Soil Properties in Relation to Topographic Aspects, Vegetation Communities and Land Use in the South-eastern Highlands of Ethiopia

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Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2007

Acta Universitatis Agriculturae Sueciae
2007:45

ISSN 1652-6880
ISBN 978-91-576-7344 -2

Tryck: SLU Service/Repro, Uppsala 2007

Abstract

Yimer, F. 2007. *Soil Properties in Relation to Topographic Aspects, Vegetation Communities and Land Use in the South-eastern Highlands of Ethiopia, Doctoral dissertation ISSN* 1652-6880*, ISBN 978-91-576-7344-2.*

Quantification of changes in soil properties (particularly organic carbon and total nitrogen) due to natural and anthropogenic influences is essential in understanding carbon fluxes between land and atmosphere. This thesis examines the effects of topographic aspect, vegetation community and land use on physical and chemical properties of soils in south-eastern Ethiopia. Soil samples were collected under three vegetation communities, *Schefflera abyssinica/Hagenia abyssinica* (SHaD), *Hypericum revoltum/Erica arborea/Schefflera volkensii* (HESD) and shrub-sized *Erica arborea* (EAD), at four topographic aspects (north/south/east/west-facing). Soil samples were also collected from three land use types (native forest, cropland, grazing) between 3000-3150 m altitude.

The soil properties examined generally exhibited significant variations with respect to vegetation and aspect. Sand, silt and clay content was high under EAD, HESD and SHaD respectively. Soil bulk density was lower in A- than B-horizons for all vegetation types and aspects. Available P was high under all south-facing communities and in east-facing A-horizon soils under SHaD. Soil pH was high in both horizons under SHaD. Base cation adsorption in soil followed the trend $Ca^{2+}>Mg^{2+}>K^{+}>Na^{+}$ for all communities and aspects. CEC was high under south- and east-facing SHaD and EAD. Overall, percentage base saturation was high under SHaD across all aspects.

Soil organic carbon (SOC) and total nitrogen (N) stocks to 1.0 m depth were highest under EAD (46.03 kg C m^{-2}, 3.61 kg N m^{-2}) and southern aspect (44.97 kg C m^{-2}, 3.75 kg N m^{-2}). Mean annual temperature was important for variations in SOC and total N stocks along vegetation gradients across all aspects. About 45% of SOC was held in the upper 0.3 m, indicating that large amounts of CO_2 can be released to the atmosphere if the vegetation communities are cleared for arable/grazing land.

Conversion of native forest into cropland significantly increased soil bulk density and pH while reducing SOC, total N and CEC concentrations by 31, 32 and 38%, respectively (1.0 m layer). Protecting remnant afroalpine/afromontane vegetation communities or improving existing cropping systems could mitigate nutrient losses while enhancing organic carbon sequestration for sustainable agriculture, ecosystem functioning and climate change mitigation.

Keywords: Carbon sequestration; forest soils; nutrient dynamics; nutrient loss; physical properties; vegetation zonation

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Dedicated to:

My late wife Yemisrach Zenebe; our children Mesay, Nardos and Natnael, who sacrificed their love during my absence; and

Neway Zenebe for shouldering all responsibilities in nurturing my children.

Contents

Appendix

Papers I-IV

The present thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Yimer, F., Ledin, S. & Abdelkadir, A. 2006. Soil property variations in relation to topographic aspect and vegetation community in the south-eastern highlands of Ethiopia. Forest Ecology and Management 232, 90-99.

II. Yimer, F., Ledin, S. & Abdelkadir, A. 2006. Soil organic carbon and total nitrogen stocks as affected by topographic aspect and vegetation in the Bale Mountains, Ethiopia. Geoderma 135, 335-344.

III. Yimer, F., Ledin, S. & Abdelkadir, A. 2007. Changes in soil organic carbon and total nitrogen contents in three adjacent land use types in the Bale Mountains, south-eastern highlands of Ethiopia. Forest Ecology and Management 242 (2-3), 337-342.

IV. Yimer, F., Ledin, S. & Abdelkadir, A. 2006. Effects of land use change on CEC, base cations and saturation of soils in the Bale Mountains, south-eastern highlands of Ethiopia. Geoderma (submitted).

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Contribution of Fantaw Yimer to the papers included in this thesis:

> As first author on all papers, I was mainly responsible for the field sampling, data analyses, data interpretation and writing, with the exception of experimental designs, which were planned together with co-authors. The co-authors also reviewed and commented on the manuscripts before submission to the journals. The input from each of the co-authors was about 10% in each paper.

Introduction

Background

Ethiopia is a tropical country located between 3-15° N and 33-48° E, with an area of about 1.13 million square km. It is a country of great topographical diversity. The climate is of tropical monsoon type with wide topography-induced variations. Most areas experience a seasonally wet and dry tropical highland climate, with a mean annual rainfall of over 1500 mm (Hurni, 1988). Despite the fact that the country occupies a zone of maximum insolation, tropical temperatures are not experienced everywhere. Mean annual temperature decreases towards the interior highland areas to less than 10 °C (Anonymous, 1988).

Because of its geographical position, ranges of altitude, rainfall and temperature variations, Ethiopia has an immense ecological diversity and a huge wealth of biological resources. The vegetation types are highly diverse, ranging from afro-alpine to desert vegetation. By the end of the 20th century, the natural high forest and their biological resources that once covered more than 42 million ha (35% of total land area) in the country had declined to an estimated 2.4% (Eshetu, Giesler & Högberg, 2004).

Ethiopia also has diverse soil types. According to Woldeab (1990), about 18 soil types are reported to occur. Given the general conditions of the Ethiopian economy regarding its overdependence on agricultural production, the survival of about 80% of the population (living in the highlands) is inextricably linked to the exploitation of the soil resources (Bekele, 1988; Hurni, 1988). As a consequence of poor land resource management practices, soil erosion accelerated by human activities poses a threat to agricultural productivity (Bhan, 1990). This is particularly serious in the northern and central highlands, where there is high population pressure (Girmay, 1990) and where the land has been cultivated for more than 3000 years (Eshetu, Giesler & Högberg, 2004). The average soil loss from cultivated land is about 42 ton ha^{-1} yr^{-1} (Hurni, 1988), and the total soil losses in the country from different land cover types is about 1.5 billion metric tons, while the formation rate varies between approx. 2 and 22 ton ha^{-1} yr^{-1} (Hurni, 1983). This is perhaps the most threatening and irreversible environmental process caused by Man and appears to be the single most important environmental process affecting the Ethiopian highland ecosystem (Hurni, 1986).

The population of Ethiopia is currently estimated to be about 75 million, with 2.31% annual growth rate (http://www.infoplease.com/ipa/A0107505.html; 2007-02-19). The rapid increase in human and livestock populations has resulted in major changes in land use systems. Conversion of native forests to farmland and grazing has been commonly practised in the highlands for several decades. Such activities have caused widespread soil nutrient losses. Consequently, many agricultural soils have reached the point of no return, for example in the mountainous areas of the northern and central highlands (Getahun, 1984). Loss of soil fertility is manifested not only through deforestation, soil erosion and forest conversion, but also through the use as household fuels and animal feeds of animal dung and crop residues that would otherwise have been left on the site to replenish soil nutrient levels.

Topographic attributes and vegetation as factors in soil property variations

The spatial variation in soil properties is influenced by biotic and abiotic factors such as topography-induced microclimate differences, altitude, landscape position, parent material and vegetation community (Johnson, Ruiz-Mendez & Lawrence, 2000; Ollinger *et al.*, 2002). Topography influences local and regional climate by changing the pattern of precipitation and temperature (Smith & Smith, 2000; Tsui, Chen & Hsieh, 2004), solar radiation and relative humidity (Finney, Holowaychu & Heddleson, 1962; Franzmeier *et al.*, 1969). Microclimate variations with altitude dramatically influence the type and composition of vegetation species, weathering rates and leaching intensity, resulting in feedback on soil properties such as amount and quality of organic matter, clay and mineralogy, cation exchange capacity and base saturation (Hutchins, Hill & White, 1976; Dahlgren *et al.*, 1997).

Topographic aspect is a potentially significant factor in generating differences in ecosystem characteristics (Sardinero, 2000; Takyu, Aiba & Kitayama, 2002). For example, the hydrological and solar energy regimes of mountainous topography differ according to aspect, leading to divergence in the composition and distribution of vegetation (Ganuza & Almendros, 2003), soil formation and organic matter decomposition (Hicks & Frank, 1984). Aspect also induces local variations in temperature and precipitation, which along with chemical and physical composition of the substrate are the main regulators of decomposition rates of soil organic matter (Liski & Westman, 1997; Mendoza-Vega, 2002).

Land use changes as factors in soil property variations

A change in land use, mainly through conversion of native vegetation to cropland and/or grazing, may influence many natural phenomena and ecological processes, leading to a significant change in soil physical, chemical and biological properties (Turner, 1989). Clearing of forests and their subsequent conversion into cropland reduces the soil C content, mainly through reduced production of litter, increased erosion rates and decomposition of organic matter by oxidation. Changes in land use over the past two centuries have caused a significant release of CO_2 to the atmosphere from the terrestrial biota and soils globally (Houghton *et al.*, 1983; Houghton, 2003). Changes in land use also deprive the soil of its water holding capacity, structural stability, nutrient supply and storage, as well as its biological component (Wairiu & Lal, 2003; Rasiah *et al.*, 2004). Accordingly, many agricultural soils in the tropics are now below their potential production levels (Sombroek, Nachtergaele & Hebel, 1993).

Grazing intensity and frequency are also important management variables that can affect soil properties. Grazing influences plant species composition, net primary productivity, and above- and below-ground allocation in plants, as well as soil compaction and bulk density (Burke *et al.*, 1998). In areas where over-grazing has seriously degraded vegetation cover and primary production, soil organic matter and associated nutrient levels are lower due to the low level of inputs from plant residues and increased erosion losses (Bruce *et al.*, 1999).

The Bale Mountains and their ecological significance

The Bale Mountains are one of the highland divisions in south-eastern Ethiopia, situated approx. 6°45'N, 39°45'E (Figure 1). Mountains are important sources of water and energy and are storehouses of biological diversity containing many types of species and ecosystems (Kräuchi, Brang & Schonenberger, 2000). The mountainous topography and the mosaic of natural vegetation cover in the Bale Mountains have substantial economic, recreational, aesthetic and scientific importance. The vegetation is unique in character, remarkably specialised and exposed to a great diversity of conditions, with steep ecological gradients that are dependent on topographic aspect, slope, climate and soil conditions (Hillman, 1990; Uhlig, 1990; Friis & Lamesson, 1993). These highland units are headwater sources for more than sixty perennial streams and major rivers that drain the south-eastern lowlands of Ethiopia and parts of Somalia.

Apart from an initial reconnaissance soil survey (Weinert & Mazurek, 1984), there has been no detailed information about the soils in the Bale Mountains in general, or about variations in soil properties in relation to vegetation community, topographic aspect or variations with respect to land use changes in particular. This has become an issue of particular concern due to the rapid land conversion practices within and around the Bale Mountains National Park (BMNP), the sensitivity to human influences and the poor agricultural management in this mountainous area. Since published information on the Bale Mountains in general is scarce, large information gaps remain in our understanding of the influence of vegetation community, topographic aspect and land use changes on soil properties in this ecologically diverse mountain ecosystem. The upslope positions and/or higher altitudes of these mountain ranges, with their more or less uniform parent materials and soil conditions, offer an excellent opportunity to study the effect of vegetation community type and topographic aspect on soil properties.

Objectives of the study

The overall objective of this study was to identify drivers of change in soil properties in mountainous ecosystems, thus obtaining information that can be used in appropriate management of the fragile mountain ecosystems of the Ethiopian highlands. The specific objectives of the component studies were to determine:

- Effects of topographic aspect and vegetation community on soil physical and chemical properties ***(Paper I)*** and more specifically soil organic carbon and total nitrogen stocks ***(Paper II)***.

- Effects of conversion of native forests into cropland and/or grazing land on soil organic carbon and total nitrogen content (***Paper III)*** and other chemical and physical soil properties ***(Paper IV)***.

Materials and methods

General description of study sites

The study was carried out in the Bale Mountains, south-eastern Ethiopian highlands (Figure 1). These mountains form a sharp transition zone from high mountain vegetation to hot savannah areas within the south-eastern highlands and associated lowland physiographical regions of the country. Geologically, the study sites are of volcanic origin with welded volcanic ash materials (Mohr, 1971; Berhe *et al.,* 1987).

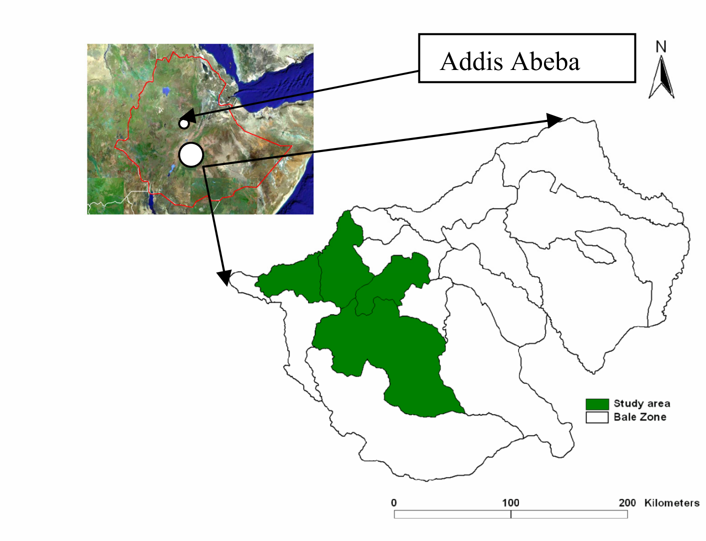

Fig. 1. Map showing location of the study area.

Long-term climatic records for the four study sites (north, south, east, west aspects) are lacking. For this reason fragmentary and discontinuous weather records from the nearby meteorological stations (Dodola, Goba, Rira and Delo Menna) were used to characterise the climate of the study sites. Moreover, from the available temperature records of these stations, a temperature decrease of 0.6 °C per 100 m increase in altitude (Lundgren, 1971) was employed to calculate the mean annual temperature (MAT) of all sites except those with an eastern aspect due to lack of representative temperature data from the stations. Accordingly the estimated ranges of MAT were 8.6-13.4 °C, 9.7-15.2 °C, and 9.1-11.1 °C for the northern, southern and western aspects, respectively. The MAT ranged from 9.2 °C in *Erica arborea*-dominated (EAD) vegetation communities to 12.1 °C in *Schefflera abyssinica/Hagenia Abyssinica*-dominated (SHaD) communities. The mean annual precipitation (MAP) varied from 870 mm for the northern and western aspects to 1064 mm for the southern and 1020 mm for the eastern aspect.

Physiognomically, vegetation formations in the Bale Mountains belong mainly to the afromontane and afroalpine (Nigatu & Tadesse, 1989), showing a marked vegetation zonation along altitudes. At altitudes between 2390 and 2800 m, the vegetation is dominated by tree species such as *Schefflera abyssinica* and *Hagenia abyssinica.* Above this vegetation zone and between 2800 m and approximately 3250 m, the most characteristic vegetation community is a mixture of *Hypericum revoltum, Erica arborea* and *Schefflera volkensii.* The upper altitudinal limit varies at different aspects and gives way to a sub-afroalpine vegetation type characterised as *Erica arborea* bushland (Nigatu & Tadesse, 1989).

In the Bale Mountains, the dominant agricultural practice is a mix of crop cultivation and livestock rearing, mainly for subsistence. Crop production through forest clearance in the southern slopes of the BMNP started in 1991 (oral communication with elder farmers). Barley, which is a major food crop, occurs almost continuously below 3300 m and may extend above depending on the soil and slope. Pressure to find arable land is enormous in the Bale Mountains. Farmers have no or limited access to commercial fertilisers due to the remoteness of the site and do not use manure in their farm fields away from the homesteads. Even though they practise combined crop cultivation and livestock rearing, nutrient flows between the two are predominantly one-sided, with feeding of crop residues to livestock around the homesteads but no dung being returned to the soil, indicating a negative nutrient balance. Grazing is mainly carried out on communal grazing land and on cropland after harvest.

Methods

Papers I and II

These studies dealt with the influence of topographic aspect, vegetation community and their interaction on physico-chemical soil properties and soil organic carbon and total nitrogen stocks. For this purpose, four topographic aspects (north-, south-, east- and west-facing) and three vegetation communities (*Schefflera-Hagenia-, Hypericum-Erica-Schefflera-* and *shrub-sized Erica arborea*-dominated communities) within each aspect were considered (Figure 2). A total of 48 soil profiles (4 aspects × 3 vegetation community types × 4 replicate profiles) were opened at the centre of each randomly selected sample plot, and soil samples were taken from diagnostic horizons. All samples were passed through a 2 mm soil sieve and sent to the National Soil Laboratory and Research Centre in Addis Abeba (Ethiopia) for analyses. Particle size fractions were determined by hydrometer after dispersion in a mixer with hexametaphosphate. Bulk density was determined for each morphological horizon using volumetric cylinders (4 cylinders per diagnostic horizon) and calculated by dividing the oven dry mass at 105 °C by the volume of the core. Exchangeable base cations were extracted with 1N ammonium acetate at pH 7. Calcium and magnesium were determined by atomic absorption spectrophotometry, while sodium and potassium were determined by flame emission spectrophotometry (Black *et al*., 1965). Available P was analysed according to the standard method described by Olsen *et al*. (1954). Soil pH was measured with a combination electrode in a 1:2.5 soil:water suspension. Cation exchange capacity (CEC) was determined titrimetrically by distillation of ammonium displaced by sodium (Chapman, 1965). Percentage base saturation was calculated by dividing the sum of the charge equivalents of the base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) by the CEC of the soil and multiplying by 100. The results of the analyses obtained for each diagnostic horizon were averaged for A- and B-horizons and then grouped for each vegetation community and topographic aspect.

For estimation of soil organic carbon (SOC) and total nitrogen (N) stocks, soil samples were taken at 0-0.3 m and 0.3-1.0 m soil depths from each soil pit. The bulk samples from each depth were aggregated and pooled into a single composite sample representing the sample plot. SOC was determined according to the Walkley and Black method (Schnitzer, 1982) while total N was measured following the Kjeldahl method (Bremner & Mulvaney, 1982).

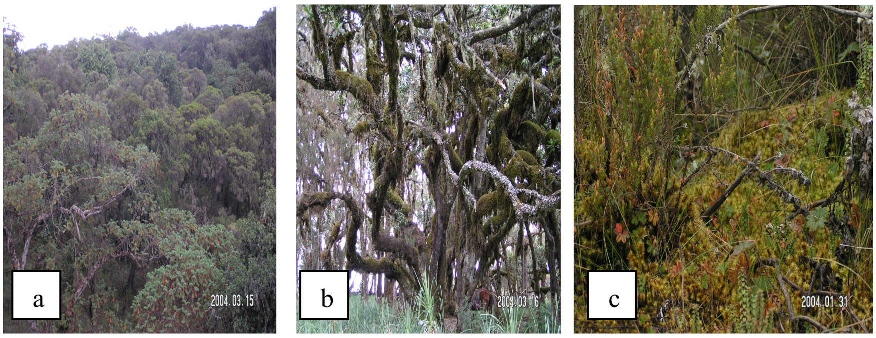

Fig. 2. Vegetation community types: a) *Schefflera abyssinica* - *Hagenia abyssinica* (SHaD); b) *Hypericum revoltum* - *Erica arborea* - *Schefflera volkensii* (HESD); and c) shrub-sized *Erica arborea* (EAD).

Bulk density, as a variable in the estimation of carbon and nitrogen stocks, was determined for each depth using volumetric cylinders (5 cylinders per depth) and the results from five core samples from each depth class were averaged to obtain representative bulk density. The SOC (kg C m^{-2}) and total N stocks (kg N m^{-2}) were calculated from concentration, bulk density and horizon thickness.

SOC, total nitrogen and other physico-chemical soil property data were subjected to two-way analysis of variance (ANOVA) to examine the effects of topographic aspect and vegetation community following the generalised linear model (GLM) procedure of SPSS Version 12.0.1 for Windows (Julie, 2001). In cases of significant ANOVA, means were compared using Tukey's Honest Significance Difference (HSD) at 5% probability level. Pearson's correlation coefficients were computed to examine the relationship between soil physico-chemical properties. A linear regression analysis was also performed to establish the relationship between SOC and MAT.

Papers III and IV

These studies were concerned with the effect of different land uses on SOC and total nitrogen content and other soil physico-chemical properties. For this purpose, three land use types were considered; namely cropland, grazing land and native forest. The cropland had been under barley cultivation for 15 years after conversion of the native forest; the grazing land was a communal grazing field open for grazing by livestock but not under crop cultivation, and the native forest was a parcel of forest land dominated by *Schefflera abyssinica* and *Hagenia abyssinica*. All land use types were replicated over three altitudinal zones ranging from 3000 m to 3150 m at an interval of 50 m in order to get a wider spatial representation of the mountainous terrain. In each land use type at each altitudinal zone, four representative soil profiles were randomly located within similar physiographical conditions such as landscape position and percentage slope. A total of 108 soil samples (3 altitudinal zones × 3 land use types × 4 replicate profiles × 3 soil depths, 0-0.2, 0.2-0.4 and 0.4-1.0 m) were collected during the cropping period for laboratory analyses. The following variables were determined: SOC, total nitrogen, exchangeable base cations, soil pH, CEC and percentage base saturation. Details of the laboratory procedures for analysing each of these variables are described above under the methods for Papers I and II.

The data were then grouped and summarised according to each land use type and soil depth and subjected to two-way analysis of variance (ANOVA) following the general linear model (GLM) procedure of SPSS Version 12.0.1 for Windows (Julie, 2001). Means that exhibited significant differences were compared using Tukey's Honest Significance Difference (HSD) at 5% probability level. Linear regression analysis was performed to examine the relationship between SOC and CEC.

Results

Influences of topographic aspect and vegetation community (Papers I & II)

Soil physical properties

Descriptions of some selected soil profiles representing each vegetation community type are presented in Table 1. The soils studied are characterised by a well-developed black (10YR 2/1, moist) to very dark brown (10 YR 2/2, moist) A-horizon and black (10YR 2/1, moist) to very dark brown (7.5 YR 2.5/2, moist) B-horizon with predominantly fine to medium granular structure. Both the surface and subsurface horizons are very friable to friable at field moisture; non-sticky to slightly sticky and plastic (wet); gradual to diffuse and smooth boundaries. In these soils, textural fractions varied significantly with respect to both topographic aspect and vegetation community ($p<0.001$). The sand content was higher in the soil under the *Erica arborea* vegetation community than under the other vegetation communities**.** Across all vegetation communities and topographic aspects, the overall mean clay content in the A-horizon was generally less than 25%.

Soil bulk density (g cm^{-3}) across all aspects and vegetation communities showed no significant difference for either the A- or the B-horizon. However, the overall average bulk density was slightly higher in the B-horizon under SHaD and HESD compared with EAD.

Soil chemical properties

Soil organic carbon and total nitrogen stocks varied significantly with respect to aspect ($p=0.003$) and vegetation community ($p<0.001$) The overall mean SOC and total N stocks to a depth of 1.0 m ranged from 32.67 to 46.03 kg C m^{-2} and 2.89 to 3.61 kg N m^{-2} among the vegetation communities; and from 35.13 to 44.97 kg C m^{-2} and 2.90 to 3.75 kg N m^{-2} among topographic aspects (Figure 3). Across all vegetation types and topographic aspects, the SOC stock in the top 0.3 m soil layer was between 11.08 kg m^{-2} and 21.67 kg m^{-2}, which accounted for 40-45% of the SOC stock held in the 0-1.0 m layer (Figure 4). The mean SOC and total N stocks were higher among the vegetation communities in the southern aspect than in the remaining aspects. Most of the variation in SOC was explained by the mean annual temperature (r^2 = 0.47, 0.82 and 0.63 for the southern, western and northern aspects, respectively). The soil C/N ratio both in the topsoil ($p<0.001$) and to 1.0 m depth ($p=0.033$) varied significantly with vegetation community. The overall mean C/N ratio for all aspects and vegetation communities ranged from 12 to 13 and 11 to 14, respectively. C/N ratio along the vegetation gradient increased with altitude at all topographic aspects ($r = 0.58$, $p<0.001$ for the top 0.3 m).

Table 1. *Selected soil profile descriptions under different vegetation community types*

	Schefflera abyssinica - Hagenia abyssinica (SHaD)
O	10-0 cm; partially decomposed litter and root mat zone; black (10YR 2/1, moist); abundant very fine and fine-medium roots; abrupt and smooth boundary.
Ah1	0-40cm; Very dark brown (10YR 2/2, moist) loam; moderate fine granular structure; very friable, non-sticky non plastic; common very fine and fine, few medium to coarse roots; many very fine and fine interstitial pores; diffuse and smooth boundary.
Ah2	40-62cm; Very dark brown (10YR 2/2, moist) loam; moderate fine granular structure; non-sticky, non-plastic; common very fine and fine, few medium and very few coarse roots; many very fine and fine interstitial pores; diffuse and smooth boundary.
Bt	62-100+cm; Very dark brown (10YR 2/2, moist) clay; moderate fine to medium granular structure; sticky and plastic; many very fine and fine, few medium roots; few very fine and fine interstitial pores.
	Hypericum revoltum - Erica arborea - Schefflera volkensii (HESD)
O	3-0 cm; black (10YR2/1, moist), root mat and partially decomposed litter layer with mosses, lichens, leaves and twigs; abundant earth worms; common very fine and fine roots; abrupt and smooth boundary.
Ah1	0-15 cm; very dark brown (7.5YR 2.5/2, moist), silt loam; moderate fine granular; very friable moist, non-sticky, non-plastic wet; common earthworm activities; common very fine and fine, few medium and coarse roots; wavy and smooth boundary.
Ah2	15-50cm; very dark brown (7.5YR 2.5/2, moist), silt clay loam; weak very fine granular; very friable moist, slightly sticky, slightly plastic wet; common annelids and unspecified worm channels; common very fine-fine, few medium and coarser roots; diffuse and smooth boundary.
Bw	50-80/100cm; very dark brown (7.5YR 2.5/3, moist), silt loam; moderate fine granular; friable moist, slightly sticky and slightly plastic wet; very few very fine and fine, few medium to coarse roots; wavy and smooth boundary.
	Erica arborea-shrub size (EAD)
O	10-0cm; black (10YR 2/1, moist), litter and root mat; many very fine to fine and few to very few medium roots; clear and smooth boundary.
Ah1	0-50cm; black (10YR 2/1, moist), loam; moderate fine granular; very friable moist, non-sticky, non-plastic wet; few fine to medium tubular pores (earth worm channels); many very fine, fine and medium roots, and very few coarse roots; diffuse and smooth boundary.
Ah2	50-75cm; black (10YR 2/1, moist) loam; moderate-strong fine-medium granular; very friable moist, non-sticky non plastic wet; few medium tubular pores (earth worm &root channels); few very fine- fine, common medium and few coarse roots; diffuse and smooth boundary.
AB	75-110+cm; very dark brown (10YR 2/2, moist) loam; moderate-strong fine granular; very friable moist, non-sticky, non-plastic wet; few very fine-fine, common medium and few coarse roots.

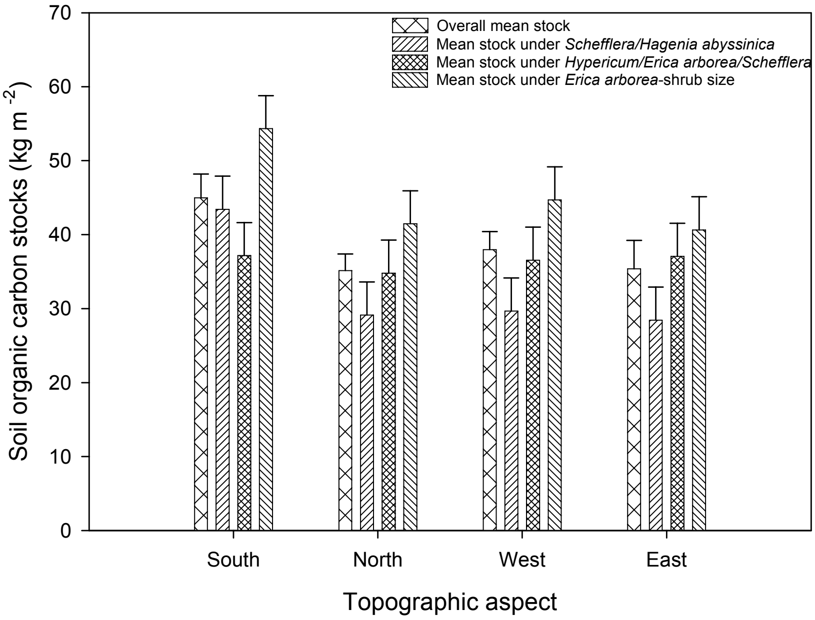

Fig. 3. Soil organic carbon stocks (kg C m^{-2}) in the 0 - 1.0 m soil layer in relation to vegetation community and topographic aspect.

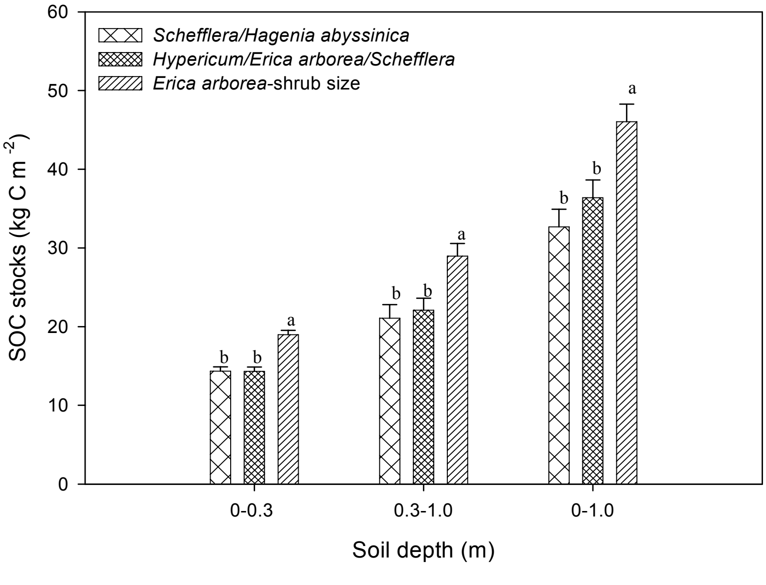

Fig. 4. Distribution of soil organic carbon stocks (SOC, kg m^{-2}) with depth under different vegetation communities. Vertical bars (means ± SE) followed by different letters are significantly different ($p<0.05$) with respect to soil depth.

The concentration of available phosphorus (P) varied significantly with respect to topographic aspect ($p=0.045$ for the A-horizon and $p<0.001$ for the B-horizon). Available P was significantly higher in the southern aspect across all vegetation types (Figure 5). Similarly, a significantly higher concentration of available phosphorus in the A-horizon was found in the eastern aspect with the SHaD vegetation type. In the subsurface layer, however, it was only in the southern aspect that there was a significantly higher concentration of available phosphorus across all vegetation communities.

The overall mean soil pH was significantly higher in the two soil horizons under SHaD than under the HESD and EAD communities, although the average pH was relatively low for the southern aspect (Figure 5). The overall mean soil pH in the A-horizon ranged from 5.3 to 6.0, showing a significant variation ($p<0.01$) with respect to topographic aspect. The range in soil pH among vegetation communities at different topographic aspects was 5.3-6.1. The Pearson's correlation results showed that significant negative relationships existed between pH and altitude in the eastern ($r = -0.72$, $p=0.008$), western ($r = -0.86$, $p<0.001$) and northern aspects ($r = -0.85$, $p<0.001$).

Almost all exchangeable cations showed significant variation with respect to topographic aspect and vegetation community type (Figure 6). The overall mean exchangeable cation (cmol kg^{-1}) composition of the A- and B-horizons followed the trend $Ca^{2+}>Mg^{2+}>K^{+}>Na^{+}$ for all vegetation communities and topographic aspects. There was more exchangeable Ca^{2+} and Mg^{2+} in SHaD than in HESD and EAD vegetation communities. The concentration of exchangeable Na^{+} in the B-horizon soil differed significantly ($p<0.001$) with respect to topographic aspect and vegetation community. The concentration of exchangeable Na^{+} was high in the B-horizon soils with southern and eastern aspects under the SHaD and HESD vegetation communities. The overall mean CEC (cmol kg^{-1}) and the percentage base saturation varied with respect to vegetation community and topographic aspect ($p<0.001$).

The CEC of both A- and B-horizon soils was significantly higher in the SHaD and EAD vegetation communities of the southern and eastern aspects (Figure 5). The percent base saturation was higher in soils under the SHaD than under the other vegetation communities across all topographic aspects. The interaction effect of vegetation and aspect was also significant for the A-horizon ($p=0.011$) and the B-horizon ($p<0.001$).

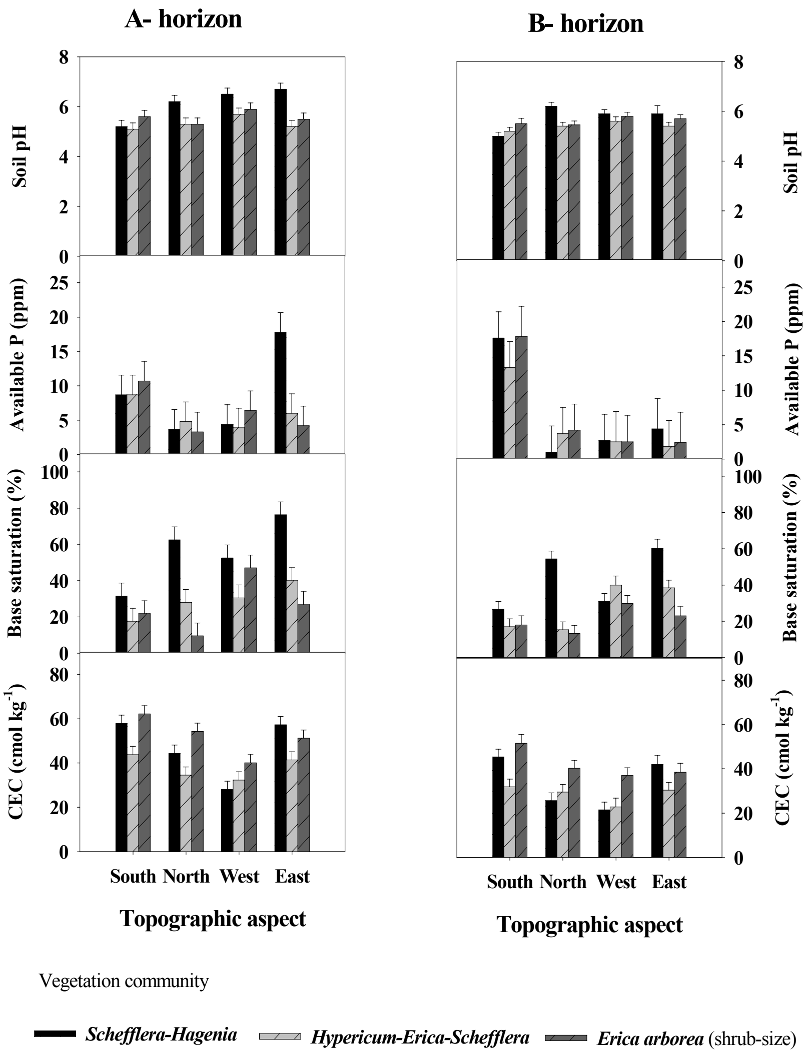

Fig. 5. Soil pH (1:2.5), available phosphorus, base saturation and cation exchange capacity (CEC) in A- and B-horizons in relation to topographic aspect and vegetation community (mean ± SE).

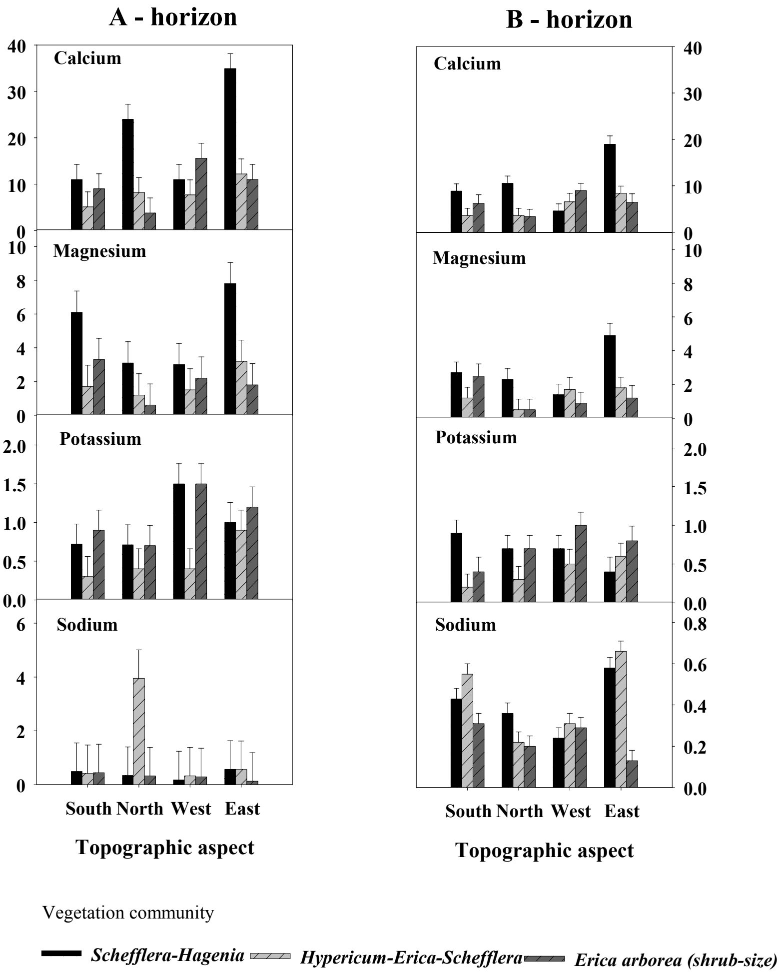

Fig. 6. Exchangeable base cations (cmol kg^{-1}) in A- and B-horizons in relation to topographic aspect and vegetation community (mean ± SE).

Variations in soil properties in relation to land use (Papers III & IV)

Soil physical properties

Soil textural fractions and bulk density showed significant variations in relation to land use and soil depth ($p<0.001$). The sand content was significantly higher in the topsoil layer and the clay content was higher in the subsurface layers below 0.4 m depth, compared with the remaining layers. With respect to land use type, sand and clay proportions were significantly higher in soils under native forest and cropland, respectively. Bulk density was lower in the native forest than in the other land use types (Paper IV).

Soil chemical properties

The effects of land use type and soil depth on SOC, total N and carbon-nitrogen (C:N) ratio were significant ($p<0.001$ for all variables). There was also a significant interactive effect on C:N ratio ($p=0.019$). The findings indicated that soils under the native forest had higher organic carbon (5.31 ± 0.27) and total N contents (0.59 ± 0.03) than soils under cropland (3.67 ± 0.31 and 0.40 ± 0.02, respectively) but the same content as the grazing land. The organic carbon and total N contents of the mineral soil were significantly lower in cropland compared with grazing land. There was a strong relationship between the organic carbon and total N contents of soils under different land use types: cropland +0.94; grazing +0.81, native forest +0.85 ($p<0.001$).

The vertical distribution of organic carbon and total nitrogen also appeared to differ with depth. Irrespective of land use type, the topsoil to 0.2 m depth showed markedly higher contents of SOC (6.00 ± 0.29) and total N (0.64 ± 0.03) compared with the 0.2-0.4 m (4.64 ± 0.27 and 0.49 ± 0.02, respectively) and 0.4-1.0 m depths (3.66 ± 0.27 and 0.39 ± 0.03, respectively). The overall mean C:N ratio was higher in grazing land than in either cropland or native forest.

Soil pH varied significantly across all land use types. The lowest pH value (5.20 ± 0. 11) occurred in soils under native forest and the highest (6.04 ± 0.08) in cropland. The soil pH in grazing land was also significantly lower than in cropland. With respect to depth, significantly lower pH was only observed below 0.2 m depth in native forest and grazing land than in cropland.

Exchangeable Na^+ ($p<0.001$) and K^+ ($p=0.008$) showed significant differences with respect to land use type. The lowest mean Na^+ (0.06 ± 0.01) and K^+ (0.47 ± 0.09) occurred in soils under cropland and the highest under native forest and grazing land. The exchangeable K^+ in soils under grazing land was also significantly higher than the content in cropland. Exchangeable Ca^{2+} and Mg^{2+} differed significantly with respect to soil depth ($p<0.001$). Irrespective of land use type, the overall mean concentrations of K^+ (1.09 ± 0.16), Ca^{2+} (9.84 ± 0.86) and

Mg^{2+} (3.62 ± 0.28) were higher in the topsoil and decreased with depth in the subsoil.

The overall mean CEC and the percentage base saturation in the soils studied showed differences with respect to land use type ($p<0.001$) and soil depth ($p<0.001$ and $p<0.015$ for CEC and percentage base saturation, respectively)**.** CEC values were lower in cropland (26.13 ± 1.09) than in native forest (41.98 ±1.51) and grazing (37.25 ± 1.01). Irrespective of land use type, CEC to 0.2 m depth varied significantly compared with the 0.2-0.4 m layer and the underlying 0.4-1.0 m soil layer. The linear regression revealed the strong correlation between CEC and SOC ($r^2 = 0.66$, $p<0.001$). Percent base saturation in soils under cultivation was higher (42.69 ± 2.70) than in native forest (25.67 ± 2.46) and grazing land (27.71 ± 1.39).

Discussion

Soil properties in relation to topographic aspect and vegetation community type

In an earlier reconnaissance study, Andosols were reported to be the most prevalent soils in the Bale Mountains (Weinert & Mazurek, 1984). Andosols have low bulk density, large variable charge, large water storage capacity, high phosphate retention and accumulation of organic matter (Shoji, Dahlgren & Nanzyo, 1993; Delvaux *et al*., 2004; Satti *et al*., 2007). The dominance of sand in these soils under the EAD community in comparison with the remaining vegetation community types was probably the result of high mean annual precipitation, which selectively transported and/or leached fine fractions from this higher altitude vegetation community down the slopes, leaving behind sand fractions. Moreover, the low temperature conditions at this higher elevation could limit the rate of weathering processes. The high proportions of sand and silt in the solum suggest that the soils are less weathered, young and rich in weatherable mineral, ensuring a gradual release of nutrients to the soil (Yimer, 1996). The clay content in some of the profiles increased with depth (B-horizon), possibly due to clay translocation from the top layer to the layers below. Soil texture is also known to vary with landscape position in mountainous topography (Kreznor *et al*., 1989; Tegene, 1997, 1998; Laurance *et al*., 1999; Rezaei & Gilkes, 2005a). This also holds true for the Bale Mountains, where the three vegetation communities investigated here were mantled on the steeper topographical positions.

The bulk density was low in the A-horizon due to the high organic matter content and low clay content in the upper soil layers**.** However, the observed values are within the range for forest soils reported by Fisher & Binkley (2000). The soil physical properties studied in the present investigation exhibited variation as a result of dynamic interactions between microclimatic conditions, vegetation community and topographic aspect. High organic matter content is recognised for its important role in supporting plant growth through storage and supply of water and nutrients, aeration and ease of penetration for roots (Schoenholtz, Van Miegroet & Burger, 2000; Rezaei & Gilkes, 2005a; Salako, Kirchhof & Tian, 2006).

Various studies indicate that soil carbon stocks increase with elevation in mountainous areas (*e.g.* Bolstad, Vose & McNulty, 2001). Differences along vegetation gradients reflect a changing balance of soil carbon inputs and soil carbon losses that are potentially related to changes in both abiotic (*e.g.* temperature, precipitation, potential evapotranspiration) and biotic (*e.g.* litter quality) factors (Lal, 2005; Garten & Hanson, 2006). The SOC stocks in the soils studied showed variations with vegetation community- and topographic aspect-induced differences in microclimatic conditions. On the slopes of the Bale Mountains, where mean annual precipitation varies between 870 mm and 1064 mm, it is likely that moisture is a less limiting factor for decomposition and therefore differences in temperature are more likely to give rise to differences in breakdown rate. Over a range of increasing moisture contents and temperatures, both factors lead to increasing decomposition rates, but in areas where the precipitation range remains small, the influence of temperature becomes more significant. Although factors affecting soil formation and organic matter accumulation (such as mineralogy, vegetation and topography) may vary dramatically along elevation gradients, mean annual temperature is unquestionably one of the most important factors controlling SOC accumulation and turnover (Trumbore, Chadwick & Amundson, 1996; Garten *et al.*, 1999). Therefore, in the Bale Mountains one would expect the temperature to be the dominant decisive factor for the decomposition and turnover rates. With temperature decreasing with increasing altitude, lower decomposition rate is expected at the higher altitudes. Naturally, the amount of litter incorporated into the soil will also influence the amount of carbon found in the profile, and in the long-run soil C stocks will approach the ratio between litter input rate and decomposition rate (Andrén & Kätterer, 1997). Related studies have also reported an increase in SOC levels with decreasing mean annual temperature (Ganuza & Almendros, 2003; Lemenih & Itanna, 2004; Wang *et al.*, 2004). In addition, as the soils were derived from air-borne volcanic materials, higher SOC contents may be expected from these volcanic materials than in non-volcanic soils. The minerals stabilise soil carbon through organo-mineral complexes and provide protection through aggregate formation. For instance, Powers & Schlesinger (2002) observed that SOC concentration was positively correlated with the amount of non-crystalline clays (*e.g.* allophone, imogolite and ferrihydrite) in the high elevation volcanic soils of Costa Rica. The strong bonds between amorphous material constituents inhibit the decomposition of the majority of the organic matter (Sombroek, Nachtergaele & Hebel, 1993). As a whole, SOC stocks (kg C m^{-2}) in the studied soils of the Bale Mountains were higher than the global average (~ 10.6 kg C m^{-2}, Post *et al.*, 1982) and comparable with the SOC stocks of the Tibetan Plateau of China (Wu, Guo & Peng, 2003) and with other studies (*e.g.* Sombroek, Nachtergaele & Hebel, 1993; Batjes, 1996).

About 40-45% of the SOC stock in the 0-1.0 m layer of the mineral soil was held in the top 0.3 m of the soil. Similar studies in Brazil (Batjes & Dijksoorn, 1999) and China (Wang *et a*l., 2004) reported that about 50% and 40% of the carbon pool to a depth of 1.0 m was stored in the top 0.3 and 0.2 m soil, respectively. The deep rooting systems of the vegetation and the mixing activities of soil fauna would supply large amounts of organic carbon deep in the soil profiles. In addition, the rate of decomposition is believed to be slower with increasing soil depth (Cole, Innis & Stewart, 1977; Degryze *et al*., 2004) and/or most of the carbon compounds accumulated in the deep layers are most likely extremely resistant to decomposition (Liski & Westman, 1997). This suggests the potential for large amounts of CO_2 to be released from the surface soil when these vegetation communities are deforested and converted into grazing and cropland, or when changes are made in forest management practices. The relative distribution between the topsoil and subsoil is comparable with results for similar tropical and subtropical soils (Sombroek, Nachtergaele & Hebel, 1993; Batjes, 1996) and Andosols of the Simen Mountains National Park, Ethiopia (Yimer, 1996).

Total N stocks in the study areas followed a similar pattern to SOC stock distribution due to the fact that most nitrogen forms part of the soil organic matter (Ganuza & Almendros, 2003). The mean total N stocks for the 0-0.3 m and 0.3-1.0 m soil layers for all aspects and vegetation communities were in agreement with the ranges for the soils of Central and Eastern Europe (Batjes, 1996), although there were slightly higher total N stocks below 0.3 m depth in this study. A C/N ratio above 12-14 is often considered indicative of a shortage of nitrogen in the soil (Batjes & Dijkshoorn, 1999). The higher C/N ratios in our study areas could be related to a lower percentage proportion of clay. According to Hassink *et al*. (1993), physically protected organic matter [SOC] has a lower C/N ratio than organic matter [SOC] that is not physically protected. An increasing trend in the C/N ratios from the SHaD to EAD vegetation communities at all aspects could partly be due to an increase in the mean annual precipitation and a decrease in the mean annual temperature along the altitudinal gradient, factors influencing the mineralisation of humus.

The concentration of available phosphorus was higher in the southern aspect across all vegetation communities. The significantly higher content of phosphorus in the A-horizon soil of the southern aspect could be related to the faster mineralisation and mobilisation of phosphorus favoured by the effect of fire, as suggested by Weinert & Mazurek (1984), although the frequency of fire at different topographic aspects was not investigated in the present study. Similarly, a significantly higher phosphorus concentration was found in the eastern aspect with the SHaD vegetation community only in the A-horizon, which may be due to downslope leaching from soils in the upper vegetation communities. A higher mean annual precipitation in the eastern and southern topographic aspects may also have had an influence, *e.g.* indirectly through promoting biomass production and thus providing more organic material for mineralisation. The significantly lower levels of available phosphorus in the other topographic aspects and vegetation communities are probably due to increased phosphorus fixation and lower rates of decomposition in the B-horizon. Phosphorus adsorption properties sometimes vary with soil depth and increase with increasing clay content (*i.e.* larger adsorption surface area). Soils with a high clay content may have the ability to neutralise the acid-extracting solution and thus reduce the amounts of extractable phosphorus (Kamprath & Watson, 1980). Therefore, in soils with similar pH values and mineralogy, phosphorus fixation tends to be higher and ease of phosphorus release tends to be lower in soils with higher clay contents (Brady & Weil, 1999). In this thesis, however, phosphorus adsorption properties of soils were not specifically investigated.

The soils studied are characterised by medium, moderately acidic to neutral pH. The soil pH was significantly higher in soils under SHaD than under HESD and EAD. Such variations are probably the result of differences in nutrient cycling characteristics by the contrasting vegetation or due to the position occupied by the vegetation in the landscape (Dahlgren *et al.*, 1997). Except in the southern topographic aspect, the soil pH showed significant negative relationships with altitude. Such negative relationships of pH with altitude could be due to the fact that increasing altitude results in increased rainfall and thus causes increased leaching and a reduction in soluble base cations, leading to higher H^+ activity and manifested as decreased pH levels (Rezaei & Gilkes, 2005b). The results from the present study are consistent with findings by Chen *et al.* (1997) in a subtropical rain forest in Taiwan and by Tegene (2000) in the northern highlands of Ethiopia.

Almost all base cations showed differences with topographic aspect and vegetation community. The exchangeable cations followed the trend $Ca^{2+}>Mg^{2+}>K^{+}>Na^{+}$ for all vegetation communities and topographic aspects. Van Breemen & Buurman (1998) and Sposito (1989) reported the adsorption affinity of base cations to the soil exchange complex to follow a similar order. The concentration of individual base cations elsewhere (Johnson, Ruiz-Mendez & Lawrence, 2000) decreased in the order $Ca^{2+}>K^{+}>Mg^{2+}>Na^{+}$. The dominance of Mg^{2+} compared with K^+ in the studied soils of the Bale Mountains may reflect similarities in the parent material at all topographic aspects. The low concentrations of exchangeable base cations in the B-horizon compared with the A-horizon may be due to the effect of weathering and leaching over time (Chadwick *et al.*, 1999) or to vegetation pumping bases from the subsoil. The concentrations of exchangeable Ca^{2+} and Mg^{2+} were higher under SHaD than under HESD and EAD, which may be due to $Ca^{2+}$and Mg^{2+} redistribution from lower soil horizons to the soil surface (Finzi, van Breemen & Canham, 1998).

CEC was significantly higher under SHaD and EAD on southern and eastern aspects, where there were high stocks of soil organic carbon, reflecting the large contribution of base cations associated with the organic matter. This result is consistent with other reports (*e.g.* Johnson, Ruiz-Mendez & Lawrence, 2000; Tegene, 2000; Eshetu, Giesler & Högberg, 2004) in that soils with high organic carbon content have a strong positive correlation with CEC.

Variations in soil properties in relation to land use

Both the soil physical and chemical properties considered in this study varied with land use type and soil depth. The soil textural differences might be attributed to natural variations in the rate of weathering and some microtopographical differences such as percentage slope rather than land management practices.

Depending on the soil type, however, the vertical distribution of soil particles could vary due to elluvation down the profiles affecting particle size distribution. Bulk densities under the native forest and in the top 0.2 m of soils were low because of the influence of higher soil organic matter contents. The lower organic carbon content was probably responsible for the higher bulk density observed in cropland, since the correlation between soil organic carbon and bulk density was highly significant. Soil compaction due to cultivation and livestock grazing is associated with higher bulk density (Tollner, Calvert & Langdale, 1990). Trampling by cattle has been reported elsewhere to cause increases in bulk density by compaction of the soil surface, whereas macropores are closed first by the mechanical impact (Taboada & Lavado, 1988; Zhang *et al.*, 2000).

The organic carbon and total nitrogen contents of the mineral soils were lower in the cropland compared with the grazing land and native forest, which is most likely the consequence of the reduced amount of organic material being returned to the soil system and high rates of oxidation of soil organic matter due to tillage and loss of organic matter by water erosion (Ohta, 1990; Aber & Melillo, 1991; Dalal & Chan, 2001; Jaiyeoba, 2003). Contents of organic carbon and total nitrogen were higher in soils under native forest as a result of higher organic matter accumulation due to increased above- and below-ground biomass (root biomass) and reduced litter decomposition rates (Reicosky & Forcella, 1998; Saikh, Varadachari & Ghosh, 1998). Conversion of native forest into cropland has depleted the SOC and total N in the upper 1.0 m soil layer by 30.9 and 32.1%, respectively. Related works elsewhere report a reduction of 20 to 50% (Schlesinger, 1986; Post & Mann, 1990; Davidson & Ackerman, 1993), 34% (Ellert & Gregorich, 1996) or ~ 30% (Post & Kwon, 2000) in the upper 1.0 m soil layer after clearing of forest and its conversion into cropland. About 58% of the SOC and total N contents to a depth of 1.0 m was found in the upper 0.2 m; a result consistent with Detwiler (1986), who reported a range of 30-80% for tropical soils. Cropland soils have a C/N ratio of less than 10, an indication of low levels of fresh organic material incorporated into the soil system (Saikh, Varadachari & Ghosh, 1998), or of a change in the type of organic material present in the soil.

A change in land use from native vegetation to cropland tends to increase soil pH in both the surface and subsurface layers (Lumbanraja *et al.*, 1998). In our study, the increase in soil pH was more pronounced in the cropland soils, most likely due to the traditional slash and burn practices. Burning releases nutrients in the ash that raise soil pH (deMoraes *et al.*, 1996).

Exchangeable Na^+ and K^+ were reduced by 75 and 54%, respectively, as a result of conversion of the native forest to cropland. The lower concentrations of base cations in the subsurface horizons compared with the topsoil suggest that the vegetation pumps bases from the subsoil to the topsoil. Furthermore, the higher topsoil base concentration (in spite of the lack of fertiliser amendment) might also be related to the slash and burn process. The results indicated that concentration of $Ca^{2+}$and Mg^{2+} generally followed the pH trend, as also reported by Young & Hammer (2000). The range in Mg^{2+} concentration of the studied soils under different land use types was higher than the critical level of 0.5 cmol kg^{-1} reported for both tropical and temperate soils (Landon, 1991; McAlister, Smith & Sanchez, 1998).

Changes in the CEC of soils with changes in land use were also quite significant. The CEC values across all land use types varied significantly due to differences in the amounts of soil organic carbon. Taking the fairly low clay content into consideration, it is obvious that the contribution to CEC by organic substances is critical. Topsoils under 15 years of crop cultivation showed a 36.7% reduction in CEC compared with the adjacent topsoils of native forest. Studies elsewhere (*e.g*. Saikh, Varadachari & Ghosh, 1998) also report soils cultivated for 5 and 16 years showing a respective 43 and 27% decline in CEC compared with forest soils. The high value of CEC in the native forest soil in the present study is consistent with other findings showing a strong relationship between CEC and soil organic carbon content (*e.g*. Ohta, 1990; Chen *et al*., 1997; Osher & Buol, 1998; Poudel & West, 1999; Tegene, 2000; Eshetu, Giesler & Högberg, 2004). The percentage base saturation of the studied soils was significantly higher in the cropland than in the native forest. Base cations stored in trees and shrubs are released during burning and replace the hydrogen at the exchange sites of the soil, thereby increasing the base saturation. The fewer exchange sites with smaller amounts of organic matter and more base cations also lead to higher base saturation.

Conclusions

Variations in soil properties in high mountain ecosystems are linked to topographic attributes such as landscape position, aspect and elevation-induced differences in temperature and precipitation, even though the soils are derived from the same parent material. Changes in land use, mainly through conversion of native vegetation to arable land and/or grazing land, are principal anthropogenic factors causing variations in soil properties. Characterising soils along vegetation gradients at different topographic aspects and on agricultural landscapes are basic requirements for the prediction of soil behaviour and its response to management options. This thesis evaluated the spatial variability in soil properties over wide ranges of the Bale Mountains in relation to topographic aspect, vegetation community and land use. Based on the findings, the following conclusions can be drawn:

- The investigated soils under native forest are young, fertile and rich in weatherable minerals and have excellent structure, low bulk density and definitely good porosity, favouring high moisture-holding capacities. Such conditions also permit good aeration and consequently deep rooting systems. The soils could retain all these ‘qualities’ as long as they are not subjected to disturbance.

- Most of the soil physical and chemical properties examined in this study exhibited variability in relation to topographic aspect and vegetation community. Soil pH, available phosphorus, percentage base saturation, CEC and exchangeable base cations were higher in the *Schefflera-Hagenia* (SHaD) vegetation community type. Further studies are required to fully identify the interactive relationships among topographic attributes such as aspect and landscape position, vegetation and soil properties for site-specific soil resource management practices.

- The empirical data obtained from this study show that aspect-induced differences in soil organic carbon stocks are highly variable between the vegetation communities. In the studied case of the Bale Mountains, higher altitudes were seen to result in a higher amount of carbon stock in comparison with lower altitudinal sites, suggesting that SOC and total N accumulations were regulated mainly by the mean annual temperature. Thus, aspect-induced variations in SOC can be used as an important parameter in prioritising mountainous areas for better ecosystem management practices and thereby improving the potential of soils to sequester more organic carbon and mitigate climate change.

- Vegetation and soils can accumulate carbon, thus reducing the rate of CO_2 build-up in the atmosphere, which is responsible for climate change. Despite the higher SOC stocks, the soils were considered to have a substantial potential as carbon sinks and sources. Therefore, the vegetation and soils of the Bale Mountains should be protected and properly managed. Otherwise, changing these native ecosystems to different unmanaged land use practices through deforestation could result in the release of large amount of CO_2 to the atmosphere.

- Soils under natural vegetation store almost all essential nutrients, as the falling litter is returned to the soil system through decomposition processes. When converted to agricultural land, however, rapid deterioration in soil properties is evident, more particularly in the contents of organic carbon and total N. Soil structure also deteriorates; concentrations of exchangeable cations, CEC and pH (in the topsoil) decline; and bulk density increases. Losses as high as 31% of the original amount of SOC were observed after cultivation for 15 years. SOC reductions generally decrease crop productivity and alter the capacity of the soil to act as a sink for atmospheric CO_2 and thus impact on global climate change. The large and relatively rapid changes in SOC with cultivation indicate that there is a considerable potential to enhance the rate of organic carbon sequestration in soil with management activities that reverse the effects of cultivation on SOC pools. Therefore, soil organic matter (carbon) and total N as key components of any terrestrial ecosystem should be protected and maintained through appropriate land resource management practices.

Future studies

Further research is needed to address the potential of different vegetation community types and soils in sequestering organic carbon or above- and below-ground carbon allocation, as well as nutrient fluxes and dynamics. Soil classification is in this case of secondary importance, but it is certainly still of scientific interest to identify the soil types in the Bale Mountains. Small changes in some environmental factors such as microclimate and topographic differences may lead to very different soil formation processes and therefore to very different soils. Therefore, further studies are recommended to characterise the soils over the wide ranges of the Bale Mountains.

On a broader perspective, consideration should be given to the unique vegetation in the Bale Mountains and how it can be protected, while at the same time allowing farmers to use small, selected areas for agricultural production in a way that ensures sustainability. This implies that it is important to further study how different agricultural systems influence the potential for sustained production. In such systems the incorporation into the soil of organic material produced on the site is of crucial importance. Promoting the use of chemical fertilisers on land with food production could be another alternative.

References

Aber, J.D. & Melillo, J.M. 1991. *Terrestrial Ecosystems*. Saunders College Publishing. pp. 200- 205.

Andrén, O. & Kätterer, T. 1997. ICBM - the Introductory Carbon Balance Model for exploration of soil carbon balances. *Ecological Applications 7(4),* 1226-1236.

Anonymous. 1988. *National Atlas of Ethiopia*. Ethiopian Mapping Authority, Addis Abeba.

Anonymous. 2007. Data from website (http://www.infoplease.com/ipa/A0107505.html (accessed on 2007-02-19).

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal Soil Science 47,* 151-163.

Batjes, N.H. & Dijkshoorn, J.A. 1999. Carbon and nitrogen stocks in the soils of the Amazon Region. *Geoderma 89,* 273-286.

Bekele, E. 1988. Ethiopia's land resource base potentials and limitations. In: *IAR Proceedings of the 19th National Crop Improvement Conference.* 22-26 April, 1987. IAR, Addis Abeba.

Berhe, S.M., Desta, B., Nicoletti, M. & Teferra, M. 1987. Geology, geochronology and geodynamic implications of the Cenozoic magmatic province in W and SE Ethiopia. *Journal of Geological Society 144,* 213-226.

Bhan, C. 1990. Spatial analysis of potential soil erosion risk in Wello Region, Ethiopia: A geomorphologic evaluation. In: Messerli, B. & Hans Hurni (Eds.), *African Mountains and Highlands: Problems and Perspectives*. African Mountains Association (AMS).

Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E. & Clark, F.E. 1965. *Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties Including Statistics of Measurement and Sampling*. Am. Soc. Agro. Inc., Madison, Wisconsin.

Bolstad, P.V., Vose, J.M. & McNulty, S.G. 2001. Forest productivity, leaf area, and terrain in southern Appalachian deciduous forests. *Forest Science 47 (3),* 419-427.

Bremner, J.M. & Mulvaney, C.S. 1982. Nitrogen-total. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis, volume 2.* American Society of Agronomy, Madison, Wis., pp. 595-624.

Brady, N.C & Weil, R.R. 1999. *The Nature and Properties of Soils.* 12th ed. Upper saddle River (NJ): Prentice-Hall., pp. 564-565.

Bruce, J.P., Frome, M., Haites, E., Janzen, H., Lal, R. & Paustin, K. 1999. Carbon sequestration in soils. *Journal of Soil and Water Conservation. First quarter*, pp 382-389.

Burke, I.C., Lauenroth, W.K.,Vinton, M.A., Hook, P.B., Kelly, R.H, Epstein, H.E., Aguiar, M.R., Robles, M.D., Aguilera, M.O., Murphy, K.L. & Gill, R.A. 1998. Plant-soil interactions in temperate grasslands. *Biogeochemistry 42,* 121-143.

Chadwick, O.A., Derry, L.A., Vitousek, P.M., Huebert, B.J. & Hedin, L.O. 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature 397,* 491-497.

Chapman, H.D. 1965. Cation exchange capacity. In: C.A. Black, et al. (Eds.), *Methods of Soil Analysis*. Agronomy 9, Am. Soc. Agro. Inc., Madison, Wisconsin, pp. 891-901.

Chen, Z.S., Hsieh, C.F., Jiang, F.Y., Hsieh, T.H. & Sun, I.F. 1997. Relations of soil properties to topography and vegetation in a subtropical rain forest in southern Taiwan. *Plant Ecology 132,* 229-241.

Cole, V.C., Innis, G.S. & Stewart, J.W.B. 1977. Simulation of phosphorus cycling in semiarid grasslands. *Ecology 58,* 1-15.

Dahlgren, A.R., Bottinger, L.T., Huntington, L.G. & Amundson, A.R. 1997. Soil development along an elevation transect in the western Sierra Nevada, California. *Geoderma 78,* 207- 236.

Dalal, R.C. & Chan, K.Y. 2001. Soil organic carbon in rainfed cropping systems of the Australian cereal belt. *Australian Journal of Soil Research 39,* 435-464.

Davidson, E.A. & Ackerman, I.L. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry 20, 181-193.*

Degryze, S., Six, J., Paustian, K., Morris, S.J., Paul, E.A. & Merckx, R. 2004. Soil organic carbon pool changes following land-use conversions. *Global Change Biology 10,* 1120-1132.

Delvaux, B., Strebl, F., Maes, E., Herbillon, A.D., Brahy, V. & Gerzabek, M. 2004. An Andosol - Cambisol toposequence on granite in the Australian Bohemian Massif. *Catena 56,* 31-43.

deMoraes, J.F.L., Volkoff, B., Cerri, C.C. & Bernoux, M. 1996. Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. *Geoderma 70 (1),* 63-81.

Detwiler, R.P. 1986. Land use changes and the global carbon cycle. *Biogeochemistry 2,* 67-93.

Ellert, B.H. & Gregorich, E.G. 1996. Storage of carbon, nitrogen and phosphorus in cultivated and adjacent forested soils of Ontario. *Soil Science 161,* 578-603.

Eshetu, Z., Giesler, R. & Högberg, P. 2004. Historical land use pattern affects the chemistry of forest soils in the Ethiopian highlands. *Geoderma 118,* 149-165.

Finney, H.R., Holowaychu, N. & Heddleson, M.R. 1962. The influence of microclimate on the morphology of certain soils of the Allegheny plateau of Ohio. *Soil Science Society of America Proclamation 26,* 287-292.

Finzi, A.C., van Breemen, N. & Canham, C.D. 1998. Canopy tree-soil interactions within temperate forests: Species effects on soil carbon and nitrogen. *Ecological Application 8,* 440-446.

Fisher, R.F. & Binkley, D. 2000. *Ecology and Management of Forest Soils*. 3rd edition. John Wiley & Sons, Inc., New York.

Franzmeier, D.P., Pederson, E.J., Longwell, T.J., Byrne, J.G. & Losche, C.K. 1969. Properties of some soils in the Camberland Plateau as related to slope aspect and position. *Soil Science Society of America Proceedings 33,* 755-761.

Friis, I. & Lamesson, J. 1993. Altitudinal zonation in the forest tree flora of northeast tropical Africa. *Opera Botanica 121,* 125-127.

Ganuza, A. & Almendros, G. 2003. Organic carbon storage in soils of the Basque Country (Spain): The effect of climate, vegetation type and edaphic variables. *Biology and Fertility of Soils 37,* 154-162.

Garten, Jr. C.T., Post, W.M., Hanson, P.J. & Cooper, L.W. 1999. Forest soil carbon inventories and dynamics along an elevation gradient in the southern Appalachian Mountains. *Biogeochemistry 45,* 115-145.

Garten, Jr. C.T. & Hanson, P.J. 2006. Measured forest soil C stocks and estimated turnover times along an elevation gradient. *Geoderma 136,* 342-352.

Getahun, A. 1984. Stability and instability of mountain ecosystems in Ethiopia. In: Ives, J. D. & Michael T, (Eds.), *Mountain Research and Development 4 (*1), 23-31.

Girmay, B. 1990. Consequences of land degradation: A call for soil conservation in Ethiopia. In: *Natural Resources Degradation: A Challenge to Ethiopia. IAR Proceedings First Natural Resources Conservation Conference*, 7-8 Feb., 1989. IAR, Addis Abeba.

Hassink, J., Bouwman, L.A., Zwart, K.B., Bloem, J. & Brussaard, L. 1993. Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. *Geoderma 57 (1-2),* 105-128.

Hicks, R.R. & Frank, P.S. 1984. Relationship of aspect to soil nutrients, species importance and biomass in a forested watershed in West Virginia. *Forest Ecology and Management 8,* 281-291.

Hillman, J.C. 1990. The Bale Mountains national park area, southeast Ethiopia, and its management plan. In: Bruno Messerli & Hans Hurni (Eds.), *African Mountains and Highlands: Problems and Perspectives.* African Mountains Association (AMA).

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B.J., Peterson, B.J., Shaver, G.R. & Woodwell, G.M. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO2 to the atmosphere. *Ecological Monographs 53(3),* 235-262.

Houghton, R.A. 2003. Why are estimates of the terrestrial carbon balance so different? *Global Change Biology 9 (4),* 500-509.

Hurni, H. 1983. *Soil Formation Rates in Ethiopia*. EHRS, Working Paper 2.

Hurni, H. 1986. *Management Plan: Simen Mountains National Park and Surrounding Rural Areas.* UNESCO World Heritage Committee and Wildlife Conservation Organization, National Resources Conservation and Development Main Department, MOA. Ethiopia.

Hurni, H. 1988. Climate, soil and water: Degradation and conservation of the resources in the Ethiopian highlands. In: *Mountain Research and Development. African Mountains and Highlands.* Vol.8, Nos. 2/3, May/August, UNU/IMS.

Hutchins, R.L., Hill, J.D. & White, E.H. 1976. The influence of soil and microclimate on vegetation of forested slopes in eastern Kentucky. *Soil Science 121,* 234-241.

Jaiyeoba, I.A. 2003. Changes in soil properties due to continuous cultivation in Nigerian semiarid Savannah. *Soil & Tillage Research 70,* 91-98.

Johnson, C.E., Ruiz-Mendez, J.J. & Lawrence, G.B. 2000. Forest soil chemistry and terrain attributes in a Catskill watershed. *Soil Science Society of America Journal 64,* 1804-1814.

Julie, P. 2001. *A Step By Step Guide to Data Analysis Using SPSS for Windows.* Open University Press.

Kamprath, E.J & Watson, M.E. 1980. Conventional soil and tissue tests for assessing the phosphorus status of soils. In: *The Role of Phosphorus in Agriculture (Chapter 16).* American Society of Agronomy, Madison, WI. pp. 433-469.

Kräuchi, N., Brang, P. & Schonenberger, W. 2000. Forests of mountainous regions: Gaps in knowledge and research needs. *Forest Ecology and Management 132 (1),* 73-82.

Kreznor, W.R., Olson, K.R., Banwart, W.L. & Johnson, D.L. 1989. Soil, landscape, and erosion relationships in a northwest Illinois watershed. *Soil Science Society of America Journal 53,* 1763-1771.

Lal, R. 2005. Forest soils and carbon sequestration. *Forest Ecology and Management 220 (1-3),* 242-258.

Landon, J.R. 1991. *A Handbook for Soil Survey and Agricultural Evaluation in the Tropics and Subtropics.* Longman, Harlow.

Laurance, W.F., Fearnside, P.M., Laurance, S.G., Delamonica, P., Lovejoy, T.E., Rankin-deMerona, J.M., Chambers, J.Q. & Gascon, C. 1999. Relationship between soils and Amazon forest biomass: a landscape-scale study. *Forest Ecology and Management 118,* 127-138.

Lemenih, M. & Itanna, F. 2004. Soil carbon stock and turnover in various vegetation types and arable lands along an elevation gradient in southern Ethiopia. *Geoderma 123,* 177-188.

Liski, J. & Westman, C.J. 1997. Carbon storage in forest soils of Finland. II. Size and Regional patterns. *Biogeochemistry 36,* 261-247.

Lumbanraja, J., Syam, T., Nishide, H., Mahi, A.K., Utomo, M., Kimura, S. & Kimura, M. 1998. Deterioration of soil fertility by land use changes in South Sumatra, Indonesia: From 1970 to 1990. *Hydrological Processes 12,* 2003-2013.

Lundgren, B. 1971. *Soil studies in a montane forest in Ethiopia*. Research notes Nr 11. Department of Forest Ecology and Forest Soils, Royal College of Forestry, Stockholm.

McAlister, J.J., Smith, B.J. & Sanchez, B. 1998. Forest clearance: impact of land use change on fertility status of soils from the São Francisco area of Niteroi, Brazil. *Land Degradation and Development 9,* 425-440.

Mendoza-Vega, J. 2002. *The Influence of Land Use/Land Cover and Soil Types on Amounts of Soil Organic Carbon and Soil Characteristics.* Doctoral thesis. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Mohr, P. 1971. *The Geology of Ethiopia*. Addis Abeba University, Addis Abeba.

Nigatu, L. & Tadesse, M. 1989. An ecological study of the vegetation of the Harenna Forest, Bale, Ethiopia. *SINET: Ethiopian Journal of Science 12(1),* 63-93.

Ohta, S. 1990. Influence of deforestation on the soils of the Pantabangan area, Central Luzon, the Philippines. *Soil Science & Plant Nutrition 36 (4),* 561-573.

Ollinger, S.V., Smith, M.L., Martin, M.E., Hallett, R.A., Goodale, C.L. & Aber, J.D. 2002. Regional variation in foliar chemistry and N cycling among forests of diverse history and composition. *Ecology 83,* 339-355.

Olsen, S.R., Cole, C.V., Watanabe, F.S. & Dean, L.A. 1954. *Estimation of available phosphorus in soils by extraction with sodium bicarbonate.* US Department of Agriculture. Cir. 939, USDA.

Osher, L.J. & Buol, S.W. 1998. Relationship of soil properties to parent material and landscape position in eastern Madre de Dios, Peru. *Geoderma 83(1-2),* 143-166.

Post, W.M., Emanuel, W.R., Zinke, P.J. & Stangenberger, A.G. 1982. Soil carbon pools and world life zones. *Nature 298,* 155-159.

Post, W.M. & Mann, L.K. 1990. Changes in soil organic carbon and nitrogen as a result of cultivation. In: Bouwman, A.F. (Ed.), *Soils and Greenhouse Effect.* Wiley, New York, pp. 401-406.

Post, W.M. & Kwon, K.C. 2000. Soil carbon sequestration and land use change: Processes and potentials. *Global Change Biology 6,* 317-327.

Poudel, D.D. & West, L.T. 1999. Soil development and fertility characteristics of a volcanic slope in Mindanao, the Philippines. *Soil Science Society of America Journal 63 (5),* 1258-1273.

Powers, J.S. & Schlesinger, W.H. 2002. Relationships among soil carbon distribution and biophysical factors at nested spatial scales in rain forest of northeastern Costa Rica. *Geoderma 109,* 165-190.

Rasiah, V., Florentine, S.K., Williams, B.L. & Westbrooke, M.E. 2004. The impact of deforestation and pasture abandonment on soil properties in the west tropics of Australia. *Geoderma 120(1-2),* 35-45.

Reicosky, D.C. & Forcella, F. 1998. Cover crop and soil quality interactions in agroecosystems. *Journal of Soil and Water Conservation 53 (3),* 224-229.

Rezaei, S.A. & Gilkes, R.J. 2005a. The effect of landscape attributes and plant community on soil physical properties in rangelands. *Geoderma 125,* 145-154.

Rezaei, S.A. & Gilkes, R.J. 2005b. The effect of landscape attributes and plant community on soil chemical properties in rangelands. *Geoderma 125,* 167-176.

Saikh, H., Varadachari, C. & Ghosh, K. 1998. Changes in carbon, nitrogen and phosphorus levels due to deforestation and cultivation: A case study in Simlipal National Park, India. *Plant and Soil 198,* 137-145.

Salako, F.K., Kirchhof, G. & Tian, G. 2006. Management of a previously eroded tropical Alfisol with herbaceous legumes: Soil loss and physical properties under mound tillage. *Soil & Tillage Research 89 (2),* 185-195.

Sardinero, S. 2000. Classification and ordination of plant communities along an altitudinal gradient on the Presidential Range, New Hampshire, USA. *Plant Ecology 148,* 81-103.

Satti, P., Mazzarino, M.J., Roselli, L. & Crego, P. 2007. Factors affecting soil P dynamics in temperate volcanic soils of southern Argentina. *Geoderma 139*, 229-240

Schlesinger, W.H. 1986. Changes in soil carbon storage and associated properties with disturbance and recovery. In: Trabalka, J.R. & Reichle, D.E. (Eds.), *The Changing Carbon Cycle: A Global Analysis*. Springer-Verlag, New York, pp. 194-220.

Schnitzer, M. 1982. Total carbon, organic matter, and carbon. In: Page, A.L., Miller, R.H.& Keeney, D.R. (Eds.), *Methods of Soil Analysis.* Part 2, 2nd Edition.

Agronomy Monograph, Vol. 9. American Society of Agronomy, Madison, WI, pp. 539-577.

Schoenholtz, S.H., Van Miegroet, H. & Burger, J.A. 2000. A review of chemical and physical properties as indicators of forest soil quality: Challenges and opportunities. *Forest Ecology and Management 138,* 335-356.

Shoji, S., Dahlgren, R.A. & Nanzyo, M. 1993. Genesis of volcanic ash soils. In: Shoji, S., Nanzyo, M., Dahlgren, R.A. (Eds.), *Volcanic Ash Soils: Genesis, Properties and Utilization.* Elsevier, Amsterdam, pp. 37-71.

Smith, R.L. & Smith, T.M. 2000. *Elements of Ecology.* 4th edition. Addison Wesley Longman, Inc. San Francisco. pp 31-42.

Sombroek, W.G., Nachtergaele, F.O. & Hebel A. 1993. Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio 22 (7),* 417-426.

Sposito, G. 1989. *The Chemistry of Soils.* Oxford University Press, New York, USA.

Taboada, M.A. & Lavado, R.S. 1988. Grazing effects of the bulk density in a natraquoll of the Flooding Pampa of Argentina. *Journal of Range Management 41 (6),* 500-503.

Takyu, M., Aiba, S.I. & Kitayama, K. 2002. Effects of topography on tropical lower montane forests under different geological conditions on Mount Kinabalu, Borneo. *Plant Ecology 159 (1),* 35-49.

Tegene, B. 1997. Variabilities of soil catena on degraded hill slopes of Watiya catchment, Wollo, Ethiopia. *SINET: Ethiopian Journal of Science 20(2),* 151-175.

Tegene, B. 1998. Pedogenesis and soil-geomorphic relationships on the piedmont slopes of Wurgo Valley, Southern Wollo, Ethiopia. *SINET: Ethiopian Journal of Science 21(1),* 91-111.

Tegene, B. 2000. Characteristics and classification of soils of Gora Daget Forest, South Wollo highlands, Ethiopia. *SINET: Ethiopian Journal of Science 23(1),* 35-51.

Tollner, E.W., Calvert, G.V. & Langdale, G. 1990. Animal trampling effects on soil physical properties of two Southeastern U.S. Ultisols. *Agriculture, Ecosystem and Environment 33,* 75-87.

Trumbore, S.E., Chadwick, O.A. & Amundson, R. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science 272 (5260),* 393-396.

Tsui, C.C., Chen, Z.S. & Hsieh, C.F. 2004. Relationships between soil properties and slope position in a lowland rain forest of southern Taiwan. *Geoderma 123,* 131-142.

Turner, M.G. 1989. Landscape ecology: The effect of pattern and process. *Annual Review of Ecology and Systematics 20,* 171-197.

Uhlig, S. 1990. Mountain forests and the upper tree limit on the south-eastern plateau of Ethiopia. In: Messerli, B. & Hurni, H. (Eds.), *African Mountains and Highlands: Problems and Perspectives.* African Mountains Association (AMA), pp. 237-248.

Van Breemen, N. & Buurman, P. 1998. *Soil Formation.* Kluwer Academic Publishers. The Netherlands.

Wairiu, M. & Lal, R. 2003. Soil organic carbon in relation to cultivation and topsoil removal on sloping lands of kolombangara, Solomon Islands. *Soil & Tillage Research 70 (1),* 19-27.

Wang, S., Shao, M., Mickler, R. & Ji, K. J. 2004. Vertical distribution of soil organic carbon in China. *Environmental Management 33 (Supplement),* 200 - 209.

Weinert, E. & Mazurek. A. 1984. Notes on vegetation and soil in Bale Province of Ethiopia. *Feddes Repertorium, Band 95 (5-6),* 373 - 380.

Woldeab, A. 1990. The role of soil fertility management in crop production. In: IAR (1990). *Natural Resources Degradation: A Challenge to Ethiopia. IAR Proceedings. First Natural Resources Conservation Conference, 7-8 Feb., 1989.* IAR, Addis Abeba.

Wu, H.B., Guo, Z.T. & Peng, C.H. 2003. Land use induced changes of organic carbon storage in soils of China. *Global Change Biology 9,* 305-315.

Yimer, F. 1996. *An Assessment of the Status of Soils, Soil Degradation and Conservations in the upper catchments of the Ansiya Valley*, *Simen Mountains National Park, Gonder, Ethiopia*. M.A thesis, Addis Abeba University, Addis Abeba.

Young, F.Y. & Hammer, R.D. 2000. Soil-landform relationships on a loess-mantled upland landscape in Missouri. *Soil Science Society of America Journal 64,* 1443-1454.

Zhang, J.H., Li, Y., Lindstrom, M.J. & Yang, Z. 2000. Soil water properties in a recently established forest as affected by grazing in a semiarid valley. *Soil Use & Management 16,* 234-235.

Acknowledgements

I am very grateful to my main supervisor Stig Ledin for accepting me as a PhD student in soil science and teaching me critical thinking and scientific reasoning, and Dr. Abdu Abdelkadir, my assistant supervisor, for his unfailing encouragement during the course of the PhD study. Had it not been for Stig's generous support and consistent encouragement throughout the course of the study period, both at professional and personal level, it would have been impossible for me to write this thesis. The assistance of both supervisors in planning, experimental design, reviewing the manuscripts and openly sharing their wealth of knowledge in soil science was instrumental for the successful compilation of this thesis.

I would like to take this opportunity to thank my friend Dr. Mulualem Tigabu, Faculty of Forest Sciences/SLU, Umeå, for his valuable comments on the manuscripts and thesis, unreserved encouragement, valuable advice and support; staff members and PhD students at the Soil Science Department; Harry, Kerstin and Bibbi for their help with administrative matters, unreserved moral support and taking care of my health. Bibbi, you are an excellent 'mom'; Ragnar Persson for his smiling face and solving computer problems; Abraham, Ingmar, Sixten, Anne, Lovisa, Åsa and Alfredo for all moral support and encouragement and Thomas Keller for his technical support in formatting the thesis. Special thanks to Ararso for sharing with me his wealth of wisdom in social matters and for being so helpful. Ararso, you are a wonderful person!! I am going to miss you and our *fika*! The editorial group, Ingvar N., Olle A. and Martin L., are also acknowledged for their constructive comments on the thesis; and Dr. Mary M., for editing the language.

Special thanks to my sisters and brothers, Neway, Etaferahu, Kedija, Eleni, Mekonnen, Gobezie and my neighbour, Medhanit, for nurturing my children in my absence and for spiritual support. My friends and family in Umeå, Sweden, Emebet Wada (Mother Emu), Alex, Wudiye, Ayalew and his family, Abebe and his family, Belay and the late Abraham; friends in Stockholm, Messay, Getachew, Tadelech and Matewos; and in Uppsala, Sweden, Ayelech and her family, Wubeshet and his family and Admassu and his family and many others made my stay hospitable, for which I convey my heartfelt gratitude. My ‘Mom’ Emebet Wada and her family deserve special appreciation which I cannot express in words. Aschalew Kindie, Adane Gebeyaw and Dessalegn Wolde (USA), Hanna Tekele, Tade, Mahlet, Kure, Etifwork and Getachew M (Germany), and Frewoine (Canada) for their unreserved moral support.

I also thank colleagues and friends in Ethiopia: the late Dr. Takele, Dr. Melaku, Dr. Kassahun, Dr. Zebene, Dr. Tarekegn, Dr. Zewdu, Dr. Mulugeta, Dr. Abdella, Dr. Bekele, Dr. Tesfaye Teklay, Zeleke, Mesele, Girma, Mohammed, Yohannes, Taye, Addisalem, Kefyalew, Mamo, Demamu, Genene, Mersha, Amlaku, Teshale, Tefera M., Birhanu, Yimer A., Meseret M., Almaz, Yebalework, Yared, Hana, Solomon H, Wegayehu, Kassahun H.M and his family, Dr. Assefa Abegaz and his family, Dr. Wosenu, Abebech, Dr. Tsegaye Gedif, the late Sileshi Kifle, Mr. Zebene Gelagle, Aklilu Ameha and Daniel Fitamo for their moral support. Mr. Abebe Abay, Kumsa and Dr. Zebene, from the National Soil Laboratory and Research Centre, for their unreserved support in the soil analyses.

Ethiopian PhD students and friends in Sweden: Solomon, Yemiru, Menfese, Gessesse and Mulugeta Z. for the friendly encouragement and weekly social affairs with beer; and Mulugeta Tibebu for moral and technical support. Yosef Mamo, Abebe Seifu, Efrem Garadew, Sisay and Yosef (Alemaya University) are also acknowledged for their moral support and my neighbour, Hammid Sherif, for his friendly social relations. Hammid, you are a wonderful guy!!

Thanks to Mr. Endale for his administrative and financial facilitation during my stay in Ethiopia; drivers Mr. Afework, Wondimu, Tirusew, Yikeber, Alemayehu and Beyene for their care during the field work; the Bale Mountains National Park Headquarters and the Adaba-Dodola GTZ project staff members and farmers around the study area for their help during my field work.

The Swedish International Development Authority (Sida) and Wondo Genet College of Forestry are gratefully acknowledged for financial support.