Title: **The impacts of household land use and socio economic factors on the soil fertility of smallholder farms in the highlands of Kenya**

Running title: **soil fertility of smallholder farms in the highlands of Kenya**

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Abstract

Raising agricultural productivity in smallholder agriculture in sub-Saharan Africa requires an understanding of if and how farm household land use and socioeconomic factors affect soil fertility. Market access, population growth, socio economic characteristics and agro ecological zones have been proposed as important drivers of land use intensity and, consequently, soil fertility. We used diffuse reflectance infrared spectroscopy to measure soil fertility, and multivariate and exogenous switching regression statistical approaches to determine if soil fertility in the smallholder farms of the highlands of Kenya is associated by region, land use categories (cash crop, food crop, fodder and pastures), and selected household socio economic factors (household income, number of adults, farm size and number of cattle). Over 2000 fields on 236 farms were sampled in Embu (eastern Kenya highlands, primarily Andosols) and Madzuu (western Kenya highlands, primarily Ferrasols). Soil fertility variables, including total soil carbon (SC), total nitrogen (TN), pH, available Olsen phosphorous (P), extractable potassium (K), calcium (Ca), and magnesium (Mg), effective cation exchange capacity (ECEC) and texture, were measured using conventional laboratory techniques on 15% of the sampled soils. From these analyses, SC, TN, P and K were all greater in Embu compared to Madzuu soils. Soil fertility variables were significantly higher in pastures compared to other land uses in Madzuu, but were comparable with other land uses in Embu. This soil data was then used to calibrate soil reflectance results in order to predict soil fertility variables for all soil samples. Principle component analysis (PCA) of soil fertility variables developed from the spectroscopy data for each soil sample indicated similarities among sites in the three most important eigenvectors: the first (soil nutrient) vector had high positive loadings for K, Ca, Mg, ECEC and pH; the second (soil organic matter, SOM) vector had high positive loadings for soil organic carbon and total nitrogen; and the third (soil texture) vector had high positive loadings for clay plus silt. However, in Embu, P was associated with the soil organic matter vector while in Madzuu it was associated with the soil nutrient vector. In comparison to pasture all other land uses were associated with lower values of soil nutrient and SOM components in Madzuu, while in Embu, these other land uses were associated with higher values of the SOM component. Number of cattle per farm had no association with any of the three soil fertility components at either site. In Embu, farm income and adult population were both positively related to SOM. In Madzuu, farm size was positively associated with SOM but negatively associated with soil nutrients. More than twice as much P fertilizer is applied on average in Embu compared to Madzuu (27 vs. 11 kg ha^{-1} $season^{-1}$). Our study supports the link between poverty dynamics and soil degradation in smallholder agriculture; wealthier households in the eastern Kenya highlands are able to invest in soil fertility management while the poorer households in western Kenya are mining nutrients in soils.

1. Introduction

One of the eight millennium development goals (MDGs), to which world leaders committed themselves in 2000, is to halve extreme hunger and poverty by 2015 (UN Millenium Project, 2003). Any attempt to halve hunger and poverty in sub-Saharan African must seek to increase agricultural productivity of the smallholder mixed farming systems. Yet soil fertility and nutrient management studies cite rapid depletion of soil fertility, as well as high population growth, as the main causes for declining per capita food production (Sanchez *et al*., 1997, Smalling *et al*., 1997, Breman *et al*., 2001, Sanchez 2002). The World Bank (2003) acknowledges the important relationship between agricultural growth and poverty reduction in the region. Soil fertility decline in smallholder farms is often attributed to poor crop and animal husbandry practices, such as continuous cultivation (Solomon *et al*., 2007, Zingore *et al*., 2007), lack of proper soil erosion conservation measures, limited adoption of new and improved crop and animal production technologies, as well as exogenous factors such as high cost of soil fertility amendments (Vlek *et al*. 1997; Sanchez, 2002; Hartemink, 2003; Sanchez, 2006).

The Kenyan highlands, one of the regions of East Africa with high agricultural potential, have high population densities, high poverty levels and depletion of soil nutrients. The Kenyan highlands occupy 40% of the area of the country and support 70% of the human population (CBS-GOK, 2003). Currently, 53 to 56% of the population in this region falls below the Kenyan poverty line of \$0.55 day^{-1} (Central Bureau of Statistics and International Livestock Research Centre, 2003). Several studies conducted in the region confirm that agricultural productivity is decreasing as a result of declining soil fertility (Jama *et al*., 1997; Palm *et al*., 1997; Kapkiyai *et al*., 1999; Solomon *et al*., 2007). Decreasing soil fertility results from an imbalance between nutrient inputs and nutrient removals through harvesting, erosion and leaching (Lynam *et al*., 1998; Zingore *et al*., 2005; Lal, 2007). The depletion rates of specific nutrients depend on a number of factors including management, soil type and climate (Davidson and Ackerman, 1993; Wopereis *et al*., 2006; Tittonell *et al*., 2007; Zingore *et al*., 2007).

Farmers in the Kenyan highlands pursue a wide range of crop and livestock enterprises in variable humid and sub humid agro-ecozones (Jaetzold and Schmidt, 1982; MOA&RD, 2001). Household characteristics, exogenous economic forces and biophysical factors interact in a complex way resulting in highly diverse, mixed smallholder agriculture systems (Shepherd and Soule, 1998, Wopereis *et al*., 2006). Differences among households in labour availability, resource endowments and other conditions give rise to different approaches to managing resources, even within the same region (Titonell *et al*., 2007). These management differences affect the type and growth of plants, the presence and productivity of livestock, the use of fertilizers and the functioning of soil micro- and macrofauna, which in turn influence soil fertility. Consequently, soil fertility management usually is related to access to resources (e.g., land, labour, and cash), history of local farming, access to markets and agricultural policy.

Variability in soil fertility can occur at different scales, including field level land use, distance of fields from the homestead, and among households (Vanlauwe *et al*., 2002; Tittonell *et al*., 2005a; Tittonell *et al*., 2005b; Tittonell *et al.,* 2006; Vanlauwe *et al.,* 2006; Tittonell *et al.,* 2007a). Raising agricultural productivity in smallholder agriculture systems requires understanding if and how the complex array of farm enterprises and household socioeconomic factors relate to soil fertility.

Mixed smallholder farming systems are commonly multifaceted, and due to their complexity, are difficult to study satisfactorily. While most farm-scale experiments are often biased towards either economic or biophysical aspects, our study seeks to integrate both socio economic and biophysical components in two major agricultural regions of the Kenyan highlands to achieve an integrated analysis of the farming system. To succeed in alleviating hunger and poverty through soil fertility improvement requires a comprehensive insight of the climatic, edaphic and socio-economic factors determining and controlling the process of soil fertility depletion and repletion (De Costa and Sangakkara, 2006). Finding ways to realize more sustainable and productive land management is an urgent need, requiring policy, institutional, and technological strategies that are well targeted to the heterogeneous landscapes and diverse biophysical and socioeconomic structures found in the East African highlands. Tittonell *et al*. (2005b), using 5 representative farm types based on socio-economic and production factors, has provided evidence for heterogeneity in soil fertility in the smallholder farms of the western Kenya highlands. To capture the complexity of Kenyan highlands agroecosystems, our study covered two highlands of Kenya (western and eastern) and used a large number of farms (236) that were part of a previous socioeconomic study of farm households in this region (Marenya *et al*., 2003; Marenya and Barrett, 2007). For the two sites, we sought to answer two questions. Does soil fertility vary among land uses within and between the two regions? Is there a relationship between soil fertility degradation and poverty? In order to answer these questions, we collected information on per capita income as indicator of financial wealth, number of livestock and land size as indicators of natural capital, and number of adults per household as indicator of human capital. Within a household, land could be supporting diverse agricultural activities. Therefore, soils from all fields within households were sampled and differentiated based on the type of crops grown.

2. Materials and Methods

2.1 Study sites and characterization

The study was part of a larger research program on poverty dynamics in smallholder farms in the highlands of Kenya (Pell et al., 2004). We selected one administrative unit, Madzuu in the Vihiga district in the western Kenya highlands and four administrative units in the Embu district in the eastern Kenya highlands, Mukangu, Kavutiri, Manyatta and Kianjuki. With population densities of approximately 1150 and 700 persons per square kilometre, respectively (CBS-GOK, 2003), Madzuu and Embu are among the most densely populated rural areas in Kenya. Farm sizes are small, ranging between 0.25 and 2.0 ha (MOA&RD, 2001, Jayne *et al.,* 2003). The selected locations were considered to be representative of smallholder-farming in the western and eastern Kenya highlands, where a number of socio-economic studies have previously been undertaken (Barrett *et al.*, 2006).

The western and eastern Kenya highlands lie to the west and east of the Great Rift Valley respectively. The western Kenya highlands extend about 1º 10’ N and 1º 10’ S of the equator and originate from intrusive (granites) and extrusive (basalts, rhyolites and trachytes) igneous rocks. The soils are highly weathered and predominantly Ferrasols (FAO 1997; Gitari *et al.,* 1999). The eastern Kenya highlands are found on the eastern and southern slopes of Mount Kenya about 0.15S, 37.15E. The eastern Kenya highlands originate from volcanic rocks of various ages. The soils are generally enriched in volcanic ash and classified as Andosols (FAO 1997; Gitari *et al.,* 1999). The natural vegetation types in both areas include grasslands, bushy grasslands, bush land and forests (Corbett et al., 1999).

Rainfall in Madzuu ranges from 1500 to 1800 mm annually and is bimodally distributed (Jaetzold and Schmidt, 1983), with the long rainy season lasting from March to July and the short rainy season from August to November. The mean annual temperature ranges from 15 to 25° C. Rainfall in Embu ranges from 1000 to 1600 mm annually, and is also bimodally distributed, with the long rainy season lasting from March to May and the short rainy season from October to December. The mean annual temperature ranges from 13 to 24° C. Farmers in both areas rely on a mix of rainfed farming, livestock rearing (cattle, small ruminants and poultry) and off-farm income for their livelihoods (Pell et al., 2004, Barrett et al., 2006). A large variety of crops are grown in both areas; annual crops include maize (*Zea mays*), beans (*Phaseolus vulgaris*), cassava (*Manihot esculenta*), finger millet (*Pennisetum bicolor*) and a variety of exotic and indigenous vegetables; perennial crops include tea (*Tea sinensis*), coffee (*Coffee arabica*), bananas (*Musa spp)*, macadamia (*Macadamia integrifolia*), trees (found in woodlots) and napier grass (*Pennisetum purpureum*). Except for tea fields that receive fertilizer supplied by a regional tea-managing agency (the Kenya Tea Development Agency, KTDA), other perennial and annual crops receive very limited amounts to no fertilizer. Cultivation of fields is generally to a depth of 10 to 15 cm using a hand hoe (MOA&RD, 2001). Most farmers rarely side dress with nitrogenous fertilizers despite recommendations by the Ministry of Agriculture (MOA&RD, 2001). In Madzuu, cattle are predominantly large humped, fairly large dewlap and droopy eared local zebus (*Bos primigenius indicus*) though a few farmers have crossbreeds. In Embu, most cattle are predominantly crossbreeds between zebus and purebred Aryshire and Friesians dairy cattle (MOA&RD, 2001; Pell *et al.,* 2004). Cattle in Madzuu are herded throughout the landscape and grazed on a tether during the rainy seasons. In Embu, management is primarily a zero or semi-zero grazing system where fodder is produced on the farm, cut in the vicinity of the farm or purchased and fed to the animals in their stalls.

2.2 Farm household land uses

The soils from 123 farms in Madzuu and 113 farms in Embu were sampled between February and April 2003. All farms in this study included more than one field. Fields were distinguished by what was growing at the time of sampling; a total of 966 and 1039 fields were sampled in Madzuu and Embu, respectively. Approximately twenty soil sub samples from 0 to 0.1 m depth were taken using a soil auger along 2 diagonal transects within each field. A one kilogram composite sample was prepared from the sub samples for each field within a farm, air dried and sieved to pass a 2 mm sieve prior to laboratory analyses.

Based on the information collected from the field at the time of sampling, each sampled field within farms was assigned to one of four categories: cash crops, fodder crops, pasture and food crops. Food crops included all fields with monoculture food crop fields plus most intercropped fields, including coffee/banana. Fields intercropped with tea and fallow fields that had been under maize/beans or non-perennial crop were excluded form the food crop category. Fodder crops included any pure stand of napier grass. Cash crops included pure stands of coffee, bananas, tea and woodlots and intercropped tea. Pasture was any area not dedicated to any of the above mentioned enterprises and this was predominantly the area around the homestead.

The range of land uses in the farms sampled in February and April 2003 was similar to that found in previous socioeconomic interviews conducted using the same farms (Marenya *et al.,* 2003). In these interviews, farmers tended to report how they normally managed a specified field season after season, rather than how they managed the field the previous season. Given the similarity between the reported land uses and those based on the February and April 2003 sampling, the latter are considered a good representation of long term land use.

2.3 Soil measurements

Fifteen percent of the soils sampled were randomly selected for conventional laboratory analysis. Standard methods for analyzing tropical soils (ICRAF, 2001) were used. Soil pH was determined in 1:2.5 (w/v) suspensions, exchangeable acidity by NaOH titration using a 1:10 soil/solution ratio (samples with pH >5.5 were assumed to have zero exchangeable acidity and samples with pH <7.5, zero exchangeable Na), exchangeable Ca and Mg by 1 M KCl extraction, and exchangeable K and available P by 0.5 M $NaHCO_3$ and 0.01 M EDTA (pH = 8.5) using 1:10 soil/solution ratio extraction method. Effective cation-exchange capacity (ECEC) was calculated as the sum of exchangeable acidity and exchangeable bases. Soil texture was determined using a Bouyoucos hydrometer after pre-treatment with H_2O_2 to remove organic matter (Gee and Bauder

1986). Total carbon and nitrogen were analysed by dry combustion using a C/N analyser (PDZ Europa Ltd., Sandbach, UK).

Diffuse reflectance infrared spectroscopy can provide inexpensive characterizations of soil chemical, physical and biological properties (Shepherd and Walsh, 2002; Islam *et al*., 2003; Brown *et al.,* 2006; Brown, 2007). This approach has previously been used in Kenya to sort soils into soil fertility classes (Shepherd et al. 2003). All sampled soils in this study, after air-drying and sieving (< 2mm), were analysed by diffuse reflectance spectroscopy, using a FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1 nm using the optical set up as described in Shepherd *et al.* (2002) and Shepherd *et al*. (2003).

Measured values of the soil samples selected for conventional laboratory analysis were calibrated to the first derivative of the reflectance spectra using partial least squares regression (PLSR) implemented using the Unscrambler software (CAMO Inc., Corvallis, OR, USA). Full-hold-out-one cross-validation was done to prevent over-fitting and provide error estimates. Jack-knifing was used to exclude 'non-significant' wavebands. All of the soil spectral data were analyzed using principal component analysis (PCA). The first eigenvector explained 62% of the variation in the spectral data and the second eigenvector explained 10% of the variation. Ordination of all soil samples based on their principle component (PC) 1 and PC 2 values indicated distinct differences between the Embu and Madzuu sites. Therefore, the two sites were treated independently in subsequent analyses. PLSR models developed (not shown) for each site were then used to predict values of the desired soil fertility parameters from the spectral data (Shepherd and Walsh 2002)

2.4 Farm household socio-economic variables

Members of farm households in the study areas were interviewed using a questionnaire (Marenya *et al*., 2003; Pell *et al.,* 2004; Marenya *et al*., 2007). Table 1 presents several descriptive statistics for the farms (households) interviewed. Average farm size of less than a hectare is typical of smallholder farms in Kenya (CBS-GOK, 2003; Jayne et al., 2003). The overall and per-hectare rates of inorganic fertilizer use fall well below those recommended for the major crops in the region (Jaetzold and Schmidt, 1983; KARI, 2003). Only four socio-economic household variables were considered: income, adult population, cattle number and farm size (Table 1). We used per capita daily income, defined as total daily income of a household divided by the total members of the household, as a measure of wealth of the households. Per capita daily income was expressed in Kenya shillings (1 USD = 76 Kenyan shillings). An adult equivalence scale was adopted as a measure of number of adults per household. A score of one was assigned to any household member over eighteen years of age and 0.5 to children below eighteen years old. Number of cattle was the sum of dairy and non-dairy animals per household. The actual area of land in hectares owned by a given a household was taken as the size of the farm.

<<Please Insert Table 1>>

2. 5 Statistical analysis

A linear mixed-effects model (SAS procedures 9.1) was used to analyze the relationship between the conventional laboratory soil data, including soil pH, extractable P, Mg, Ca, SC and TN, and the four land use categories: cash crop, food crop, pasture and fodder. Because fields were nested within farms, both household and fields within household were considered as random variables in the model and were used to assess variability between households and within fields in a household. The fitted residual maximum likelihood (REML) model allowed us to partition the variance of the soil fertility variables into differences between households and differences between sampled fields within households. Tukey's test was then used to test whether the four categories of land use were significantly associated with measured soil variables.

To avoid redundancy in the soil fertility parameters developed from spectral analyses and to determine more important components, data were subjected to principle component analysis (PCA). Principle component analysis was used to handle any multicolinearity and construct new variables that allowed reduction of the dimensions of the data. Each component was examined using several selection criteria, including eigenvalue, scree test (Cattell, 1966), variance explained and Kaiser's criterion (Jassby, 2000). The number of components considered was determined from the amount of variance explained by the eigenvalues to include a substantial (> 0.8) part of the total variability. Prior to PCA, we checked for normality of data sets using the Kolmogorov–Smirnov test.

Exogenous switching regression analysis (Maddala, 1983; Song, 2007), S Plus software, Version 9.2, was used to assess the relationships among the soil fertility components PC1, PC2 and PC3 (the dependent variables), and land use categories and income, household area, adult population and number of cattle (independent variables). All the PC values used in the regression analysis were standardized and had a mean value of zero. Differences between significant variables were determined by Wald's test in STATA software using parameter restriction function.

3. RESULTS

3.1 Analysis of conventionally measured soil properties

In Madzuu, soil under pasture had significantly higher values for all measured soil chemical properties and on average was coarser textured (Table 2). This was not the case in Embu. In both Madzuu and Embu, soil under cash crops (primarily tea) was more acidic than other land use categories. Component variance analysis of the predicted soil fertility variables indicates that variability of P among the four land use categories could be primarily attributed to differences between sampled fields within farms in both Madzuu and Embu. In Madzuu, the variability in SC among and within farms was similar, whereas in Embu most of the variability in SC was between farms (Table 2).

Soil carbon, K and P levels were greater in Embu than Madzuu, while pH was lower. In Embu, P levels ranged between 18.5 and 20 mg kg^{-1} and did not differ significantly among the land use categories. In contrast, in Madzuu P levels ranged from 6.0 to 12.7 mg kg^{-1} (Table 2). Olsen P values of less than 15 mg P kg^{-1} when SC is less than 15 mg kg^{-1} and less than 10 mg P kg^{-1} for all Ferralsols, irrespective SC levels, are considered limiting (Nandwa, 2001)

<<Please Insert Table 2>>

3.2 Principal components analysis of soil properties

The results of the PC analyses, after orthogonal rotation of the variables developed from the spectral analysis of soils from each field, are given in Table 3. The three most important eigenvectors for the two soil data sets scored eigenvalues of > 0.8 and explained more than 87% of the total variation at both sites. At both sites, vector 1 had high positive loadings (> 69%) for exchangeable K, Ca and Mg, CEC and pH and is referred to as the soil nutrient component. At both sites, vector 2 had high positive loadings (> 86%) for total soil carbon and total nitrogen and is referred to as the soil organic matter component. Finally, vector 3 had high positive loading (> 95%) for clay plus silt and is referred to as the soil texture component. Interestingly, in Madzuu, P was strongly associated with the soil nutrient component (vector 1), while in Embu P was associated with the soil organic matter component (vector 2) (Table 3).

<<Please Insert Table 3>>

3.3 Association of land use categories and household characteristics with soil fertility PC scores

Tables 4 and 5 summarise exogenous switching regression analyses of the land use categories and socio-economic variables on soil PC scores in Madzuu and Embu, respectively. For analysis of both fixed variables and interaction terms at both sites, pasture was used as the reference point for land use category assessment. The soil texture component is not presented, as there was no significant relationship with land use or household variables in Embu and in only instance, with area, in Madzuu.

<<Please Insert Table 4>>

In Madzuu, fodder and cash crop land uses were associated with a decrease in soil nutrients and SOM components, and food crop land use was associated with a decrease in SOM compared to pastures (Table 4). After accounting for all other variables, household income was positively associated with the soil nutrient component but had no effect on the SOM and soil texture components. Farm size had a positive impact on the SOM component but negative association with the soil nutrient. Number of cattle per farm had no effect on any of the three soil fertility components.

<<Please Insert Table 5>>

In comparison to pasture, cash crops, food crops and fodder crops all had significant positive impacts on the SOM component in Embu (Table 5). After accounting for all other variables in the regression analysis, income and adult population had significant positive association with the SOM component and the effect was significantly higher in the food crop compared to other land uses. Number of cattle per farm was not associated with any of the three soil fertility components.

4. Discussion

4.1 Soil nutrients and land use

Results of this study indicate that soil fertility between the two sites differed significantly. This is likely to be a consequence, at least in part, of the soil parent material (Jaetzold and Schmidt, 1983). Soils enriched in volcanic ash, as is the case in Embu, generally have a higher surface area (and therefore potentially more adsorbed organic matter) and higher levels of potassium (Parfitt *et al.,* 1997). In addition, available records (MOA&RD, 2001) and personal interviews with farmers indicate that farming activities in Embu were primarily initiated in the late 1940s, when part of the Mount Kenya forest was designated a settlement area and converted to both annual crops and perennial crops, particularly tea and coffee. Consequently, perennial crops such as tea and coffee were introduced on uncultivated fields, which were probably fairly high in soil fertility. Soils developed from parent material of intrusive origin (granite) found in Madzuu are inherently less fertile than those of volcanic origin (Brady and Weil, 2002). Since Madzuu was one of the designated reserve areas for native Kenyans during the colonial rule (Hilhorst and Muchena, 2000), agricultural activities in the area date back to as early as 1900 (farmer interviews and records from government offices). Perennial crops such as tea and coffee (cash crops) were introduced more recently on cultivated fields, which were probably already nutrient depleted. In addition, agroecological zone, land use, population density, policy and accessibility to urban centres and markets are other biophysical and socioeconomic factors that have been cited as main drivers for soil fertility in the smallholder agriculture of the East Africa highlands (Pender et al., 2004; Ehui and Pender, 2005); all these factors could have also contributed to soil fertility differences between the two regions.

For smallholder agriculture, decline in the stock of soil nutrients is the result of soil fertility management practices that cannot support continuous cultivation under increasing population pressure. Small farm sizes (Table 1) necessitate continuous cropping, and without sufficient nutrient inputs to balance nutrient loss through crop harvest and leaching, soil fertility levels will decline (Solomon et al., 2007; Ringius, 2002). Soil carbon and major plant nutrients are lost as well through failure to return aboveground plant residue to the soil, and the destruction of soil aggregates during tillage (Six et al., 2000; Zingore *et al.*, 2005; Murage *et al.,* 2007). This also makes soils more vulnerable to erosion leading to further loss of soil fertility.

Depletion and repletion of soil nutrients and other natural resource assets are dependent on poverty dynamics, as the farmers' abilities to invest in their environment is determined by their economic status (Pell *et al.,* 2004; Barrett *et al*., 2006; Marenya and Barrett, 2007). Although farmers in Madzuu used mineral fertilisers, in agreement with other studies in the region (Braun *et al.,* 1997; Titonell, 2005), the application rates were extremely low (Table1). Our study indicates that majority of the households in Madzuu fell below the Kenyan poverty line of Ksh 40 ($0.55) day^{-1}. A 50 kg bag of diammonium phosphate fertilizer costs about a month's household income for those at the poverty line (Central Bureau of Statistics & International Livestock Research Centre, 2003). This amount of fertilizer can provide sufficient fertilizer for only half a hectare of maize using current fertilizer recommendations for western Kenya (Pell *et al.,* 2004). Farmers are likely to invest in improving their land for annual crop production only if that land is a significant part of their livelihood strategy and only if the investments compete favourably with alternative opportunities (Scherr and Hazell, 1994). Because Madzuu has limited access to Kisumu, Kenya's third largest city (Pell et al., 2004), commercial production of high value commodities such as horticultural crops and dairy is problematic (Staal *et al.,* 2002). Long distances to market coupled with poor road networks increase marketing costs and hence lower profits from selling crops and livestock, which may discourage farmers from investing in fertilizers in Madzuu. Pockets of high fertilizer use have been reported in areas with good market access and very low fertilizer use in poorly accessible areas, which incur higher transport costs (MSU, 1999).

According to Barrett *et al*. (2006), smallholder agricultural areas of Embu have good enough access to markets to be able to engage in regular commercial transactions, and sufficient water to sustain livestock and crops year-round. Farmers in the highlands of eastern Kenya are wealthier (Table 1) because of investment in commercial production of high value farm products (Staal *et al.*, 2002), consequently the majority of households are above the Kenyan poverty line (Table 1). Households may have invested more in soil fertility management in cash crop and fodder crop fields because of greater economic return on money spent on fertilisers compared to Madzuu. Our results are consistent with Van den Bosch *et al*. (1998), who found that nutrient inflow of soil nutrients through fertilizers was highest for Embu farms because of considerable use of inorganic and organic inputs, especially P-fertilizer, in the cash crops tea, napier and coffee on the higher slopes of mount Kenya. De Jager *et al*. (1998) reported that substantial amounts of soil amendment inputs were applied to high earning cash crops, such as tea and coffee in Embu, whereas very few inputs were applied to food crops.

Land use had a significant impact on soil nutrient variability within the two sites but no consistent trend was found. Any land use can impact soil organic carbon and nutrient concentrations (Solomon *et al.,* 2000, Solomon *et al*., 2007). This is because anthropogenic activities such as tillage, planting, and harvesting could affect soil nutrient decomposition or loss; soil perturbation may affect soil moisture by changing micro-climate (Davidson and Ackerman, 1993, Lal, 2001), and species have different nutrient requirements, exploiting nutrients with varying efficiency and storing or converting nutrients at different rates (Aerts and Chapin, 2000).

In Madzuu, except for pasture, which is usually located near the homestead, soil fertility status among land use types was not strikingly different and was generally low (Cochrane *et al.,* 1995 and Nandwa, 2001). Between farms and between fields within farms variances were about equal. This was probably due to the extreme extent of soil fertility depletion in the highlands of western Kenya (Sanchez et al., 1997; Soule and Shepherd, 2000) and the inherent low soil nutrient availability.

Higher SC, TN and P in pastures in Madzuu could be explained by the fact that this area is generally the uncultivated part of the farm and is under grass vegetation throughout the year. Hence, higher levels of SC, TN and P in pasture could be the result of greater root production in these fields that contributes both to higher SC and nutrient retention relative to fields being continuously tilled and cropped (Hussain *et al.,* 1999). Woomer *et al.,* (1994) reported that root debris decomposed less rapidly than shoot material mainly found on the cultivated fields because of its higher lignin content. Grasses have also been shown to enhance carbon storage more than most cover crops (Lal *et al*., 1999, Lewandrowski *et al*., 2004), as well as protect against erosion and decrease runoff (Wuest *et al*., 2006). However, the higher level of SC, TN and especially P in pasture relative to cash crops (primarily the perennial tea) and fodder (primarily napier) would suggest that pastures are receiving relatively high levels of manure and urine, probably primarily from tethered animals, relative to other land uses.

Napier grass is mainly grown on terraces and in small portions not exceeding one fifth of the farm (MOA& RD, 2001). Van den Bosch *et al*. (1998) reported that P recycling in napier grass fields in the highlands of Kenya was low because of the low P values in both napier grass and applied farm yard manure. Lower Olsen P content in fodder crop soils in Madzuu is due to the depletion of soil P through the removal of harvested napier grass and non application of P fertilizers, especially in households without cattle that produce napier grass for a source of income.

Unlike Madzuu, in Embu most soil sampled had relatively high values for the different soil fertility indicators (Cochrane *et al.,* 1985, Nandwa, 2001). Differences in soil fertility among land uses were generally small, though food crop fields were significantly lower in SC. The greater variability in SC between farms in Embu compared to the variability within the farm could be a consequence of individual farms' long-term management history, as only small SC differences were observed among various land use categories (Table 2).

At both sites, soil under cash crops was more acidic than other land use categories as a consequence of a considerable amount of cash crop acreage under tea. The low pH values could be attributed to the sulphur based fertilizer supplied by the Kenyan Tea Development Authority (KTDA) for application in tea fields. Addition of sulphur in soil increases hydrogen activity in the soil solution and hence acidity (Brady and Weil, 2002). For optimum tea production, the most suitable pH range is 4.5–5.5 (Illukpitiya et al., 2004). Our results indicate cash crop fields were within the critical pH level for tea production.

4.2 Land use categories and socio economic variables association with soil fertility

Principle component analysis (PCA) of soil fertility variables for each site indicated similarities in the three most important PCs (Table 3) and grouped soil characteristics were highly correlated. Swaine (1996) found similar trends in Ghana forest soils. However, our results show that P was strongly associated with the soil nutrient component in Madzuu but with SOM component in Embu.

In Madzuu, fodder and cash crop land uses are associated with a decrease in soil nutrients and SOM components and food crop land use is associated with a decrease in SOM component compared to pastures. In Embu, cash crops, food crops and fodder crops all had significant positive association with the SOM component compared to pastures. This is consistent with our soil chemical results (Table 2; Section 4.1).

Our results indicate that the presence of cattle, a proxy for manure availability, was not significantly associated with any of the soil fertility components. Cattle, through manure, can import significant quantities of nutrients to their farms from grazing of crop residues on communal grazing areas, other farmers' fields and purchased napier grass (Achard and Banoin, 2003). Consequently, nutrients accumulate on cattle farms, often at the expense of non cattle owners. Our results may suggest low quantity and/or quality manure in these two regions which could be attributed to reduced land sizes, poor cattle livestock management practices, and low number of cattle (Table 1). Household in Madzuu smear fresh cow dung on their house walls and floors, which is likely to lower the quantity of manure applied to fields in Madzuu (personal communication with the farmers) However, even under relatively high manure application, significant positive change in soil fertility may not occur on such highly degraded soils (Kapkiyai *et al.,* 1999).

The number of adults per household (family labour availability) was significantly and positively associated with the SOM component in Embu. This may indicate the important role family labour plays in the management of soil fertility in Embu. Family labour is very valuable in low income, smallholder agriculture and requires low supervision cost. Given that one of the most important inputs in the agricultural production process is labour, with approximately 90% of farming activities carried out by household members (Kipo, 1993), lack of adequate family labour coupled with inability to hire labour can seriously constrain labour intensive and costly household farm activities. Smallholder agriculture is generally directed and worked by one household except in peak labour seasons (Obschatko, 2006). Activities such as compost making, storage and spreading in food crop and fodder fields are labour intensive. The differences among land uses in SOM (Marenya and Barrett, 2007) and nutrient components with family size suggest different family labour priority allocation among farm activities. Considerable labour is needed to manage food crop and fodder crop fields as opposed to non cultivated pasture fields. Our results suggest that more labour is required for the food crop operations than fodder crop.

Farm size was positively associated with the SOM component but negatively associated with the soil nutrient component in Madzuu. Given that the soil nutrient component in Madzuu included P, this finding suggests smaller farms were more likely to have higher P levels than large farms. Increasing farm size may be associated with other variables not included in our model, especially farm activities that are labour intensive and/or require large amounts of inputs, e.g. growing of tea and coffee or other cash crops which may require large applications of inorganic fertilizer. Consequently, larger farms would require more labour for farm operations and investments in fertilizer. Small farms face lower labour transaction costs than larger farms (Jha *et al.,* 2000) and as a result, smaller farms have higher labour/land ratios and (Feder, 1985; Kimhi, 2006). On the other hand, larger farms may permit fallow periods between seasons and consequently could be less intensively cultivated compared to smaller land sizes. As a consequence, SC loss may be less.

Income was significantly and positively associated with the soil nutrient component in Madzuu, and the SOM component in Embu. Given that soil P was associated with the soil nutrient component in Madzuu and SOM component in Embu (Table 3), this suggests that households with higher income invested more in soil fertility management by utilizing P fertilizers. Income level can influence soil fertility in several ways; higher income farmers may be less risk averse, have more access to information, have a lower discount rate and longer-term planning horizon, and have greater capacity to mobilize cash resources for input (e.g. mineral fertiliser, hire labour) (CIMMYT, 1993). Shepherd and Soule (1998), and Tittonell *et al.* (2005a) reported different soil nutrient balances among farms in different income categories. Income in the form of cash is essential in the purchase of both inorganic and organic fertilizers and in hiring of labour for farm activities such as establishing soil conservation structures and planting trees. Studies in western Kenya (Barrett, 2005; Tittonell *et al.,* 2005a) found that differences in the wealth status of the farmers contributed significantly to the variability of fertilizer use, as the richer farmers purchase and use larger amounts of mineral fertilizers.

5. Conclusions

The large number of farms (236 households and over 2000 fields) used in this study represented the diverse nature of smallholder farming in the western and eastern Kenya highlands. PCA showed that sources of soil P were dissimilar between the two highlands suggesting differences in soil properties and possibly management strategies. Soil fertility in smallholder agriculture was influenced by both farm household and land use factors. Number of cattle per farm had no effect on the soil fertility at either site. The low levels of SC and soil P in uncultivated pasture, food, fodder and cash crop fields in the western Kenya highlands (Madzuu) indicate that soil fertility is severely depleted. Both uncultivated and cultivated fields in the eastern Kenya highlands (Embu) were more fertile. Higher per capita income may have enabled households in Embu to invest in soil fertility management especially in land dedicated to cash crops and food crops. Our study supports the relationship between poverty dynamics and soil degradation in the smallholder agriculture; wealthier households in the eastern Kenya highlands are able to invest in soil fertility management while the poorer households in western Kenya are caught in a cycle of poverty, mining natural resources, such as nutrients in soils, to meet the short-term needs of their families (World Bank, 1996). Poverty results in poor land management, which, in turn, results in more poverty (Blaikie and Brookfield, 1987).

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References

Achard, F., and Banoin, M.. 2003. Fallows forage production and nutrient transfers by livestock in Niger. Nutrient Cycling In Agroecosystems 65:183-189.

Aerts, R., and Chapin, F. S. 2000. The mineral nutrition of wild plants revisited: A re-evaluation of processes and patterns. In: Advances in Ecological Research 30:1-67.

Barrett, C. B. 2005. Rural poverty dynamics: development policy implications. International Association of Agricultural Economics, Agricultural Economics 32:45-60.

Barrett, C. B., Marenya, P. P., McPeak, J., Minten, B., Murithi, F., Oluoch-Kosura, W., Place, F., Randrianarisoa, J. C., Rasambainarivo, J., and Wangila, J., 2006. Welfare dynamics in rural Kenya and Madagascar. Journal of Development Studies 42:248-277.

Blaikie, P., and Brookfield, H., 1987. Land and Degradation and Society. Methuen & Co Inc., London, UK.

Breman, H., J. Groot, J. R., and van Keulen, H., 2001. Resource limitations in Sahelian agriculture. Global Environmental Change-Human and Policy Dimensions 11:59-68.

Brown, D. J. 2007. Using a global VNIR soil-spectral library for local soil characterization and landscape modeling in a 2nd-order Uganda watershed. Geoderma 140:444-453.

Brown, D. J., Shepherd, K. D., Walsh, M. G., Mays, M. D., and Reinsch, T. G., 2006. Global soil characterization with VNIR diffuse reflectance spectroscopy. Geoderma 132:273-290.

Cattell, R. B. 1966. Scree Test for Number of Factors. Multivariate Behavioral Research 1:245-276.

CBS-GOK. 2003. Central Bureau of Statistics, Statistical Abstracts. Central Bureau of Statistics-Government of Kenya, Nairobi, Kenya.

Central Bureau of Statistics and International Livestock Research Centre. 2003. Geographic dimensions of well-being in Kenya. Kenyan Ministry of Planning and National Development, Nairobi, Kenya.

CIMMYT. 1993. The Adoption of Agricultural Technology: A Guide for Survey Design. Economics Program, International Maize and Wheat Improvement Center, Mexico City, Mexico.

Cochrane, T. T., Sanchez, L. G., De Azevedo, L. G., Porras, J. A., and Garver, C. L., 1985. Land in Tropical America Vol. 1., Centro Internacional de Agricultura Tropical, Colombia.

Corbett, J. D., Collis, S. N., Bush, B. R., Muchugu, E. I., Jeske, R. Q., Burton, R. A., Martinez, R. E., White, J. W., and Hodson, D. P., 1999. East African country almanacs. A resources base for characterizing the agricultural, natural, and human environments of Kenya, Ethiopia, Uganda, and Tanzania. Blackland Research Center Report No. 99-06, September 1999, documentation and CD-ROM.

Davidson, E. A., and Ackerman, I. L., 1993. Changes in Soil Carbon Inventories Following Cultivation of Previously Untilled Soils. Biogeochemistry 20:161-193.

De Costa, W., and Sangakkara. U. R., 2006. Agronomic regeneration of soil fertility in tropical Asian smallholder uplands for sustainable food production. Journal of Agricultural Science 144:111-133.

De Jager, A., Nandwa, S. M., and Okoth, P. F., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON) - I. Concepts and methodologies. Agriculture Ecosystems & Environment 71:37-48.

Ehui, S., and Pender, J., 2005. Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. Agricultural Economics 32:225 - 242.

FAO. 1997. FAO/UNESCO Soil Map of the World, Revised Legend with Corrections and Updates World soil resources, Report No. 60, ISRIC, Wageningen, The Netherlands.

Feder, G. 1985. The Relation between Farm Size and Farm Productivity - The Role of Family Labor, Supervision and Credit Constraints. Journal of Development Economics 18:297-313.

Gee, G. W., and Bauder, J. W., 1986. Particle-size Analysis. In: Page, A. L. (Eds.), Methods of soil analysis, Part1, Physical and mineralogical methods. Second Edition, Agronomy Monograph 9. American Society of Agronomy, Madison, WI.

Gitari, J. N., Matiri, F. M., Kariuku, I. W., Muriithi, C. W., and Gachanja, S. P., 1999. Nutrient and cash flow monitoring in farming systems on the eastern slopes of Mount Kenya. Pages 211-228 In: Smaling, E. M. A., Oenema, O., and Fresco, L. O. (Eds.), Nutrient Disequilibria in Agroecosysems: Concepts and Case Studies. CABI Publishing, Wallingford, U.K.

Hartemink, A. E. 2003. Soil fertility decline in the tropics with case studies on plantations. CABI, Wallingford.

Hilhorst, T., and Muchena, F., (Eds), 2000. Nutrients on the Move. Soil Fertility Dynamics in African Farming Systems. International Institute for Environment and Development, London.

Hussain, I., Olson, K. R., and Ebelhar, S. A, 1999. Long-term tillage effects on soil chemical properties and organic matter fractions. Soil Science Society of America Journal 63:1335-1341.

ICRAF. 2001. International Centre for Research in Agroforestry, Laboratory methods for soil and plant analysis. ICRAF, Nairobi, Kenya.

Illukpitiya, P., Shanmugaratnam, N., and Kjosavik, D., 2004. Tea Agroecosystems in the Uva Highlands of Sri Lanka. Mountain Research and Development 24:52-59.

Islam, K., Singh, B. and McBratney, A, 2003. Simultaneous estimation of several soil properties by ultra-violet, visible, and near-infrared reflectance spectroscopy. Australian Journal of Soil Research 41:1101-1114.

Jaetzold, R., and Schmidt, H., 1982. Farm management handbook of Kenya. Natural conditions and farm management information. Part A. Western Kenya (Nyanza and Western provinces). Kenya Ministry of Agriculture and German agricultural team.

Jaetzold, R., and Schmidt, H., 1983. Farm management handbook of Kenya (Vol.2). Rossdorf, Germany: Typo-Druck.

Jama, B., Swinkels, R. A., and Buresh, R. J., 1997. Agronomic and economic evaluation of organic and inorganic sources of phosphorus in western Kenya. Agronomy Journal 89:597-604.

Jassby, A. D. 2000. Uncovering mechanisms of interannual varivariability from short ecological time series. Pages 285–306. In: Scow, K. M., Fogg, G. E., Hinton, D. E., and Johnson, M. L. (Eds), Integrated assessment of ecosystem health, Boca Raton, Fla.

Jayne, T. S., Yamano, T., Weber, M. T., Tschirley, D., Rui, B. F., Chapoto, A., and Zulu. B., 2003. Smallholder income and land distribution in Africa: implications for poverty reduction strategies. Food Policy 28:253-275.

Jha, R., Chitkara, P., and Gupta, S., 2000. Productivity, technical and allocative efficiency and farm size in wheat farming in India: a DEA approach. Applied Economics Letters 7:1-5.

Kapkiyai, J. J., Karanja, N. K., Qureshi, J. N., Smithson, P. C., and Woomer, P. L., 1999. Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management. Soil Biology & Biochemistry 31:1773-1782.

KARI. 2003. Annual Report 2002. Kenya Agricultural Research Institute, Nairobi, Kenya.

Kimhi, A. 2006. Plot size and maize productivity in Zambia: is there an inverse relationship? Agricultural Economics 35:1-9.

Kipo, T. 1993. Farmers perception of the factors of production and agriculture in Northern Region. In: Mercer-Quashie, H., Marfo, K. O., Langyintuo, A. S., and Owusu, R. K., (Eds), Proceedings of the Third Workshop on Improving Farming Systems in the Interior Savannah Zone of Ghana. Nyankapala Agricultural Experimental Station, NAES, Tamale, Ghana.

Lal, R. 2001. World cropland soils as a source or sink for atmospheric carbon. Advances in Agronomy 71:145-191.

Lal, R. 2007. Anthropogenic influences on world soils and implications to global food security. Advances in Agronomy 93: 69-93.

Lal, R., Hassan, H. M., and Dumanski. J., 1999. Desertification control to sequester C and mitigate the greenhouse effect. Pages 83-130. In: Rosenberg, N. J., Izaurralde, R. C., and Malone, E. L., (Eds), Carbon Sequestration Soils, Science Monitoring and Beyond. Battelle Press, Columbus, OH, USA.

Lewandrowski, J., Peters, M., Jones, C., House, R., Sperow, M., Eve, M., and Paustian, K., 2004. Economics of Sequestering Carbon in the U.S. Agricultural Sector. Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Lynam, J. K., Nandwa, S. M., and Smaling. E. N. A., 1998. Nutrient balances as indicators of productivity and substainability in Sub-Saharan African agriculture. Agriculture Ecosystems & Environment 71:1-4.

Maddala, G. S. 1983. Limited-dependent and qualitative variables in econometrics. Cambridge University Press, Cambridge.

Marenya, P. P., and Barrett, C. B., 2007. Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. Food Policy 32:515-536.

Marenya, P. P., Oluoch-Kosura, W., Place, F., and Barrett, C. B., 2003. Education, Nonfarm Income, and Farm Investment in Land-Scarce Western Kenya. BASIS Brief No. 14. February 2003. PN-ACS-339.

MOA&RD. 2001. Ministry of Agriculture and Rural Development Western Kenya Province 2000 Annual Work Programme, Government of Kenya. Ministry of Agriculture and Rural Development, Kenya.

MSU. 1999. Successes and challenges of food market reform: experiences from Kenya, Zambia and Zimbabwe. In: International Development Working Paper No. 72 Department of Agricultural Economics, Michigan State University (MSU, East Lansing, MI.

Murage, E. W., Voroney, P. R., Kay, B. D., Deen, B., and Beyaert, R. P., 2007. Dvnarnics and turnover of soil organic matter as affected by tillage. Soil Science Society of America Journal 71:1363-1370.

Nandwa, S. M. 2001. Soil organic carbon (SOC) management for sustainable productivity of cropping and agro-forestry systems in Eastern and Southern Africa. Nutrient Cycling In Agroecosystems 61:143-158.

Obschatko, E. 2006. The Importance of Small Farmers from an Economic and Labour Perspective. Comuniica Online. sixth edition (April-June 2006).

Palm, C. A., Myers, R. J. K., and Nandwa, S. M., 1997. Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment. In: Buresh, R. J., and Sanchez, P. A., (Eds),. Replenishing soil fertility in Africa. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, U.S.A, pp. 193-217

Parfitt, R. L., B. K. G. Theng, J. S. Whitton, and T. G. Shepherd. 1997. Effects of clay minerals and land use on organic matter pools. Geoderma 75:1-12.

Pell, A. N., Mbugua, D. M., Verchot, L., Barrett, C. B., Blume, L. E., Gamara, J. G., Kinyangi, J. M., Lehmann, C. J., Odenyo, A. O., Ngoze, S. O., Okumu, B. N., Pfeffer, M. J., Marenya, P. P., Riha, S. J., and Wangila. J., 2004. The Interplay Between Smallholder Farmers and Fragile Tropical Agroecosystems in the Kenyan Highlands, paper presented to the American Association for the Advancement of Science annual meetings, Seattle, WA.

Pender, J., Nkonya, E., Jagger, P., Sserunkuuma, D., and Ssali. H., 2004. Strategies to increase agricultural productivity and reduce land degradation: evidence from Uganda. Agricultural Economics 31:181-195.

Ringius, L. 2002. Soil carbon sequestration and the CDM: Opportunities and challenges for Africa. Climatic Change 54:471-495.

Sanchez, P. 2006. Investing in Soil Health: The Entry Point of the African Green Revolution, African Fertilizer Summit, Abuja, Nigeria 9 June 2006.

Sanchez, P. A. 2002. Ecology - Soil fertility and hunger in Africa. Science 295:2019-2020.

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Mokwunye, A. U., Buresh, R. J., Kwesiga, F. R., Izac, A. N., Ndiritu, C. G., and Woomer, P. L., 1997. Soil fertility replenishment in Africa: An investment in natural resource capital, In: Buresh, R. J., and Sanchez, P. A., (Eds), Replenishing soil fertility in Africa. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, U.S.A, pp. 1-46

Scherr, S. J., and Hazell, P. B. R., 1994. Sustainable Agricultural Development Strategies in Fragile Lands. International Food Policy Research Institute, Washington DC.

Shepherd, K. D., Palm, C. A., Gachengo, C. N., and Vanlauwe, B., 2003. Rapid characterization of organic resource quality for soil and livestock management in tropical agroecosystems using near-infrared spectroscopy. Agronomy Journal 95:1314-1322.

Shepherd, K. D., and Soule, M. J., 1998. Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture Ecosystems & Environment 71:131-145.

Shepherd, K. D., and Walsh, M. G., 2002. Development of reflectance spectral libraries for characterization of soil properties. Soil Science Society of America Journal 66:988-998.

Six, J., Elliott, E. T., and Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biology & Biochemistry 32:2099-2103.

Smalling, E. M. A., Nwanda, S. M., and Janssen, B. H., 1997. Soil fertility in Africa is at stake. In Buresh, R. J., and Sanchez, P. A., (Eds), Replenishing soil fertility in Africa.

Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, U.S.A, pp. 47-63

Solomon, D., Lehmann, J., Kinyangi, J., Amelung, W., Lobe, I., Pell, A., Riha, S., Ngoze, S., Verchot, L., Mbugua, D., Skjemstad, J., and Schafer, T., 2007. Long-term impacts of anthropogenic perturbations on dynamics and speciation of organic carbon in tropical forest and subtropical grassland ecosystems. Global Change Biology 13:511-530.

Solomon, D., Lehmann, J., and Zech, W., 2000. Land use effects on soil organic matter properties of chromic luvisols in semi-arid northern Tanzania: carbon, nitrogen, lignin and carbohydrates. Agriculture Ecosystems & Environment 78:203-213.

Song, Wei-Ling. 2007. Why do some firms make seemingly inferior decision? Department of Finance, E. J. Ourso College of Business, Louisiana State University & Wharton Financial Institutions Center.

Staal, S. J., Baltenweck, I., Waithaka, M. M., deWolf, T., and Njoroge, L., 2002. Location and uptake: integrated household and GIS analysis of technology adoption and land use, with application to smallholder dairy farms in Kenya. Agricultural Economics 27:295-315.

Swaine, M. D. 1996. Rainfall and soil fertility as factors limiting forest species distributions in Ghana. Journal Of Ecology 84:419-428.

Tittonell, P., Leffelaar, P. A., Vanlauwe, B., van Wijk, M. T., and Giller, K. E., 2006. Exploring diversity of crop and soil management within smallholder African farms: A dynamic model for simulation of N balances and use efficiencies at field scale. Agricultural Systems 91:71-101.

Tittonell, P., Vanlauwe, B., de Ridder, N., and Giller, K. E., 2007a. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? Agricultural Systems 94:376-390.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C., and Giller, K. E., 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya - I. Heterogeneity at region and farm scale. Agriculture Ecosystems & Environment 110:149-165.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Shepherd, K. D., and Giller, K. E., 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya - II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture Ecosystems & Environment 110:166-184.

UN Millenium Project. 2003. "The global challenge: Goals and targets". www.undp.org, New York City, New York USA.

Van den Bosch, H., Gitari, J. N., Ogaro, V. N., Maobe, S., and Vlaming, J., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). III. Monitoring nutrient flows and balances in three districts in Kenya. Agriculture, Ecosystems & Environment 71:63- 80.

Vanlauwe, B., Diels, J., Lyasse, O., Aihou, K., Iwuafor, E. N. O., Sanginga, N., Merckx, R., and Deckers, J., 2002. Fertility status of soils of the derived savanna and northern guinea savanna and response to major plant nutrients, as influenced by soil type and land use management. Nutrient Cycling In Agroecosystems 62:139-150.

Vanlauwe, B., Tittonell, P., and Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutrient Cycling in Agroecosystems 76:171-182.

Vlek, P. L. G., Kuhne, R. F., and Denich, M., 1997. Nutrient resources for crop production in the tropics. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 352:975-984.

Weil, R. R., and Brady, N. C., 2002. The Nature and Properties of Soils, 13 th edn. Pearson education, Inc., Prentice Hall, Upper Saddle River, New Jersey, USA.

Woomer, P. L., Martin, A., Albrecht, A., Resck, D. V. S., and Scharpenseel, H. W., 1994. The importance of management of soil organic matter in the tropics. In: Woomer, P. L., and Swift, M. J., (Eds), Biological management of tropical soil fertility. John Wiley, Chichester, UK, pp 74 - 80.

Wopereis, M. C. S., Tamelokpo, A. , Ezui, K., Gnakpenou, D., Fofana, B., and Breman, H., 2006. Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crops Research 96:235- 362.

World Bank, 1996. Kenya Poverty Assessment. Report No. 13152-KE. World Bank, Washington, D.C.

World Bank, 2003. Millennium Development Goals: A Compact among Nations to end Human Poverty, Human Development Report. World Bank, Washington D.C.

Wuest, S. B., Williams, J. D. and Gollany, H. T., 2006. Tillage and perennial grass effects on ponded infiltration for seven semi-arid loess soils. Journal of Soil and Water Conservation 61:218-223.

Zingore, S., Manyame, C., Nyamugafata, P., and Giller, K. E., 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. European Journal of Soil Science 56:727-736.

Zingore, S., Murwira, H. K., Delve, R. J., and Giller, K. E., 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agriculture Ecosystems & Environment 119:112-126.

Table 1. Farm household socioeconomic indicators

Site	Variable	Mean	SD
Madzuu	Cattle (number)	1.6	0.81
	Income (Ksh)	32	25
	Adults* (number)	3.9	1.4
	Farm size (ha)	0.32	0.21
	N (kg ha^{-1})	21	22
	P (kg ha^{-1})	11	9.7
	K (kg ha^{-1})	-	-
Embu	Cattle (number)	2	1.5
	Income (Ksh)	74	67
	Adults* (number)	4.5	1.9
	Farm size (ha)	0.57	0.5
	N (kg ha^{-1})	27	48
	P (kg ha^{-1})	26	49
	K (kg ha^{-1})	33	56

1 USD (US Dollar) = 76 Ksh (Kenya Shillings); SD = Standard Deviation
Dairy and per capita income expressed on farm level basis where n=1021(Embu) and 872(Madzuu)

*Adult equivalence scale = people age 18 or over assigned a weight of 1, children below18 assigned a weight of 0.5.

N, P and K calculated based on the applied fertilizers; calcium ammonium nitrate (CAN 21-0-0), diammonium phosphate (DAP, 18-45-0), triple super phosphate (TSP, 0-45-0), urea (46.4-0-0) and NPK (25-5-5 s)

Table 2. Soil fertility variables from conventional laboratory analyses by land use categories in Embu and Madzuu

Area	Land use	SC	TN	C-N ratio	pH ($H_2$0)	P mgkg^{-1}	K	ECEC	Ca	Mg	Clay	Sand	Silt	Soil texture*
		-------g kg^{-1}-----					---------------cmol$_c$ kg^{-1}--------------				------------g kg^{-1}----------			
Madzuu	Cash crop	18 b	1.7b	10.2a	5.5 c	7.8 bc	0.49b	6.4 c	3.8c	1.5 c	440	410	150	Clay
	Food crop	16 c	1.6c	10.0a	5.8 a	8.9 b	0.54b	7.5 b	4.6a	1.7 b	430	420	150	Clay
	Fodder crop	15 c	1.5c	10.0a	5.6 b	6.0 c	0.43b	6.6 c	4.2b	1.6 bc	440	420	140	Clay
	Pastures	23 a	2.2a	10.3a	5.9 a	12.7 a	0.88a	9.1 a	4.9a	2.1 a	400	450	160	Sandy clay
	σ^2 Farm	0.100	0.001	1.84	0.071	20.4	0.365	3.63	1.00	0.141				
	σ^2 Fields	0.092	0.001	8.27	0.236	50.8	0.120	5.10	0.633	0.142				
Embu	Cash crop	40 a	3.8 a	10.4a	4.9 b	20.0 a	0.73 a	5.5 c	3.2 b	1.4 b	470	350	180	Clay
	Food crop	33 b	3.3 b	10.3a	5.2 a	18.5 a	0.88 b	6.9 ab	3.9 a	1.7 a	490	330	180	Clay
	Fodder crop	38 a	3.6 ab	10.3a	5.0 ab	19.6 a	0.78 a	6.1 bc	3.4 b	1.5 ab	490	350	170	Clay
	Pastures	37 ab	3.5 ab	10.3a	5.1 a	18.0 a	0.83 a	7.3 a	3.9 a	1.6 a	510	330	160	Clay
	σ^2 Farm	1.59	0.009	0.327	0.081	5.57	0.020	4.11	0.744	0.243				
	σ^2 Fields	0.44	0.003	0.221	0.088	28.5	0.061	3.51	0.564	0.130				

Means in a column followed by the same letter are not significantly different ($p<0.05$), Tukey test.

*Soil texture classification based on the USDA system.

σ^2 Farm are estimates of variance associated with the farm , σ^2 Fields (within farm) are estimates of variance associated with sampled plots within farms using Restricted Maximum Likelihood estimation. Farms are synonymous with Household. A farm could have more than one field (plots) under different land use systems.

SC= Soil carbon, TN= Total nitrogen, C-N=carbon to nitrogen ratio, pH= pH (1:2.5 water), K= Extractable potassium, P= Extractable phosphorus, ECEC= effective cation exchange capacity, Ca=Exchangeable Calcium, Mg = Exchangeable magnesium.

Table 3. Summary of the principal component analysis of soil variables; Eigenvector loadings, eigenvalues, variances and cumulative variance.

Soil Characteristic	Embu			Madzuu		
	Eigenvector					
	SN	SOM	ST	SN	SOM	ST
	Loadings			Loadings		
Soil Carbon	-37	**86***	-21	30	**94***	0
Total Nitrogen	-36	**87***	-22	28	**95***	4
Phosphorous	22	**87***	9	**66***	47	36
ECEC	**93***	-8	15	**83***	46	8
Potassium	**82***	17	26	**69***	58	-16
Calcium	**90***	-22	3	**86***	30	14
Magnesium	**87***	-23	21	**79***	47	12
Soil pH	**92***	-18	5	**94***	7	-9
Texture (Clay+Silt)	19	-15	**95***	3	2	**97***
Eigenvalue	5.02	2.03	0.84	5.85	1.15	1.04
Variance (%)	55.7	22.5	9.37	65	12.8	11.5
Cumulative variance (%)	55.7	78.3	87.6	65	77.8	89.3

* Bold indicates loadings over 65%, contributing most to the latent theme of the subclass,
The loadings are correlations between the original variables and the components,
SN= soil nutrient, SOM = soil organic matter, ST= soil texture and ECEC= effective cation exchange capacity.

Table 4. Effect of land use categories and socioeconomics factors on soil fertility PC scores in Madzuu: estimates, p value and variances of exogenous switching regression analysis.

Variable	Estimate	p-value	Estimate	p -value
	--------SN component-----		------SOM component-------	
Constant	15.3	0.128	-19.1	0.062*
Cash crop	-1.68	0.003*	-0.698	0.191
Food crop	-0.642	0.092*	-0.889	0.013*
Fodder	-1.13	0.019*	-0.826	0.068*
Income	0.010	<0.001*	0.002	0.659
Area	-1.96	<0.001*	0.850	0.038*
Cattle	-0.10	0.194	0.065	0.366
Adult pop.	-0.036	0.616	0.070	0.292
Cash crop: Income	-0.005	0.440	-0.004	0.535
Cash crop: Area	1.54	0.019*a	-0.405	0.512
Cash crop: Cattle	-0.064	0.618	-0.057	0.637
Cash crop: Adult pop.	-0.064	0.618	0.001	0.990
Food crop: Income	-0.004	0.364	-0.001	0.998
Food crop: Area	1.02	0.036*a	-1.14	0.012*a
Food crop: Cattle	0.017	0.841	-0.112	0.163
Food crop: Adult pop.	0.072	0.357	-0.034	0.640
Fodder crop: Income	-0.002	0.720	-0.003	0.611
Fodder crop: Area	1.62	0.006*a	-1.05	0.058*a
Fodder crop: Cattle	0.106	0.325	-0.025	0.808
Fodder crop: Adult pop.	0.009	0.939	-0.047	0.664
σ^2 Constant	0.007		0.008	
σ^2 Farm	<0.0001		<0.0001	
σ^2 Residual	0.828		<0.0001	

* indicates significant (P<0.10).
Estimates in a column followed by the same letter are not significantly different (p<0.10) method = Wald test.
σ^2 = Variance by using Restricted Maximum Likelihood estimation.
Pasture was used as reference group for dummy variables: Cash crop, Food crop, Fodder.
SN= soil nutrient, SOM = soil organic matter

Table 5. Effect of land use categories and socioeconomics factors on soil fertility PC scores in Embu: estimates, p value and variances of exogenous switching regression analysis.

Variable	Estimate	p -value	Estimate	p -value
	--------SN component-----		------SOM component-------	
Constant	1.11	0.227	-1.90	0.039*
Cash crop	-1.11	0.235	1.76	0.062*
Food crop	-1.10	0.233	1.95	0.035*
Fodder	-1.10	0.255	1.83	0.058*
Income	-0.001	0.938	0.009	0.050*
Area	0.456	0.410	-0.554	0.318
Cattle	0.178	0.427	-0.109	0.627
Adult pop.	-0.288	0.122	0.351	0.061*
Cash crop: Income	-0.003	0.451	-0.005	0.222
Cash crop: Area	-0.179	0.755	0.436	0.448
Cash crop: Cattle	-0.164	0.471	0.112	0.626
Cash crop: Adult pop.	0.251	0.187	-0.293	0.121
Food crop: Income	-0.001	0.954	0.007	0.101*
Food crop: Area	-0.305	0.584	0.558	0.319
Food crop: Cattle	-0.149	0.509	0.092	0.684
Food crop: Adult pop.	0.312	0.096*	0.388	0.040*a
Fodder crop: Income	-0.001	0.829	-0.004	0.337
Fodder crop: Area	-0.159	0.784	0.705	0.227
Fodder crop: Cattle	-0.199	0.387	0.047	0.838
Fodder crop: Adult pop.	0.247	0.204	0.358	0.067*b
σ^2 Constant	0.007		0.007	
σ^2 Farm	<0.0001		<0.0001	
σ^2 Residual	0.9274		0.9351	

* indicates significant (P<0.10).
Estimates in a column followed by the same letter are not significantly different (p<0.10) method = Wald test.
σ^2 = Variance by using Restricted Maximum Likelihood estimation.
Pasture was used as reference group for dummy variables: Cash crop, Food crop, Fodder.
SN= soil nutrient, SOM = soil organic matter