssinica*
	Podocarpus g .	>100	*Croton macrostachys*
	Olinia rochetiana	>90	*Olea hochetetteri, olea europea, Podocarpus g. Juniperous procera, Techea nobilis*
	Croton macrostachys (old forest)	>100	
	Arundinaria alpine	>100	
Secondary forests Pure stand Plantation	*Juniperous procera*	64	
	Gravillea robusta	20	
	Pinus patula	16	
	Eucalyptus grandis	5	
Secondary forests Mixed stand Plantation	*Juniperous procera*	Range 11-75	*Juniperous procera, Podocarpus g. Olea europea, Prunus africana*
	Podocarpus g	64	*Podocarpus g. Juniperous procera, Olea europea,*
Cultivated	Tea	10-23	
	Coffee	Range 23-80	Small holder coffee *(Coffea canephora var robusta)* -beans-maize intercropped
	Small holder maize-beans –banana farms	Aprox 90	Small holder maize-beans –banana Cultivation since settlements in 1920
	Coffea canephora var robusta)		
	Regenerating Forest	2	Regenerating shrub Previously under maize beans cultivation for 10 years

3.3 Soil Sampling and analysis

Soil samples were collected from the top soil (0-10 cm) and sub soil (10-20 and 20-30 cm) layers in each stratified site in April, 2010. Soils were sampled from 4 points in a grid spaced 7 meters apart along a diagonal. Four soil pits measuring 100 by 100 cm were excavated up to a depth of 30 cm within each plot along a diagonal, 5 meters from the centre of the plot. The four samples within each depth interval were bulked to form one composite sample. Two sets of soil samples were acquired from the site at a depth of 0-10, 10-20 and 20-30 cm. The first set of soil samples were taken using core samplers (5 cm in diameter and 6 cm high) and used for bulk density measurements. The second set of soil samples were taken within each pit and were used for determination of total organic carbon, total nitrogen, Soil reaction (pH), Soil bulk density (BD), and exchangeable cations. Samples were transferred to plastic bags, transported to the laboratory for further processing and analyses.

3.3.1 Soil Organic Carbon

The SOC concentration was determined by the dichromate redox titration method (Okalebo *et al.*, 2002). About 0.5 g of air dried soil sieved through a 60 mesh sieve (μm) was weighed into a block digester tube, 5ml potassium dichromate ($K_2Cr_2O_7$) and 7.5 ml concentrated sulphuric acid (H_2SO_4) added. The mixture were heated on a digestion block for 30 minutes and after cooling the digest transferred quantitatively into a conical flask. Indicator solution (1,10 phenanthroline monohydrate) were added, stirred and titrated against ferrous ammonium sulphate $(Fe(NH_4)_2(SO_4)_2$, until end point when the colour changed from green to brown. The titre was recorded and corrected with blank readings. The difference between added and residual dichromate was inferred as SOC of the soil sample. The % soil carbon content was then calculated using the equation:

$$\textbf{Organic Carbon (g kg}^{-1}\textbf{)soil} = \frac{(B-T) \times M \times 3}{w}$$

Where

B and T = Titres in ml of blank and sample

M = Molarities of $(Fe(NH_4)_2(SO_4)_2$ solution (0.2M)

w = Sample weight (g)

To compare soil C among the different vegetation cover, all data were expressed on an equivalent-mass basis based on the sampled depths (0-10, 10-20 and 20-30 cm) as recommended for this type of study (Ellert *et al.*, 2008; Powlson *et al.*, 2011). To be able to capture the variability in SOC content within each soil depth, soils representing each depth were analysed separately as suggested by Kravchenko and Robertson (2011). This ensured that any differences between the land uses per depth were detectable and not masked by high variability in one depth than another. The soil carbon stock per ha was calculated using the following equation:

$$C\ (t\ ha^{-1}) = [(\text{soil bulk density}, (g/cm^{3}) \times \text{soil depth (cm)} \times \text{Organic carbon (g/kg)}] \times 1000$$

The soil carbon stock in each sampled depth in each dominant land use system was estimated by multiplying the SOC stock per hectare by the area covered. The total SOC for study site was estimated by multiplying SOC concentration (from addition of the three soil depths) by the estimated area covered by the study site.

3.3.2 Total Nitrogen

Total Nitrogen was determined by acid digestion outlined by Okalebo *et al* (2002). A 0.3 g of soil sieved through a 2mm sieve were weighed into a digestion tube and 2.5 ml digestion mixture. (prepared by dissolving 3.2 g salicylic acid in 100ml of H_2SO_4 – selenium mixture) added. The mixture were digested at 110^{0}C for 1 hour, cooled and 1ml hydrogen peroxide added then further heated at a raised temperature of 330^{0}C until the solution turned colourless. After cooling, 25 ml distilled water was added, mixed, cooled and filled to 50ml. The %N in the sample was determined using a flow analyzer.

3.3.3 Exchangeable Cations

Exchangeable potassium (K), calcium (Ca) and magnesium (Mg)) were determined as described by Okalebo *et al.* (2002). Cations were extracted from soil using excess 1 *M* ammonium acetate (NH_4OAc). About 5 g of air dried soil sieved through 2 mm sieve was weighed into a clean plastic bottle, 100 ml 1 *M* NH_4OAc was added, bottle stoppered and shaken for 30 minutes on a mechanical shaker. After shaking the contents were filtered through a No. 42 whatman paper into 500ml flasks. To determine K, and Ca, 50 ml of the leachate was transferred using a pipette into a 50 ml volumetric flasks, 1M of 26.8% lanthanum chloride (releasing agent) added and the contents made up to volume with 1 *M* ammonium acetate. To determine Mg, 20 ml of the leachate was transferred using a pipette into a 50 ml volumetric flasks and made up to volume with 1 *M* NH_4OAc. The amount of cations in extract was measured by atomic absorption spectrophotometer (AAS) for Ca and Mg, and flow analyzer for Na and K. The concentration of K, Na, Ca and Mg in soil samples was calculated as follows:

$$\mathbf{M' \; cmol \; kg^{-1} = C \; cmol \; L^{-1} \; x \; (V / wt \; soil \; g) \; x \; f \; x \; 1000 \; g \; kg^{-1}}$$

Where

M' is the concentration of adsorbed cation, (cmoll/ kg) ,

V is volume of extract (cm^3)

f is the dilution factor

C is the concentration of cation in ammonium acetate extract ($cmoll\ L^{-1}$)

3.3.4 Soil pH

Soil reaction (pH) was determined with a pH electrode at soil /water ratio of 1:2.5 (w/v) ratios according to the procedure outlined by Okalebo *et al* (2002). About 20 g of air-dry soil (2 mm) were weighed into the plastic bottles and 50 ml of distilled water added. The bottles were stoppered, shaken for 10 minutes, and then allowed to stand for 30 minutes and pH determined by inserting the pH meter glass electrode into the supernatant.

3.3.5 Soil Bulk Density

Soil bulk density (D_b) described as a ratio of the mass of oven dried soils to the bulk volume (V) of the soil which includes the volume of the solids and the pore space between the soil particles (Blacke and Hartge, 1986). Bulk density was calculated using the formula:

$$D_b = \frac{\underline{\textbf{Mass dry soil- mass wet soil}}}{\textbf{V}}$$

The volume (V) in cm^3 was calculated as

$$V = \frac{1}{4} \pi d^2 h$$

Where

d (cm) = internal diameter of core ring cylinder,

h (cm) height of core ring.

3.3.6 Soil Particle Sizes

Soil texture was determined using a simplified hydrometer method outlined in Okalebo *et al.* (2002). Fifty (50) g of air-dried samples sieved through 2 mm were weighed into flasks and wetted using 125 ml distilled water. The samples were placed in a water bath at 85^0 C. About 5ml of 30% hydrogen peroxide was added to destroy organic matter, portions of 5 ml being added until frothing ceased. Beakers were removed from the bath, cooled and 10 ml sodium hexametaphosphate (calgon solution) added. The mixture were allowed to stand for 10 minutes and transferred into leak-proof shaking bottles and shaken overnight on a shaker. After shaking the suspension was transferred into 1000ml measuring cylinder and filled to the mark. Readings were taken after 40 seconds (H1) and after 2 hours (H2) and used to calculate different soil sample particle sizes as follows:

1. Sand % = $100 - \frac{[(R_{40s} - R_b) + (T_{40s} - 20)0.36] \times 100}{\text{Dry soil (weight in grams)}}$
2. Clay % = $\frac{[(R_{2hrs} - R_b) + (T_{2hrs} - 20)0.36] \times 100}{\text{Dry soil (weight in grams)}}$
3. Silt % = 100- (Sand % + Clay %)

3.4 Statistical analysis

To determine the effect of land use and soil depths on total soil organic carbon, % nitrogen, texture, pH, calcium and magnesium , acquired data were subjected to analysis of variance (ANOVA) using Genstat statistical program (Genstat, 2008)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Land use effects and soil organic carbon

4.1.1 Soil Organic Carbon Stock

Soil organic carbon stock varied between land uses and depth (Table 2). There were significant differences between soil organic carbon stock with depth ($P<.001$) and land use ($P<.001$).

Table 2: Soil Organic Carbon Stock in three depths under various land use system within Mt. Elgon study sites, Kenya.

Land use and dominant vegetation	Number of samples (N)	SOC (t / ha) Depth 10 cm	20 cm	30 cm
Natural forests				
Prunus africana	4	83.47	55.20	41.90
Podocarpus g.	4	67.87	67.65	35.82
Croton macrostachys	4	65.25	37.04	28.04
Olinia rochetiana	8	46.04	45.32	31.26
Croton macrostachys (old Forest)	4	44.88	38.17	34.67
Mean		61.50	48.68	34.34
Arundinaria alpine	8	38.42	34.20	32.77
Plantation forests				
Gravillea robusta (P)	8	49.02	35.39	29.10
Podocarpus g (Mixed stand)	8	43.34	37.65	37.57
Juniperous procera (Mixed stand)	8	43.62	18.91	12.35
Eucalyptus grandis	4	42.26	39.68	26.08
Pinus patula	4	37.92	61.96	27.12
Mean		43.23	38.72	26.4
Cultivated land				
Tea	8	49.05	47.86	43.27
Regenerating shrubs	5	41.55	50.10	45.71
Coffee	4	37.23	39.80	31.00
Mean	2	25.06	37.30	39.75
Lsd $P_{<.001\ \text{land use}}$	8.39			
Lsd $P_{<.001\ \text{land depth}}$	4.54			
Lsd $P_{<.001\ \text{Land use X and depth}}$	14.52			
CV%	37.9			

Soils under forested land-use had higher carbon stocks when compared to soils. under cultivated land-uses. Soils under primary forests dominated with *Prunus africana* accumulated more soil organic carbon compared to all other land uses. Among the agricultural land uses tea plantations accumulated more SOC than plantation forests, coffee and maize field. This is attributed to high litter input from tea production (Kamoni *et al.*, 2007). Soil organic carbon distribution was higher in the top 10 cm depth of soil than in other depths of the same land use. This observation agrees with Bajtes (1996) who showed a relatively higher SOC within the top layer (0-15 m) of soils. The primary forests, secondary plantation forests and bamboo soils had higher SOC in the 0-10 cm depth compared to cultivated land uses. *Prunus africana* dominated soils had the highest SOC content followed *Podocarpus g* and *Croton macrostachys* natural forests. Generally there was a varying decrease in SOC with depth in most land-use systems. This trend was however different in tea plantations which had a more uniform distribution across the three depths. The natural forest soils however had a more pronounced decrease of SOC with the increase in depth. The higher content of SOC in the top 0-10 cm in undisturbed soils can be attributed to decomposition of organic matter and accumulation in this layer.

More than half of the estimated SOC within the ecosystem was in the top 0-10 cm depth of the soils. This trend has been observed by Lantz, *et al.*, (2002) and Woomer *et al.*, (2004). The lower SOC content in cultivated land uses may be attributed to soil mixing during land ploughing which lead to breakdown of soil aggregates and increased mineralization (Lal, 1999;

Reicosky *et al.*, 2000). The lower layers of soil (20-30 cm) contained a smaller concentration of SOC.

Across the landscapes studied, forested soils consistently had a larger soil carbon stocks compared to the non forested soils. The comparatively higher organic carbon stock in forests soils confirms the role of biomass inputs in accumulating soil organic carbon. The differences between land-use systems in this study is explained by the carbon inputs and removals (Sanderman *et al.*, 2010).

4.1.2. Total Soil Organic Carbon

Total soil organic carbon in the soil profile up to 30 cm depth was estimated at 6,688.4 GT carbon (Table 2). The naturally occurring forest accounted for more than 50% of the SOC stocks in the ecosystem.

Table 3: Total Soil Organic Carbon in Mt. Elgon study sites, Kenya.

Land use and area	Depth	SOC stock ($t\ ha^{-1}$)	C stored (GT of carbon)
Natural (27,480.65 ha)	0-10 cm	61.50	1,690.1
	10-20 cm	48.68	1,337.7
	20-30 cm	34.34	943.6
Plantation (6,872.55 ha)	0-10 cm	43.20	297.1
	10-20 cm	38.72	266.1
	20-30 cm	26.44	181.7
Bamboo (12,135.55 ha)	0-10 cm	38.42	466.3
	10-20 cm	34.20	415.0
	20-30 cm	32.77	397.7
Tea (4,944 ha)	0-10 cm	49.05	242.5
	10-20 cm	47.86	236.6
	20-30 cm	43.27	213.9
Total			**6,688.4**

Natural forests had a higher SOC compared to other land-uses and this can be due to biomass quantities added through litter fall on over the years and the vast area it covers. Natural forests therefore have large reserves of SOC stocks. Plantation forests and tea plantations contributed up to 22% of the estimated total SOC (Table 3). These occupy a smaller area compared to natural forests. However, this amount is similar to the total amount contributed by bamboo (22%). The reduced SOC stock may be a result of the small relative area covered by the plantations, the length of time since plantation establishment and the management practice. On average the plantation stand age within Mt Elgon ranged from 2 to 70 years while the natural forests have occupied the sites for more than 100 years (Mt Elgon Management Plan, 2007) Taking into account the relative age and area covered by plantation forests, the differences in SOC are considered minimal. The ecosystem can be considered to have low anthropogenic influences if incidences of logging are minimized then it can be considered a net C sink.

4.2. Land use effects on soil properties

Strong land use effects were observed for soil properties assessed (Table 4), indicating that values differed significantly across all land- use systems. Depth had a significant effect on soil parameters tested Soil pH had significant land-use and depth effects with no land –use: depth interaction. This indicates that soil pH differed amongst the land- uses and depths. Bulk density showed a strong land use effect along with significant depth and land –use:

depth interactions. This indicates that this property changed with depth in the soil and the nature of the change differed between the land- uses.

Table 4. F statistics and probability (*P*) values for the analysis of variance for soil properties in Mt Elgon study sites

Source of variation	Df	pH		Bulk density (g/cm^3)		Total Nitrogen (%)		Carbon (%)		Ca (cmol/kg)		K (cmol kg)		Mg (cmol/kg)		%Clay		% silt		% Sand	
		F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value	F ratio	*P* value
Land- use	14	18.26	<.001	8 60	< 001	77 42	< 001	6.6	< 001	10 08	< 001	16.33	< 001	52.91	< 001	5 05	<.001	9.94	<.001	8.56	< 001
Depth	2	17.89	< 001	399.88	< 001	6.39	0 002	97.0	< 001	56.65	< 001	16.75	<.001	59 39	< 001	28.58	<.001	7.48	<.001	31 56	< 001
Land- use x.Depth	28	1.25	0.189	6.10	<.001	1.01	0.458	2.0	0.003	1 79	0.011	0 41	0.997	3.29	<.001	0 90	0.622	1.36	0.115	1.36	0.117

Df = degrees of freedom.

Significant land-use :depth interaction were also found for bulk density and soil carbon suggesting that these properties changed with depth in the soil and the nature of the change differed between land uses studied. Differences in bulk density between land-uses were more significant near the soil surface and increased with depth. Forested soils typically had small bulk densities and cultivated soils had large bulk densities (Table 5). Differences in bulk density with depth are partially attributed to the SOC content In general lower bulk densities were associated with high SOC content, while higher BD values were associated with soils having low SOC content. This trend is expected as organic matter has a much lower density than mineral particles and its aggregation effect on soil structure plays a dominant role in bulk density of the soil (De vost *et al.*, 2005).

Soil carbon and nitrogen showed a strong land-use and depth effects (Table 4) although land-use: depth interaction was not a significant factor for N alone The differences in carbon and nitrogen content between land uses decreased with depth Cultivated land had the lowest amounts of nitrogen compared to land-uses under forests (Table5). Significant land-use and depth effects were found for calcium, magnesium and potassium. This indicates that calcium, magnesium and potassium concentrations differed between land uses and changed with depth. Significant interaction between land-use:depth were also found for magnesium indicating that differences in calcium concentration between land uses was depth dependent. land-use: depth interaction effect was not significant for soil particle size distribution (% clay, % silt and % sand) (Table 4). However they showed a significant depth alongside a significant land-use effect. This indicates that there were differences in particle sizes distribution between land uses and depth though these differences were not depth dependent.

Carbon and nitrogen content in the land-uses studied showed a decreasing order of cultivated soils> plantation forests > natural forests> (Table 5). Cultivated soils had lowest soil C and N concentrations near the soil surface. The more C concentration in plantation forest and natural forest is due to high litter input. The differences in carbon and nitrogen, between land uses resulted from reduced inputs and removal of nutrients by harvested crops. Large inputs from litter fall also account for the higher concentrations in natural and plantation forests. Globally carbon trends largely follow that of plant biomass production (Wong *et al.*, 2010).

Table 5. Means of soil properties for soil depths in Mt. Elgon study sites, Kenya

Land use		Depth (cm)	pH	Bulk density (g cm^{-3})	Total N %	Total C %	Calcium (cmol/kg)	Mg (cmol/kg)
Natural Forest	*Prunus africana*	0-10	6.2	0.9	0.6	8.9	20.3	4.2
		10-20	5.8	1.1	0.5	5.3	13.1	3.0
		20-30	5.8	1.1	0.5	3.7	9.5	3.2
	Podocarpus g	0-10	5.9	0.9	0.6	7.2	19.6	4.3
		10-20	5.5	1.1	0.5	6.4	10.0	2.6
		20-30	5.0	1.1	0.2	3.1	2.1	0.9
	Croton macrostachya	0-10	7.1	0.9	0.7	7.5	22.4	5.1
		10-20	6.5	1.0	0.4	3.8	11.4	3.7
		20-30	6.2	1.1	0.3	2.6	9.4	3.3
	Olinia rochetiana	0-10	6.6	0.8	0.7	5.3	19.8	2.7
		10-20	6.2	1.2	0.4	3.7	20.7	1.8
		20-30	6.2	1.2	0.3	2.6	15.1	1.6
	Croton macrostachya (old forest)	0-10	6.4	0.7	0.5	6.5	29.6	3.1
		10-20	6.2	1.2	0.3	3.2	19.1	2.2
		20-30	6.1	1.2	0.3	2.9	16.5	1.3
Plantation forest	*Grevillea robusta*	0-10	5.8	0.9	5.8	5.7	22.1	1.8
		10-20	5.5	1.0	5.5	3.4	9.5	1.2
		20-30	5.1	1.2	5.1	2.4	7.7	1.2
	Podocarpus g	0-10	6.3	0.8	0.4	5.4	25.4	2.1
		10-20	6.0	1.1	0.4	3.4	14.5	1.4
		20-30	5.7	1.3	0.3	3.0	10.2	1.4
	Juniperous procera	0-10	6.0	0.8	2.4	5.3	21.7	2.0
		10-20	4.9	1.1	0.8	1.7	3.5	0.7
		20-30	4.7	1.2	0.7	1.1	1.6	0.4
	Eucalyptus grandis	0-10	5.3	0.9	1.2	4.7	8.5	1.1
		10-20	5.6	1.0	1.7	3.9	7.6	0.9
		20-30	5.2	1.1	0.3	2.5	4.0	0.8
	Pinus patula	0-10	6.1	0.7	0.5	5.5	22.2	2.2
		10-20	5.7	1.2	0.4	5.2	17.7	1.9
		20-30	5.8	0.9	0.3	3.0	13.4	1.7
Cultivated land	Tea	0-10	4.5	1.0	0.4	5.8	4.9	0.4
		10-20	4.5	1.1	0.4	5.0	6.8	0.4
		20-30	4.8	1.1	0.1	4.7	5.8	0.5
	Regenerating shrub	0-10	5.8	0.9	0.4	4.8	11.1	2.9
		10-20	5.9	1.0	0.5	5.1	12.9	3.1
		20-30	5.6	1.1	0.3	4.2	10.8	2.9
	Coffee	0-10	5.6	1.0	0.4	3.8	7.7	1.1
		10-20	5.4	1.2	0.3	3.3	5.1	0.8
		20-30	5.2	1.3	0.2	2.5	3.1	0.6
	Maize	0-10	5.8	0.7	0.3	3.6	7.1	1.1
		10-20	5.7	1.1	0.1	1.4	7.1	1.1
		20-30	5.8	1.3	0.3	3.2	5.8	1.0

Natural forests had higher pH than agricultural fields (Table 5). The primary forests had a pH range of 5.5-7.1 while plantation forest soils ranged from acidic to moderately acidic pH (<5.5). Tea plantation soils had the lowest pH (4.5) compared to all other land uses. Expansion of tea growing as a forest buffer should therefore consider the associated potential soil degradation. Some land-use systems (*Juniperous procera, Podocarpus g.* and *Gravillea robusta*) induced sub surface acidity and had low pH at 10-30 cm soil depth. This feature of soil acidification by trees is observed in other forested environments (Binkley and Valentine, 1991; Augusto *et al.*, 2002; Jobbágy and Jackson, 2003) and is mainly attributed to the biological pumping process (Dijkstra & Smits, 2002; Noble *et al.*, 1999, 2006; Noble & Randall, 1998)

Soils sampled were classified as clay loams for most of the land uses except for *Juniperous procera* dominated mixed plantations, *Pinus patula* pure stand plantation and regenerating forest (clay) and *Gravillea robusta* pure stand plantation (silty clay) (Table 6). Despite the similar proportion of soil particles, there was a higher content of clay particles in forested soils compared to cultivated soils indicating the some effects of soil cultivation on soil texture a key contributor to soil aggregate formation and stabilization. Soil texture plays an important role in influencing the amounts and turnover rates of SOC. Mineralization of SOC is more rapid in coarse-textured soils than in fine-textured soils. The high clay content observed (25- 70 %) in the soils can therefore explain the relatively high SOC content recorded across the land uses in the region

Table 6: Soil texture from different depths in land uses in Mt. Elgon study sites, Kenya

Land use	Dominant vegetation	Depth (cm)	% clay	%Silt	% sand
Natural forest	*Prunus africana*	0-10	40.1(4.5)	15.3 (6.9)	44.6(4.7)
		10-20	52.1(7.6)	18.6(2.9)	29.3(4.7)
		20-30	45.6(3.9)	20.4(3.9)	34.1(6.9)
	Podocarpus g.	0-10	43.3(7.5)	14.3(1.4)	42.4(7.4)
		10-20	53.2(5.2)	19.4(2.2)	27.4(3.2)
		20-30	70.4(6.7)	15.9(2.1)	13.7(5.8)
	Croton macrostachys	0-10	12.8(16.2)	50.6(18.6)	36.6 (6.2)
		10-20	20.1(12.6)	53.1(21.6)	26.7(9.2)
		20-30	34.3(19.8)	47.3(20.0)	18.4(0.5)
	Olinia rochetiana	0-10	48.2(8.4)	20.7(7.2)	31.1(9.7)
		10-20	53.1(15.3)	25.4(9.0)	21.5(9.8)
		20-30	45.7(22.1)	28.7(17.3)	23.5(8.1)
	Ref Croton macrostachys (N)	0-10	38.7(7.5)	38.3(4.5)	23.0(7.0)
		10 20	52.4(19.0)	35.7(19.7)	11.9(0.8)
		20-30	64.2(11.0)	24.0(9.6)	11.8(2.7)
Plantation forest	*Grevillea robusta (P)*	0-10	15.4(10.0)	31.3(8.1)	33.3(12.2)
		10-20	44.5(13.8)	26.9(9.0)	28.6(13.4)
		20-30	47.4(15.1)	21.4(2.2)	31.2(13.1)
	Podocarpus g. (Plta)	0-10	28.4 (24.1)	39.3(13.0)	36.4(15.0)
		10-20	52.0 (16.3)	27.6(9.7)	20.4(10.0)
		20-30	47.9(16.9)	29.0(12.7)	23.1(8.3)
	Juniperous procera	0-10	38.2(17.1)	23.6(5.9)	38.3(15.5)
		10-20	47.4(12.5)	23.8(4.1)	28.8(12.1)
		20-30	47.6(12.3)	25.1(5.6)	27.3(10.8)
	Eucalyptus grandis	0-10	27.9(12.7)	22.1(3.0)	49.9(14.5)
		10-20	42.8(6.1)	22.9(2.7)	34.3(4.0)
		20-30	47.6 (13.7)	23.7(2.6)	28.8(12.4)
	Pinus patula	0-10	29.4(16.7)	52.4(18.4)	18.2(2.7)
		10-20	42.9(26.1)	39.9(26.1)	17.2(0.0)
		20 30	53.7(25.8)	30.9(24.6)	15.5(1.1)
Cultivated land	Tea	0-10	38.6(7.6)	27.1(3.4)	34.2(5.5)
		10-20	46.8(12.0)	25.9(9.8)	27.3(11.7)
		20-30	56.7(9.1)	21.2(3.0)	22.1(7.8)
	Regenerating forest	0-10	43.0 (8.8)	19.7(2.2)	37.3(7.0)
		10-20	55.9(1.3)	17.2(0.6)	27.0(1.9)
		20-30	66.0(8.3)	16.8 (3.5)	17.1(4.8)
	coffee	0-10	42.4(8.8)	29.1(2.4)	28.6(8.1)
		10-20	49.9(3.7)	27.6(3.8)	22.6(4.4)
		20-30	58.0(4.6)	24.1(2.8)	17.9(3.2)
	Maize	0-10	38.5(10.6)	25.5(4.9)	36.0(5.7)
		10 20	42.5(3.5)	23.5(4.9)	34.0(8.5)
		20-30	25.0(4.2)	[illegible]	47.0(1.4)

Figures in parenthesis show the standard deviations (SD)

CHAPTER FIVE

CONCLUSIONS AND RECCOMENDATIONS

5.1. Conclusions

Land-use systems had effects on soil organic carbon, nitrogen, pH, texture, bulk density, calcium and magnesium content. Soils under forest land-uses had higher soil organic carbon stocks compared to soils under cultivation. Lower bulk densities were associated with high soil organic carbon content, while higher bulk density values were associated with soils having low soil organic carbon content. Cultivation of soils and annual cropping resulted in decline in soil nitrogen. Soil acidification was associated with tea cultivation and land uses dominated with some tree species which might also be associated with soil degradation. The study concludes that forest vegetation cover provide the best potential for enhancing organic carbon accumulation in soil. It can thus be concluded that due to minimal disturbance in the naturally occurring and plantation forests, there is reduced organic matter decomposition and mineralization resulting to minimal losses of carbon and nitrogen thus significant soil carbon storage.

5.2. Recommendations

From the results of this study, the following recommendations are proposed.

1. Further studies to better understand effects of land use on soil organic carbon accumulation in the deeper soil depth with the potential to store more carbon and consequently enhance carbon sequestration in the ecosystem

2. Development of sustainable land management practices for cultivated soils in the ecosystem to improve soil carbon and nitrogen status

3. Further studies to better characterize soil organic carbon and nitrogen dynamics incorporating other variables such as rainfall, litter additions and microbial biomass.

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APPENDICES

Appendix 1

Analysis of variance

pH Analysis of Variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	70.1541	5.0110	18.26	<.001
Depth	2	9.8160	4.9080	17.89	<.001
Land- use x Depth	28	9.6030	0.3430	1.25	0.189
Residual	228	62.5523	0.2744		
Total	272	152.1255			

Bulk density Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	0.814428	0.058173	8.60	<.001
Depth	2	5.408867	2.704433	399.88	<.001
Land- use x depth	28	1.155908	0.041282	6.10	<.001
Residual	228	1.541987	0.006763		
Total	272	8.921191			

%N Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	562.6298	40.1878	77.42	<.001
Depth	2	6.6380	3.3190	6.39	0.002
Land-usexDepth	28	14.6681	0.5239	1.01	0.458
Residual	228	118.3497	0.5191		
Total	272	702.2856			

%C Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	173.331	12.381	6.60	<.001
Depth	2	363.943	181.972	97.00	<.001
Land- use x Depth	28	105.172	3.756	2.00	0.003
Residual	228	427.733	1.876		
Total	272	1070.180			

Calcium (cmoll/kg) Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	8568.79	612.06	10.08	<.001
Depth	2	6879.33	3439.66	56.65	<.001
Land- use x Depth	28	3035.84	108.42	1.79	0.011
Residual	228	13842.88	60.71		
Total	272	32326.84			

K (cmoll/kg) Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	119.7023	8.5502	16.33	<.001
Depth	2	17.5476	8.7738	16.75	<.001
Land- use x Depth	28	6.0431	0.2158	0.41	0.997
Residual	228	119.4132	0.5237		
Total	272	262.7062			

Mg(cmoll/kg) Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	243.2968	17.3783	52.91	<.001
Depth	2	39.0144	19.5072	59.39	<.001
Land- use x Depth	28	30.2193	1.0793	3.29	<.001
Residual	228	74.8915	0.3285		
Total	272	387.4220			

% Clay Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	15143.0	1081.6	5.05	<.001
Depth	2	12233.2	6116.6	28.58	<.001
Land- use x Depth	28	5366.0	191.6	0.90	0.622
Residual	228	48803.6	214.1		
Total	272	81545.9			

% Silt Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	14588.6	1042.0	9.94	<.001
Depth	2	1569.2	784.6	7.48	<.001
Land- use x Depth	28	3993.5	142.6	1.36	0.115
Residual	228	23905.0	104.8		
Total	272	44056.3			

% Sand Analysis of variance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land- use	14	11318.66	808.48	8.56	<.001
Depth	2	5961.60	2980.80	31.56	<.001
Land- use x Depth	28	3588.43	128.16	1.36	0.117
Residual	228	21537.08	94.46		
Total	272	42405.77			