Effects of land-use changes on the properties of a Nitisol and hydrological and biogeochemical processes in different forest ecosystems at Munesa, south-eastern Ethiopia

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Vorgelegt von

Yeshanew Ashagrie

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List of abbreviations

BD	Bulk density
C/N	Carbon to nitrogen ratio
C/S	Carbon to sulphur ratio
CSA	Central Statistical Authority
D	Depth
dbh	Diameter at breast height
EFAP	Ethiopian Forestry Action Program
FAO	Food and Agriculture Organisation
ICP-AES	Inductively Coupled Plasma- Atomic Emission Spectrometry
iPOM	Intra particulate organic matter
LF	Light fraction
MEDaC	Ministry of Economic Development and Cooperation
MoFED	Ministry of Finance and Economic Development
MWD	Mean weight diameter
N/S	Nitrogen to sulphur ratio
NMSA	National Metrological Service Agency
OM	Organic matter
POM	Particulate organic matter
SOC	Soil organic carbon
SOM	Soil organic matter
TF	Throughfall
VWMC	Volume weighted mean concentration
WSA	Water stable aggregates

Organisation of the Thesis

This thesis is based on the following six papers (A–F) which are referred to in the text by their respective capital letters:

A. Yeshanew Ashagrie, Wolfgang Zech and Georg Guggenberger. 2005. Transformation of a *Podocarpus falcatus* dominated natural forest into a monoculture *Eucalyptus* globulus plantation at Munesa, Ethiopia: Soil organic C, N and S dynamics in primary particle and aggregate-size fractions. *Agriculture, Ecosystems & Environment 106, 89-98.*

B. Yeshanew Ashagrie, Wolfgang Zech, Georg Guggenberger and Tekalign Mamo. 2004. Soil aggregation and total and particulate organic matter as affected by conversion of native forests to 26 years continuous cultivation in Ethiopia.

C. Yeshanew Ashagrie, Wolfgang Zech, Georg Guggenberger and Demel Teketay. 2003. Changes in soil organic carbon, nitrogen and sulphur stocks due to the conversion of natural forest into tree plantations (*Pinus patula* and *Eucalyptus globulus*) in the highlands of Ethiopia. *World Resource Review 15, 462-482.*

D. Yeshanew Ashagrie and Wolfgang Zech.Water and nutrient inputs by rainfall into natural and managed forest ecosystems in south-eastern highlands of Ethiopia.

E. Yeshanew Ashagrie and Wolfgang Zech. Dynamics of dissolved nutrients in forest floor leachates: Comparison of a natural forest ecosystem with tree species plantations in south-east Ethiopia.

F. Yeshanew Ashagrie. Geochemistry of inorganic nutrients in water percolating through the mineral soils under two exotic tree species plantations and an adjacent natural forest in south-east Ethiopia.

Contributions of co-authors

This work is part of a DFG funded multidisciplinary research project comprising the following disciplines: Biogeography, Ecophysiology and Soil science. Prof. Zech and Prof. Guggenberger prepared the project proposal for the soil science part and designed the experimental work in the field. Prof. Zech gave me the topic of my thesis; we thoroughly discussed the schedule and the scope of the field and laboratory work and he supervised my work both in the field and laboratory. Interpretation of analytical results was discussed with Prof. Zech and Prof. Guggenberger, finally both read and improved the manuscripts.

Dr. Demel Teketay and Dr. Tekalign Mamo were our Ethiopian counter parts. They contributed in preparing the project proposal, supported me logistically during the field work, and read and improved the manuscripts.

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SUMMARY

The effects of conversion of natural forest into different exotic tree species plantations and crop cultivation were investigated at Munesa, south-eastern Ethiopia with the objectives of (i) determining changes on soil physical and chemical properties, (ii) quantifying water and nutrient fluxes under the different forest ecosystems, and (iii) assessing nutrient dynamics in water flowing through the soil under the different forest ecosystems. Soil samples were taken from the organic layer and at 0−20, 20−40, 40−70, 70−100 cm depths from the mineral soil. Rainfall and throughfall were collected using plastic funnels mounted 1 m above the ground. Soil solutions were collected with zero-tension (organic layer) and tension (mineral soil at the depth of 20, 50 and 100 cm) lysimeters. After 26 years of cultivation, surface (20 cm depth) soil structure was deteriorated and total soil organic carbon (SOC) and N contents both in bulk soil and water stable aggregates were significantly reduced. Below 21 years old *Eucalyptus* plantation no significant changes on the above mentioned parameters could be identified, but significant reductions in SOC, N and S concentrations associated with the sand and silt separates were evident. There were also significant reductions both in quality and quantity of particulate organic matter (POM) due to cultivation and only in quality of POM due to 21 years *Eucalyptus* plantation. The organic layer mass under 21 years old *Pinus patula*, 21 years old *Eucalyptus globulus* and third rotation *Eucalyptus globulus* (established 42 yr ago) decreased by 43%, 57% and 15%, respectively, relative to the natural forest. There were also significant reductions in the organic layer C and N stocks (9 to 60% and 25 to 68%, respectively), being highest under *Pinus* and lowest under third rotation *Eucalyptus*. In the mineral soil, to 1 m depth, there was a significant ($P<0.05$) reduction (16 to 20%) in SOC stock after conversion of natural forest into forest plantations. The N stocks under the 21 years old *Pinus* and third rotation *Eucalyptus* plantations were significantly reduced amounting 27 and 20% respectively, whereas 21 years old *Eucalyptus* had nearly an equivalent amount of N as that of the natural forest, probably due to a dense forest floor

vegetation, fixing N. The changes in the organic layer and mineral soil S stocks after plantation establishment were not significant.

Of the total annual rainfall (1190 mm) recorded during the monitoring period (October 2001 to September 2002), about 47% and 18% were intercepted by the canopies of *Cupressus* and the natural forest, and *Eucalyptus*, respectively. Total annual nutrients (Ca, Cl, K, Mg, Na, NH_4–N, NO_3–N, PO_4–P, SO_4–S) deposition by rainfall was 12 kg $ha^{-1}yr^{-1}$. Throughfall K, Mg, Ca and Cl fluxes were enriched relative to rainfall, whereas Na, NO_3–N, NH_4–N, PO_4–P and SO_4–S were depleted. Total annual throughfall nutrient inputs (Ca, Cl, K, Mg, Na, NH_4–N, NO_3–N, PO_4–P, SO_4–S) were 14 kg $ha^{-1}yr^{-1}$ under *Cupressus*, 21 kg $ha^{-1}yr^{-1}$ under the natural forest and 24 kg $ha^{-1}yr^{-1}$ under *Eucalyptus*. Water passing through the different forest floors differed only in K, Mg and NO_3–N concentrations, the latter two being higher under the natural forest and *Eucalyptus* plantation than *Cupressus*. Potassium was greater under *Eucalyptus* than the natural forest and *Cupressus*. Except for NH_4–N in the natural forest, forest floor leachate nutrient concentrations were enriched in all forest types in relation to throughfall. Most nutrient fluxes to the mineral soil decreased in relation to throughfall fluxes, whereas NO_3–N fluxes increased by over 50% in all forest types. At all soil depths, the concentrations of most nutrients in the mineral soil solution decreased relative to the concentrations in the forest floor leachate, but Mg, Na and NO_3–N at all depths in *Cupressus* plantation and SO_4–S and Na at some soil depths in the natural forest and *Eucalyptus* plantation had increased. The vertical trends in soil solution nutrient concentrations showed a decreasing trend with depth increments for most of the nutrients, but the concentrations of Cl and Na in all forest types and Ca, Mg and NO_3–N in *Cupressus* increased with increasing soil depth. At 1 m soil depth, the concentrations of Ca, Mg and NO_3–N in *Cupressus,* respectively, were 8, 7 and 23 times higher than in the natural forest and 3, 4 and 81 times higher than in *Eucalyptus* indicating losses by leaching. Generally, the results of this study emphasize the importance of forest type, species composition and management in affecting carbon and nutrient storage, water and nutrient fluxes and dynamics.

ZUSAMMENFASSUNG

Im Munesa-Wald, Südostäthiopien, wurden die Auswirkungen der Umwandlung von Naturwald in Pflanzungen mit unterschiedlichen ausländischen Baumarten bzw. in Ackerland untersucht. Die Zielsetzung war, (i) die Änderungen in bodenphysikalischen und -chemischen Eigenschaften zu ermitteln, (ii) die Wasser- und Nährstoffflüsse in den unterschiedlichen Waldökosystemen zu quantifizieren und (iii) die Nährstoffdynamik im Bodenwasser der unterschiedlichen Waldökosysteme zu beurteilen. Bodenproben wurden von der organischen Auflage und vom Mineralboden in 0–20, 20–40, 40–70 und 70–100 cm Tiefe genommen. Freiland- und Bestandesniederschlag wurden mit Kunststofftrichtern gesammelt, die 1 m über dem Boden angebracht waren. Bodenlösungen wurden mit freidränenden (organische Auflage) bzw. Unterdruck-Lysimetern (Mineralboden in 20, 50 und 100 cm Tiefe) gewonnen. In 26 Jahren Ackerbau verschlechterte sich die Struktur des Oberbodens (0–20 cm) und die Gehalte an organischem Kohlenstoff (SOC) und Stickstoff in Gesamtboden und wasserstabilen Aggregaten nahmen beträchtlich ab. Unter einer 21-jährigen *Eucalyptus*-Pflanzung konnten keine signifikanten Änderungen dieser Parameter festgestellt werden, aber signifikante Abnahmen von organischem Kohlenstoff, Stickstoff und Schwefel traten in der Sand- und Schlufffraktion auf. Auch zeigten sich signifikante Minderungen in Qualität und Quantität der partikulären organischen Substanz (POM) infolge von Ackerbau bzw. nur in der Qualität der POM in der 21-jährigen *Eucalyptus*-Pflanzung. Die Masse der organischen Auflage unter einer 21-jährigen *Pinus patula*-Pflanzung, einer 21-jährigen *Eucalyptus globulus*-Pflanzung und unter *Eucalyptus globulus* in der dritten Rotation (angelegt vor 42 Jahren) nahm gegenüber dem Naturwald um 43%, 57% bzw. 15% ab. Auch die Vorräte an organischem Kohlenstoff und Stickstoff in der Auflage zeigten signifikante Abnahmen (9–60% bzw. 25–68%), am meisten unter *Pinus* und am wenigsten unter *Eucalyptus* in der dritten Rotation. Im Mineralboden bis 1 m Tiefe gab es eine signifikante Abnahme von 16–20%

($P<0,05$) im SOC-Vorrat nach der Umwandlung des Naturwalds in Pflanzungen. Die N-Vorräte unter der 21-jährigen *Pinus*-Pflanzung und der *Eucalyptus*-Pflanzung in der dritten Rotation waren signifikant um 27 bzw. 20% reduziert, während die 21-jährige *Eucalyptus*-Pflanzung nahezu den gleichen N-Vorrat aufwies wie der Naturwald, wahrscheinlich aufgrund des dichten, N-fixierenden Unterwuchses. Die Veränderungen der Schwefel-Vorräte in organischer Auflage und Mineralboden nach dem Anlegen der Pflanzungen waren nicht signifikant.

Vom gesamten Jahresniederschlag während der Messperiode (1190 mm von Oktober 2001 bis September 2002) wurden etwa 47% durch das Kronendach von *Cupressus* und Naturwald bzw. 18% von *Eucalyptus* zurückgehalten. Die gesamte jährliche Deposition von Nährstoffen (Ca, Cl, K, Mg, Na, NH_4–N, NO_3–N, PO_4–P, SO_4–S) im Niederschlag betrug 12 kg ha^{-1} $Jahr^{-1}$. Die Flüsse von K, Mg, Ca, und Cl im Bestandesniederschlag waren höher als im Freilandniederschlag, die von Na, NO_3–N, NH_4–N, PO_4–P und SO_4–S dagegen niedriger. Die gesamten jährlichen Nährstoff-Einträge (Ca, Cl, K, Mg, Na, NH_4–N, NO_3–N, PO_4–P, SO_4–S) mit dem Bestandesniederschlag betrugen 14 kg ha^{-1} $Jahr^{-1}$ unter *Cupressus*, 21 kg ha^{-1} $Jahr^{-1}$ unter dem Naturwald und 24 kg ha^{-1} $Jahr^{-1}$ unter *Eucalyptus*. Das Sickerwasser aus den verschiedenen Auflagen unterschied sich nur in den Konzentrationen von K, Mg und NO_3–N, wobei die beiden letzteren unter Naturwald und *Eucalyptus* höher waren als unter *Cupressus*. Kalium war unter *Eucalyptus* höher als unter Naturwald und *Cupressus*. Die Nährstoff-Konzentrationen im Auflagen-Sickerwasser waren im Vergleich zum Bestandesniederschlag in allen Waldtypen erhöht mit Ausnahme von NH_4–N im Naturwald. Die Flüsse in den Mineralboden waren für die meisten Nährstoffen niedriger als die Flüsse mit dem Bestandesniederschlag, während die von NO_3–N in allen Waldtypen um über 50% höher waren. Die Konzentrationen der meisten Nährstoffen waren in den Mineralbodenlösungen aller Tiefen gegenüber dem Auflagen-Sickerwasser vermindert, die von Mg, Na und NO_3–N aber in allen Tiefen unter *Cupressus* und die von SO_4–S und Na in einigen Bodentiefen unter Naturwald und *Eucalyptus* erhöht. Der vertikale Verlauf der Nährstoffkonzentrationen in den Bodenlösungen zeigte eine Abnahme mit den Tiefenstufen für der meisten Nährstoffen. In allen Waldtypen nahmen aber die Konzentrationen von Cl und Na mit der Tiefe zu, in der *Cupressus*-Pflanzung auch die von Ca, Mg und NO_3–N. In 1 m Bodentiefe unter *Cupressus* waren die Konzentrationen von Ca, Mg und NO_3–N um den Faktor 8 bzw. 7 bzw. 23 höher als unter Naturwald und um den Faktor 3 bzw. 4 bzw. 81 höher als unter *Eucalyptus* und wiesen somit auf Auswaschungsverluste hin. Insgesamt unterstreichen die Ergebnisse dieser Studie die Bedeutung von Waldtyp, Artenzusammensetzung und Wirtschaftsweise für die Kohlenstoff- und Nährstoff-Speicherung, die Wasser- und Elementflüsse sowie die Nährstoff-Dynamik.

1. GENERAL INTRODUCTION

1.1 Socio-economic setup

Ethiopia is located between 3°N and 15°N, and 33°E and 48°E and covers an area of about 1130 000 km^2 (FAO, 2003). It has diverse topographic features with high mountains, deep gorges, flat-topped plateaus, and rolling plains. The altitude ranges from the highest peak at Ras Dejen (4620 m) down to the Dallol depression (110 m below sea level). The physical conditions and variations in altitude have resulted in a great diversity of climate, soil and vegetation (Asrat Abebe, 1992). Ethiopia's population is estimated at 67 million (MoFED, 2002) with an annual growth rate of 3 percent (MEDaC, 2001). The Ethiopian economy is highly dependent on agriculture, which accounts for 50 percent of the gross national product and contributes to more than 88 percent of exports and 85 percent of employment (CSA, 1999). The agricultural sector is dominated by the subsistent smallholder farmers, which contributes 95 percent of the agricultural production, and pastorals with a nomadic form of production. The country also has the largest livestock population in Africa (Mengiftu, 2002). About 88 percent of the human population and 70 percent of the total cattle population live in the highlands (above 1500 m) which make up 44% of the total land area (Hurni, 1988; Asrat Abebe, 1992, EFAP, 1993), making it the most densely populated agricultural areas in Africa (Anonymous, 2004). This has placed high pressure and a greater burden on the vulnerable land, forest and soil resources.

1.2. Rationale and research problem

In historic times, Ethiopia was believed to be extensively covered with dense forests. Over the last few hundred years, however, human actions have caused the country's forest cover to shrink significantly (von Breitenbach, 1962; EFAP, 1993). Documented evidences on the original extent of forest prior to human impact are scarce, but scientists estimate the losses by looking at remnant scattered trees as well as by using knowledge of the soil, elevation, and climatic conditions required by forests where forest could potentially exist if it were not for human actions. Comparing this "potential" forest area with the existing forest cover, Evans (1982) has estimated historical forest losses to be 36% since 1850. The major cause for the disappearance of forests is rapid population growth leading to extensive forest clearing for cultivation and grazing, exploitation of forests for fuel wood and construction material (EFAP, 1993, 1994). The destruction of forests has widespread implications for all mankind and has wider implications of global importance (Redhead and Hall, 1992), but is clearly of most immediate importance to rural populations living in and near the forest areas. The consequences are very severe; the cumulative results are shortage of wood and ecological imbalance, manifestations of which are noticed in recurrent droughts, reduced water resources, extinction of flora and fauna and heavy soil erosion. It is estimated that the country is loosing over 2 billion tons of fertile top soil every year, most of it from the highlands, as a result of soil erosion by water (FAO, 1986). This has resulted in a massive environmental degradation and serious threat to sustainable agriculture and forestry.

In the last few decades, large areas of forest plantations (*ca*. 200,000 ha), predominantly exotic species (*Eucalyptus* spp., *Cupressus lusitanica* and *Pinus* spp.) have been established to satisfy the growing wood demands of the population and to rehabilitate degraded lands (Pohjonen, 1989; EFAP, 1994; FAO, 2003). Also the fast growing nature of exotic species and favourable economic returns from tree plantations have encouraged the conversion of slow-growing and low-productive secondary natural forests into plantations. Recent estimates of the distribution of forest and woodland areas made by FAO (2001) indicated that about 4.2% of the land is covered by forests and the areas under planted forests are small (about 0.2%) compared with the size and needs of the population. The remaining natural forests are, therefore, under constant pressure from rising population in the wake of expansion of agricultural land and widening gap between demand and supply of forest products (EFAP, 1994). The current rate of deforestation is estimated to be 0.8% per year while the current expansion of planted forests is about 0.18% per year (FAO, 2001) which does not compensate for the loss of natural forests. There is no prospect of an early end to the pressures causing the clearing of the scarce forest resources to agricultural use, and cutting for fuelwood will continue. The challenge is not to prevent these activities but to manage them. The aim must be to ensure that wood and other forest products are harvested sustainably and that the subsequent land uses are productive and sustainable. Management of fast-growing and high-yielding short rotation plantations, with long-term stability of soil fertility and nutrient balance, to sustain high biomass production and quality of the environment is an important challenge.

The future of Ethiopia is linked with the judicious and efficient management of its natural resources and restoration of its environment. Although intensive management of exotic tree species may provide rapid growth and a higher economic return than would native tree species, little is known about the environmental impacts of this practice, such as on hydrology, soil quality and long-term productivity. The conversion of natural forest ecosystems into cultivation and monoculture plantations can change the nutrient cycling processes through changes in plant cover and species composition owing to differential patterns among plant species in litter production and turnover and nutrient accumulation (Gosz, 1981; Brown and Lugo, 1990; Lugo, 1992). Frequent harvesting of forest plantations result in long-term decline in soil organic carbon (SOC) and nutrient content due to disruption of the flow of carbon and nutrients through litter, removal of large amounts of nutrients from the soil through biomass and also losses by erosion and leaching (Zech and Drechsel, 1998). Human-induced land-use changes are known also to affect the spatial and temporal patterns of landscape water fluxes (Bosch and Hewlett, 1982) because forest stands of different tree species differ in their aboveground vegetation surface area, stand structure and morphology, and can have a differential impact on rain water interception and evapotranspiration losses, hence, on soil water regimes (Pritchett, 1979; Cape et al., 1991). For example Swank and Douglass (1974) in the United States found that streamflow was reduced by 20% by converting a deciduous hardwood stand to a *Pinus strobus* L. plantation.

Previous investigations on the effects of plantations on soil properties in Ethiopia have focused on changes to solid phase soil properties (Michelsen et al., 1993; Betre et al., 2000; Lemenih et al., 2004). These studies generally indicate that the changes in soil properties after plantation establishment are species specific. Moreover, to date, studies on the hydrology of forest ecosystems in Ethiopia have not been conducted. Nutrient cycling within ecosystems forms the major source of nutrients for plant use and nutrient inputs from the atmosphere are important to the long-term development of soils and ecosystems (Binkley, 1986). The input of nutrients from the atmosphere and the dynamics of nutrients in soil solution, which are an important aspect in studying nutrient cycling in forest ecosystems, are only beginning to be investigated in Ethiopia. In contrast to bulk soil properties, which are typically slow to respond to a change in land-use, soil solution chemistry is often a sensitive indicator of biogeochemical processes in forests responding quickly to various changes and may provide an early indication of the long-term changes in soils associated with land-use changes (Ranger et al., 2001; McDowell et al., 2004). Studies of solute concentrations and fluxes through forest ecosystems have been conducted mainly in North America (Likens et al., 1977) and Europe (Ulrich, 1983; Gundersen et al., 1998; De Vries et al., 2003) with greater risk of air pollution (Krupa, 2002). However, even in the absence of air pollution risks, such studies are also of critical importance because of the potential ecological significance of atmospheric depositions in forest ecosystems nutrient cycling and the need for such information to make reliable forest management decisions.

2. OBJECTIVES

The overall objective of the study was to determine the effect of land-use changes on soil properties and understand ecosystem specific hydrological and biogeochemical processes under the different forest ecosystems. The specific objectives were (i) to assess the effect of natural forest conversion on soil physical and chemical properties, (ii) to quantify water and element fluxes under the different forest ecosystems, and (iii) to assess nutrient dynamics in water flowing through the forest floor and mineral soil under the different forest ecosystems.

3. MATERIALS AND METHODS

3.1. Location and general description of the study area

The Munesa Shashemene forest (7°34´N and 38°53´E; 240 km south east of Addis Ababa) is located in the eastern escarpments of the central Ethiopian rift valley within the Bale/Arsi highlands massif (Fig. 1). The Munesa Shashemene forest consists of three branches, namely Degaga, Gambo and Sole. The forest cover at Degaga, where this study was conducted, comprises 8527 ha of disturbed natural forest and 2518 ha of forest plantations. The altitude ranges from 1500 m in the foothills to 3500 m at the peak. The climate is sub-humid with a long-term mean annual rainfall of 1250 mm and mean annual temperature of 19°C (Solomon et al., 2002). The distribution of rainfall is bimodal, most of it falling during the main rainy season (June to September) with peaks in July and August, and small rains from February to May. Generally, mean annual rainfall increases and mean annual temperature decreases with increasing altitude. Geologically, the area lies on tertiary volcanic deposits and the soils developed from these rocks are principally Nitisols (Anonymous, 2004). The topography and vegetation change rapidly with increasing altitude. Generally, vegetation varies from savannah and open woodland in the foothills at 1500 m to some disturbed forests and alpine vegetation closer to the peak (Müller-Hohenstein and Abate, 2004). The vegetation of the study area is described in detail by Abate (2004).

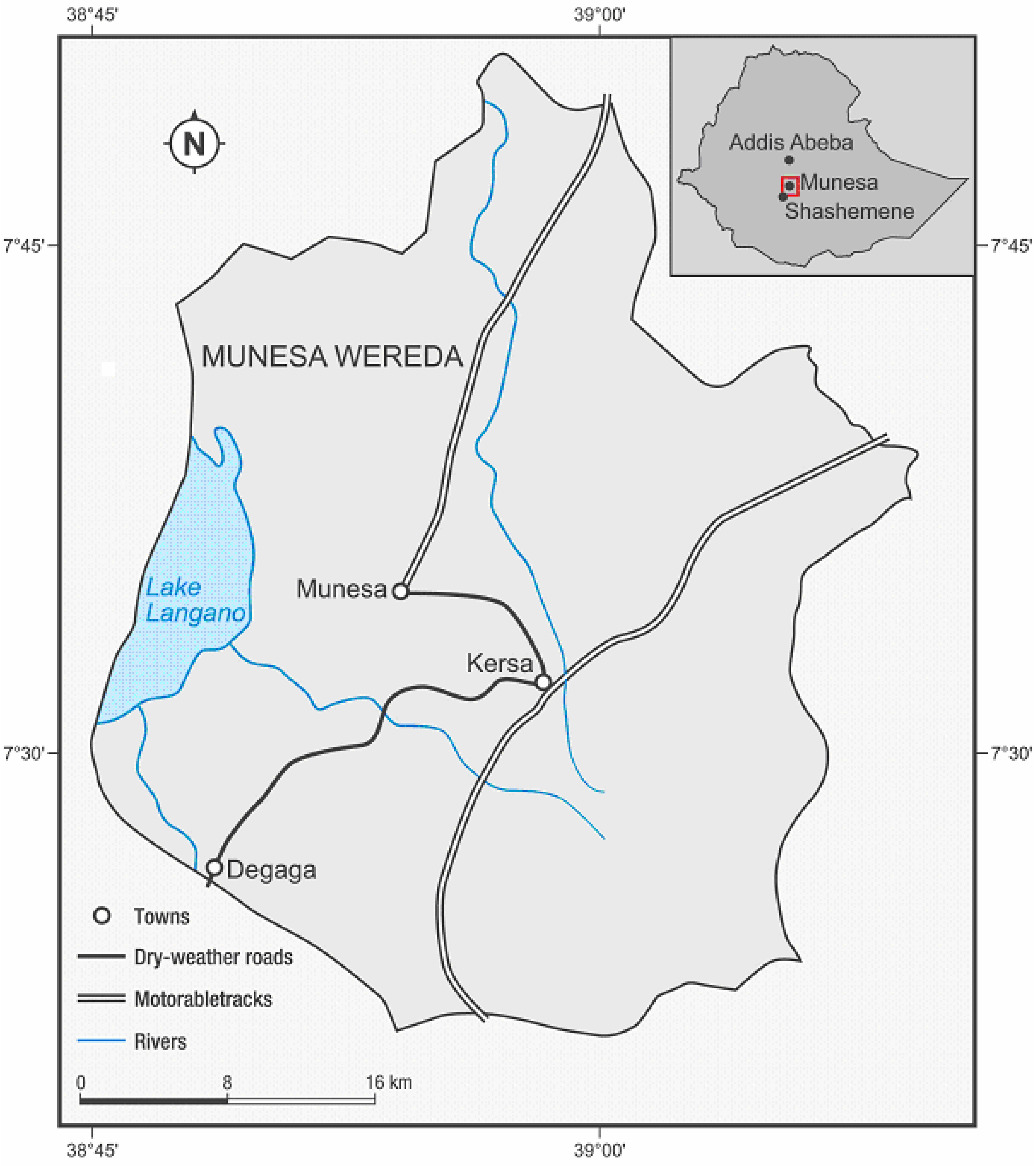

Figure 1. Map of the study area.

3.2. The studied forests and experimental design

Two monoculture exotic tree species plantations (*Cupressus lusitanica* and *Eucalyptus globulus*) and an adjacent natural forest were selected to undertake multidisciplinary (Ecophysiology, Geobotany and Soil Science) field investigations. The natural forest is dominated by old growth *Podocarpus falcatus* trees and other common medium sized canopy tree species include *Croton macrostachys*, *Olea hochstetterii* and *Scheffelera abyssinica*. The *Eucalyptus* plantation is sparsely stocked (595 trees ha^{-1}) relative to the *Cupressus* plantation (672 trees ha^{-1}) and has a native understorey canopy tree (*Croton* m*acrostachys*) and shrubs notably *Acanthopale pubescens*, *Achyrospermum schimperi*, *Bothriocline schimperi*, *Carex spicato-paniculata*, *Hypoestes forskaolli*. The forest floor in the natural forest and *Eucalyptus* plantation consists of dense grass and broad-leaved herbaceous species. The mean height of *Eucalyptus* is 30–40 m and the mean diameter at breast height (dbh) is 19–39 cm. The *Cupressus* plantation has almost no ground vegetation. The mean height of *Cupressus* is 18–20 m and dbh is 29 cm. In addition, two plantations (*Pinus patula*) and third rotation (*Eucalyptus globulus*) and an adjacent crop field were included to compare some soil related parameters with those in forests selected by the multidisciplinary research team. All of the plantations and the crop field were established after clearing of part of the existing natural forest at different time scales. The third rotation *Eucalyptus* was established in 1960 while all the other plantations were established in 1980. The crop field was established in 1975. The natural forest is approximately 3 to 4 thousand years old (Zech pers. communication). In each forest type and the crop field three 0.04–0.06 ha permanent plots were randomly located. In the two plantations (*Cupressus* and *Eucalyptus*), which were selected by the multidisciplinary research team, and the natural forest, about 20–25 m^2 of the area was fenced at the centre of each plot for the installation of field equipment. In addition a soil pit was excavated to the depth of 1.2 m within in each plot. Soil properties under the plantations and the crop field prior to their establishment were assumed to have been similar to those under the natural forest.

3.3. Equipment

An automatic weather datalogger was placed in a big opening between the natural forest and the plantations. To monitor water and nutrient dynamics, rain water collectors were placed at three locations (three collectors per location) close to the automatic weather data logger in the open area. Within the fenced areas of the permanent experimental plots of each forest, throughfall collectors (five per plot) were placed around the sample tree at a distance of 0.8 to 1 m from the trunk. Rainfall and throughfall were collected using plastic funnels of 12 cm diameter and 2 l capacity mounted 1 m above the ground. Table tennis balls were put inside each collector to prevent loss of water by evaporation. In addition, tension and zero-tension lysimeters and tensiometers (each of them three per plot) were installed. The zero-tension lysimeters made of plastic boxes (0.15 x 0.15 m) were placed horizontally in the contact zone between the forest floor and the mineral soil. The boxes were connected to a 2 l bottle placed in a soil pit. To avoid any solid material entering the boxes and bottles, a fine wire mesh (0.5 mm) was attached to the upper part of each plate. Tension lysimeters and tensiometers were installed at three depths (0.2, 0.5 and 1 m below soil surface). The three suction cups per depth and per plot were connected to one collecting bottle. Tensiometers were placed approximately 0.5 m away from the suction lysimeters. All equipments were installed in May 2001.

3.4. Sampling and sample preparation

Soil samples were taken at 0–20, 20–40, 40–70 and 70–100 cm depths from the three sides of the pit. In addition, two 1 m^2 plots were marked randomly within each plot and samples were taken by auger at three points within the 1 m^2 area and mixed for the above mentioned depth classes. Soil samples were put in individual polyethylene bags, air-dried and passed through a 2-mm sieve. Samples for the mineral soil bulk density determination were taken by 100 cm^3

Aluminium cylinder at seven points for each soil depth. Sampling of the organic layer (3 samples per plot) was done by pressing a 30 x 30 cm steel sheet sampling frame into the organic layer. The surrounding organic matter was removed leaving a block of the organic layer in which the litter (L) and fermentation (Of) horizons were identified and the thickness of the different horizons was measured with a ruler. The materials (excluding woody debris > 2 cm) from the different horizons were put in separate paper bags. The organic layer samples were dried in an oven at 65 °C and weighed. After drying, the three samples of each plot were mixed and the final number of samples was reduced to three.

Rainfall and throughfall water and litter leachates were sampled from October 2001 to September 2002. Mineral soil solutions were sampled only during the main rainy season (June to September). Samples retrieved during June to September 2001 were discarded to allow ions on the exchange surfaces of the ceramic to equilibrate with the soil solution. Samples collected during the main rainy season of 2002 were used for chemical analysis. Soil solution samples were taken by applying vacuum produced by vacuum pumps based on the tensiometer readings at each soil depth. Sampling was done on a weekly basis and during sample collection the volume of water was registered. After each collection, the collectors were washed with deionized water or with a portion of the sample water. On each sampling day, water samples were transported to the storage facility and kept frozen. All samples were transported in cool boxes to Germany for chemical analysis. Solution samples were filtered through 0.45 µm glass fibre filters (Schleicher & Schuell). After filtration, samples from the rainfall and throughfall collectors and zero-tension lysimeters in one plot were proportionally bulked per source per plot prior to chemical analysis, yielding one sample per sampling day. The dried samples of the organic layers and mineral soil horizons were finely ground with a rotary ball mill for chemical analysis.

3.5. Laboratory analysis

3.5.1. Soil particle and aggregate-size fractionation

Air-dried and sieved (2 mm mesh) 30 g samples were put in a centrifuge tube and dispersed ultrasonically at a soil: water ratio of 1:5 (w/v), with an energy input of 60 J ml^{-1}using a probe type sonicator (Branson Sonifier W–450). Coarse sand fraction (250–2000 µm) was separated by wet sieving, and the remaining material in the <250 µm fraction was further sonicated at a soil: water ratio of 1:10 (w/v), with an energy input of 440 J ml^{-1}. The clay-size separates (< 2 µm) were isolated from the silt (2–20 µm) and fine sand (20–250 µm) by repeated centrifugation, while the silt-size separates were isolated from the fine sand by wet sieving. After fractionation, the different particle-size fractions were dried at 50 ^{o}C.

The size distribution of aggregates was measured by wet sieving through a series of sieves (2, 1, 0.5, 0.25 and 0.053 mm) following the procedures of Cambardella and Elliott (1993). A 70–80 g sample of air-dried soil passed through a 5 mm sieve was spread on the top of a 2 mm sieve submerged in a bucket of deionized water. The water level was adjusted so that the aggregates on the sieve were just submerged. Soils were left immersed in the water for 10 min and then sieved by moving the sieves 3 cm vertically 50 times during a period of 2 min. During the sieving process, floatable materials >2 mm were removed and discarded. According to Six et al. (1998) materials > 2mm are not considered an integral part of SOM. The material remaining on the 2 mm sieve was transferred to a glass pan. Soil plus water that passed through the sieve were poured onto the next finer sieve and the processes were repeated, but floatable materials were not removed and discarded. The different aggregate sizes were dried in the oven at 50 °C overnight for chemical analysis.

3.5.2. Separation of particulate organic matter (POM)

The separation of POM followed the procedure of Six et al. (1998). Prior to POM separation, the fractions in the >0.25 mm size aggregates were bulked as macroaggregates and the 0.053–0.25 mm size as microaggregates. After the aggregates were dried (105 °C) in the oven overnight and cooled in a desiccator to room temperature, about 10 g of each aggregate fraction was taken in a conical centrifuge tube and suspended in 35 ml sodium polytungstate (adjusted to a density of 1.8 g cm^{-3}) by hand shaking. The suspension was allowed to stand for 20 min before centrifugation at 1250 rpm for 60 min. After centrifugation, the floating material was collected on filters and rinsed thoroughly with deionized water to remove sodium polytungstate, this material is referred to as free light fraction (LF). The heavy fraction remaining in the tube was washed twice with 50 ml deionized water and dispersed in 50 ml of 5% sodium hexametaphosphate by shaking in a reciprocal shaker for 18 hours. The dispersed heavy fraction was rinsed through a 0.053 mm sieve with deionized water. The material remaining on the sieve is intra-particulate organic matter (iPOM) + sand. Both the free LF and iPOM were dried in the oven at 50 °C overnight. The dried subsamples from each aggregate size class, particle size fraction, the free light fraction, and iPOM were finely ground in a rotary ball mill for chemical analysis.

3.5.3. Chemical analysis

Organic C, N and S concentrations in bulk soil, size fractions and POM were determined using a CHNS–analyzer (Vario EL, Elementar Analysensysteme GmbH, Hanau, Germany). The pH_{KCl} (soil:solution ratio 1:2.5) of the soil was determined with a standard pH electrode (Orion U402–S7). Bulk density was determined after drying a defined volume of soil in an oven at 105°C. Solutions were analysed for pH, total content of Ca^{2+}, K^{+}, Mg^{2+}, Na^{+} (plasma emission spectroscopy, ICP-AES, Integra XMP), and Cl^{-}, NO_3^{-}, NH_4^{+}, PO_4^{3-}, SO_4^{2-} (ion chromatography, Dionex 2000i-SP). Detection limits (mg l^{-1}) were: 0.025 for NH_4^{+}, 0.2 for

Ca^{2+}, Na^+ and Mg^{2+}, 0.25 for K^+, 0.27 for Cl^-, 0.34 for NO_3^-, 0.28 for PO_4^{3-} and 0.32 for SO_4^{2-}.

3.6. Calculations and data analysis

Element stocks (kg m^{-2}) were calculated as a product of bulk density, depth of sampling and element's concentration per unit of soil samples (Guo and Gifford, 2002).

$$C = BD \times C_c \times D/10 \qquad (1)$$

where BD is the soil bulk density (g cm^{-3}), Cc (%) the soil element concentration, and D is the soil sampling depth (cm).

The mean weight diameter (MWD) of water stable aggregates was determined as the sum of the percentage of soil on each sieve multiplied by the mean intersieve diameter of adjacent sieves (Haynes, 1999).

$$MWD = \sum \text{(percent of sample on sieve x mean intersieve size)} \qquad (2)$$

All calculations for a particular parameter in rainfall, throughfall and litter leachate of each season, i.e. dry season (October–January), small rainy season (February–May) and main rainy season (June–September) were based on mean values of three plots per forest type. Volume weighted concentrations (VWMC) and fluxes of elements in rainfall, throughfall and litter leachate for a given season were estimated from the paired measurements of element concentration and rainfall, throughfall and litter leachate volume in each plot (Tobon et al., 2004).

$$VWMC_i = \sum^{n}_{j=1} C_{ij} \, . \, TF_j / \sum^{n}_{j=1} TF_i \qquad (3)$$

where C_{ij} is the i-element concentration in throughfall on the j-collection day, TF is the total throughfall water volume and n is the total number of sampling dates. The same procedure was used for rainfall and litter lecheate element concentrations. Using rainfall, throughfall and litter leachate water volume, concentrations were converted into gram quantities of various nutrients for each season and summed to yield annual inputs. Canopy exchange (i.e. canopy leaching and canopy uptake) was calculated as the difference between throughfall flux of a particular element and its atmospheric deposition to the rain collectors.

Data for each parameter in rainfall, and throughfall and litter lecheate of the different treatments were assessed using MSTAT–C version 2.10 statistical package. Differences between and among treatment means were considered significant at $P \leq 0.05$. Correlation analysis was conducted between pairs of elements in rainfall, throughfall, litter leachate and soil solution, and rainfall, throughfall and litter leachate volume and element concentrations.

4. RESULTS AND DISCUSSION

4.1. Soil physical and chemical properties

4.1.1. Soil aggregation

Clearing of the natural forest and reforestation with *Eucalyptus* did not significantly affect the distribution of water-stable aggregates (WSA), but after 26 years of continuous crop cultivation, the amount of water-stable macroaggregates was significantly reduced from > 70% in the natural forest soil to 50% in the cultivated soil, indicating that cultivation resulted in the structural degradation of this soil (Table B1 & Table A4). In the two forest types, 87–90% of the total soil mass remained as water-stable aggregates with >74% as macroaggregates (> 0.25 mm), and 14–17% as microaggregates (0.05–0.25 mm). In contrast, in the cultivated soil, significantly large proportion of the soil was retained as microaggregates and small macroaggregates (0.25–0.5 mm). This could be attributed mainly to the breakdown of aggregates by tillage and differences between the two land use types in annual organic matter input which gives cementing agents. These results confirm earlier observations that macroaggregates are dynamic in nature and the size distribution of macroaggregates is affected by the change in land use and management (Dormaar, 1983;

Elliott, 1986; Beare et al., 1994; Puget et al., 1995; Spaccini et al., 2001). The effect of cultivation was much more evident in the larger macroaggregates (>1mm) than the smaller macroaggregate size classes (Table B1). The >2 mm and >1 mm classes of the natural forest soil were 13 and 4 times, respectively, larger than in the cultivated soil.

The relatively higher reduction in larger macroaggregates compared to the smaller aggregates upon cultivation could be mainly due to the fact that the former are largely dependent on live and decaying plant roots and fungal hyphae and probably casts of earthworms and termites which are rapidly destroyed by tillage (Tisdall and Oades, 1982). A greater shift in water-stable aggregates from large macroaggregates to smaller macroaggregates and microaggregates upon cultivation had also led to a significant reduction of MWD from 0.92 mm in the natural forest soil to 0.36 mm in the cultivated soil (Table B1). Spaccini et al. (2001) reported MWD reductions of 37 to 76% for cultivated Ethiopian Vertisols, Alfisols, Entisols, and Andisols relative to the forest soil, being highest in Vertisols and lowest in Andisols.

4.1.2. Total SOC, N and S concentrations in particle- and aggregate-size fractions

Conversion of the natural forest into a monoculture *Eucalyptus* plantation 21 years ago resulted in the depletion of mean SOC concentrations of sand and silt fractions, and N and S concentrations of the sand fraction (Table A2). The coarse sand fraction showed the highest losses of all three elements, suggesting that organic matter associated with the coarser fractions is more labile and the first to be affected by changes in land-use and soil management (Christensen, 1996; Solomon et al., 2002; Zinn et al., 2002). The loss of OC was larger than the losses of N and S. Mean C/N and C/S ratios of all the particle-size fractions and N/S ratio of the clay fraction were also significantly narrowed after conversion of the natural forest into *Eucalyptus* plantation (Table A3). In both forest types, the C/N and C/S ratios of the coarse and fine sand and silt fractions were higher than in the bulk soil, whereas those of clay were lower (Tables A1&A3). This might be due to the more aliphatic and humified nature of the clay-associated organic matter (OM) in comparison to the OM in the bulk soil and coarser fractions (Buyanovsky et al., 1994; Mahieu et al., 1999).

In the two forest types, C, N and S concentrations were not significantly different among the different aggregate size fractions (Fig. A1). In contrast, in the cultivated soil, the OC and N concentrations were significantly different among the different size classes, and appeared to decrease as size increases from 0.053 to 2 mm diameter (Table B3). This could be attributed partly to the redistribution and / or transfer of organic matter from the large aggregates to smaller ones either in the process of biodegradation or by mechanical disruption of the large macroaggregates (Dormaar, 1983; Christensen, 1992). Conversion of the natural forest into *Eucalyptus* plantation did not significantly affect the OC, N and S concentrations associated with each water-stable aggregate size class. However, although the differences generally are not statistically significant, the OC and N concentrations associated with each maroaggregate-size class in the natural forest were 2–3 times higher than the corresponding values in the cultivated soil (Table B3).

The average C/N ratios of the larger aggregates (> 0.5 mm) were significantly wider in the soil under natural forest than in the soil under *Eucalyptus*, whereas C/S and N/S ratios were not different between the two forest types (Fig. A2). In the cultivated soil, C/N ratios of the different aggregate-sizes were not significantly different from the natural forest soil aggregates, but the overall mean C/N ratio of the water-stable aggregates was significantly narrowed from 11 in the natural forest soil to 9 in the cultivated soil. The mean C/N, C/S and N/S ratios of the aggregates in both forest types and C/N ratio in the cultivated soil were nearly the same as those of the corresponding bulk soil (Table A1, Fig. A2 and Tables B2& B3).

4.1.3. Free LF and iPOM C, N and S concentrations associated with soil aggregates

Conversion of the natural forest into a monoculture *Eucalyptus* plantation significantly reduced the free LF C associated with both aggregate-sizes and N associated with macroaggregates (Table A5). The iPOM C, N and S associated with macroaggregates and S associated with microaggregates below *Eucalyptus* were also significantly reduced relative to the natural forest soil (Table A6). Cultivation of the natural forest soil for 26 years also significantly reduced the mean C and N concentrations in both the free LF and iPOM fractions (Table B5). The effect of cultivation was more pronounced on the iPOM C than on the free LF C concentration. Similarly, although the *Eucalyptus* plantation had nearly the same level of soil aggregation (Table A4) as in the natural forest, the losses in iPOM C and N concentrations were more pronounced than losses from the free LF. This could be due to (i) the input of organic material to the LF material from the previous crop and year-round input of litter from the plantation and (ii) gaseous losses of OM inside the aggregates caused by high fire temperatures during clearing and site preparation; otherwise biodegradation is normally nearly three times as fast outside aggregates as within them (Besnard et al., 1996) and in addition deterioration of aggregation in the cultivated soil was another reason. According to Jastrow (1996) and Six et al. (1998), the amount of total occluded POM C and nutrients per unit soil is mainly a function of aggregation, whereas the free light POM C i.e., LF C is mostly affected by residue input. Buschiazzo et al. (2001) linked the large decrease of OC after cultivation of a forest soil to the occurrence of natural fire before cultivation.

The effect of changes in land use was more drastic on macroaggregate-associated POM C, N and S than on POM associated with microaggrates (Tables A5&A6 and Table B5). This confirms the conclusions of several authors (Elliott, 1986; Gupta and Germida, 1988; Besnard et al., 1996) that organic matter associated with macroaggregates is more labile than organic matter associated with microaggregates. Jastrow (1996) found relatively higher proportions of

POM C inside the macroaggregates of a virgin prairie soil compared to corn field and restored prairie soil. Six et al. (1998) also reported higher iPOM levels in water-stable macroaggregates sampled from native sod soil than those from cultivated soil. Overall, the results showed that the effect of conversion of the natural forest into tree plantation and cultivation was more pronounced on the POM C and N than those observed in the whole soil and in water-stable aggregates, indicating that POM constitutes soil organic matter fraction more sensitive to the effects of land-use change and soil management.

4.1.4 Dry mass accumulation, and SOC, N and S storage

The effect of clearing and reforestation of the natural forest soil with different plantation species significantly influenced the accumulation of dry mass in the organic layer (Table C3). Organic layer mass was highest under the natural forest followed by third rotation *Eucalyptus* and lowest under *Pinus*. The reductions in average litter mass after clearing and replacement of the natural forest ranged from a low of 6.4 t ha^{-1} (–14%) under third rotation *Eucalyptus* to a maximum of 24.2 t ha^{-1} (–57%) under *Pinus* (Table C3). Such variations in the organic layer mass accumulation may be due to differences in rate of litter production, litter quality, age and species composition. The greatest mass under third rotation *Eucalyptus* compared to the other two plantations is due to the accumulation of litter after each harvest and differences in time since establishment. Zinn et al. (2002) reported an increase in litter mass after conversion of native *Cerrado* to *Pinus* and a decrease after conversion to *Eucalyptus* for sub humid site conditions in Central Brazil.

Clearing and replacement of the natural forest by tree plantations significantly affected the organic layer C concentration, being greater under third rotation *Eucalyptus* compared to the natural forest and 21 years *Eucalyptus*, but differences between *Pinus* and the other forest types were not significant. Total N and S concentrations were higher under 21 years *Eucalyptus* in comparison to the other two plantation species but were not different from the natural forest (Table C2). The C/N ratios under *Pinus* and third rotation *Eucalyptus* organic layers were significantly ($P<0.01$) higher than under the natural forest, but 21 years *Eucalyptus* had an equivalent C/N ratio as the natural forest probably due to the presence of N-fixing plants in the understorey vegetation. From the ecological point of view, litter with high nutrient contents or low C/N ratio play an important role in plantation forestry because rather than immobilising nutrients it releases them for rapid recycling (Lugo et al., 1990).

The mean C, N and S stocks of the organic layers under the different forest types ranged from 6.5–16.4 t ha^{-1}, 0.3–0.7 t ha^{-1} and 0.03–0.1 t ha^{-1}, respectively, (Table C3). Wilcke et al. (2002) reported 103, 5.53 and 0.77 t ha^{-1} C, N and S stocks, respectively, in the tropical montane rainforest of Ecuador. Higher litter mass accumulation in the natural forest and third rotation *Eucalyptus* resulted in a significantly ($P<0.01$) higher C and nutrient storage in comparison to the other two plantation treatments. C stock under the natural forest (16.4 t ha^{-1}) was found to be significantly reduced by 8.2 t ha^{-1} (–50%) and 9.9 t ha^{-1} (–60%) after conversion to 21 years *Eucalyptus* and *Pinus* plantations, respectively, while third rotation *Eucalyptus* had an equivalent amount of C (15 t ha^{-1}) as the natural forest probably due to the greater amount of litter accumulated after each harvest. Like that of C, the reductions in N and S stocks under *Pinus* were much higher followed by 21 years *Eucalyptus* (Table C3).

There were no considerable variations in the mineral soil mean bulk densities to the depth of 1 m among the different forest types (Table C4). Mean SOC concentration of the mineral soil under the natural forest was significantly higher than under the 21 years *Eucalyptus* and *Pinus* stands. The natural forest and 21 years *Eucalyptus* had greater N concentration compared to third rotation *Eucalyptus* and *Pinus* stands, but there were no considerable differences between the former and the latter two. In the surface 20 cm soil layer, the natural forest and

21 years *Eucalyptus* had higher SOC, N and S concentrations compared to third rotation *Eucalyptus* and *Pinus* stands, but differences between the former two were not significant (Table C4). Below the 20 cm soil depth, except OC and N in the 20–40 cm layer, all forest types had nearly the same OC, N and S concentrations. Mean C/N ratio to the depth of 1 m under 21 years *Eucalyptus* (9) was significantly ($P<0.01$) lower than the C/N ratios under third rotation *Eucalyptus* (11), and under the natural forest and *Pinus* (12). In all forest types, with the exception of 21 years *Eucalyptus*, C/N ratio tended to decrease with increasing depth (Fig. C1) probably due to leaching of N-rich materials from the upper soil layers.

Average SOC stocks in the mineral soil horizons in this study ranging from 26.2–32.7 kg m^{-2} to 1 m depth (Table C5) were higher than the world average (11.7 kg m^{-2} to 1 m depth) based on the data of Eswaran et al. (1993) and several other authors (Brown and Lugo, 1982; Lugo et al., 1986; Brown and Lugo, 1990; Zinn et al., 2002). Differences between our study and others could be due to differences in soil forming factors, including climate, parent material, topography, vegetation, and human impact. Soil OC under the different plantations varied from 26.2–27.5 kg m^{-2} representing 80–84% of the SOC stock under the natural forest (32.7 kg m^{-2}) (Table C5). Since there is about three times as much C in the world's soils as in the atmosphere (Follett, 2001), the observed changes (–16 to –20%) in this pool can have considerable feed-back effects on the amount of CO_2 in the atmosphere and thereby on global warming.

Mean N stocks to 1 m soil depth (Table C5) differed among forest types ($P<0.01$), being highest under the natural forest and 21 years *Eucalyptus* plantation compared to third rotation *Eucalyptus* and *Pinus* stands, but both the former and the later two were not significantly different from each other. The reductions in N stocks relative to the natural forest varied from a maximum of 0.78 kg m^{-2} (–27%) under *Pinus* to a low of 0.04 kg m^{-2} (–1.4%) under third rotation *Eucalyptus* (Table C5). The changes in S stocks due to the transformation of the natural forest into different forest plantations were non-significant, being 0.05 kg m^{-2} (–13%) under *Pinus* and 21 years *Eucalyptus*, while there was a net gain of 0.02 kg m^{-2} (+5 %) under third rotation *Eucalyptus* (Table C5).

The distribution of SOC, N and S stocks across the profile (Table C5) tended to follow the general trend in SOC, N and S concentrations (Table C4), decreasing from the surface to the subsoil although bulk density values increased in this direction. Nearly one-third of the total SOC, N and S stocks to 1 m depth in all forest types (Table C5) were found in the surface 0–20 cm layer. This points out the need for proper management as it represents the pool most exposed to management effects that may accelerate its decomposition and release of CO_2 to the atmosphere. Surface soil OC, N and S stocks under the natural forest (Table C5) were not significantly different from the 21 yr *Eucalyptus*, however, the natural forest and 21 years *Eucalyptus* stored greater amounts of OC, N and S in the surface 20 cm depth compared to *Pinus* and third rotation *Eucalyptus*. For the depth 20–100 cm, treatment effects on SOC, N and S stocks were less clear, but the losses range from 2.73–5.89 kg m^{-2} (13–28%) for SOC, 0.21–0.4 kg m^{-2} (11–20%) for N and 0.06 kg m^{-2} (21%) for S (Table C5). This indicates that any conclusion based on surface soil responses to changes in soil OC and nutrients such as N and S that occurred after forest clearing is conservative.

4.2. Water and nutrient fluxes

4.2.1. Water flux

Total rainfall amount during the one year study period amounted 1190 mm (Table D1), lying very close to the past long-term value (1250 mm) from the nearby meteorological station (Solomon et al., 2002). There was a marked variation in the distribution of rainfall among the different seasons because in Ethiopia rainfall is mainly associated to a change in the predominant wind direction (monsoon); northeast winds prevail during the dry season and westerly to southwesterly winds during the rains (NMSA, 1996). Of the total annual rainfall, the highest amount (60%) fell during the main rainy season (June to September) and the minimum (12%) during the dry season (October to January) (Table D1). The monthly maximum and minimum rainfalls, respectively, were 67.4 and 6.2 mm in the dry season, 136.4 and 20.8 mm in the small rainy season and 268.2 and 120 mm in the main rainy season. Daily minimum rainfall was the same in all the three seasons (0.2 mm) while the daily maximum was variable: amounting 8.2 mm in the dry season, 39.2 mm in the small rainy season and 60 mm in the main rainy season. Of the 12 months, monthly rainfall was less than 100 mm from October to February and was above 200 mm only in August.

The proportions of annual incident rainfall that reached the forest floor were 82% under *Eucalyptus* and 53% under *Cupressus* and the natural forest (Table D1). This variation was mainly attributed to the difference in stand density and total canopy area, leaf morphology, branch geometry and hydrophobicity among species. However, the possibility of spatial variations in rainfall intensity within the study area could not be ruled out. In general, interception loss was highest during the dry season (65% in *Cupressus*, 63% in the natural forest and 32% in *Eucalyptus*) (Table D1) not only due to the pronounced sunny days before and after rain events, but also rainfall intensity for most of the rain events was very low (< 5 mm) to produce throughfall. During the monitoring period, throughfall water fluxes under the different forest types were generally less than rainfall (Table D1) which is expected since cloud water is not a factor. Throughfall values ranging from 62–88% have been reported for different montane tropical forests (Veneklaas, 1990, 1991; Cavelier et al., 1997; Schrumpf, 2004). In Brazil, Lilienfein and Wilcke (2004) found that throughfall was 75–85% of incident rainfall (1682 mm) under *Pinus caribaea* plantation. Variability in throughfall amount between different studies can be attributed in part to differences in climatic patterns, meteorological conditions, and stand density and species composition. In the Munesa forest, long sunny periods were common even during the wetter months and so there was usually plenty of time for the canopy to dry out.

4.2.2. Nutrient concentrations and fluxes

The volume weighted mean (VWM) nutrient concentrations in rainfall ranged from 0.09 mg l^{-1} for Mg to 3.29 mg l^{-1} for Na (Table D2). VWM concentration of NH_4–N was 1.78 times higher than that of NO_3–N. Rainfall at Munesa was weakly acidic (mean pH 6.7) with most of the potential acidity being neutralised by Na and Ca. On an equivalent basis, Na was accompanied by Cl and Ca. In all forest types, canopy interactions produced throughfall more alkaline than bulk precipitation (Table D2). The VWM nutrient concentrations in throughfall were dominated by K>Cl>Ca>Na>SO_4–S in all forest types. Throughfall nutrient concentrations were found to be consistently greater for the natural forest than for the two plantations although the differences for some of the nutrients were not significant (Table D2). This might have been caused by differences in dry deposition and canopy interception capacity which is a result of several factors such as stand density, canopy area and roughness, and leaf morphology.

In each forest type, VWM throughfall Ca, K, Mg and Cl concentrations were significantly increased in relation to rainfall. The increases in K and Mg concentrations relative to those of rainfall were highest under the natural forest compared to the two plantations. Throughfall NH_4–N concentration was lower in each forest type and PO_4–P was lower in the two plantations in relation to rainfall. The concentration of NO_3–N in rainfall was significantly lowered after passing through the canopy of *Cupressus* plantation, while under *Eucalyptus* plantation and the natural forest the reverse holds true. Although statistically not significant in *Eucalyptus*, the concentration of SO_4–S in all forest types increased after the passage through the canopy. With few exceptions, nutrient concentrations in rainfall and throughfall of our study site were higher than those summarized for other montane tropical forest sites (Table

D2). The seasonal patterns in nutrient concentrations in throughfall of each forest type (Table D4) were similar, being highest, with few exceptions, during the dry season (October–January) presumably due to wash-off of dry deposition accumulated on the canopy during dry periods by intermittent low-volume rain events. There was no discernible trend with time in rainfall nutrient concentrations except for Na which showed a slight increasing tendency from the dry season to the wet season (Table D4).

The annual total amounts of nutrients (Ca, K, Mg, Na, Cl, NH_4–N, NO_3–N, SO_4–S, PO_4–P) reaching the soil (Table D5) in throughfall were 14 kg $ha^{-1}yr^{-1}$ under *Cupressus*, 24 kg $ha^{-1}yr^{-1}$ under *Eucalyptus* and 21 kg $ha^{-1}yr^{-1}$ under the natural forest. Of these, 12 kg $ha^{-1}yr^{-1}$can be explained by the rainfall while 2, 9, and 12 kg $ha^{-1}yr^{-1}$ under *Cupressus*, natural forest and *Eucalyptus*, respectively, derived from dry deposition and leaching of intracellular solutes from the canopy. In spite of the same amount of throughfall water with that of *Cupressus* and about 30% less than *Eucalyptus*, the observed annual total weight of nutrients in the natural forest suggests that the much rougher surface of the natural forest canopy increased the deposition area and allowed interception of dust carrying winds. Except NH_4–N and PO_4–P in all forest types, Ca and NO_3–N in *Cupressus* and the natural forest, and SO_4–S in *Eucalyptus* the fluxes of all other nutrients in throughfall of each forest type were significantly different from that of rainfall (Table D5). Annual fluxes of nutrients in rainfall and throughfall in the Munesa forest (Table D5) were lower than the values summarised for other montane tropical forests (Table D5). The greatest variability in rainfall and throughfall inputs between our study and others could be due to variability in rainfall amount, species composition and canopy structure, and the availability of nutrients from atmospheric and rock weathering processes and exposure to acid precipitation. Throughfall inputs of Ca, Mg, Na and Cl were significantly different among forest types. Although statistically not significant for some of the nutrients, throughfall in *Cupressus* had the lowest fluxes of each nutrient compared to the natural forest and *Eucalyptus*, NH_4–N was an exception. *Eucalyptus* was found to have relatively the highest throughfall input of Ca, Mg, Na, NO_3–N and SO_4–S compared to the natural forest mainly due to high volume of water reaching at the soil surface under the *Eucalyptus* plantation. The inputs of Cl and PO_4–P were slightly highest under the natural forest compared to *Eucalyptus* mainly resulting from high concentration. Nutrient fluxes varied considerably from season to season and were higher during the wet season (Table D7) because of higher rainfall volume or rainfall intensity, although concentrations of most nutrients tended to be higher in the dry season. This seasonal pattern of variation in fluxes indicated that except for the few relatively high-volume dry season rain events, throughfall in dry season is not likely to provide a major nutrient source via root uptake for overstorey tree species.

The data in net throughfall Na, NH_4–N, NO_3–N, SO_4–S and PO_4–P fluxes (Table D5) indicate absorption by the canopies of all forest types, whereas net throughfall Ca, K, Mg and Cl fluxes indicate canopy leaching. The magnitude of absorption and canopy leaching were both nutrient and tree species specific. Comparison of net throughfall fluxes among seasons indicated clear temporal patterns of canopy leaching and very different chemical speciation associated with biological uptake (Fig. D1). Ammonium–N and PO_4–P were taken up in larger quantity during the small rainy season in all forest types while Na, NO_3–N and SO_4–S were mainly taken up during the main rainy season. Calcium in *Cupressus* and natural forest indicated intermediate behaviour: a tendency towards absorption during the main rainy season and canopy leaching during the dry and small rainy seasons. A similar behaviour was also observed for NO_3–N in *Eucalyptus* and the natural forest.

4.3. Nutrient dynamics in soil solution

Water passing through the forest floor under the different tree species did not differ in mean nutrient concentrations except for K, Mg and NO_3–N (Table E2). Magnesium and NO_3–N concentrations were significantly higher under the natural forest and *Eucalyptus* plantation than under *Cupressus*. Potassium concentration was higher under *Eucalyptus* than under the natural forest and *Cupressus*. The low C/N ratio in the forest floors of *Eucalyptus* and natural forest might have triggered nitrification in comparison to *Cupressus* which had high C/N ratio in the organic layer. Soils with C/N ratios >25-30 and low nutrient concentrations are reported to be poor-nitrifying (Gundersen and Rasmussen, 1990). In each forest type, after K, Ca and Cl were the most abundant nutrients leached from the litter layer (Table E2). PO_4–P was the least of all the nutrients followed by NH_4–N. Except for NH_4–N in the natural forest, forest floor leachate nutrient concentrations were enriched in all forest types in relation to rainfall and throughfall, being more pronounced in NO_3–N, Ca, Mg and PO_4–P concentrations. Leaching of nutrients from decaying vegetation and microbial mineralization of elements within organic matter contribute to the observed enrichment of forest floor leachates.

Nutrient fluxes from the forest floor to the mineral soil were not significantly different among forest types, but were slightly highest under *Eucalyptus* (Table E4). In general, large fluxes were observed for Ca and Cl. Measured nutrient exports from the forest floor to the mineral soil decreased in relation to throughfall fluxes for most of the nutrients indicating that nutrients that are deposited from throughfall as well as those released from decomposition are effectively taken up by plant roots or immobilised. The nutrients that decreased most were NH_4–N≈K>Cl>SO_4–S under the natural forest, SO_4–S >Na> Ca≈ Mg under *Eucalyptus*, and NH_4–N >SO_4–S>Na>Ca under *Cupressus*. Nitrate–N exports from the forest floor exceeded the inputs via throughfall by about 161% for *Cupressus* and 70% for the natural forest and *Eucalyptus*. Calcium and PO_4–P exports by leaching out of the *Cupressus* forest floor were 34% and 33% higher than the corresponding throughfall inputs; below *Eucalyptus* as high as 50% more PO_4–P was exported in comparison to the input by throughfall.

The median mean nutrient concentrations in the soil solutions of the mineral soil were in the order: Na>Cl>Ca>SO_4–S>Mg>NO_3–N>K>NH_4–N below the natural forest, Na>Ca> SO_4–S>Cl>Mg> NO_3–N>K> NH_4–N below *Eucalyptus* and NO_3–N>Ca>Na>Cl> SO_4–S>K> NH_4–N below *Cupressus* (Table F4). The concentration of PO_4–P in the mineral soil solution was generally below the detection limit in the three forest types. Phosphorus is relatively insoluble and readily fixed by soil minerals (Brady and Weil, 1999). Potassium was also often below the detection limit in the mineral soil solution under the natural forest and under *Cupressus* plantation probably due to the high biological demand for this element. The lower NH_4–N concentration relative to NO_3–N in both the forest floor leachate and mineral soil solution was probably a result of nitrification, vegetation uptake, adsorption or assimilation by microbes. With the exceptions of Mg, Na and NO_3–N concentrations at all depths below *Cupressus* plantation and SO_4–S and Na at some soil depths below the natural forest and *Eucalyptus* plantation, all other nutrients decreased relative to the concentrations in the forest floor leachate. Potassium, Mg, NH_4–N and PO_4–P decreased to a great degree compared to the other nutrients. An increase in NO_3–N concentration in the mineral soil solution relative to forest floor leachate below *Pinus* was also reported by Lilienfein et al. (2001) in Brazil. Schrumpf (2004) observed a decrease in Ca, K, Mg, Na and NH_4–N concentrations and an increase in NO_3–N concentration in the mineral soil solution of Andisols in Kilimanjaro in relation to the forest floor leachate. In Congo, Laclau et al. (2003) reported an increase in NH_4–N, NO_3–N and SO_4–S and a decrease in Ca, K, Mg and Na in the mineral soil solution relative to the forest floor leachates below *Eucalyptus* plantation.

The concentrations of K, NH_4–N and SO_4–S in all forest types and Ca, Mg and NO_3–N concentrations below *Eucalyptus* and the natural forest decreased steadily with increasing soil depth, presumably due to adsorption by the soil colloid or to plant and microbial uptake (Table F4). In contrast, below *Cupressus,* the concentrations of Ca, Mg and NO_3–N decreased from 0.2 m depth to 0.5 m depth and then increased at the depth of 1 m. This pattern appears to follow the root distribution and concurrent nutrient uptake as the roots of *Cupressus* are confined to the surface 0.5 m (Ashagrie, pers. observation). Median Ca, Mg and NO_3–N concentrations below *Cupressus*, respectively, were 4, 3.37 and 17 times higher than below the natural forest and 2, 2.41 and 7 times higher than below *Eucalyptus* (Table F4). The higher Ca, Mg and NO_3–N concentrations in the soil solution under *Cupressus* relative to the other two forest types were probably due to the fact that these nutrients were in excess of tree and microbial requirements. Much of the observed differences in median mean nutrient concentrations were attributed to the large differences at the depth of 1 m, being 3 and 8 times, 4 and 7 times and 81 and 23 times more for Ca, Mg and NO_3–N under *Cupressus* than under *Eucalyptus* and the natural forest, respectively (Table F4). In a ^{15}N tracer study made by Fischer (2004) at the same experimental plots, large proportion of the ^{15}N applied at the surface (0 m soil depth) under *Cupressus* was found in the deeper soil layer (0.3–0.6 m) confirming that leaching had occurred below *Cupressus*. Lilienfein et al. (2000, 2001) reported two times higher Ca, K, Mg, Na and NO_3–N concentrations in soil solution under *Pinus* than under *Cerrado* in sub humid Central Brazil.

5. GENERAL CONCLUSIONS

This study showed that conversion of natural forest into crop land had more deleterious effects on soil aggregation, SOC and nutrient contents than conversion into *Eucalyptus* plantation. Direct measurement of short-term SOM losses or gains resulting from variations in land-use may not clearly reflect the effects of land use and soil management because of the generally high background soil C pool (Haynes, 1999). Physical fractionation of soils into aggregate and particle-size fractions enabled separation of SOM into pools of differing composition and biological function and turnover, thus allowing sensitive detection of changes in SOM dynamics and soil fertility resulting from changes in land-use. In general, losses of SOC and nutrients associated with the different size/density fractions resulting from the conversion of the natural forest into *Eucalyptus* plantation and crop cultivation were more pronounced than losses observed in the bulk soil and total water stable aggregates. Plantations of several tree species growing under similar site conditions offer an opportunity to evaluate species´ effects without confounding problems of prior soil differences. The results of the present study on SOC and nutrient stocks as affected by conversion of the natural forest into different exotic tree species plantations emphasise the importance of forest type, stand age and management in affecting the size of C and nutrient stocks. In general, the effect of tree species appear limited largely to the forest floor, with little change in mineral soils. The accumulation of organic detritus and the relative losses or accumulation rates of C and nutrients in the soil depends on the rate of decomposition of the plant material which is influenced by litter quality, acidity, soil moisture and temperature, and the kinds of micro flora and fauna present. Hence, many of the above mentioned factors that affect ecosystem processes and C and nutrient storage, and the relationships between substrate quality and decomposition rates need to be further investigated.

The results of the present study also showed that water and nutrient inputs into and nutrient outputs from the studied ecosystems were affected after conversion of the natural forest into managed forest plantations. Because *Eucalyptus* leaves often are held vertically on the twigs, the leathery nature of the leaves, and the overall low stand density, the amount of rain water intercepted and lost by evaporation was lower in comparison to the natural forest and *Cupressus* plantation. The higher rainfall interception under the natural forest and *Cupressus* means reduced rainfall infiltration and insufficient rainy season replenishment of ground water reserves that may in the longer-term affect plant productivity and dry season stream flows. Canopy characteristics such as leaf area and canopy density, as well as canopy roughness relative to wind and the amount of water reaching the soil affected the input of nutrients by rainfall and throughfall. Rainfall chemistry at Munesa showed no evidence of acid or polluted deposition of anthropogenic origin. However, except for K and Mg, the annual levels of mineral–element accession in rainfall can augment the nutrient stocks in the soil. The input of most nutrients by throughfall under *Cupressus* was lower than under the natural forest and *Eucalyptus*. Ecosystem-specific patterns of vegetation composition and associated demand for nutrients appear to control the dynamics of nutrients in soil solution. In general, forest ecosystems retain nutrients very efficiently. Exceptions to this general pattern are ecosystems with low nutrient uptake by plants and immobilization cannot compensate for reduced plant uptake. Plant uptake is a major sink of available nutrients. Apparently, the movement of Ca, Mg, and NO_3–N out of the rooting zone were higher under *Cupressus* than under the other forest types. The fact that NO_3–N and basic cations leached from relatively low or non nitrifying soils such as in *Cupressus* with high C/N ratio in the organic layer may, indicate that plant uptake for Ca, Mg and NO_3–N periodically did not match mineralization in the soil or mineralization has exceeded the retention capacity of the system. From the ecological point of view, the presence of basic cations and mineralised nitrogen in subsoil solution under *Cupressus* indicates leaching, and that the ecosystem is not characterised by tight nutrient-cycling.

Generally, considering the high C/N ratio in the organic layer of the studied *Cupressus* stand that will negatively influence the rates of litter and nutrient turnover, loss of basic cations from the rooting zone may, in the short-term, reduce site fertility and contribute to the onset of nutrient deficiencies. However, in the long-term, the positive impacts of annual cycling of nutrients through uptake by roots, fine root turnover, and above-ground litter deposition and atmospheric inputs act to maintain fertility of the soil. Weathering, one of the chief sources of nutrients, also acts to counteract loss of cations from the system. In *Eucalyptus* plantation, the presence of diverse shrub and herbaceous understorey vegetation might have contributed in nutrient retention. These aspects reveal some characteristics that could be important to *Cupressus* plantation management. In light of the poor nutrient retention capacity of *Cupressus*, future monoculture plantations with high tree density should be discouraged. Rather mixed stands formed by several tree species or monocultures with minimum tree density that allow the growth of understorey shrub and herbaceous vegetation should be encouraged so as to maintain the fertility status of the soil for future rotations. Furthermore, such practices may also ensure input of sufficient rain water to the soil and enhance the regeneration of native plant species which is now lacking under *Cupressus*. Unfortunately, it is impossible to estimate the total loss rate due to the inherent methodological problems in quantifying the total water flow rates through the soil, but enlighting the general trends and patterns found in comparison of the different forest ecosystems may be more important than the precise budgetary calculations. Generally, drawing conclusions or making inferences solely based on a one year ecosystem analysis studies that focus on elucidating processes would be difficult, therefore, continuous monitoring of water and nutrient input and output patterns in the studied ecosystems is needed to reach a valid conclusion.

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7. PAPERS (A−F)

A Transformation of a *Podocarpus falcatus* dominated natural forest into a monoculture *Eucalyptus globulus* plantation at Munesa, Ethiopia: Soil organic C, N and S dynamics in primary particle and aggregate-size fractions

Y. Ashagrie[1]*, W. Zech[1] and G. Guggenberger[1,2]

[1]*Institute of Soil Science and Soil Geography, University of Bayreuth, D-95440 Bayreuth, Germany*
[2]*Present address: Institute of Soil Science and Plant Nutrition, Martin Luther University, D-06099 Halle, Germany*
* Correspondence: yeshanew@hotmail.com, Tel: ++49-921-55-21-46 Fax: ++49-921-55-22-46

Abstract

Changes in land-use and management can affect soil structure, soil organic carbon (SOC) and other nutrients reserve (such as N, P, S). We analysed organic carbon (OC), total nitrogen (N), and total sulfur (S) in particle-size, aggregate-size and size/density fractions of soil organic matter (SOM) in order to identify the SOM pools most affected by the conversion of a *Podocurpus falcatus* dominated mixed natural forest into a monoculture *Eucalyptus globulus* plantation 21 years ago on a reddish brown Nitisol at Munesa, Ethiopia. Bulk soil OC, N, and S concentrations and stocks in soil to 20 cm depth were not significantly changed after the conversion of the natural forest into Eucalyptus plantation, but C/N ratio narrowed significantly. Soil organic C, N and S concentrations, and C/N and C/S ratios in sand and silt separates from the plantation samples were significantly reduced, while clay N and S concentrations had slightly increased. The losses of SOC, N and S in the sand fraction were more pronounced than that in the silt. Aggregate stability and total SOC, N and S concentrations of the aggregates were not significantly different in samples from the *Eucalyptus* plantation and the natural forest. In the plantation samples, both the free light fraction (LF) and the intra-particulate organic matter (iPOM) C, N and S concentrations associated with the macroaggregates were significantly reduced. Differences in the total amount of the free LF (on the basis of water-stable aggregates proportion) between the two forest types were not apparent, suggesting that SOM quality is more prone to changes in land-use and soil management strategies than the total amount of SOM. The loss of iPOM was higher than that of free LF probably due to gaseous losses of organic matter (OM) inside the aggregates caused by high fire temperatures during clearing and site preparation. In both forest types, the LF OM comprised the highest percentage of whole soil OM and the loss of particulate organic matter (POM) accounted for much of the losses of OM. Overall, the results showed that analysis of OC, N and S concentrations in soil particle and aggregate-sizes, and size/density fraction of SOM allowed sensitive detection of changes in SOM dynamics and soil fertility resulting from changes in land-use.

Key words: Land-use change; Soil organic carbon; Nitrogen, Sulfur, Eucalyptus plantation; Particulate organic matter; Nitisol; Ethiopia.

1. Introduction

In Ethiopia, massive deforestation of natural forests and extensive use of agricultural lands have resulted in soil degradation and loss of environmental quality (EFAP, 1994). To reduce land degradation, and to satisfy the demand for timber and timber products of the local population, extensive afforestation with fast-growing exotic tree species has been carried out on degraded agricultural lands (Pohjonen and Pukkala, 1990). Sometimes, degraded secondary forests containing low quality and non-uniform stands of several species were also transformed into forest plantations. Of the total area of 200, 000 ha covered by plantations in 1992 more than 60% is under *Eucalyptus* species (EFAP, 1994). Although intensive management of exotic tree species may provide rapid growth and a higher economic return than would native tree species, little is known about the environmental impacts of this practice, such as on soil quality and productivity. Following refforestation, changes inevitably occur in the quantity, quality, temporal and spatial distribution of soil organic carbon (SOC) inputs, depending on type of forest established (Brown and Lugo, 1990). For example, in Ethiopia, Solomon et al. (2002) reported losses of about 27% of SOC and 13% of N and S after 25 years of conversion of the natural forest into *Cupressus* plantations. Zinn et al. (2002) found about 23 to 48% SOC loss after conversion of Brazilian native wooded savanna to *Eucalyptus* plantations.

Maintenance and improvement of soil organic matter (SOM) content is generally accepted as being an important aim for any sustainable soil fertility management because it is a major reservoir of nutrients such as N, S and P, and influences soil structure, water availability and other important chemical, physical and biological properties of soil (Haynes and Beare, 1996). Carbon is stored in terrestrial ecosystems in diverse organic forms with a wide range of mean residence times (Balesdent and Mariotti, 1996). The organic matter associated with different size fractions of soil, and that of the organo-mineral fractions of specific particle and aggregate sizes, exhibit distinct properties with respect to their composition and turnover (Christensen, 2001). The initial impact of land-use or management change occurs disproportionately in pools with short residence times (Cambardella and Elliott, 1992), whereas the effect on stable SOC pools occurs slowly over a much longer time period.

Direct measurement of short-term SOM losses or gains resulting from variations in land-use may not clearly show the effect of land use and soil management because of the generally high background soil C pool (Haynes, 1999). Therefore, approaches based on characterization of active SOM with comparatively rapid turnover rates have been suggested as a more sensitive indicators of soil fertility that allow early detection of changes in soil fertility before soil degradation becomes apparent (Cadisch et al., 1996; Haynes and Beare, 1996). Physical fractionation of soil into aggregate and particle-size fractions in studies of SOM has received increased attention because it enables separation into pools of differing composition and biological function (Christensen, 1992, 2001).

Among the different labile SOM pools, those associated with the sand fraction (Christensen,

2001) and particulate organic matter (POM), a pool that is functionally similar to light fraction (free LF) organic matter (Cambardella and Elliott, 1994), closely reflect early changes in SOM resulting from changes in land use and soil management. Similarly, the OM that binds microaggregates to macroaggregates is labile and responds more sensitively to changes in land use than the organic matter that binds microaggregates (Elliott, 1986; Gupta and Germida 1988; Cadisch et al. 1996; Christensen, 1996). Most of the labile organic matter within macroaggregates could be free light-fraction POM of relatively low-density, mineral-associated OM (Cambardella and Elliott, 1993). Several authors (Guggenberger et al., 1994; Solomon et al., 2002; Zinn et al., 2002) found differences in the quality and amount of SOM associated with mineral particles of different sizes. They also reported relatively greater losses of OC in the coarser particle-size separates than in the finer particle-size separates as a result of changes in land use from native vegetation to plantation.

The presence of a monoculture *Eucalyptus* plantation side by side with the natural forest from which it was established 21 years ago provided the opportunity to determine if soil structure and the quantity, as well as the quality, of organic matter in the mineral soil had changed as result of land-use change in the highlands of Ethiopia.

2. Materials and methods

2.1. Site description

The study was conducted at the Munesa/Shashemenie forest enterprise site (7°34´N and 38°53´E) located about 240 km south east of Addis Ababa at an altitude of 2400 m.a.s.l. Rainfall is bimodal with mean annual precipitation of 1250 mm most of it falling in July and August, and mean annual temperature is 19 °C with little seasonal variation. The soils are clayey and very deep with reddish brown colour, and are moderately acidic at or near the surface and slightly acidic at depth. The principal parent materials are of volcanic origin from which Rhodic Nitisols were derived (FAO, 1997). A *Podocarpus falcatus* dominated mixed natural forest (ca. 3 to 4 thousand years) and an adjacent 21 years *Eucalyptus* plantation were selected for this study. The natural forest is one of the few remaining natural forest reserves in the country. Eucalyptus plantation in the study area covers about ca. 1, 620 ha comprising different species, and was established after clearing and burning of part of the natural forest. Clearing was done manually and the surface biomass was burned on site. Tree density in the studied plantation compartment was about 595 tree ha^{-1} and tree diameter at breast height (dbh) ranged from 19 to 39 cm with a height of 30 to 40 m. The studied plantation is open to light penetration with dense understorey grass and broad-leaved herbaceous, and different species of shrub vegetation, and is occasionally grazed by free grazing cattle.

2.2. Sampling

In each forest type, three 0.06 ha plots ca. 100 m apart from each other were located randomly and a pit was excavated to the depth of 1.2 m at the centre of each plot. In addition, four 1 m^2 sub plots were marked randomly at 10 m radius from the centre of each plot. Soil samples ca. 500 g were taken from the three sides of the pit by a shovel, and at three points within each of the 1 m^2 sub plots by an auger to the depth of 0–20 cm. All the auger and pit samples in the 0.06 ha plot were mixed and the final number of samples were reduced to three per land use. After air drying, a sub sample was sieved through 5 mm sieve size for aggregate fractionation, and the remaining was sieved through 2 mm sieve size for bulk soil C, N and S analysis, and particle size fractionation. Soil samples for bulk density determination were taken from the wall of the three pits by a 100 cm^3 metal cylinder; totally seven per land use.

2.3. Soil particle size fractionation

Air-dried and sieved (2 mm mesh) 30 g samples were put in a centrifuge tube and dispersed ultrasonically at a soil: water ratio of 1:5 (w/v), with an energy input of 60 J ml^{-1}using a probe type sonicator (Branson Sonifier W–450). Coarse sand fraction (250–2000 µm) was separated by wet sieving, and the remaining material in the <250 µm fraction was further sonicated at a soil: water ratio of 1:10 (w/v), with an energy input of 440 J ml^{-1}. The clay-size separates (< 2 µm) were isolated from the silt (2–20 µm) and fine sand (20–250 µm) by repeated centrifugation, while the silt-size separates were isolated from the fine sand by wet sieving. After fractionation, the different particle-size fractions were dried at 50 ^{o}C.

2.4. Soil aggregate size fractionation and separation of particulate organic matter

The size distribution of aggregates was measured by a wet sieving through a series of sieves (2, 1, 0.5, 0.25 and 0.053 mm) following the procedures of Cambardella and Elliott (1993). A 70–80 g sample of air-dried soil passed through a 5 mm sieve size was spread on the top of a 2 mm sieve submerged in a bucket of deionized water. The water level was adjusted so that the aggregates on the sieve were just submerged. Soils were left immersed in the water for 10 min and then sieved by moving the sieves 3 cm vertically 50 times during a period of 2 min. During the sieving process, floatable materials >2 mm were removed and discarded. According to Six et al. (1998) materials > 2mm are not considered an integral part of SOM. The material remaining on the 2 mm sieve was transferred to a glass pan. Soil plus water that passed through the sieve were poured onto the next finer sieve and the processes repeated, but floatable materials were not removed and discarded. The different aggregate sizes were dried in the oven at 50 °C overnight for chemical analysis.

The separation of POM followed the procedure of Six et al. (1998). Prior to POM separation, the fractions in the >0.25 mm size aggregates were bulked as macroaggregates and the 0.053–0.25 mm size as microaggregates. After the aggregates were dried (105 °C) in the oven overnight and cooled in a desiccator to room temperature, about 10 g of each aggregate fraction was taken in a conical centrifuge tube and suspended in 35 ml sodium polytungstate (adjusted to a density of 1.8 g cm^{-3}) by hand shaking. The suspension was allowed to stand for 20 min before centrifugation at 1250 rpm for 60 min. After centrifugation, the floating material was collected on filters and rinsed thoroughly with deionized water to remove sodium polytungstate, this material is referred to as free LF. The heavy fraction remaining in the tube was washed twice with 50 ml deionized water and dispersed in 50 ml of 5% sodium hexametaphosphate by shaking in a reciprocal shaker for 18 hours. The dispersed heavy fraction was rinsed through a 0.053 mm sieve with deionized water. The material remaining on the sieve is intra-particulate organic matter (iPOM) + sand. Both the free LF and iPOM were dried in the oven at 50 °C overnight. The dried subsamples from each aggregate size class, particle size fraction, and the free light fraction and iPOM were finely ground in a rotary ball mill for chemical analysis.

2.5. Soil analysis

Organic C, N and S concentrations in bulk soil, size fractions and POM were determined using a CHNS–analyzer (Vario EL, Elementar Analysensysteme, GmbH, Hanau, Germany). Element stocks (kg m^{-2}) were calculated as a product of bulk density, depth of sampling and element´s concentration per unit of soil samples. The pH_{KCl} (soil:solution ratio 1:2.5) of the soil was determined with a standard pH electrode (Orion U402–S7). Bulk density was determined after drying the soil in an oven at 105°C.

2.6. Statistical analysis

One way analysis of variance (ANOVA–1) was performed to asses the effect of change in land-use on soil aggregate stability, and soil organic C and nutrients associated with the different particle size/density fractions using the MSTATC statistical package. Separation of means were performed using Tukey´s honestly significance difference test with a significance level of $P < 0.05$.

3. Results and discussion

3.1. Organic C, N, and, S in bulk soil samples

Analysis of variance performed on the data showed that mean SOC, N and S concentrations and the C/S and N/S ratios in bulk soil samples did not differ significantly in the natural forest and *Eucalyptus* plantation (Table A1). The changes in bulk density after the establishment of *Eucalyptus* was also not significant, and varied from 0.86 g cm^{-3} under the natural forest to 0.91 g cm^{-3} under *Eucalyptus*. On an area basis, the two forest types had almost the same level of SOC and S stocks, but there appeared to be a slight and non significant gain of N in the *Eucalyptus* plantation (Table A1). This relative gain could perhaps be attributed to the recycling of N via excreta of free grazing cattle. In contrast to our results, Michelsen et al. (1993) reported significantly lower OC and nutrient concentrations under a 40 years *Eucalyptus* plantation than under an adjacent natural forest on a reddish brown soil in

Table A1. Soil organic C, N and S concentrations and stocks, and element ratios and bulk density (Bd) under the different land use types, results refer to the 0–20 cm soil depth.

	C	N	S	C/N	C/S	N/S	Bd	C	N	S
	------g kg^{-1}------						g cm^{-3}	-----kg m^{-2}------		
Natural forest	72	6	0.72	12**a**	100	8	0.86	12.4	1.0	0.12
	(7.4)	(0.6)	(0.07)	(0.6)	(3.5)	(0.3)	(0.02)	(0.9)	(0.1)	(0.01)
Eucalyptus plantation	61	7	0.75	9**b**	81	9	0.91	11.1	1.3	0.14
	(4.9)	(0.5)	(0.03)	(0.9)	(3.7)	(0.3)	(0.02)	(1.3)	(0.1)	(0.01)

Means followed by different lower case letters in a column are significantly different from each other at $P<0.05$. Numbers in parentheses are standard errors (n=7 for bulk density and n=3 for other parameters).

Ethiopia. There was a significant decrease in the C/N ratio from 12 in the natural forest to 9 in the *Eucalyptus* plantation, indicating that changes in organic matter quality took place (Table A1).

3.2. Particle size distribution, and concentrations of OC, N, and S in particle size fractions

The proportional distribution of the different primary particles in the different size classes were similar in soils under the two land use types (Table A2) suggesting that the textural composition of the soils under the two land use types were comparable which further confirms similar origin of the two soils. Table A2 shows that, with the exception of S which was significantly higher in the clay fraction than the other fractions, OC and N did not differ significantly in the different particle-size fractions in the natural forest. In soil under *Eucalyptus* forest, however, OC, N and S concentrations were highest in the clay fraction; this indicates a preferential shift of the organic matter to the finer fractions during the decomposition process. The redistribution of sand-sized OM to clay-complexed OM during decomposition has already been shown by other authors (Anderson et al., 1981; Zinn et al., 2002).

Element ratios (C/N, C/S, and N/S) differed significantly among some of the size fractions at both sites, and tended to decrease in the order sand>silt>clay (Table A3). This could be attributed mainly to the accumulation of newly added and less decomposed organic matter in the coarser fractions (Guggenberger et al., 1994; Gerzabek et al., 2001). In both forest types, the C/N and C/S ratios of the coarse and fine sand, and silt fractions were higher than in the bulk soil, where as that of clay was lower. This might be due to the more aliphatic and humified nature of the clay-sized OM in comparison to the OM in the bulk soil and coarser fractions (Buyanovsky et al., 1994; Mahieu et al., 1999). The proportion of whole soil OC, N and S associated with the different particle size fractions calculated by multiplying the quantity of each particle size by the element concentrations showed that most of the whole soil OC, N and S in both land use types were associated with the finer particle sizes (<20 µm), being highest in the clay fraction (data not shown). This is in agreement with the observations of Desjardins et al. (1994) and Solomon et al. (2002) for tropical soils.

Table A2. Particle size distribution (%), and organic C, N and S concentrations (g kg^{-1} size fraction) in soil under natural forest (NF) and in soil 21 yr after conversion of natural forest into *Eucalyptus* plantation (EP), results refer to the 0–20 cm soil depth.

	Size distribution		C		N		S	
Particle Size	NF	EP	NF	EP	NF	EP	NF	EP
Cs	0.09	0.08	67**A** (9.1)	22**bB** (0.7)	4.0**A** (0.9)	2.0**bB** (0.3)	0.47**bA** (0.1)	0.23**bB** (0.03)
Fs	0.09	0.09	90**A** (1.6)	30**bB** (5.4)	4.5**A** (0.8)	2.3**bB** (0.2)	0.43**bA** (0.1)	0.23**bB** (0.03)
Si	0.28	0.30	62 **A** (0.3)	32**bB** (1.8)	4.1**A** (0.3)	3.3**bA** (0.1)	0.47**bA** (0.03)	0.37**bA** (0.03)
Cl	0.50	0.51	56 **A** (0.5)	53**a A** (2.4)	5.9**A** (0.5)	7.2**aA** (0.5)	0.77**aA** (0.1)	1.00**aA** (0.1)

Different lower case letters in a column indicate significant differences ($P<0.05$) between means under each land use according to Tukey´s HSD mean separation test. Different upper case letters in a row indicate significant differences between means at $P<0.05$.

Cs: Coarse sand; Fs: Fine sand; Si: Silt; Cl: Clay. Numbers in parentheses are standard errors (n=3).

Table A3. Element ratios of particle-size fractions as influenced by conversion of the natural forest (NF) into a *Eucalyptus* plantation (EP); results refer to 0–20 cm soil depth.

Particle size	C/N		C/S		N/S	
	NF	EP	NF	EP	NF	EP
CS	18**aA** (2.7)	11**abB** (0.9)	156**bA** (4)	96**abB** (10)	9**abA** (1.1)	9**abA** (0.2)
FS	20**aA** (0.5)	13**aB** (1.3)	245**aA** (3)	131**aB** (21)	13**aA** (0.6)	12**aA** (1)
Si	15**abA** (0.7)	10**abB** (0.5)	149**bA** (10)	90**abB** (10)	10**abA** (0.4)	9**abA** (0.6)
Cl	9**bA** (0.2)	7**bB** (0.2)	76**cA** (0.2)	54**bB** (3)	8**bA** (0.2)	7**bB** (0.2)

Different lower case letters in a column indicate significant differences between means at $P < 0.05$ according to Tukey´s HSD mean separation test. Different upper case letters in a row indicate significant differences between means at $P<0.05$. Cs: Coarse sand; Fs: Fine sand; Si: Silt; Cl: Clay. Numbers in parentheses are standard errors (n=3).

Mean OC of sand and silt fractions and, N and S of sand fraction concentrations, and C/N and C/S ratios of all the particle size fractions and N/S of clay fraction declined significantly after conversion of the natural forest to 21 years *Eucalyptus* plantation (Tables A2 & A3). The coarse sand fraction showed the highest losses of all three elements (Table A2), suggesting that organic matter associated with the coarser fractions is more labile and the first to be affected by changes in land use and soil management (Christensen, 1996; Solomon et al., 2002; Zinn et al., 2002). The degree of OC loss was larger than the losses of N and S. The changes in the clay-associated OC, N and S were not significantly affected by the change in land use, suggesting that the OM pool attached to clay is more stable. In tropical soils, clay associated SOM may contain the most stable OC, while in temperate soils OM in silt appears more stable than clay (Christensen, 1996). Results on the calculated enrichment factors (g kg $^{-1}$ separate)/ (g kg $^{-1}$ whole soil), which take account of the effects of different SOM levels in whole soils (Christensen, 1992) indicated that clearing of the natural forest and replacing it by the *Eucalyptus* plantation resulted in the depletion of OC, N and S from the sand-sized fractions and enrichment of OC, N and S in the clay-sized fraction (data not shown).

3.3. Aggregate distribution, and OC, N, and S concentrations

Clearing and reforestation of the natural forest with *Eucalyptus* did not significantly affect the distribution of WSA (Table A4). In both forest types, the distribution of WSA among the different size classes was significantly different, with > 85% of the total soil mass, remaining as water stable aggregates, >73% as macroaggregates (> 0.25 mm), and 14–17% as microaggregates (0.05–0.25 mm). Except N in microaggregates, the mean OC, N and S concentrations of the different aggregate sizes did not differ significantly between the natural and *Eucalyptus* forests (Fig A1a, b, c). This is not surprising since both land use types had almost the same level of soil aggregation (Table A4). The average C/N ratios of the larger aggregates (> 0.5 mm) were significantly wider in the natural forest than *Eucalyptus* plantation (Fig. A2a), where as C/S and N/S were not influenced by land use (fig. A2b, c). The mean C/N, C/S and N/S ratios of the aggregates in both soil types were nearly the same as those of the corresponding bulk soil.

3.4. Free light fraction OC, N and S

The data on the free LF mean OC and N concentrations (Table A5) demonstrate that there were significant reductions in these elements concentration after conversion of the natural forest into the *Eucalyptus* plantation. However, differences in the total amount of the above parameters (on the basis of water-stable aggregates proportion) between the two forest types were not apparent, suggesting that SOM quality is more prone to changes in land use and soil management strategies than the total amount of SOM. This situation is further illustrated by the significantly narrower mean C/N (11) and C/S (94) ratios in the *Eucalyptus* forest than those of 16 and 146, respectively, in the natural forest. The magnitude of reductions in both OC and N was much higher than the magnitude observed in the whole soil and total water stable aggregates. Cadisch et al. (1996) found 10 times more light fraction C (>100 μm) in the surface (0–2 cm) soil of a Brazilian rain forest than in a papaya plantation, and three-to-five times more than a pasture soil.

Table A4. Distribution of water-stable aggregates (WSA) (%) among different aggregate-size classes to 0–20 cm soil depth as influenced by replacement of natural forest with the *Eucalyptus* plantation 21 years ago.

Size class (mm)	Natural forest	*Eucalyptus* plantation
2–5	10**b** (0.2)	8**c** (1.6)
1–2	21**a** (1.4)	18**ab** (0.3)
0.5–1	21**a** (1.3)	23**ab** (1.9)
0.25–0.5	22**a** (1.6)	25**a** (1.8)
0.053–0.25	14**b** (3.1)	17**b** (0.5)
Total	87	90

In a column, means followed by the same lower case letter are not significantly different from each other at $P<0.05$ according to Tukey´s HSD mean separation test. Numbers in parentheses are standard errors (n=3).

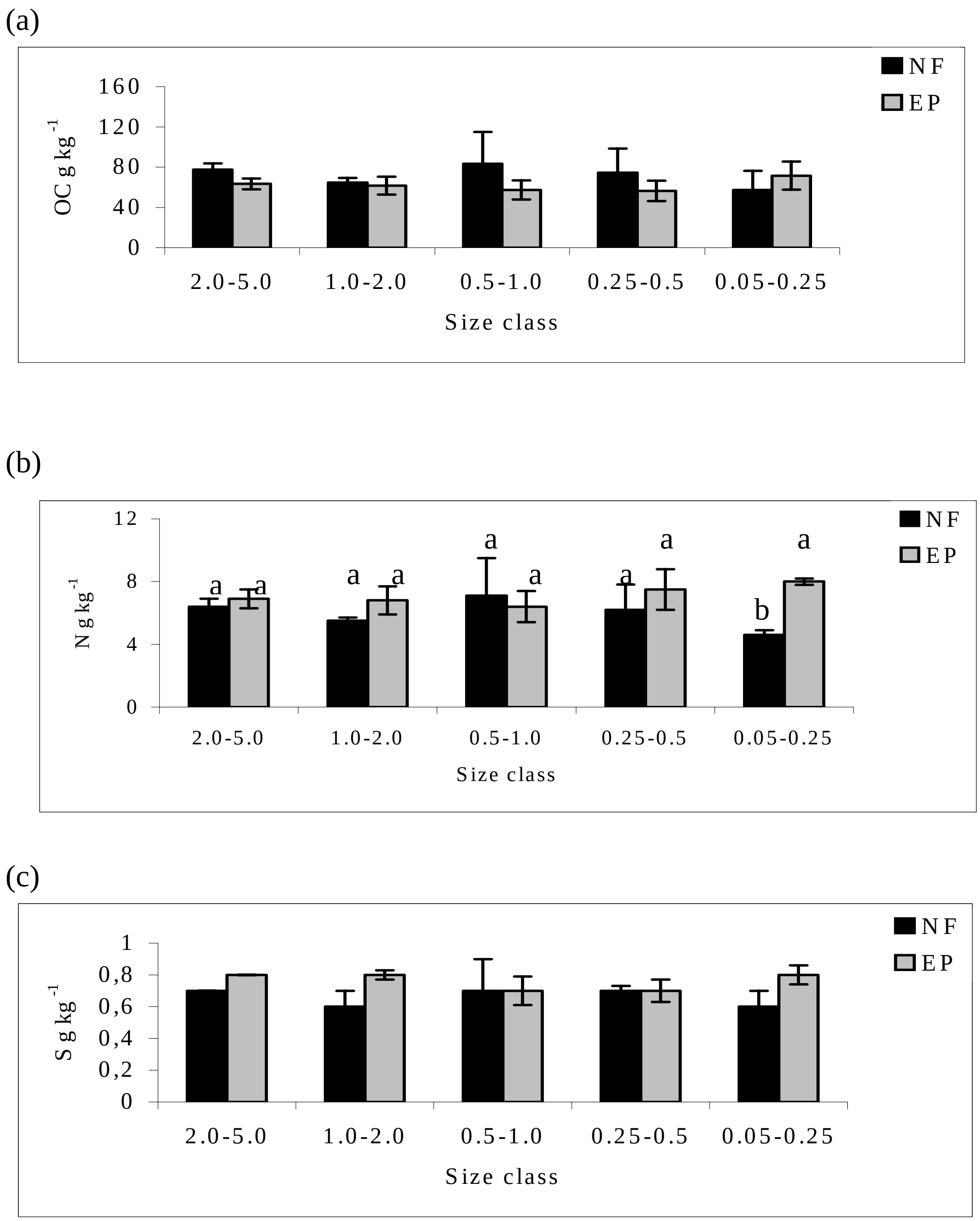

Fig. A1. Organic C (a), N (b) and S (c) concentrations (g kg^{-1} aggregate) of aggregate-size classes in soil at 0–20 cm depth under the natural forest (NF) and *Eucalyptus* plantation (EP). Vertical lines are standard errors (n=3).

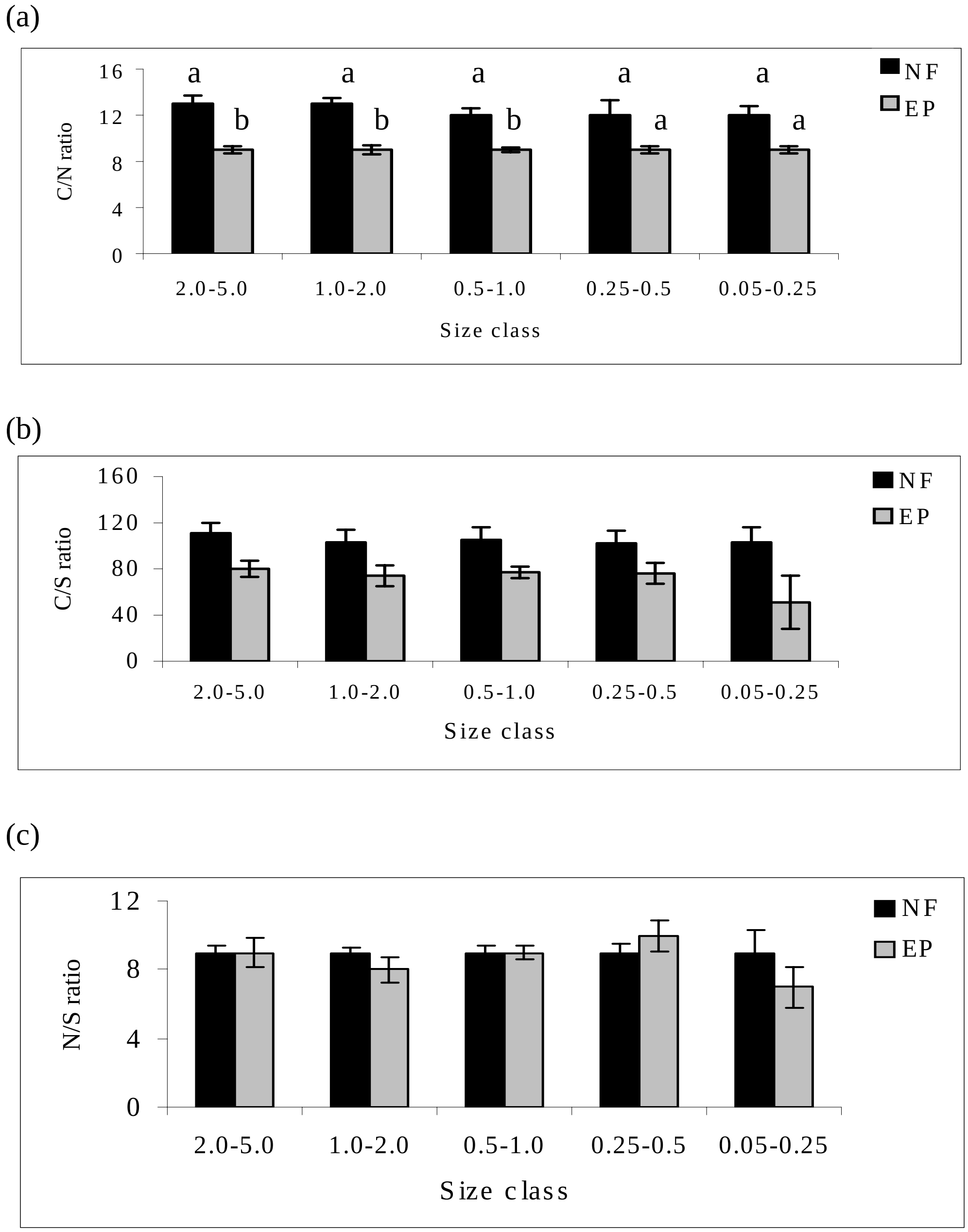

Fig. A2. C/N (a), C/S (b) and N/S (c) ratios of soil aggregate-size classes as affected by conversion of the natural forest (NF) into *Eucalyptus* plantation (EP), results refer to 0–20 cm depth. Vertical lines are standard errors (n=3).

The effect of changes in soil management on soil quality rather than on total SOM was also reported by Janzen et al. (1992) and Biederbeck et al. (1994). Mean S concentration and N/S ratio were not significantly different between the two land use types (Table A5). In the natural forest, the macroaggregate-associated LF had significantly larger OC, N and S concentration than the microaggregate-associated LF, while in the *Eucalyptus* plantation, the difference between the two size fractions was not significant. The mean OC and N concentrations, and C/N and C/S ratios of the macroaggregates in the natural forest were significantly higher than both the macro and micro aggregates in the *Eucalyptus* plantation (Table A5). Differences in microaggregate element concentrations and element ratios between the two land use types were not apparent with the exception of C/S ratio which was significantly higher in the natural forest than in the Eucalyptus plantation.

Table A5. Characteristics of the free light organic matter fractions to the soil depth of 0–20 cm.

	C	N	S			
	(mg g^{-1} fraction)			C/N	C/S	N/S
Natural forest						
Macroaggregates	138**a***	9.9**a***	1.0**a**	14**a***	144**a***	10**a**
	(6)	(0.4)	(0.07)	(0.07)	(3.4)	(0.3)
Microaggregates	84**b***	5.2**b**	0.6**b**	17**a**	148**a***	9**a**
	(12)	(1.4)	(0.07)	(2.2)	(4.4)	(1.3)
***Eucalyptus* plantation**						
Macroaggregates	56**a**	5.9**a**	0. 7**a**	9**a**	87**a**	9**a**
	(8)	(0.9)	(0.2)	(0.5)	(9)	(0.8)
Microaggregates	57**a**	4.4**a**	0.6**a**	13**a**	101**a**	8**a**
	(0.2)	(0.4)	(0.03)	(1.4)	(7)	(0.6)

Values followed by different lower case letters within a land use are significantly different ($P<0.05$). Values followed by * in the natural forest are significantly higher ($P<0.05$) than the corresponding values in the *Eucalyptus* plantation. Numbers in parentheses are standard errors (n=3).

The proportion of whole soil OC, N and S contained as free LF calculated by multiplying the quantity of the fraction recovered by concentration of each element were as much as 55, 47, and

39%, respectively, in the natural forest, and 57% of the whole soil OC, 34% of whole soil N and 36% of whole soil S in the *Eucalyptus* plantation. The C concentration of the free LF we report here is half of that reported by Besnard et al. (1996) for a French forest soil, whereas the N concentration is comparable; their values averaged about 250 mg OC and 9 mg N g^{-1} light fraction. This site difference could have resulted from variations in climate and vegetation type, and partly from the removal of large and recognisable plant materials during the sieving of our samples.

3.5. Intra-particulate OC, N, and S

After the conversion of the natural forest into the *Eucalyptus* plantation 21 years ago, total iPOM C, N and S concentrations in the 0–20 cm soil depth were significantly reduced (Table A6). The mean C/N and C/S ratios of the iPOM were also significantly narrowed from 17 and 108 in the natural forest to 9 and 50 in the *Eucalyptus* plantation, respectively, suggesting that soil organic matter under *Eucalyptus* plantation has undergone more decomposition. However, the mean N/S ratio was not significantly different between the two land use types. According to Jastrow (1996) and Six et al. (1998), the amount of total occluded POM C and nutrients per unit soil is mainly a function of aggregation., whereas the free light POM C i.e., LF C is mostly affected by residue input. In this study, although the *Eucalyptus* plantation had a slightly higher iPOM dry weight (data not shown) and nearly the same level of soil aggregation (Table A4) as in the natural forest, the losses in aggregate-protected OC and N (Table A6) were more pronounced than losses from the free LF (Table A5). This could be due to (i) a year-round input of organic material to the LF material after refforestation and (ii) gaseous losses of OM inside the aggregates caused by high fire temperatures during clearing and site preparation; otherwise biodegradation is normally nearly three times as fast outside aggregates as within them (Besnard et al., 1996). Buschiazzo et al. (2001) linked the large decrease of OC after cultivation of a forest soil to the occurrence of natural fire before cultivation. In our study, in contrast to the observations of Besnard et al. (1996) in French forest soils, the LF OC, N, and S concentrations in both forest types were always larger than the iPOM C, N, and S values. In the natural forest, the amounts of iPOM C, N, and S comprised 8, 6 and 4%, respectively, of the whole soil; while in the plantation these values were low, amounting 4% for OC, 2% for N, and 3% for S.

Table A6. Characteristics of the intra-particulate organic matter fractions to the soil depth of 0–20 cm.

	C	N	S	C/N	C/S	N/S
	(mg g^{-1} fraction)					
Natural forest						
Macroaggregates	44**a***	2.5**a***	0.3**a***	17**a***	155**a***	9**a**
	(17)	(0.8)	(0.07)	(0.9)	(21)	(0.7)
Microaggregates	14**b**	0.9**b**	0.3**a***	16**a***	61**b**	4**b**
	(3)	(0.2)	(0.1)	(2)	(25)	(1.6)
***Eucalyptus* plantation**						
Macroaggregates	8**a**	0.9**a**	0.13**a**	9**a**	62**a**	7**a**
	(2)	(0.1)	(0.03)	(0.8)	(5)	(0.7)
Microaggregates	5**a**	0.6**a**	0.13**a**	8**a**	38**b**	5**a**
	(0.6)	(0.0)	(0.03)	(1)	(5)	(1)

Values followed by different lower case letters within a land use are significantly different ($P<0.05$). Values followed by * in the natural forest are significantly different compared with the corresponding values in the *Eucalyptus* plantation. Numbers in parentheses are standard errors (n=3).

In the natural forest, significantly larger amounts of iPOM C and N were contained in macroaggregates than in the microaggregates, which contained only 36% of the C and 43% of the

N contained in macroaggregates. However, the concentrations of iPOM S in the natural forest and iPOM C, N and S in the Eucalyptus plantation were similar in both aggregate size fractions (Table A6). In both land use types, no significant differences were detected in iPOM element ratios between the macro and microaggregates (Table A6). In a study by Cadish et al. (1996) and Six et al. (1998) macroaggregate iPOMC and N concentrations were found to be higher than microaggregate iPOMC and N concentrations. Macroaggregate iPOM C, N and S concentrations in the natural forest were significantly higher than either macro or microaggregate iPOM C, N and S concentrations in the *Eucalyptus* plantation (Table A6), where as the changes in microaggregate associated element concentrations and element ratios, with the exception of S and C/N ratio, were not significant. This confirms the conclusions of Elliott (1986), Gupta and Germida (1988) and Besnard et al. (1996) that organic matter associated with macroaggregates is more labile than organic matter associated with microaggregates. Because floatable and easily recognizable materials were removed during aggregate size fractionation, the C/N ratios of the LF and iPOM fractions did not differ from one another in either forest types. In a similar study dealing with French forest soils, Besnard et al. (1996) even with out removing the floatable and easily recognisable materials also found that C/N ratios of LF and iPOM did not differ significantly from one another.

4. Conclusions

Bulk soil OC, N and S concentrations did not show significant change as a result of changes in land-use and management. However, physical fractionation of the soils into size and size/density fractions clearly showed the effect of land use and management on the quantity and quality of SOM. Our results showed that organic matter associated with the sand and silt fractions appeared to be more sensitive to changes in land use and management compared with that in clay.

Similarly, both free LF and iPOM associated with macroaggregates were found to be much more affected by changes in land use and management than that associated with microaggregates. Although the level of soil aggregation was the same between the two land-use types, loss of aggregate protected POM was higher than that of free LF after conversion to *Eucalyptus* plantation. Our results suggest that the amount of aggregate protected OM is not only influenced by aggregation but also by soil management. We conclude that high fire temperature used for site clearing and preparation resulted in gaseous losses of aggregate protected POM in the *Eucalyptus* plantation. As a result the observed change in POM resulting from changes in land-use was more evident on the quality than on the total amount. In general, losses of OM associated with the different size and size/density fractions resulting from the conversion of the natural forest to the *Eucalyptus* plantation were more pronounced than losses observed in the bulk soil.

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B Soil aggregation, and total and particulate organic matter as affected by conversion of native forests to 26 years of continuous cultivation in Ethiopia

Y. Ashagrie[1*], W. Zech[1] , G. Guggenberger[1,3] and T. Mamo[2]

[1]*Institute of Soil Science and Soil Geography, University of Bayreuth, D-95440 Bayreuth, Germany*
[2]*Winrock International, Addis Ababa, Ethiopia*
[3]*Present address: Institute of Soil Science and Plant Nutrition, Martin Luther University, D-06099 Halle, Germany*
* Correspondence: yeshanew@hotmail.com, Tel: ++49-921-55-21-46 Fax: ++49-921-55-22-46

Abstract

Conversion of native forests to cultivation is usually accompanied by a decline in soil organic carbon (SOC) and nutrients, and deterioration of soil structure. The effect of 26 years of continuous cultivation was studied on soil aggregation, and total and particulate organic matter in a Rhodic Nitisol at Munesa, south eastern Ethiopia. The objectives of this study were (i) to assess the effect of cultivation on aggregate stability, (ii) to evaluate the hierarchical model of soil aggregation and the effect of soil aggregation on soil organic matter (SOM) protection, and (iii) to determine the effect of cultivation on the quantity and quality of particulate organic matter (POM). Samples were collected from a cropland cultivated for 26 years and an adjacent natural forest. After cultivation, the proportion of water-stable macroaggregates was significantly reduced from >70% in the natural forest soil to 50% in the cultivated soil, being more pronounced in the >1 mm size aggregates. Cultivation also induced significant losses of OC and N both in bulk soil and water-stable aggregates. The OC and N associated with the larger aggregates were more affected by cultivation than the smaller aggregates. The amounts of free light fraction (free LF) C and N were more affected by cultivation than the amounts of intraparticulate organic matter (iPOM) C and N. POM C and N associated with the macroaggregates were highest compared to those of microaggregates and the effect of cultivation was more pronounced on macroaggregates associated POM relative to the microaggregates. The effect of cultivation on POM C and N was more pronounced than on total aggregate and whole soil OC and N suggesting that POM constitutes a more sensitive soil organic matter (SOM) fraction to the effects of cultivation. The data show that after 26 yr continuous cultivation both the physical and chemical properties of the soil are deteriorated.

Key words: Aggregate stability, POM, Cultivation, Nitisol, Ethiopia.

1. Introduction

Maintenance of SOM is important for sustainable use of soil resources due to the multiple effects of SOM on soil nutrient status and soil structural stability. Conversion of native forests to cultivation is usually accompanied by a decline in SOC and nutrients, and deterioration of soil structure (Dormaar, 1983, Detwiler, 1986; Brown and Lugo, 1990; Balesdent et al., 1998; Spaccini et al., 2001; Solomon et al., 2002). Cultivation effects on SOM are caused by complex interactions of the physical, chemical and biological soil processes including reduced inputs of plant residues and increased soil disturbance, but the exact nature of the changes induced by cultivation depend on the particular agronomic practices adopted and on the properties of the virgin soil (Christensen, 1992). Identification of the magnitude of such management induced changes in SOM and associated nutrients is needed to select appropriate management options.

Tillage of a soil breaks soil aggregates and exposes the previously protected OM within aggregates to microbial decomposition. According to the conceptual models of soil aggregation (Oades, 1984; Oades and Waters, 1991), aggregates of different sizes have different strength, and are stabilised by different agents. On the basis of their temporal persistence, Tisdall and Oades (1982) classified the organic binding agents of soil aggregates into: (i) transient or temporary such as polysaccharides, roots, fungal hyphae, bacterial cells, and algae which are responsible for stabilising macroaggregates (0.25–2 mm) and (ii) persistent aromatic humic materials associated with polyvalent metal cations and polymers strongly sorbed to clays mainly responsible for the integrity of the microaggregates (0.05 to

0.25 mm). The organic binding agents keep the aggregates intact and protect them against deformation from heavy rain drop impacts especially in the tropics (Spaccini et al., 2001).

Due to the labile nature of their binding agents, the effect of soil management on macroaggregates and the OM retained in it are greater than those on microaggregates with its stable and more humified organic binding agents (Oades, 1984; Elliott, 1986; Gupta and Germida, 1988; Miller and Jastrow, 1990; Cambardella and Elliott, 1993; Puget et al., 1995; Dalal and Bridge, 1996). Several authors have demonstrated that macroaggregates contain more OC and N than microaggregates (Elliott, 1986; Gupta and Germida, 1988; Beare et al., 1994a, 1994b; Cambardella and Elliott, 1993; Puget et al., 1995; Spaccini et al., 2001). The decline in total SOM during cultivation of native grassland and forest soils has been largely attributed to losses of POM (Besnard et al., 1996; Buyanovsky et al., 1994; Cambardella and Elliott, 1992, 1994; Janzen et al., 1992; Lehmann et al., 2001; Six et al., 1998). Large stocks of POM in a soil have been associated with pronounced mineralization of organically-bound nutrients such as N and are therefore intimately linked to higher soil fertility and productivity (Yakovchenko et al., 1998). POM can also serve as a sensitive indicator of changes in SOM because of its responsiveness to management (Janzen et al., 1992; Dalal and Mayer, 1987).

Except a few (Elliott et al., 1991; Lehmann et al., 2001, Spaccini et al., 2001), studies dealing with sensitive OM fractions have focused on few soil groups of temperate ecosystems only. But soils developed under different vegetation types and climate may have different modes of SOM stabilisation (Elliott, 1986). The importance of aggregate formation and stabilisation in regulating the accumulation or loss of SOM and nutrients in differently managed tropical soils is not well understood. Understanding these relationships may be of particular importance for evaluating the applicability of the hierarchical model of aggregate formation (Tisdall and Oades, 1982) to a broader range of soils and management conditions, and for developing management options for sustainable crop production systems. The objectives of this study were (i) to assess the effect of cultivation on aggregate stability, (ii) to evaluate the hierarchical model of aggregation and its effect on soil organic matter (SOM) protection, and (iii) to determine the effect of cultivation on the quantity and quality of particulate organic matter (POM).

2. Materials and methods

2.1. The study site

The study was conducted at the Munesa/Shashemenie forest enterprise site (7°34´N and 38°53´E) located about 240 km south east of Addis Ababa at an altitude of 2400 m. The area has a sub-humid tropical climate with a bimodal rainfall pattern most of it falling in July and August. Mean annual rainfall is about 1250 mm, and mean annual temperature is 19 °C with little seasonal variation. The soils are clayey and very deep with reddish brown colour, and are moderately acidic at or near the surface and slightly acidic at depth. The principal parent materials are of volcanic origin from which Rhodic Nitisols were derived (FAO, 1997). A *Podocarpus falcatus* dominated mixed natural forest and an adjacent cropland situated side by side were selected for this study. The cropland was established after clearing of part of the natural forest some 26 years ago and has been used continuously for annual crops such as maize (*Zea mays*), bread-wheat (*Triticum aestivum*), faba bean (*Vicia faba*) and sorghum (*Sorghum bicolor*) and fertilised with di-ammonium phosphate annually depending on the crops' fertiliser requirement.

2.2. Sampling

We chose three 0.06 ha plots in the natural forest and three 0.04 ha plots in the cropland randomly, and a pit was excavated to the depth of 1.2 m at the centre of each plot. In addition, four 1 m^2 sub plots were marked randomly at 6−10 m radius from the centre of each plot. Soil samples ca. 500 g were taken from the three sides of the pit by a shovel and, at three points within each of the 1 m^2 sub plots by an auger to the depth of 0−20 cm. All the auger and pit samples in each plot were mixed and the final number of samples was reduced to three per land use. After air drying, a sub sample was sieved through 5 mm sieve size for aggregate fractionation, and the remaining was sieved through 2 mm sieve size for bulk soil C and N analysis. Soil samples for bulk density determination were taken from the three sides of each pit with a 100 cm^3 metal ring.

2.3. Soil aggregate size fractionation and separation of POM

The size distribution of soil aggregates was measured by wet sieving technique following the procedures of Cambardella and Elliott (1993). A 70–80 g sample of air dried soil that passed through a 5 mm sieve size was spread on top of five stacked sieves (2, 1, 0.5, 0.25 and 0.053 mm) submerged in a bucket of deionized water. The water level was adjusted so that the aggregates on the upper sieve were just submerged. Soils were left immersed in the water for 10 min and then sieved by moving the sieve 3 cm vertically 50 times during a period of 2 min. During the sieving process, floatable materials >2 mm were removed and discarded. The material remaining on the 2 mm sieve was transferred to a glass pan. Soils plus water that passed through the sieve was poured onto the next finer sieve and the processes repeated, but floatable materials were not removed and discarded. The different aggregate sizes were dried in the oven at 50°C overnight for chemical analysis. The mean weight diameter (MWD) of water stable aggregates was then determined as the sum of the percentage of soil on each sieve multiplied by the mean diameter of adjacent sieves i.e. MWD=∑ (percent of sample on sieve x mean intersieve size).

The separation of POM was done following the procedure of Six et al. (1998). The fractions in the >0.25 mm size aggregates were bulked as macroaggregates, and the 0.053 to 0.25 mm size was taken as microaggregates. After drying (105°C) in the oven overnight and cooling in a decicator to room temperature, about 10 g macro and microaggregates was suspended in 35 ml sodium polytungstate adjusted to a density of 1.8 g cm^{-3} in a conical centrifuge tube and hand-shaken until all the material was suspended. The suspension was allowed to stand for 20 min before centrifugation at 1250 rpm for 60 min. After centrifugation, the floating material was collected on 2 µm pore size filter paper and rinsed thoroughly with deionized water to remove sodium polytungstate. The material in the < 1.8 g cm^{-3} fraction is referred to as free LF. The heavy fraction remaining in the tube was washed twice with 50 ml deionized water and dispersed in 50 ml of 5% sodium hexametaphosphate by shaking in a reciprocal shaker for 18 hours. The dispersed heavy fraction was rinsed through a 0.053 mm sieve with deionized water. The material remained on the sieve is iPOM + sand. Both the free LF and iPOM + sand were dried in the oven at 50°C overnight. The dried sub samples from each aggregate size class, and the free LF and iPOM + sand were finely ground in a rotary ball mill for chemical analysis.

2.4. Laboratory analysis

Bulk density was determined after drying the soil in an oven at 105°C. Organic C and N concentrations in bulk soil, size fractions and POM were determined using CHNS–analyzer (Vario EL, Elementar Analysensysteme GmbH, Hanau, Germany).

2.5. Statistical analysis

The experiment had a split-plot design (three replications) with land use as a main plot and soil aggregate size as a subplot. Analysis of variance (ANOVA) was conducted using MSTAT-C version 2. One way ANOVA was conducted to detect significant differences between land use and, among aggregate size means within a land use. Two way ANOVA was performed to test significant differences in aggregate size means between land use types.

Significant treatment means were separated using Tukey´s honestly significance difference test (HSD) at $P < 0.05$.

3. Results and discussion

3.1. Aggregate size distribution and stability

Table B1 shows that, in the forest soil, after 10 min of slaking, most soil was found in 0.25 to 2 mm size macroaggregates and to a lesser extent in microaggregates (0.053 to 0.25 mm). In contrast, in the cultivated soil, significantly large proportion of the soil was retained as microaggregates and small macroaggregates (0.25 to 0.5 mm).

Table B1. Distribution and MWD of water-stable aggregates after 26 years continuous cultivation of the natural forest soil.

Aggregate size (mm)	Distribution (%) Natural forest	Cultivated	MWD (mm) Natural forest	Cultivated
2–5	10**bA** (0.22)	0.8**eB** (0.09)	0.35**aA** (0.01)	0.03**cB** (0.003)
1–2	21**aA** (1.4)	5**dB** (0.87)	0.32**aA** (0.02)	0.08**bB** (0.01)
0.5–1	21**aA** (1.3)	17**cA** (0.62)	0.16**bA** (0.01)	0.13**aA** (0.005)
0.25–0.5	21**aA** (1.6)	27**bA** (2.4)	0.08**cA** (0.01)	0.10**abA** (0.01)
0.053–0.25	14**bB** (2.6)	35**aA** (0.84)	0.01**dA** (0.002)	0.02**cA** (0.001)
Total	87	85	0.92	0.36

Means followed by the same lower case letter in a column and by the same upper case letter in a row are not significantly different. Numbers in parentheses are standard errors (n=3).

After 26 years continuous cultivation, the amount of water stable macroaggregates was significantly reduced from > 70% in the natural forest soil to 50% in the cultivated soil, while that of microaggregates increased by a factor of 2.5, indicating that cultivation resulted in the structural degradation of this soil. This could be attributed to the breakdown of aggregates by tillage, differences between the two land use types in annual organic matter input which gives cementing agents and the enmeshing effects of roots and associated mycorrhizal hyphae. These results confirm earlier observations that macroaggregates are dynamic in nature and the size distribution of macroaggregates is affected by the change in land use and management (Dormaar, 1983; Elliott, 1986; Beare et al, 1994b; Puget et al., 1995; Spaccini et al. 2001). The relatively higher proportions of soil in the macroaggregates of the forest soil further suggest that the soil aggregates under forest were not greatly affected by slaking or were more stable than the cultivated soil.

There was a significant land use x aggregate-size interaction on the distribution of water stable aggregates indicating that the effect of cultivation was much more evident in the larger macroaggregates i.e >1–2 mm size than the smaller macroaggregate-size classes (Table B1). As with the findings of Haynes (1999) in pasture soil and Spaccini et al. (2001) in forest soil, in this study, the >2–5 mm and >1–2 mm classes of the forest soil were 13 and 4 times, respectively, larger than in the cultivated soil (Table B1). The relatively higher level of reduction in larger macroaggregates compared to the smaller macroaggregates up on cultivation could be mainly because the former are largely dependent on live and decaying plant roots and fungal hyphae and probably casts of earthworms and termites which are rapidly destroyed by tillage (Tisdall and Oades, 1982). Beare et al. (1994b) also reported a reduction in the >2 mm aggregates of cultivated surface soil and redistribution of particles to smaller size classes in conventional tillage than in no tillage soil. Tisdall and Oades (1979) and Angers (1992) reported that the effects of cropping treatments on soil aggregates were mostly apparent in the >2 mm size fractions. A greater shift in water stable aggregates from large macroaggregates to smaller macroaggregates and microaggregates up on cultivation had also led to a significant reduction of MWD from 0.92 mm in the forest soil to 0.36 mm in the cultivated soil (Table B1). Spaccini et al. (2001) reported MWD reductions of 37 to 76% on cultivated Ethiopian Vertisols, Alfisols, Entisols, and Andisols relative to the forest soil, being highest in Vertisols and lowest in Andisols.

3.2. Whole soil C and N

Conversion of the natural forest into continuous cultivation had resulted in significant reductions of both the concentrations and stocks of OC and N (Table 2). C/N ratio was also significantly narrowed from 12 in the forest soil to 9 in the cultivated soil (Table B2). The substantial losses of organic C and N after 26 years of cultivation were expected since the break-up of soil aggregates and increased aeration caused by tillage both favour decomposition of soil organic matter. In addition, reduced inputs of organic matter because of the removal of large amounts of above-ground biomass at harvest and burning of crop residues during land preparation are also responsible for the lower C and N content of the cultivated soil. Comparable losses of SOC and nutrients due to cultivation of forest soils have been reported in many studies (Brown and Lugo, 1990; Davidson and Akerman, 1993; Buschiazzo et al., 2001; Spaccini et al. 2001; Solomon et al., 2002).

Table B2. Bulk soil chemical and physical properties under the different land-use types, results refer to the 0-20 cm soil depth.

	C (g kg^{-1})	N	C/N	Bd (g cm^{-3})	C (kg m^{-2})	N
Natural forest	72**a**	6**a**	12**a**	0.86**b**	12.4**a**	1.0**a**
	(7.4)	(0.6)	(0.6)	(0.02)	(0.9)	(0.01)
Cultivated	34**b**	3.9**b**	9**b**	0.99**a**	6.7**b**	0.76**b**
	(4.9)	(0.5)	(0.2)	(0.03)	(0.2)	(0.03)

Bd: bulk density

Means followed by different letters in a column are different from each other. Numbers in parentheses are standard errors (n=3).

3.3. Total OC and N of aggregates

Data on the OC and N concentrations (g kg^{-1} aggregates) and, C/N ratio of the different aggregate size classes are reported in Table B3. In the soil under natural forest, none of the parameters showed significant differences among aggregate size classes. In contrast, in the cultivated soil, the OC and N concentrations were significantly different among the different size classes, and appeared to decrease as size increases from 0.053 to 2 mm diameter (Table B3). This could be attributed partly to the redistribution and / or transfer of organic matter from the large aggregates to smaller ones either in the process of biodegradation or by mechanical disruption of the large macro-aggregates (Dormaar, 1983; Christensen, 1992). Oades and Waters (1991) suggested that when roots and hyphae that hold the macroaggregates die and disrupted by tillage or fauna, the decomposed fragments probably become the organic core in the 0.02 to 0.25 mm size microaggregates. Alternatively, the extent of OM decomposition under arable use may be different for the different aggregate fractions. Our results in the cultivated soil contrast with the observations of Elliott (1986), Cambardella and Elliott (1993) and Puget et al. (1995), who observed an increase in OC concentration of the cultivated soil with an increase in diameter of the fractions. The OC and

N concentrations associated with each maroaggregate size in the natural forest were two to threefold higher than the corresponding values in the cultivated soil, although the differences generally are not statistically significant. The effect of cultivation was more pronounced on OC than on N. This was further reflected by a significantly narrower mean C/N ratio in the cultivated soil aggregates (9–10) than in the forest soil aggregates (12–13). In both land use types, C/N ratios of the bulk soil and the different water stable aggregates were nearly the same (Tables B2 & B3).

Table B3. Organic C and N concentrations (g kg^{-1} aggregate) and C/N ratios of soil aggregate size classes to the depth of 0−20 cm as affected by 26 years continuous cultivation.

Aggregate size	OC		N		C/N	
(mm)	NF	Cu	NF	Cu	NF	Cu
2-5	78**a** (6.1)	23**c** (2)	6.4**a** (0.5)	2.5**d** (0.1)	12**a** (0.8)	9**a** (0.2)
1-2	65**a** (4.4)	27**bc** (1)	5.5**a** (0.2)	2.9**cd** (0.3)	12**a** (0.5)	10**a** (0.7)
0.5-1	84**a** (32)	33**ab** (4)	7.1**a** (2.4)	3.7**ab** (0.5)	12**a** (0.6)	9**a** (0.03)
0.25-0.5	74**a** (24)	31**b** (1)	6.2**a** (1.6)	3.4**bc** (0.1)	12**a** (1.3)	9**a** (0.1)
0.053-0.25	57**a** (11)	40**a** (1)	4.6**a** (0.3)	4.3**a** (0.03)	13**a** (0.8)	9**a** (0.2)

NF: Natural forest; Cu: cultivated. In a column, means followed by the same lower case letter are not significantly different. Numbers in parentheses are standard errors (n=3).

Mean total amounts of OC and N (g kg^{-1} whole soil) of the different aggregate size classes did not significantly differ between the two land use types (Table B4), but land use x aggregate size interaction was significant. With the exception of N in the 0.25-0.5 mm size class, the amounts of C and N in the different macroaggregate size classes of the cultivated soil were significantly lower than those in the natural forest. However, the amounts of microaggregate associated C and N were significantly higher in the cultivated soil than that of the natural forest mainly due to large proportion of soil in this size class. In the natural forest, although the proportion of water stable aggregates was different among the different size classes, differences in the amounts of C and N (g kg^{-1} whole soil) among the different size classes did not reach significance.

Table B4.Total amounts of OC and N (g kg^{-1}whole soil) associated with each aggregate-size in natural forest and cultivated field soils.

	Size fractions (mm)				
	2–5	1–2	0.5–1	0.25–0.5	0.053–0.25
Organic C					
Natural forest	8**a** (0.4)	14**a** (1.4)	18**a** (5.7)	16**a** (3.5)	8**b** (1.8)
Cultivated	0.18**bD** (0.02)	1.4**bD** (0.24)	5.6**bC** (0.65)	8.4**bB** (1.0)	14**aA** (0.11)
Total N					
Natural forest	0.64**a** (0.04)	1.2**a** (0.09)	1.5**a** (0.43)	1.3**a** (0.22)	0.64**b** (0.14)
Cultivated	0.02**bD** (0.003)	0.15**bD** (0.03)	0.63**bC** (0.09)	0.93**aB** (0.08)	1.5**aA** (0.03)

Means followed by the same lower case letter in a column and by the same upper case letter in a row are not significantly different. Numbers in parentheses are standard errors (n=3).

In contrast, in the cultivated soil, the amounts of C and N were significantly different among the different aggregate sizes; increasing steadily as the proportion of water stable aggregates and concentrations of C and N increased (Tables B1, B3 &B4). Significant reductions in OC and N concentrations due to cultivation of a native vegetation soil were reported by Buschiazzo et al. (2001) from macroaggregates of Typic Ustipsament. Spaccini et al. (2001)

reported better protection of carbohydrates associated with smaller aggregate size classes for Ethiopian and Nigerian soils when forests are converted to cultivation.

The relationship between WSA and, OC and N concentrations did not show significant coorelations (data not shown) suggesting that other factors such as inorganic soil constituents (Tisdall, 1996) and, the arrangement of the organic compounds other than the absolute organic matter quantity present might be responsible for the aggregation of this tropical soil (Hamblin and Greenland, 1977; Dormaar, 1983). It has been suggested that diverse organic and inorganic constituents participate in the binding of soil particles in to water stable aggregates and the relative importance of each varies in differing situations (Haynes and Beare, 1996). Our results agree with Dormaar (1983) and Lehmann et al. (2001), who observed no relationship between WSA and organic carbon.

3.4. Free LF and iPOM C and N

The mean C and N concentrations (g kg^{-1} fraction) in both the free LF and iPOM fractions were significantly reduced after cultivation with much of the reductions occurring from the macroaggregate associated fractions (Table B5). The effect of cultivation was more pronounced on the iPOM C than on the free LF C. This was further evidenced by a significantly narrower iPOM C/N ratio under cultivation than the natural forest (Table B5) suggesting that much of the readily decomposable components have been lost, leaving old and more humified components. However, the free LF C/N ratio (Table B5) was not significantly changed after cultivation probably due to recent inputs of less decomposed fresh organic residues from roots of the previous crop. The mean C/N ratios of the free light and iPOM fractions in both land use types were relatively wider than the corresponding whole soil C/N ratios (Tables B2&B5). Christensen (1992) suggested that SOM in LF has usually a wider C/N ratio than in whole soils and heavy fractions. In the present study, no significant difference was detected between the C/N ratios of free LF and iPOM in either of the land use types probably due to the removal of free and released floatable easily recognisable fresh plant residues from the samples soon after slaking. However, this is not unusual as Besnard et al., (1996) also found no significant difference in POM C/N ratio of different positions.

Table B5.Characteristics and total amounts of POM associated with each aggregate size in natural forest and cultivated field soils

	C	N		C	N
	(g kg^{-1} fraction)		C/N	(g kg^{-1}whole soil)	
Natural forest					
Free LF					
Macroaggregates	138**a***	9.9**a***	14**a**	38**a***	2.7**a***
	(0.6)	(0.04)	(0.1)	(9.3)	(0.6)
Microaggregates	84**b***	5.2**a**	17**a***	1.5**b**	0.10**b***
	(1.2)	(0.1)	(2.2)	(0.8)	(0.06)
iPOM					
Macroaggregates	44**a***	2.5**a**	17**a***	5.6**a**	0.31**a**
	(1.7)	(0.08)	(0.9)	(2.4)	(0.1)
Microaggregates	14**b***	0.9**a**	16**a***	0.3**b**	0.02**a**
	(0.3)	(0.02)	(2.1)	(0.01)	(0.08)
Cultivated					
Free LF					
Macroaggregates	59**a**	4.6**a**	13**a**	3.9**a**	0.3**a**
	(0.3)	(0.02)	(0.3)	(0.8)	(0.06)
Microaggregates	38**a**	3.1**a**	12**a**	0.39**b**	0.03**a**
	(0.3)	(0.03)	(0.1)	(0.1)	(0.01)
iPOM					
Macroaggregates	12**a**	1.2**a**	10**a**	1.5**a**	0.15**a**
	(0.1)	(0.02)	(0.5)	(0.2)	(0.02)
Microaggregates	4.3**b**	0.43**a**	10**a**	0.3**a**	0.03**a**
	(0.04)	(0.003)	(1)	(0.07)	(0.01)

Means followed by the same letter within land use for each POM fractions associated with macro and microaggregates are not different. Means followed by * in the natural forest are significantly different from the corresponding values in the cultivated soil. Numbers in parentheses are standard errors (n=3).

The total amounts of the free LF and iPOM C and N (g kg^{-1}whole soil) were significantly larger in the natural forest than in the cultivated soil (Table B5). Cultivation had resulted in the depletion of over 80% of the free LF C and N, and 69% of the iPOM C and 45% of iPOM N. This could be attributed mainly to the reduced inputs of organic matter and, faster biodegradation of POM due to the more favourable environmental conditions for biological activity such as higher temperature and moisture, and aeration created by tillage under the cultivated soil. The relative losses of POM C and N were larger than those observed in the whole soil and in water stable aggregates, indicating that POM constitutes soil organic matter fraction more sensitive to the effects of cultivation. Similar results have been reported for situations dealing with the conversion of native forest to corn cultivation (Besnard et al., 1996) and native grassland soil to cultivation (Cambardella and Elliott, 1992; Six et al., 1998). After 35 years continuous cultivation of a soil under virgin brigalow (*Acacia harpophylla*), Skjemdstad et al. (1986) reported as much as 95% OC loss from the light fraction. Gregorich et al.(1997) also reported losses of substantial amounts of both free and physically protected organic matter after 32 years cultivation of a sod soil. Averaged over aggregate sizes, much of both the free LF and the iPOM C and N were associated with the macroaggregates compared to the microaggregates, with the LF accounted for much of the POM C and N associated with both aggregate size fractions.

A significant land use x aggregate size interaction indicates that the amounts of the free LF C and N associated with both macro and micro aggregates were significantly larger in the forest soil than in the cultivated soil (Table B5). With respect to the amounts of iPOM C and N, however, the effect of cultivation was evident only in the macroaggregate associated fraction due to the reduction of the proportion of macroaggregates by tillage and due to the labaile nature of macroaggregate associated OM to accelerated decomposition induced by cultivation (Skjemstad et al., 1990; Buyanovsky et al., 1994; Jastrow et al., 1996). Jastrow (1996) found relatively higher proportions of POM C inside the macroaggergates of the virgin prairie soil compared to corn field and restored prairie soil. Six et al. (1998) also reported higher iPOM levels in water stable macroaggregates sampled from native sod soil than those from the cultivated soil. In the natural forest, the proportion of whole soil organic C and N found in free LF accounted for 55% and 47%, respectively, and that of iPOM C and N comprised 8% and 6%, respectively. After 26 years cultivation, the free LF C and N represented 13% of whole soil OC and 8% of whole soil N and the corresponding proportions in iPOM C and N were 5%. These results indicate that the free LF accounted for much of the losses of whole soil OC and N due to cultivation, whereas the iPOM C and N appeared to be a relatively constant fraction of the total OC and N pool, as was also observed by Jastrow (1996). In Jastrow´s (1996) study about 12 to 17 % of the total amount of OC in soils under cornfield and restored prairie and about 14% in virgin prairie soil were found to be composed of POM. In a similar study conducted by Cambardella and Elliott (1992), it was found that POM C comprised about 39% of the total SOC in Nebraska native sod.

4. Conclusions

Cultivation had lead to a reduction of the proportion of water stable macroaggregates and an increase in the proportion of microaggregates. The effect of cultivation on the amount of macroaggregates was most evident in the > 1 mm size aggregates. The breakdown of larger aggregates up on slaking to smaller aggregates in both soil types demonstrated the hierarchical concept of aggregate formation in this Nitisol. The result also shows that the OM that binds microaggregates in to macroaggregates was found to be the most prominent sources of OC and N lost due to cultivation. However, there was no correlation between SOC and N, and aggregate stability. The POM C and N were much more affected by cultivation than the whole soil and, total aggregate OC and N, being highest from the macroaggregates. Of the different POM fractions the losses of the free LF C and N due to cultivation were more pronounced than the iPOM fraction, making it a more biodegradable organic matter pool. Generally the results indicate that cultivation of the natural forest soil for 26 years resulted in the reduction of organic matter and deterioration of soil structure.

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