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Forest Soils of Ethiopian Highlands: Their Characteristics in Relation to Site History

Studies based on stable isotopes

Zewdu Eshetu

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

Forest soils of Ethiopian highlands: Their characteristics in relation to site history. Studies based on stable isotopes.

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Abstract

Isotopic composition and nutrient contents of soils in forests, pastures and cultivated lands were studied in Menagesha and Wendo-Genet, Ethiopia, in order to determine the effects of land use changes on soil organic matter, the N cycle and the supply of other nutrients.

In the Menagesha forest, which according to historical accounts was planted in the year 1434-1468, $\delta^{13}C$ values at > 20 cm soil depth of from -23 to -17‰ and in the surface layers of from -27 to -24‰ suggest that C_4 grasses or crops were important components of the past vegetation. At Wendo-Genet, the $\delta^{13}C$ values in the topsoils of from -23 to -16‰ and in the > 20 cm of from -16 to -14‰ indicated more recent land use changes from grassland to forest. At Menagesha, $\delta^{15}N$ values shifted from -8.8‰ in the litter to +6.8‰ in the > 20 cm. The low $\delta^{15}N$ in the litter (-3‰) and topsoils (0‰) suggest a closed N cycle at Menagesha. At Wendo-Genet, the high $\delta^{15}N$ (3.4-9.8‰) and low total N concentrations suggests a more open N cycle with greater N losses.

At Menagesha, the variation in soil nutrient contents followed the patterns of %C and %N. At the mid-altitudes, where there had been undisturbed forest cover for > 500 years, %N and %C were higher and the surface layers showed high accumulation of Ca and S. The strong relation between %C and CEC_t suggests that organic matter increases the nutrient retention capacity of these soils. Exchangeable and total Ca were strongly related ($r^2 = 0.95$, $P < 0.001$). It is suggested that the presence of forests in this otherwise bare landscape leads to interception of base cations in dust, which can help to sustain a productive forest. The studies show that the approach to combine stable isotopes with nutrient elements is especially useful when studying the chemical properties of forest soils in relation to site history. They also show that productive forests with a high soil organic matter content can be established on fairly steep slopes in the Ethiopian highlands.

Key words: closed and open N cycle, elevational transect, Ethiopia, forest soils, land use, site history, soil chemistry, stable isotopes

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At Menagesha, the variation in soil nutrient contents followed the patterns of %C and %N. At the mid-altitudes, where there had been undisturbed forest cover for > 500 years, %N and %C were higher and the surface layers showed high accumulation of Ca and S. The strong relation between %C and CEC_t suggests that organic matter increases the nutrient retention capacity of these soils. Exchangeable and total Ca were strongly related ($r^2 = 0.95$, $P < 0.001$). It is suggested that the presence of forests in this otherwise bare landscape leads to interception of base cations in dust, which can help to sustain a productive forest. The studies show that the approach to combine stable isotopes with nutrient elements is especially useful when studying the chemical properties of forest soils in relation to site history. They also show that productive forests with a high soil organic matter content can be established on fairly steep slopes in the Ethiopian highlands.

Key words: closed and open N cycle, elevational transect, Ethiopia, forest soils, land use, site history, soil chemistry, stable isotopes

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Contents

Introduction, 7

Objectives, 10

Material and methods, 10
Description of study areas, 10
Geology, soils and climate, 11
Vegetation and land use history, 12
Sampling and analysis, 13
Soil sampling and chemical analysis, 13
Statistics, 14

Results and discussion, 15
Land cover changes as revealed by stable C isotopes, 15
Closed N cycle forest ecosystem resulting from long-term plantation forest cover, 18
Changes in soil chemical properties resulting from long-term plantation forest cover, 20

Conclusions, 22

References, 23

Acknowledgements, 26

Appendix

Papers I-III

This doctoral thesis is based on studies reported in the following papers, which will be referred to in the text by the corresponding Roman numerals.

I. Zewdu, E. and P. Högberg. 2000. Reconstruction of forest site history in Ethiopian highlands based on ^{13}C natural abundance of soils. *Ambio 29*, 83-89.

II. Zewdu, E. and P. Högberg. 2000. Effects of land use on ^{15}N natural abundance of soils in Ethiopian highlands. *Plant and Soil*, in press.

III. Zewdu, E., R. Giesler and P. Högberg. 2000. Historical land use pattern affects the chemistry of forest soils in the Ethiopian highlands. Manuscript (submitted).

Introduction

The Ethiopian highlands (> 1500 m a.s.l.) are generally perceived as areas where rainfall, soils and other environmental conditions important for human life are much better than in the surrounding semi-arid and arid lowlands. They are also relatively less infected by tropical human and animal diseases than the hotter low-land areas sur-rounding them. Hence, the highland areas of Ethiopia have been very attractive for human land use and are known to have been settled by a significant human population for more than 5000 years (e.g., Hurni, 1982). About 95% and 65% of the country's cropped land and livestock grazing occur in the highland areas, respectively (Anon., 1988; Ermias, 1986). Thus, deforestation of forests for fuel wood, construction, grazing and cultivation has been underway for several thousand years. Ecological consequences of such activities often include changes in the physical, biological and chemical properties of soils.

Several lines of evidence indicate that there have been long-term vegetation shifts in the highlands of Ethiopia (e.g., Bonnefille, 1983; Bonnefille and Buchet, 1986; von Breitenbach and Koukol, 1962; Hamilton, 1982; Horvarth, 1969; Hurni, 1987; Tewolde, 1989). Relevant to the studies reported here are palaeobotanical studies from Mt. Bada (4040 m), 108 km northeast of Wendo-Genet, and from Wenchi (2890 m), 80 km west of Menagesha, presented by Hamilton (1982) and Bonnefile and Buchet (1986), respectively. In the deeper peat core zone at Bada (Hamilton, 1982), which corresponds to c. 10 000 B.P., the high abundance of pollens of *Chenopodiaceae* and *Suada* suggest the occurrence of semi-desert or salt pans in a much drier climate at sites of the higher altitudes. The zone corresponding to c. 3700-1850 B.P. is characterized by high abundance of *Juniperus*, *Podocarpus* and *Olea* pollens which provide evidence of dry montane forests at higher elevation sites. The upper zone dated c. 1850 B.P. has a decline of *Podocarpus* pollen and an increase in the relative abundance of pollen of *Celtis*, *Dodonaea*, *Hagenia*, *Myrica*, *Chenopodiaceae*, *Plantago* and *Rumex*, which suggests devastation of the montane forests by man and its replacement by secondary forests and agricultural land. The studies from lake Wenchi (Bonnefille and Buchet, 1986), indicate a stable situation over the last 1000 years. Apart from a small peak of *Juniperus* at about 700 B.P., a relative decrease in the abundance of *Juniperus* pollen and an increase in *Rumex* provide evidence of quite recent human disturbance around the 13^{th} century. Generally, the palaeobotanical evidences suggest anthropogenic forest disturbances that first appeared around 1850 B.P. However, C datings from charcoal (Hurni, 1987) suggest a relatively early extensive destruction of forests in the Ethiopian highlands starting c. 2450 B.P. Overall, it seems that the Ethiopian highland areas were settled by a larger human population for not less than 5000 years.

Several reports (e.g., von Breitenbach and Koukol, 1962; Horvarth, 1969; Pohjonen and Pukala, 1990; Tewolde, 1989) suggest that deforestation of highland forests for fuel wood, construction, grazing and cultivation was aggravated by several factors particularly after the 16th century. Amongst others were several relocations of the capital city and administrative head quarters, social instabilities due to wars among the kings, changes in social organizations and land tenure. It is noteworthy that afforestation of mountainous areas started as early as the 15th century; beneficial influences of forests on public welfare, water regime, climate, vegetation and control of soil erosion were recognized since the time of King Zera-Yakob (1434-1468), who made watershed reserves and ordered afforestation of the mountain slopes of the central Ethiopian highlands. Hence, historical patterns of vegetation shifts in the highlands of Ethiopia are of both natural climatic and anthropogenic origins.

Despite ample evidence of the vegetation history of Ethiopia, information on how soil properties vary in relation to the long-term land use changes is lacking at present for most soils of Ethiopian forest lands. Most soil studies reported so far are usually based on measurements of soil chemical properties in relation to soil classification, genesis and management (e.g., Mesfine, 1998; Mitiku, 1987) and focus on the status of nutrients such as, P (e.g., Miressa and Robarge, 1999; Piccolo and Huluka, 1986; Tekalign and Haque, 1987, 1991) and N (Ali, 1992) as well as on how soils vary with topography (e.g., Belay, 1982), but not with respect to the effects of long-term land use changes on soil properties. Attempts have, however, been made to study nutrient cycling in relation to forest management practices with an emphasis on a comparison between natural and plantation forests (Lisanework and Michelsen, 1993; Michelsen et al., 1996). Studies in other areas in the tropics have compared the impacts of various vegetation types and land uses on the status of soil organic matter and the supply and availability of nutrient elements (e.g., Asio et al., 1998).

The history of a forest site is important for it's productivity. During the recent years, substantial progress has been made concerning the interpretation of stable isotopes, mainly the variation in the natural abundances of ^{13}C and ^{15}N in soil profiles, and their implications in studies of ecosystem dynamics (e.g., Balesdent and Mariotti, 1996; Boutton, 1996; Högberg, 1997; Nadelhoffer and Fry, 1994).

Carbon occurs naturally as a mixture of two stable isotopes (and with traces of radioactive ^{14}C), with the lighter ^{12}C isotope being much more abundant than the heavier ^{13}C. Variations in the ratio $^{13}C/^{12}C$ are expressed in δ units, which are part per thousand (‰) deviations of the $^{13}C/^{12}C$ ratio from the international standard Vienna Pee Dee Belemnite (V-PDB with a $^{13}C/^{12}C$ ratio of 0.011237) (Craig, 1953).

Ecosystem components vary in their $^{13}C/^{12}C$ ratio (e.g., Boutton, 1991). Generally, plants contain less ^{13}C than atmospheric CO_2, because of fractionation against the heavier isotope during diffusion of CO_2 and during photosynthesis. Because of isotopic fractionation that occurs during photosynthesis (Farquhar et al., 1982; Farquhar, 1983), plants with C_3 photosynthesis (C_3 plants, such as most trees and shrubs) have $\delta^{13}C$ values between -33 and -23‰ (average -28 to -26‰), while those with C_4 photosynthesis (C_4 plants, such as most tropical grasses) have $\delta^{13}C$

values ranging from -16 to -9‰ (average -14 to -12‰) (Deines, 1980; Smith and Epstein, 1971). Both types of plants coexist in the tropics (e.g., Tieszen et al., 1979; Young and Young, 1983).

With respect to the plant-soil system, the ^{13}C natural abundance in soil organic matter is closely related to the isotopic composition of plants growing there, and a difference of ~14‰ in ^{13}C signature between C_3 and C_4 plants is large enough for quantifying the fractional contribution of C_3 and C_4 plant derived C to soil organic matter, SOM, (e.g., Trouve et al., 1994). This provides substantial evidence regarding the variation in the relative abundance of plant species with C_3 and C_4 photosynthetic pathways in past plant communities. Because C_3 and C_4 plants are photosynthetically (e.g., Farquhar et al., 1982; Farquhar, 1983) and ecologically (e.g., Tieszen et al., 1979; Young and Young, 1983) distinctive, any changes in the relative C_3-C_4 abundance reflects changes of both ecosystem structure and ecosystem functions, which are often attributable to consequences of climate changes and human disturbances. Since the ^{13}C natural abundances in soils mainly display both vertical and horizontal variations in the fractional contributions of C_3 and C_4 C, a site-specific historical patterns of the C_3-C_4 relative abundance can be reconstructed from measurements of the $\delta^{13}C$ of SOM at different depths in the soil profile. Thus, several studies in the tropics have used soil $\delta^{13}C$ values to document patterns of vegetation dynamics in natural ecosystems resulting from climate changes or anthropogenic causes and to determine the previous shifts in the boundaries between forests and grasslands (e.g., Ambrose and Sikes, 1991; Desjardins et al., 1996; Mariotti and Peterschmitt, 1994; McPherson et al., 1993). Moreover, C and N, and therefore the two stable isotopes, ^{13}C and ^{15}N, are frequently correlated because of links through the growth and nutrition of organisms as well as processes of organic N transformations in soils, i.e., N mineralization and immobilization are intimately associated with C transformations in soils.

The natural abundance of ^{15}N, whose δ units denote parts per thousand deviations, ‰, from the ratio ^{15}N:^{14}N in atmospheric N_2, 0.0036765, (Mariotti, 1983), varies in the biosphere as a result of isotope discrimination against ^{15}N as N cycles through plant-soil system. Thus, isotope fractionation causes in the long-term vegetation and litter to be depleted in ^{15}N, while the SOM becomes enriched in ^{15}N. Processes of N losses through ammonia volatilization, nitrate leaching and plant uptake discriminate against ^{15}N (Högberg, 1997) and ecosystems with large losses of N are known to be enriched in ^{15}N, as shown in experimental studies (Högberg, 1990; Högberg and Johannisson, 1993; Johannisson, 1996). Disturbances of natural ecosystems such as forest fire and clearfelling (Högberg, 1997) and land use changes from forest to grassland or cropland (e.g., Karamanos et al., 1981; Mariotti et al., 1980) are known to increase $\delta^{15}N$ values in plants and soils. Studies in the Brazil, however, showed that conversion of forests to pastures decreases soil $\delta^{15}N$ values indicating inputs from organisms fixing atmospheric N_2 (e.g., Piccolo et al., 1994). In a comparison of $\delta^{15}N$ values between tropical and temperate forests, Martinelli et al. (1999) found that tropical forests and their soils are more enriched in ^{15}N as compared with temperate forests; which suggests that tropical forests have a more open N cycle with greater N losses through fractionating pathways (Högberg, 1990, 1997; Högberg and Johannisson, 1993; Johannisson, 1996). Soil ^{15}N natural abundance can therefore be used as an indicator of changes in N dynamics and soil N sources that follow a change in the land use. Thus, a comparison between the patterns of $\delta^{15}N$ and $\delta^{13}C$ values in soils could provide possibilities to reconstruct ecosystem changes.

In the studies of soil conditions, in areas where land use changes are thought to be of importance, measurements of the contents of soil nutrient elements combined with a simultaneous analysis of the stable isotope ^{13}C, may, therefore, reveal if variations in the chemistry of forest soils are related to site history or other site differences. This approach of soil study may provide direct biogeochemical evidence of the importance of the history of a site and could help to predict future changes in the status of soil nutrient elements and forest site productivity caused by changes in the land use.

Objectives

The present study focused on how land use changes have affected the properties of Ethiopian forest soils. It was conducted in two areas with different land uses and according to historical accounts, also different land use histories. The study had the following specific objectives:

- To reconstruct forest site history in these areas using variations in soil ^{13}C natural abundance,

- To asses the impacts of land use changes on the N cycle using ^{15}N natural abundance of soils,

- To assess the long-term influence of forest plantations on soil chemical properties and to determine the major causes of variations in nutrients in forest soils along an altitudinal gradient.

Material and methods

Description of study areas

The two study areas were the Menagesha forest and the Wendo-Genet areas, which are situated 30 km west and 250 km south of Addis Abeba, respectively (Fig. 1).

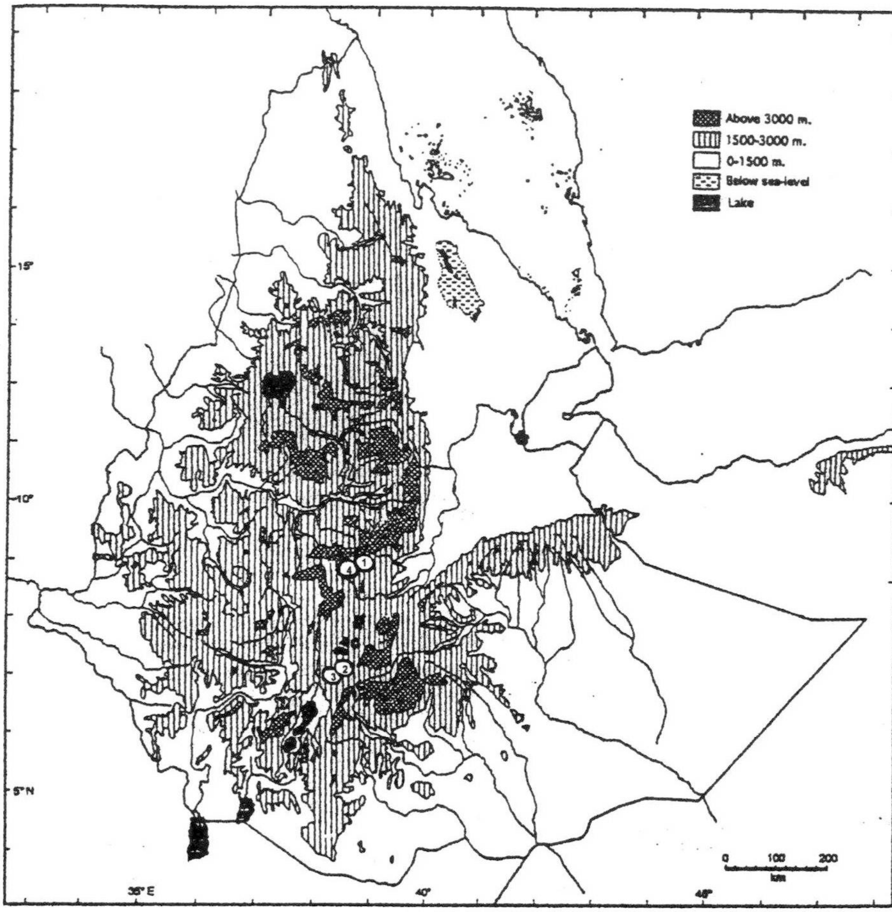

Fig. 1. *Topographic map of Ethiopia and Eritrea showing the location of the study sites: 1) Addis Abeba; 2) Shashemene; 3) Wendo-Genet; 4) Menagesha forest.*

Geology, soils and climate

Detailed descriptions of the geology of Ethiopia is given by Mohr (1961) and Merla et al. (1979). The study area at Menagesha consists of typical features of undulating and rolling terrain with some outlying hills within the altitudes between the low-lying flat lands (2200 m) to the volcanic cone of Mount Wachacha (3385 m). The geology of Wachacha is dominated by various types of basaltic trachyte rocks. Age determinations from samples collected from Wachacha range from 2.5 to 4.6 my, and the Wachacha trachytes have yielded an average age 4.5±0.1 my. These time spans are corresponding to that of marginal lava fields and silicic centres related to transverse tectonic lines, which yielded radiometric ages not older than 6 my, and mostly younger than 3 my. A similar time span (4.5±0.16 my) was dated by Jestin-Visentin et al. (1974) from rhyolites of south and west of Addis Abeba. These data indicate that the formation of Wachacha is associated to the full development of the Rift structure with a powerful upward movement of the adjoining plateaus, which is about the last phase of volcanic activity in the Upper Pliocene period.

The study area at Wendo-Genet with an elevational gradient between the low-lying lake Cheleleka (1700 m) and the summit of the Abaro and Gina mountains (2580 and 2614 m, respectively), is situated at the main eastern escarpment of the Rift, where it forms a single huge and somewhat denuded wall with a total displacement of about 1000 m (Mohr, 1961). The bedrock consists mainly of volcanic rocks, e.g., basalts, ignimbrites of the rift floor and associated pumices (Anon, 1988; Merla et al., 1979). The ignimbrites of the rift floor have an estimated age ranging from 0.5 to 7.7 my (Merla et al., 1979).

The landscape of the area can be defined by upper, lower and base slope units. The upper slope is vertically faulted, on which the gradient becomes progressively steeper downwards. The lower is a colluvial foot slope, where colluvial deposition has occurred. The base slope is characteristically a flood plain that can be defined as an alluvial toe slope, and where fluvial sediments and swamps occur.

The two study areas show great variations in soil types in relation to the variation in the relief. At Menagesha, soils are shallow brown soils (Chromic Luvisols, FAO-Unesco, 1988) on steep slopes and deep red soil profiles (Rhodic Nitisols, FAO-Unesco, 1988) mainly in the depressions and on gentle sloping sites. The soil profiles consist of an about 3-cm thick litter layer, an about 15-cm mollic A horizon and an underlaying argic B horizon. In the Luvisols, the argic B horizon is overlaying a C horizon of gray cemented volcanic ashes. The soil texture varies from silt clay loams in the surface soils to clay or silt clay loams in the B horizon. In the Wendo-Genet area, many soils are characterised by layers of homogenous materials with various textural sizes (gravel, course sand, silt, clay) and shapes (smooth, round and angular). These types of soils are commonly found at the colluvial foot and alluvial toe slopes and are classified as Eutric Fluvisols (Anon., 1988).

The climate of the Menagesha and Wendo-Genet areas with average annual rainfalls of 1017 and 1244 mm, and mean annual temperatures of 14 and 19°C at Holeta and Wendo/Gabicha-Genet, the nearest long-term weather stations to Menagesha and Wendo-Genet, respectively, is characterised by two rain seasons. The short rainy season from February to April is followed by a short dry season in May and then by a long rainy season from July to September that terminates abruptly before the following long dry season from October to February.

Vegetation and land use history

The two study areas have different site histories. According to historical accounts (von Breitenbach and Koukol, 1962; Sebsebe, 1982, 1988), the Menagesha forest in its virgin state was devastated in ancient times; and the present forest is said to have been established by planting *Juniperus* seeds from trees found in the Wof-Washa forest by the order of king Zera Yakob (1434-1468) and thereafter reserved as crown land. The planting successfully resulted in *Juniperus* stands, which have been protected by imperial edict since the 1600's (Gilbert, 1970), Later Menilik II (1888-1912) proclaimed its conservation and protection with special mention of *Juniperus*, *Podocarpus* and *Olea* (Gilbert, 1970), which suggest that the forest must have been at least partly affected by exploiters. However, exploitation re-commenced and a steam powered saw mill was established in 1900 by a German industrialist, and harvesting of the natural forest continued until the saw mill plant was abandoned in 1955 in order to protect the small remains of the natural forest. Since 1956, various tree species such as *Juniperus procera*, and *Eucalyptus*, *Cupressus*, *Pinus* spp. are planted at the lower and higher elevation sites (Anon, 1990; Sebsebe, 1988). Because of its proximity to surrounding settlement areas, the forests of the higher and lower elevation sites have been exploited and are under more intense disturbance compared with the adjacent forests at the mid-altitudes, where the overstory of the natural forests is dominated by old *Juniperus* trees. The understory vegetation at the mid-altitudes consists of shrubs and small tress with dense crowns of mainly *Syzygium guineense* and *Spiniluma oxyacantha* (Tamirat, 1994) at between 4 and 7 m above the ground.

In contrast to at Menagesha, the land use changes in the Wendo-Genet area are thought to be more recent. The study sites include forests (natural and planted forests), pastures and cultivated lands. Some of the characteristic tree species, which the natural forest consists of, are *Celtis africana*, *Albizia gumifera*, *Podocarpus gracilor*, *Milletia* sp. and *Phoenix* sp. Amongst the plantation tree species are *Eucalyptus* spp. *Pinus patula*, *Grevillea robusta* and *Juniperus procera*. The forests are commonly found on the upper slopes above c. 1900 m altitude, while the pastures are found at lower elevations at about 1700 m altitude and around the margins of wet lands and streams.

Sampling and analysis

Soil sampling and chemical analysis

The samples used in the three consecutive studies (**I, II, III**) were collected from the Menagesha forest and the Wendo-Genet areas. At Menagesha, circular plots of 400 m^2 each were located in the forest at 100 m altitude interval along two transect lines across a range of elevations from 2350 to 2850 m altitude (**I**). At Wendo-Genet, similar circular plots were located in pastures, forests and cultivated lands at various altitudes (**I**). At both sites, four sub-plots were randomly marked within each circular plot. In each sub-plot, five mineral soil samples were collected from each soil depth interval (i.e., 0-10, 20-40, 60-80, 120-140 cm at Menagesha and 0-20, 20-40, 40-60 cm at Wendo-Genet). The five samples were then mixed together in order to get a composite soil sample for the corresponding soil depth interval in the sub-plot. At Menagesha, also litter samples were collected from the surface at 5 (10 × 10 cm) quadrats per sub-plot and then mixed together to represent one composite litter sample per sub-plot. All the samples were used for studies of ^{13}C and ^{15}N natural abundances of forests and soils in the two study areas (**I, II**). Analyses of ^{13}C, ^{15}N, %N and %C were made simultaneously on an automatic, on-line N and C analyzer coupled to an isotope ratio mass spectrometer (Barrie and Lemley, 1989; Ohlsson and Wallmark, 1999).

In the third study (**III**), the variation in the chemistry of forest soils in relation to site history and altitude was studied only in the Menagesha forest. Determination of total and exchangeable nutrient elements, total and exchangeable acidity, CEC, pH etc., are described in detail in paper (**III**). Additionally, a batch equilibrium experiment was conducted on selected samples from litter layer and surface mineral soils to test for possible equilibria with carbonate or sulfates in soil solutions. The saturation indices was determined for $CaCO_3$, $MgCO_3$ and $CaSO_4$ according to Sposito (1989) and Stumm and Morgan (1996). Mineralogical composition of soils was determined on selected soil samples from four profiles by X-ray diffraction analysis according to Ondrua (1993) and Ondrua and Skála (1997).

Statistics

In the first study (**I**), a balanced ANOVA model was used to test for significant effects of land use on the ^{13}C natural abundance and organic C contents of soils in the two study areas. In this model, the significance of the variations in %C and $\delta^{13}C$ values with depth, altitude and land use were tested.

The values of soil chemical properties measured in particular during the studies **II** and **III** are largely determined by pedogenesis. By virtue of the effect of time on soil development, these properties are strongly related to those same properties in the depth intervals immediately above and immediately below that interval within any one depth increment in a soil profile. Thus, in order to determine the significance of the variations with soil depth, soil depth intervals were considered as repeated measures to replace the time passed between measurements in a conventional repeated measure (Zar, 1996). The significant effect of depth, altitude and land use on the properties measured were tested according to a GLM-Repeated Measures ANOVA model. In the model, altitude and transect at Menagesha and land use at Wendo-Genet were considered as the between-subjects factors, while soil depth intervals were treated as effects of the within-subject factors. Plot differences between subject factors (i.e., among altitudes at Menagesha and among land uses at Wendo-Genet) were tested by the interactions of the within subjects factors with the between-subjects factors (i.e., altitude × depth for Menagesha and land use × depth for Wendo-Genet). The four sub-plots within a circular plot were considered as pseudoreplicates and their average values were used to test effects of altitude and land use on the observed soil chemical properties.

Results and discussion

Land cover changes as revealed by stable C isotopes

The forest history of Ethiopia is far from being completely understood. This is partly because of the controversy over the precise size of the former forest cover as suggested in several reports (e.g., von Breitenbach, 1961; Ermias, 1986; Pohjonen and Pukkala, 1990; Rodgers, 1992). Also, earlier afforestation of non-forested areas has often been reported as oral traditions or legends (von Breitenbach and Koukol, 1962; Gilbert, 1970; Sebsebe, 1988) and legends are not always true. However, from documents of historical events that potentially caused deforestation (e.g., Horvarth, 1969; Tewolde, 1989) and palaeobotanical studies (e.g., Bonnefille, 1983; Bonnefille and Buchet, 1986; Hamilton, 1982), we know that there have been long-term vegetation shifts in the highlands of Ethiopia due to climate changes and anthropogenic causes.

In the study (**I**), the natural abundance of ^{13}C in soils of forests, pastures, and cultivated lands was studied at Menagesha and Wendo-Genet areas to infer historical patterns of land use changes in the highlands of Ethiopia. At Menagesha, it was found that the average $\delta^{13}C$ values in the > 20, 0-10 cm mineral soils and litter layer were -19.9, -24 and -26‰, respectively (Fig. 2a). The values in the litter and 0-10 cm soil layers were closely related to the isotopic composition of typical C_3 plants (Deines, 1980; Smith and Epstein, 1971) and agreed with the existing forest cover. Generally, the $\delta^{13}C$ profile indicated significant isotopic shifts from lower $\delta^{13}C$ values at the surface layer towards higher $\delta^{13}C$ values in the deeper soil horizons, suggesting that C_4 plants were important in the past. However, differences in $\delta^{13}C$ values between soil organic matter and vegetation could occur even with the absence of a C_3-C_4 vegetation shift because increases of 1-3‰ in $\delta^{13}C$ of soil organic matter due to fractionation against ^{13}C during decomposition (Balesdent and Maritti, 1996; Boutton, 1996; Nadelhoffer and Fry, 1988). Furthermore, decreases of ~1.3‰ in $\delta^{13}C$ of atmospheric CO_2 owing to input of ^{13}C depleted C to the atmosphere particularly after the 1850s from burning of fossil fuels (Friedli et al., 1986) could be superimposed on the major patterns of $\delta^{13}C$ values in a soil profile. These, however, can not explain the larger differences in $\delta^{13}C$ values (> 6‰) between the deeper soil horizons and surface layers observed at Menagesha. Also, the effect of potentially high $\delta^{13}C$ values of pedogenic carbonate C on the ^{13}C signature in soil organic C (Cerling et al., 1989; Cerling and Quade, 1993) was not significant (**I**). Thus, the observed differences in $\delta^{13}C$ values between the surface and deeper soil horizons indicated a land use change from C_4 grass- or cropland to C_3 forest which support the legends about the Menagesha forest (e.g., von Breitenbach and Koukol, 1962; Gilbert, 1970; Sebsebe, 1988). Accordingly, the $\delta^{13}C$ values in the deeper soil layers correspond to 54% of soil organic C derived from C_3 vegetation, while in the surface mineral soils the relative abundance of C_3 C amounted to 82%. Along elevational gradient, the lower $\delta^{13}C$ values at the mid-altitudes compared with the values at the lower- and higher-altitudes (Fig. 3a) were consistent with the presence of the old forest stands as well as the long-term protection of the forests at the mid-altitudes. The sites with the lower $\delta^{13}C$ values showed always a higher content of organic C, which suggest that productive forests with high biomass production could be established after several years of cultivation or grazing.

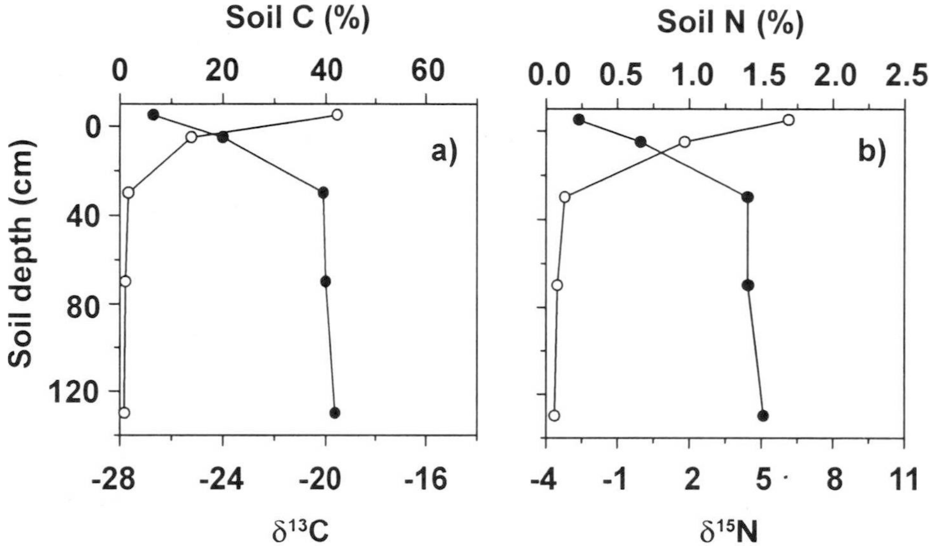

Fig. 2. *The vertical distribution of a)* ^{13}C *and %C and b)* ^{15}N *and %N in the Menagesha forest.*

In contrast, the sites in Wendo-Genet areas with soil $\delta^{13}C$ values ranged between -16‰ in the deeper soil horizon and -23‰ in the surface mineral soil suggest more recent shifts from C_4 grassland to C_3 forest land (**I**).

Overall, the results described in study **I** are consistent with palaeobotanical studies and historical documents reporting on the vegetation history of Ethiopian highlands. In the following, it will be discussed how these earlier long-term changes in the land use pattern have changed the chemical properties of forest soils in a wider perspective, based on ^{15}N natural abundances in soils of forests, pastures, and cultivated lands (**II**) and based on measurements of soil nutrient elements along the elevational gradient in the Menagesha forest (**III**).

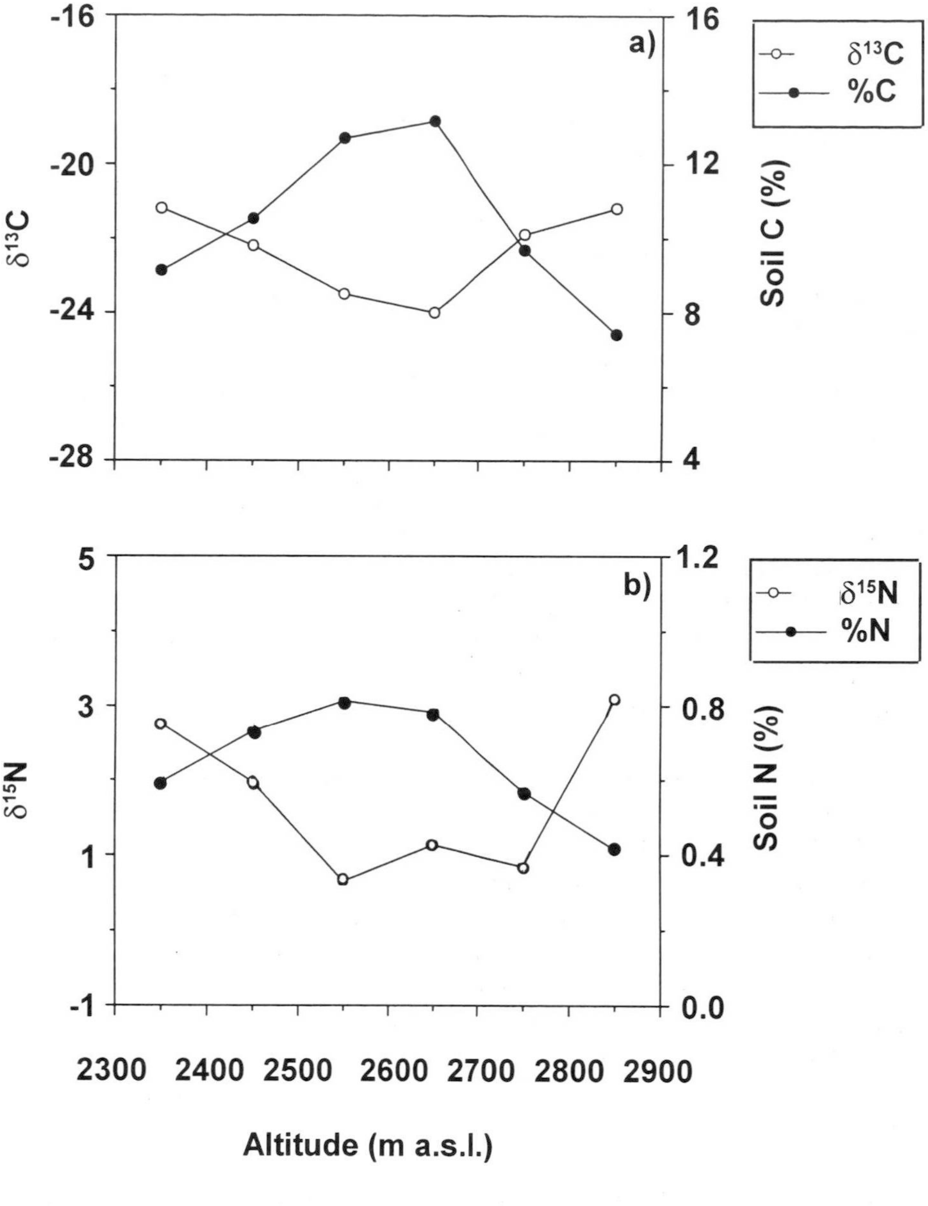

Fig. 3. *Altitudinal profiles of a) ^{13}C and %C and b) ^{15}N and %N in the Menagesha forest.*

Closed N cycle forest ecosystem resulting from long-term plantation forest cover

It has been suggested that N-limited closed temperate forests, which are not subjected to significant N inputs, have closed N cycles and low $\delta^{15}N$ values particularly at the surface layer (e.g., Högberg et al., 1996; Högberg, 1997; Johannisson, 1996; Nadelhoffer and Fry, 1988, 1994). In contrast, in tropical forests, where N is not limiting, $\delta^{15}N$ values are higher and vary less within the soil profile (Martinelli et al., 1999). The main reason given for the low $\delta^{15}N$ values at the surface layer in the temperate forests is that plants obtain N from sources, which are slightly depleted in ^{15}N compared to soil total N, and when this N is returned to the soil by litterfall, a soil profile with a surface layer with a low $\delta^{15}N$ develops, but with $\delta^{15}N$ values that increase with soil depth (e.g., Högberg et al., 1996; Nadelhoffer and Fry, 1994; Högberg, 1997). Several lines of evidence suggest that N is more available in tropical forest ecosystems as compared to in temperate forests, and that N even may function as an excess nutrient in many tropical forest ecosystems (Martinelli et al., 1999). Hence, excess N can move from the system via solution losses and gas fluxes (Matson et al., 1999). Thus, it has been suggested that tropical forests become more enriched in ^{15}N than temperate forests, because pathways of N losses fractionate N isotopes, which cause the N remaining within the system to be enriched in ^{15}N (Högberg, 1997). Isotopic enrichment of the N remaining in the system will occur after, e.g., N removal by fire and clear-felling, NH_3 volatilization, NO_3 leaching and denitrification (e.g., Högberg, 1997).

Several studies have shown that changes in land use patterns have noticeable effect on the $\delta^{15}N$ values in soils, particularly at the surface layer (e.g., Karamanos et al., 1981; Mariotti et al., 1980; Piccolo et al., 1994). Agreements, however, have not been reached between the studies in the temperate and tropical forests as regards the patterns of $\delta^{15}N$ values following conversion of forests to pastures or agriculture, i.e., in the temperate zone, pastures or cultivated soils are more enriched in ^{15}N than forest soils (Karamanos et al., 1981; Mariotti et al., 1980), while in the tropics, the pastures are typically more depleted in ^{15}N than forests soils (Piccolo et al., 1994). The results in study (**I**) show that afforestation in the highlands of Ethiopia leads to soils with a low $\delta^{15}N$, which in turn suggests that a closed N cycle operates.

At Menagesha (**II**), patterns of variations in ^{15}N natural abundance within a soil profile and also with the elevational gradient were consistent with the patterns of ^{13}C natural abundance (Figs. 2-3). Within a soil profile, $\delta^{15}N$ values increased while concentration of total soil N decreased with depth and was consistent with the results from several studies in tropical (e.g., Piccolo et al., 1994, 1996) and temperate (e.g., Mariotti et al., 1980; Nadelhoffer and Fry, 1988; Shearer et al., 1978) forest ecosystems. Along the elevational transect, there was variation in the $\delta^{15}N$ values of the mineral soils, i.e., the mid-altitudes showed relatively lower soil ^{15}N signature compared with at the lower- and higher-altitudes. The difference in $\delta^{15}N$ values between the mid-altitude sites and the others was supported by their differences in site history, i.e., with much longer duration of undisturbed forest cover (> 500 yr) replacing the previous grass- or cropland at the mid-altitudes than at the higher- and lower-altitudes.

Thus, generally low $\delta^{15}N$ values at the mid-altitudes can be related to long-term cumulative inputs of ^{15}N depleted plant N into the soil by litter-fall and to less forest disturbance, hence, less N losses; while the higher $\delta^{15}N$ values at the lower- and higher-elevations can be linked to the more intense forest disturbance and possibly to previous forest harvesting. In the litter layer, however, there was no variation in $\delta^{15}N$ values with altitude, and the values in the forest litter were low (< -2‰) even at the higher- and lower-altitudes. Also, unpublished data on several tree species in the Menagesha forest showed that the leaves and litter layer all had negative $\delta^{15}N$ values. It should, however, be noted that the low $\delta^{15}N$ values at the surface layer do not necessarily imply that this site was N-limited. At the mid-altitudes, where relatively low $\delta^{15}N$ values were observed, concentrations of extractable inorganic N (NH_4 and NO_3) were also higher than at the lower- and higher-altitudes (**III**). There was also a strong correlation between inorganic and total N and total N and organic C (**III**), which suggest that the high total and available N may have been retained within the forest soils as a result of less forest disturbance, hence, under conditions of small N losses, which supports the observed $\delta^{15}N$ patterns.

At Wendo-Genet soil $\delta^{15}N$ values were in general high throughout the soil profiles. It was found that there were no major differences between forests, pastures and cultivated soils, which was supported by the site history, i.e., the land use changes from grassland to forest land are more recent (**I**). The soils were also much more enriched in ^{15}N (4-8‰) than the Menagesha forest soils. The $\delta^{15}N$ values were also higher compared with temperate forest soils (e.g., Mariotti et al., 1980; Nadelhoffer and Fry, 1988; Shearer et al., 1978), but were similar to other tropical forest soils (e.g., Piccolo et al., 1994, 1996). Generally, the high $\delta^{15}N$ values suggest that open N cycles occur at Wendo-Genet. Several factors could be suggested to be responsible for elevated soil ^{15}N signal and substantial losses of N from soils at Wendo-Genet, e.g., frequent major disturbances like biomass removal by fire and tree felling and mixing of soil layers by ploughing (Högberg, 1997). The relatively low $\delta^{15}N$ values in soils under the young plantations of *Pinus* and *Eucalyptus* indicated that a closed N cycle may develop quite rapidly, however.

Overall, the results of the study in paper **II** suggest that the development of a closed forest ecosystem with a more closed N cycle at Menagesha is a cumulative effect of a longer duration of forest cover.

Changes in soil chemical properties resulting from long-term plantation forest cover

Earlier studies in temperate zones (e.g., Hüttl and Schaaf, 1995) and in the tropics (e.g., Asio et al., 1998) suggest that land use history may have a large influence on the availability of soil nutrients. For example, depletion of organic matter is of prime importance in the changes in the chemical properties of soils following conversion of forests to other land uses as discussed in detail in several studies (e.g., Lugo and Brown, 1993; Nye and Greenland, 1964; Sombroek et al., 1993). Asio et al. (1998) found that forest conversion to other land uses such as pastures, grass- and bushlands decreased the organic matter, total and available N, available K, but increased pH, available Ca and Mg. Other studies (e.g., Nye and Greenland, 1964; Sombroek et al., 1993), however, argued that land use conversion results in organic matter depletion only during the first few years after conversion and that the effect could vary depending upon the geomorphology, geology and the type of land use and soil. However, data on how the earlier land use history has affected the soil chemical properties and site productivity is scarce, especially in Ethiopia.

At Menagesha, the soils along the elevational transect developed on the same parent material (Merla et al., 1979; Mohr, 1961) and the soil profiles showed only small variations in the mineralogical composition (**III**). In the study **III**, it was found that most soil nutrient elements measured in the deeper soil horizons (> 20 cm soil depth) showed no significant variation with altitude. This may suggest that topo-graphic related site differences had no significant effect on the observed soil chemical properties at Menagesha. It may also indicate that these soils may have retained the chemical properties from the previous land use, i.e., from the time when the sites were under grass vegetation cover or cultivation (as described in paper **I**). Significant variation with altitude in the concentrations of most nutrient elements was found in the litter layer and surface mineral soils. However, at the mid-altitudes, where relatively low ^{13}C and ^{15}N natural abundances and high contents of organic C and total N were explained by a long duration of undisturbed forest cover, concentrations of total and available base cations and total S were higher in the litter- and 0-10 cm soil layers relative to at the sites at the lower- and higher-altitudes (**III**). Generally in the mineral soils, a significant relationship was found between total cation exchange capacity (CEC_t) and organic C content ($r^2 = 0.93$, $P < 0.001$, Fig. 4a), which suggests that organic matter content increases the retention capacity of these soils for easily available nutrient cations. Similar results have been reported in several studies (e.g., Kalisz and Stone, 1980; Kamprath and Welch, 1962; Poudel and West, 1999). Moreover, exchangeable and total Ca were strongly related ($r^2 = 0.95$, $P < 0.001$, Fig. 4b). From the batch experiment conducted during the study **III**, it was found that the litter and surface mineral soils were saturated with calcite. This easily soluble Ca pool can be expected to be in close equilibrium with soil solution and the cation exchange complex and, hence, can explain the strong relationship between total and exchangeable Ca.

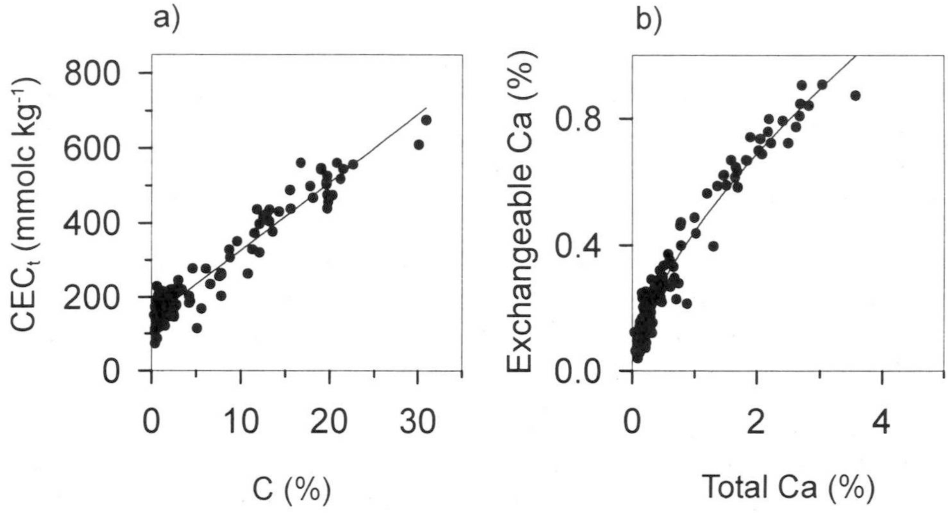

Fig. 4. *The relationship between a) CEC$_t$ and organic C and b) between exchangeable Ca and total Ca in the 0-140 cm mineral soils in the Menagesha forest.*

The elevated concentrations of nutrient elements, particularly Ca and S, in the surface soils of the mid-altitudes have been of special interest in the study **III**, especially as regards to their relation to site history or other site factors. Earlier studies (Sebsebe, 1980) suggest that the ability of trees for nutrient uptake at depth and redistribution onto the soil surface by litter-fall may contribute to nutrient accu-mulation in the topsoils. This, however, can not be the case for the elevated con-centrations of total Ca and S in the surface layers of the mid-altitudes, as this was not supported by the estimates of the pool size of total nutrient elements down to the depth of 100 cm (**III**).

As discussed in paper **III**, the likely explanation for the high Ca concentration in these highly weathered soils, particularly at the surface layers of the mid-altitudes, was that the Ca source is exogenous. The causes for the possible occurrence of exogenous Ca source is that the forests at this higher altitudes can be a sink for wind blown dust and cloud water intercepted cations (Lovett, 1994). These inputs of elements from atmosphere could be supplied by dusts from the large desert areas surrounding the Ethiopian highlands. From studies in the Hawaiian rain forest, it has been shown that inputs from the atmosphere are important sources of base cations in plant-soil system and can sustain the productivity of forests on highly weathered soils (Chadwick et al., 1999; Dahms, 1993; Kennedy et al., 1998; Vitousek et al., 1999). The results in paper **III** suggest that atmospheric inputs are important sources of a nutrient element such as Ca in the Menagesha forest.

Conclusions

The results of soil organic carbon isotopic studies for reconstruction of forest site history in the highlands of Ethiopia is consistent with the accounts of Ethiopian forest history and palaeobotanical records. They clarify our understanding about the historical patterns of land use changes and their influences on changing the forest ecosystems in the Ethiopian highlands. Briefly it could be stated that:

- The Menagesha forest, particularly the sites at the mid-altitudes, have a high soil organic carbon indicating high forest biomass production. This suggest that a forest ecosystem with sustainable forest production can be reestablished on highly degraded mountain slopes after centuries of intensive cultivation or grazing.

- The positive correlation between the natural abundances of ^{13}C and ^{15}N, as found at Menagesha, and the more variable nature of $\delta^{15}N$ profiles at Wendo-Genet, are supported by the respective site histories. The results indicated that a closed N cycle forest ecosystem with relatively high concentrations of total and extractable inorganic N has been established for a long time at Menagesha following the conversion of grass- or cropland to forests.

- The variations in soil chemical properties, i.e., contents of nutrient elements with depth in a soil profile and along an altitudinal gradient are closely related to differences in site history. The availability and supply of nutrient elements increased progressively from the deeper soil horizons towards the surface layers and from the higher- and lower-altitudes towards the mid-altitudes at Menagesha as a result of a long duration of plantation forest cover after con-version of grass- or cropland to forest land. The results suggest that forest land use improves the status of nutrient supply and availability by increasing soil organic matter, total and exchangeable nutrient pools and nutrient retention capacity of soils. The forests at Menagesha can also be a sink for deposition of base cations in dust from the atmosphere, which could contribute to the supply of nutrient elements in more available forms for plants. This mechanism can increase the forest productivity, particularly in areas, where the inherent nutrient pool is depleted after several thousand years of cultivation and grazing.

The three consecutive studies (**I**, **II**, **III**) show that the approach to combine simultaneous analysis of stable isotopes, ^{13}C and ^{15}N, with measurements of nutrient elements is especially useful when studying the chemical properties of soils in relation to the effects of site history or other site differences, as the variations in the natural abundances of the stable isotopes reflect ecosystem changes attributable to consequences of climate changes and anthropogenic causes.

From the results of these studies it could be suggested that planting of trees should not be seen only as an action to counteract soil erosion or to supply wood to the people, but also as a means to restore plant nutrient elements that have been lost from soils for several thousand years by increasing the possible sources of nutrient inputs to soils.

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