Temporal Changes of Biomass Production, Soil Properties and Ground Flora in *Eucalyptus globulus* Plantations in the Central Highlands of Ethiopia

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Abstract

Blue gum (*Eucalyptus globulus*) plantations are managed as a successive short rotation coppice system for more than a century in the central Ethiopian highlands. Consecutive cutting cycles of these plantations may alter forest site productivity, soil physico-chemical properties, and forest floor environment. To test this hypothesis, ten plantations ranging from 11-60 years (2-10 cutting cycles), with 1, 4, 5, 7 and 9 years old coppice-shoots were selected in the central highlands of Ethiopia, where the most extensive and oldest *Eucalyptus* plantations exist within the country.

The thesis summarizes the temporal dynamics of above-ground biomass and nutrient partitioning (Paper I & II), soil physical and chemical properties (Paper III), ground flora composition and diversity (Paper IV) in a number of *Eucalyptus globulus* plantations along a chronosequence.

Mean above-ground biomass ranged from 11 to 153 ton ha^{-1} in 1 and 9 year old plantations, respectively. In contrast, above-ground biomass production declined markedly across the total plantation ages (cutting cycles). On average, stand biomass production was reduced by 14% from the second and third cutting cycles to the sixth and seventh cycles, and by a further 86% from the second and third to the tenth cutting cycles. Although non significant, a similar declining trend was observed for the vegetation cover, species composition and diversity of the ground flora in consecutive cutting cycles.

The macro-nutrient concentrations (N, P, K, Ca and Mg) in above-ground tree biomass showed significant differences between tree components. The nutrient concentrations (N, P, K, Ca and Mg) were highest in foliage, while the lowest concentrations were obtained in stemwood and branch tree parts. The nutrient content (kg ha^{-1}) followed the order: leaves > stemwood > stembark > twigs > branches. For most components, neither coppice-shoot age nor cutting-cycle number had a significant influence on the macronutrient concentrations. Although not significant, a decreasing nutrient concentration trend was generally observed with the coppice-shoot age.

Soil nutrient concentrations (N, Ca and Mg) showed a statistically significant decline with the advancement of cutting cycles. Thus, the soil nutrient stock (kg ha^{-1}) in the tenth cycle was the poorest of all the stands. The reduction of macronutrient stock in consecutive cutting cycles appears to be related to repetitive harvests in short rotations, whole-tree harvesting and nutrient loss caused by complete forest litter removal. Hence, deleterious anthropogenic practices associated with consecutive cutting cycles may eventually lead to yield decline and forest site degradation on a long-term basis. Therefore, it can be suggested that with appropriate silvicultural and management interventions, it could be possible to mitigate site quality decline over the successive cutting cycles of *Eucalyptus* plantations. For long-term site quality and sustainability of biomass production, prolonging the length of cutting cycles, and prohibiting or controlling recurrent litter raking appears to be imperative, because these practices may jeopardize the sustainable management of *Eucalyptus globulus* plantations in the central highlands of Ethiopia.

Keywords: Above-ground biomass, allometric relationships, chronosequence, central Ethiopia, coppice-shoot age, cutting cycles, deforestation, ground flora composition and diversity, nutrient concentration, nutrient stock, plantation age.

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Dedication

Dedicated to: my late mom, Beshewa G/Michael and my late dad, Zewdie Askale.

Contents

Appendix

This thesis is based on the following papers, which are referred in the text by their corresponding Roman numerals:

I. Zewdie, M., Olsson, M. & Verwijst, T. 2008. Biomass production and allometry of *Eucalyptus globulus* coppice plantations along a chronosequence in the central highlands of Ethiopia (*Under submission to Biomass & Bioenergy*).

II. Zewdie, M., Olsson, M. & Verwijst, T. 2008. Nutrient content and distribution in above-ground biomass of *Eucalyptus globulus* coppice plantations in the central highlands of Ethiopian (*Under submission to Forest Ecology and Management*).

III. Zewdie, M. & Olsson, M. 2008. Soil physical and chemical properties status in *Eucalyptus globulus* plantations chronosequence in the central highlands of Ethiopia (*Manuscript*).

IV. Zewdie, M., Olsson, M. & Verwijst, T. 2008. Ground flora composition, diversity and biomass production in consecutive cutting cycles of *Eucalyptus globulus* plantations in the central highlands of Ethiopia (*Manuscript*).

Abbreviations

AfDB	African Development Bank
ECA	European Commission for Africa
EFAP	Ethiopian Forestry Action Programme
DANIDA	Danish International Development Agency
GDP	Gross Domestic Product
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel of Climate Changes
IMF	International Monetary Fund
MoNRDEP	Ministry of Natural Resources Development and Environmental Protection
SIDA	Swedish International Development Agency
UNESCO	United Nation Educational Scientific and Cultural Organization
UNFP	United Nations Population Fund
UNSO	United Nations Sudano-Sahelian Office
WB	World Bank
WFP	World Food Program

1 Introduction

1.1 General background

1.1.1 Threats, challenges and opportunities to forest resources in the tropics

The deteriorating global environment has never made its impact more strongly felt today than ever before. People from all areas of the world and from all walks of life are talking about global warming, the thinning of the ozone layer, tropical deforestation in developing countries, and the threat of pollution to our environment. Rising concentrations of greenhouse gases, especially carbon dioxide released by the burning of fossil fuels, are leading to global warming. Based on the intergovernmental Panel of Climate Changes (IPCC), if the current trend continues unabated, temperature will rise by 1.4-5.8 °C over the next century. Furthermore, sea water level will rise by about just a meter, and coastal cities and deltas will be inundated. Already global warming had an alarming impact in some developing countries, particularly in the tropical regions causing a significant food supply decline (IPCC, 2001). The recent synthesis report by the IPCC scientists in Bali (IPCC, 2007) expressed very high confidence that anthropogenic activities have warmed the climate since 1750. Currently, tropical forest conversion, shifting cultivation, clearing for secondary vegetation make significant contribution to global emission of greenhouse gases, and have the potential for large scale emissions in future decades (Fearnside, 2000).

Over the past decade there has been a growing serious concern regarding the status and use of global natural forests in the tropics (Udarpe & Chai, 1992; Pearce & Brown, 1996). Most of the current decline in the world forest cover is taking place in developing countries that are primarily in tropical and subtropical regions. Prominent among the causes of decline in forest area in these regions are unregulated timber removal and conversion of forests to farm and pasture lands (Onyekwelu, 2006). Deforestation and land degradation in the tropics are proceeding at an unprecedented rate. FAO (2005) reported that each year, an estimated 15.4 million ha of tropical forests and woodlands are destroyed or seriously degraded. Tropical forest degradation affects not only wood production but also global warming, and thereby exacerbates the desertification process in the tropics (Evans, 1992).

To avert the environmental degradation caused by tropical forests destruction, launching and promoting tree plantations world wide and particularly in the tropics have been stressed (Nambiar & Brown, 1997). During the 1990s, while natural forest and total forest areas continued to dwindle world wide, forest plantation areas increased by 20 and 12 million hectares in tropical and non-tropical regions (Carnus et al., 2006). Further the authors noted that between 1990 and 2000, the rate of conversion from natural to plantation forests in the tropics was about similar magnitude to the increase in natural forests, resulting from natural regeneration of non-forest areas, and only 7% of the area of natural forest converted to non-forestland uses. Globally forest plantations currently cover approximately 187 million ha, which is an increase of about 20 million ha since 1995, and the rate of expansion is being continuing at 4.5 million ha annually (FAO, 2001a). Of the total plantation area world wide, approximately 10 million ha are estimated to be fast growing tree species (Cossalter & Smith, 2003). In contrast to plantation forests increase over the last decade, the total natural forest area has declined by 14.6 million ha. According to the European Commission Joint Research Center Report (2002), Southeast Asia had the highest annual rate of deforestation at 0.91%, followed by Africa which was losing its forests at about half this rate, at 0.43% and at 0.37% Latin America showed the lowest deforestation rate over 1990-1997.

Higher production rate per unit area, opportunity for genetic improvement, and feasibility for applying intensive management on short rotation have contributed to the rapid expansion of forest plantations in the tropics (Tiarks et. al., 1998; Evans, 1992). Between 1965 and 1980, the area under forest plantations in the tropics tripled; this area further doubled during the 1980s (Evans, 1992). According to data summarized by Evans (1992) and the Food and Agriculture Organization of the United Nations, the plantation area in the tropics amounts to 40 to 50 million ha more than 15 years ago, and this area is supposed to increase in the future. In general, a third of today's plantations are found in the tropics and two thirds in temperate and boreal zones.

In Ethiopia, the natural forests that once covered over 40 million ha (c. 35%) of the land area have, as in most tropical countries, been declining both in size and quality (EFAP, 1994; Bekele, 2001). Best estimate made by FAO (2000) and Earth Trends (2003) indicate that in 1997 the total area of natural forest was 5.8 million hectares and later reduced to 4.4 million ha in 2000 with an annual loss of 375,000 ha. It has been projected that if the rate of deforestation continues unabated, the area cover by natural forests in 2015 will be reduced to scattered minor stands of heavily disturbed forests in remote parts of the country (Stiles et al., 1991). Overall, massive deforestation coupled with rapid demographic growth engender twin development problems: extreme poverty and environmental crises that lead to land and water resources degradation as well as loss of biodiversity (Demel, 2002; Jagger & Pender, 2003) in Ethiopia.

Ethiopia is ranked as one of the poorest countries in the world and has a per capita GDP of US$ 153 (IMF, 2006). The population is expanding by about 2.5% annually and in 2005 numbered 81.2 million (UNFPA, 2007) which places the country as one of the most densely populated countries in the sub-Saharan African region (IAEA, 2005). Approximately 85% of the population is supported by agriculture, mainly in the form of subsistence farming. Large natural forest areas have been cleared mainly for agriculture. Those that remain are being used unsustainably to provide fuelwood and construction materials for household usage. According to the World Bank (2001), fuelwood and charcoal accounts for 94.7% of Ethiopia's energy consumption. This figure may rise to 99% for household consumption in rural areas.

1.2 Significance, extent and growth performance of *Eucalyptus* plantations in Ethiopia

To cope with the deepening shortage of wood, mainly fuelwood, Ethiopia launched already at 1890s, during the reign of Emperor Menelik II, a plantation program with fast growing exotic trees such as *Eucalyptus*. In the 1970s, the plantation area around Addis Ababa was about 15,000 ha and in other parts of the country approximately 76,000 ha of plantations were established. Between 1975 and 1994, further new plantations were established mainly in peri - urban areas with aid from international donors (AfDB, DANIDA, SIDA, UNSO, WFP and WB). Regardless of tree species, a recent estimate puts the total plantation area in the country at 491,000 ha, and annual planting rate is said to be about 12, 000-17,000 ha (Berhanu, 2005; FAO, 2006). It needs to be noted that the available information on the country's forest resources, extent and rate of depletion are scarce and sometimes inconsistent (Halvor, 1995).

In the Ethiopian highlands, which suffer from severe deforestation and biomass fuel crises, *Eucalyptus* is the prominent tree in government and community estate plantations because of its readily propagation through coppicing, resistance to browsing by livestock, and rapid growth rate. Currently, about 55 species are available in Ethiopia (Friis, 1995). However, the most common and widespread *Eucalyptus* species include: *Eucalyptus globulus* Labill., *Eucalyptus camaldulensis* Dehnn., *Eucalyptus saligna* Sm., *Eucalyptus grandis* W. Hill ex Maid. and *Eucalyptus tereticornis* Sm. Planting *Eucalyptus* is expanding from state owned forestry enterprises and projects to community woodlots, household and farm field boundaries. *Eucalyptus* plantations occupied about 148,000 ha in year 2000 and the area of planting is increasing (FAO, 2000).

Eucalyptus globulus converts energy and available water into biomass more efficiently compared with exotic coniferous tree species under most conditions of the Ethiopian highlands (Pohjonen & Pukkala, 1990). It is usually harvested at an age of 5-7 years for pole and construction materials. However, the maximum wood production is commonly attained at 18 years (Pohjonen & Pukkala, 1990). Estimates of mean annual increment (MAI) in Ethiopian *Eucalyptus* woodlots range from approximately 10 m^3 ha^{-1} $year^{-1}$ (Newcombe, 1989; Pohjonen & Pukkala, 1990), to 57 m^3 ha $year^{-1}$ (Stiles et al., 1991). Estimates for other coniferous plantation species range from 4.2 m^3 ha^{-1} $year^{-1}$ on low potential sites, to 9.6 m^3 ha^{-1} $year^{-1}$ on high potential sites, whereas the MAI of natural wood land is approximately 1.2 m^3 ha^{-1} $year^{-1}$ (EFAP, 1994). Hence, *Eucalyptus* is an out performing exotic tree species that would alleviate an ever increasing wood demand of the country.

1.3 An overview on nutrient cycling in forest plantations

The uptake of nutrients by plant roots, their incorporation into living tissue, and the release of nutrients during organic matter decomposition cause nutrients to flow or cycle within terrestrial ecosystems. Nutrient cycles are biogeochemical processes, because they are controlled by the physiological activities of soil micro-organisms, and the geochemical processes in soil that control nutrient supply (Schlesinger, 1991). Nutrient cycling and energy flow are inherently linked in such way that the cycling of nutrients is concomitant to the transfer of energy (in some form) from one compartment to the others. If an element cycles between the atmosphere and organisms, then the flow primarily is a biochemical cycle, i.e., internal cycle within organisms system. Both types of chemical cycles, i.e. biogeochemical and biochemical cycles exchange nutrients through different input and output fluxes. Nutrient cycling in forest plantations can be defined as the exchange of elements between the living and non-living components of an ecosystem. The nutrient cycling process includes: nutrient uptake and storage in vegetation in perennial tissues, litter production, litter decomposition, nutrient transformations by soil fauna and flora, nutrient input from the atmosphere and the weathering of primary minerals, and nutrient export from the site by harvest, leaching, erosion and gaseous transfers (Johnson, 1994; Heilman & Norby, 1997) and litter raking (Fig. 1).These processes are controlled mainly by climate, abiotic (topography, parent material), and biotic factors (Marker, 2002).

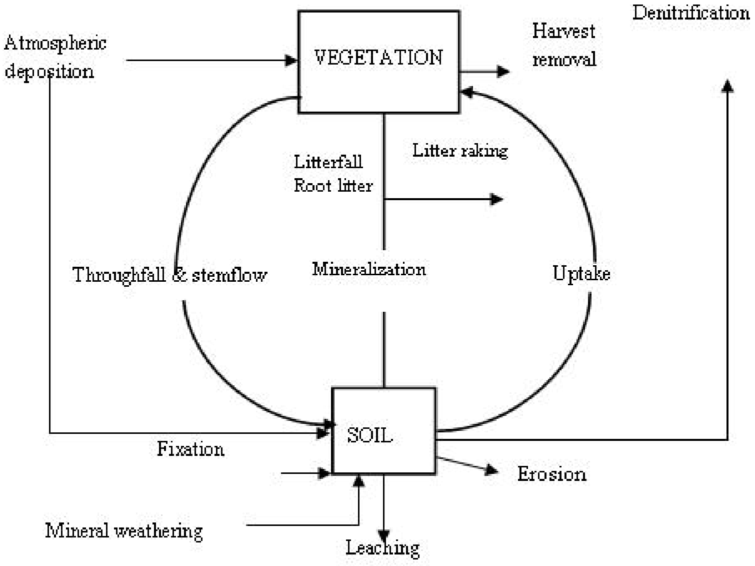


Figure 1. Schematic presentation of nutrient cycling processes in forest plantation ecosystem.

1.4 Environmental effects of forest plantations with particular emphasis on *Eucalyptus*

1.4.1 Fast growing tree plantations effect on soil properties

Soil degradation has become an increasingly serious problem, especially in the tropics and subtropics, where many soils are inherently poor in nutrients and at high risk of erosion. The main causes for soil degradation are poor agricultural practices, deforestation and overgrazing, but also fast growing tree plantations which, when poorly planned and managed, may lead to soil quality decline. Nevertheless, the impact of tree plantations upon soil resources has been very much debated and any complete consolidated view doesn't exist, partly due to the fact that the impact is much dependent on variable site and forest conditions. A number of studies indicated that changes in some soil properties are influenced by tree species (Malik & Fries, 1985; Poore & Fries, 1985; Lugo et al., 1990; Lemenih et al., 2004; Lemma, 2006). The changes depend on stand age (Jaiyeoba, 2001; Binkley et al., 2004: Zhang et al., 2004), biological factors (Burgess et al., 1993), and intensity of forest management (Shan et al., 2001; Mendham et al., 2002; Zhang et al., 2007).

Species vary widely in their inherent nutrient requirements and use (Cole & Rapp, 1981). Fast growing tree plantations such as *Eucalyptus* are associated with a more intense uptake of nutrients from the soil into vegetation compared to slow growing forests. Likewise, much of the current environmental concern about short rotation forestry management revolves around nutrient removal with harvest (Heilman & Norby, 1997). The authors argue that whole tree harvesting coupled with short harvest cycles possibly result in soil nutrient depletion far greater than conventional forest harvest. A comparison made between 1 to 8 years old *Eucalyptus* (the hybrid *E. tereticornis*) plantations and natural mixed broad leaved forest in the central Himalaya showed a soil quality decline (Bargali et al., 1993). Various soil physical characteristics decreased with increasing age; soil chemical properties, notably organic carbon, total N, P and K decreased as a result of reforestation with *Eucalyptus* and further decreased with increasing age. Also plantations of first and second rotation Hoop pine (*Araucaria cunninghamii* Aito ex A. Cunn.) on Typic Durusutalf soil in subtropical Australia showed a declining trend for some soil basic properties (Chen et al., 2004) with an increased number of cutting cycles. The content of soil C was significantly higher in first rotation than in the second rotation. Sheng et al. (2004) reported decreases in soil microbial activity, soil structure, soil nutrient storage and nutrient availability as the number of cutting cycles increased in Chinese fir (*Cunninghamia lanceolata* (Lambert) Hooks) plantations.

Further, Turner & Lambert (2000) observed a decreased soil organic content when they compared *Eucalyptus* cultivation with the adjacent native forests in south-eastern Brazil.

Several studies have indicated significant differences in soil nutrient status between plantation forests and adjacent natural forest in Ethiopia and Africa as well. The possibility of changes in the chemical status of the soil induced by a plantation has been indicated, but there have been differing reports (Cornforth, 1970; Lundgren, 1978; Hase & Fölster, 1983; Kadeba & Aduayi, 1985; Yirdaw, 2002; Lemenih, 2004; Lemma, 2006). According to Lemenih (2004), the soil pH as well as base saturation exhibited a marked decrease under *Eucalyptus* compared to adjacent natural forest and other exotic tree species. Furthermore, Lundgren (1978) evaluated the soil conditions and nutrient content under soft wood plantations with natural forest in Tanzania. Both potassium and calcium decreased considerably under the conifer crops over a 30-year rotation in relation to the natural forest soils. And he generally argued that a reduction in soil nutrients possibly occurred due to nutrient drain through harvest removals. He estimated the mean annual removal of nutrients to 40 kg ha^{-1} for N, 4 kg ha^{-1} for P, 23 kg ha^{-1} for K, 25 kg ha^{-1} for Ca, and 6 kg ha^{-1} for Mg. Hase and Fölster (1983); Jorgensen and Wells (1986); and Pennington et al. (2001) have also collected and summarized many data from across the tropics for pines, *Eucalyptus* and *Leucaena*. They reported that the rates of removal were high except for *Leucaena*, which enhanced soil fertility. Moreover, Aborisade & Aweto (1990) found that on moist sites where teak and *Gmelina* were planted, total exchangeable basic nutrients in the topsoil showed a definite decrease over those in the primary rain forest. However, it is also a widely held view that forest plantations could improve physico-chemical soil properties through litter-fall addition, decomposition, and soil microbiological processes such as nitrogen fixation and mycorrhizal activity on previously degraded lands (Evans, 1992).

In general, monoculture plantation forestry may affect soil chemical properties in two important ways. First, there is a nutrient depletion from the soil into the tree components (leaves, twigs, branches and stem log). Secondly, change could take place in the chemical status of the soil surface as the litter layer and organic matter becomes dominated by one species. Forest management practices may have a profound impact on soil nutrient status as well. Pennington et al. (2001) found a significant soil quality change after clear felling and high intensity burning in Australian *Eucalyptus* plantations. Soil bulk density increased from 0.58 Mg m^{-3} to 0.70 Mg m^{-3}, while there was a loss of 3850 kg C ha^{-1} and 107 kg ha^{-1}of N. Ghosh et al. (1978) reviewed the literature available on the effect of *Eucalyptus* plantations on hydrology and soil properties in a number of countries and came to the conclusion that in contrast to some suggestions, the benefits of these plantations outweighed any adverse effects. By comparing *Eucalyptus* to natural forest, Jha & Pande (1984) indicated that the area under *Eucalyptus* tended to retain more moisture and to show an increase in pH while Sal lowered the pH; both available P and total N were lower under Sal compared to eucalyptus. Both authors concluded that *Eucalyptus* monocultures in natural Sal areas cause no damage to soil fertility and are superior to Sal monocultures.

1.4.2 *Eucalyptus* plantations impact on biodiversity

As the global forest extent changes through loss of cover and conversion to plantations and other similar land uses, several issues have evolved regarding forest plantations impact on biodiversity (Stephens & Wagner, 2007). At the turn of the 20th century, the world population has used 39-50% of the earth's biological production, through agriculture, forestry and other activities (Vitousek, 1997). According to Bryant et al. (1997), half of the global forests have disappeared since the end of the latest Ice Age, and only 22% of the primary forest cover remains intact without considerable anthropogenic disturbance. Deforestation rates in the last few decades have reached the highest levels, as the number of global population size increased. This in turn threatens the wellbeing of both people and the forests they depend on.

At the current rapid deforestation rate in the tropics, and in the absence of any appropriate intervention, the last significant primary forest could disappear within 50 years (Terborgh, 1999). Because habitat destruction is the principal cause of species extinction, the shrinkage of tropical forest cover is likely to lead to a considerable and irreversible decline in global biodiversity (Sala, 2000). As elsewhere in the tropics, the destruction of forests and woodlands is the most frequently cited cause of genetic erosion in Africa in general as reported by over 74% of the countries (FAO, 1998). In Ethiopia alone, 25% of plant families, which form close relatives to cultivated crops are distributed in the forest areas. This resource is sharply declining due to over-exploitation of natural forests, woodlands, bush lands, and intensive forest plantations management at a rate higher than natural regeneration (FAO, 1996).

The effects of plantations on undergrowth vegetation composition and diversity differ strongly based on the characteristics of the surrounding landscape (agriculture, savannah, or native forest), uniformity of horizontal (spatial heterogeneity) and vertical (stratification) structural diversity of overstorey tree species and management regimes (Malcolm et al., 2001; Kint, 2005). Some authors indicated a negative impact of forest plantations on biodiversity (e.g., Peterken, 1996; Kidanu, 2004). In contrast, several studies compared the undergrowth vegetation composition in plantations and natural forests (Parrotta, 1995; Senbeta et al., 2002; Lemenih et al., 2004; Montes et al., 2005; Rouvinen & Kuuluvainen, 2005) and concluded that forest plantations may promote the regeneration of native species and foster the subsequent succession processes. On the other hand, some scientists indicated the negative effects of *Eucalyptus* on agricultural crops. For instance, Kidanu (2004) reported soil bioassay studies with three agricultural crops: chickpea (*Cicer arietinum*), tef (*Eragrostis tef*) and durum wheat (*Triticum turgidum*) under laboratory and field conditions. According to his findings, bioactive compounds from *Eucalyptus globulus* decomposing litterfall did not affect test crop seed germination and root growth. However, litter extract with 5% dry matter concentration significantly impeded germination and root growth of the tested agricultural crops. On a farm field experiment, a declining barley yield was observed in proximity to *E. globulus* plantation in the Ethiopian highlands (Kidanu et al., 2005). Similarly, monoculture *Eucalyptus* plantations have the potential to alter the diversity of plant and animal species across landscapes (Lugo**,** 1997; Souto et al., 2001). According to Souto et al. (2001) a soil bioassay showed clear inhibitory effects on germination and growth of understorey plants, particularly soils from *Eucalyptus globulus* Labill., and *Acacia melanoxylon* R.Br. stands compared to *Pinus radiata* D.Don. in Spain. Harrington & Ewel (1997) found that 26-32 years old plantations of *Eucalyptus saligna* in Hawaii contained 42 species in the understorey. In contrast, Hüttl & Loumeto (2001) found that afforestation of savannas with *Eucalyptus* facilitated the establishment of native forests; bird and mammal use of the plantations was also substantial, and varied with the tree species planted (Brosset, 2001).

Allelophatic exudates from *Eucalyptus* tree components showed an inhibiting effect on undergrowth vegetation regeneration and growth (Poore & Fries, 1985). Allelopathic or phytotoxic compounds are known to be mainly phenolic acid (Glass, 1976; Rice, 1984). These phenolic compounds are degraded with decomposition of plant residues, resulting in alleviation of phytotoxicity of the decomposing plant residues (Tian et al., 1992). *Eucalyptus* leaves have been reported to have phenolic acids, tannins and flavonoids (Babu & Kandasamy, 1997; Chapuis-Lardy et al., 2002). Bioassay experiment with eucalyptus litter extracts and leaf leachate showed a high level of phytoxocity (Michelsen et al., 1993; Bernhard-Reversat, 1998). Moreover, Konar & Kushari (1989) in west

Bengal have examined the inhibiting effect of *E. globulus* foliage leachate on the growth of *Costus speciousus*, a shade-loving, rhizomatous crop important as a commercial source of the steroid diogenin. A recent study by Jayakumar et al. (1990) investigated the effect of aqueous extracts of freshly fallen leaves of *E. globulus*, raised along river banks in Tamil Nadu in southern India. It was observed that the growth of weeds and grasses beneath these trees seemed inhibited, and thus the author sought to study the effect of eucalypt leaf extracts on the growth of peanut (*Arachis hypogaea*) and corn (*Zea mays*) seedlings. The leaf area, plant height, and leaf chlorophyll content of both test species were significantly inhibited by the *Eucalyptus* aqueous leaf extracts. In consistency with this effect, Molina et al. (1991) suggested that eucalyptus releases toxic allelo-chemicals into the soil system mainly through litter decomposition products. In fact, the effects of plantations on undergrowth vegetation composition and diversity differ strongly based on the characteristics of the surrounding landscape (agriculture, savannah, or native forest), tree species and management regime.

1.5 The rationale for the study

During the past decade there has been a marked shift away from considering the forests as only production systems for wood, towards realizing the environmental impacts and ecosystem functions and services. Increased demand for forest products, the search for renewable resources or raw materials, and an increased concern for the well being of forest and neighbouring ecosystems are incentives for intensified studies on total forest biomass production and nutrient dynamics (Grove & Malajczuk, 1985; Pearson *et al.*, 1987; Wang & Xu, 1995; Xue, 1996). Quantifying above-ground biomass over time is important to evaluate forest ecosystem productivity, nutrient and carbon cycle (Parresol, 1990; Brown, 2002; Jenkins et al., 2003; Specht & West., 2003; Zhang et al., 2004). Partitioning of standing biomass into respective plant components has become a requirement in forest inventory schemes, especially for plantation forests. Direct measurement of plant biomass, employing destructive sampling, is tedious and requires time (Antonio et al., 2007). To ease laborious work, models must be developed to estimate total and tree components. Such models play a significant role for the determination of forest growth and for understanding forest ecosystem functions (e.g., helpful to quantify the amount of nutrients locked up in tree biomass components).

Forest trees as all plants require mineral nutrients to live and grow. The nutrients that are taken up into the trees are eventually returned to the soil through the litter, and as dissolved organic matter through the washing and leaching effects of rain on the tree foliage and stem (Spurr & Barnes, 1980). Knowledge of nutrient cycling is equally an essential prerequisite for understanding and predicting forest plantations tree species' effect on the environment (Turner et al., 1976; Landsberg, 1986).

As one of exotic tree species, *Eucalyptus globulus* was introduced to Ethiopia more than a century ago but still its ecological impacts over successive cutting cycles have not been sufficiently researched to provide us with knowledge about their biomass production and the impact they induce on soil and ground flora attributes. Biomass, which is currently the fourth largest energy source in the world and the main source in Ethiopia, includes firewood from plantations, agricultural residues, forestry residues, animal wastes, etc. Fuelwood is the dominant biomass demand on forests, which may also lead to forest land degradation (Newcombe, 1987; Bewket, 2003). The estimated demand in Ethiopia for fuelwood in 2000 was 58.4 million m^3 (EFAP, 1994) whereas the supply was 11.2 million m^3 and the projected demand was estimated at 100 million m^3 by 2020 (EFAP, 1994). As there is a net deficit in the supply with respect to the demand of forest biomass to provide the required needs, the forests in Ethiopia are under extreme pressure vis-a-vis what they can supply as a matter of sustained productivity (Bekele, 2001). The quantity of biomass in a forest determines the potential amount of carbon that can be added to the atmosphere or sequestered in soil and vegetation when forests are managed for mitigating global warming (Brown et al., 1999). The biomass assessment studies are important for providing nutrient budgets and render an insight to evaluate the sustainability of a forest ecosystem (Turner, 1986; Das & Ramakrisshnan, 1987; Ranger & Collin-Belgrand, 1996; Uri et al., 2003). On the other hand, determining stand biomass and its nutrient stock distribution over time would contribute to detect site quality change (Zhang & Allen, 1996; Saur et al., 2000; Zas & Serrada, 2003).

Nutrients in various pools in forest ecosystems, such as the standing biomass, the soil organic matter, the soil exchange complex and in soil minerals are in a dynamic process. Some pools constitute a source of nutrients that are readily available to plants, whereas other pools have nutrient reserves that could become available to plants over a time scale ranging from years to decades (Attiwill & Leeper, 1987). Nutrients locked in pools that turn over on a time scale of hundreds to thousands years can be treated as effectively unavailable to plants (Bed du & Mary, 2002; Du Toit, 2003).

Nutrient concentrations in different tree components (roots, stemwood, branches, twigs and leaves), which commonly are used for evaluation of plant nutrient status, soil nutrient availability and as indicators of forest health (Zöttl & Hüttl, 1986; Innes**,** 1993), among others are dependent on tree species, plant parts or developmental stage/shoot age. The nutrient concentrations in plant compartments, particularly in leaves, presumably undergo considerable changes with time depending on various factors, including the species, relative proportion of leaves and twigs, age of the tissue, thinning and pruning frequency, soil, climate and many other factors (Palm, 1995; Palm & Rowland, 1997).

Perennial tree crops have distinct phases which differ in the rate of aboveground and belowground biomass accumulation, and in the relative contribution of various pools and fluxes to nutrient cycles. Biomass accretion in standing biomass attains a maximum between the initial growth phase (i.e. establishment) and that in which a relative equilibrium in stand biomass is reached at maturity (Blackman, 1968). Among nutrient cycling processes, nutrient re-translocation becomes a more important component of the cycle as the tree biomass increases over time (Bowen & Nambiar, 1984). In the context of nutrient cycling, quantifying biomass and nutrient allocation in different plant components are helpful for estimating tree nutrient uptake and nutrient removal with harvest, and are thus important for understanding nutrient cycling process and for evaluating site quality change in a forest ecosystem (Bergman, 1992; Stefan et al., 1997).

Eucalyptus globulus serves as a main tree species for millions of people and forms an integral land use feature of Ethiopian highlands. *Eucalyptus* is one of the most preferred and widely planted species in the region with the following justifications:

1. Its wood has multi-utilitarian values as fuel, construction material, and for making traditional farming implements;
2. Traditionally, *Eucalyptus* leaves are used as medicine to treat flu and respiratory tract infection;
3. *Eucalyptus* planted at homesteads is an additional source of income for the farmers living in the central highlands of Ethiopia;

4. It is a fast growing crop, which is easy to cultivate and manage in short rotation coppicing system. This makes *Eucalyptus* as a good converter of solar energy into economically useful biomass production, and it is more profitable than many other indigenous and exotic tree species.

However, despite its multitude benefits, there are uncertainties about the positive and the negative effects of planting *Eucalyptus* species on the environment (e.g., Poore & Fries, 1985; Poschen, 1987; Davidson, 1989; Pohjonen & Pukkala, 1990; Michelsen et al., 1993; Turnbull, 1999; Doughty, 2000; Yirdaw, 2002; Jagger & Pender, 2003; Kidanu, 2004). The environmental impact of *Eucalyptus* plantations, in particular on soil water and nutrients, understorey vegetation and biodiversity became in recent years a controversial issue. The *Eucalyptus* dilemma is most serious in the Ethiopian highlands (> 1500 m a.s.l) which cover 45% of the total land area (i.e., 100 million ha) and support 85% the human and 75% of the livestock population, and account for more than 90% of the regularly cultivated arable lands (FAO, 1986).

In this challenging but interesting site of *Eucalyptus*, empirical evidence to either support or refute the supposed ecological impacts of the tree species in the Ethiopian highlands is scanty, anecdotal and poorly understood. Therefore, it is essential to seriously assess the evidence for and against large scale or farm boundary *Eucalyptus* planting before any decision is taken. For African conditions, particularly in Ethiopia, there is a lack of studies that deal with the impact of *Eucalyptus* consecutive cutting cycles on soil properties. Most soil studies reported so far were usually based on a comparison between different tree species and/or land uses (e.g., Michelsen, 1993; Zerfu, 2002; Lemenih, 2004; Asferachew, 2004; Lemma, 2006). The present study attempts to address some issues associated with the ecological effect of *Eucalyptus globulus* coppice cutting cycles (total plantation age) and coppice-shoot age on the above-ground biomass production and nutrient distribution (Paper I & II), soil nutrient status (Paper III), and ground flora composition and diversity (Paper IV) in the central highlands of Ethiopia. Quantifying the changes in biomass, plant nutrient stock (e.g., Ca, N) and soil quality along a chronosequence of forest plantations is essential to develop useful policies coping with climate change, timber harvesting, and environment (Arthur et al., 2001). The findings from the research and the recommendations to be made would be helpful for sustainable *Eucalyptus globulus* management in the central highlands of Ethiopia.

1.6 Objectives

We hypothesized that consecutive cutting cycles as currently practiced in the Ethiopian *Eucalyptus* plantations negatively affect biomass production and nutrient distribution, soil physico-chemical properties, ground flora composition and diversity over time.

The objectives of the study were to:

i. Estimate the standing above-ground biomass production in *Eucalyptus globulus* plantations across a number of cutting cycles and coppice-shoot ages (Paper I).

ii. Determine changes in macro-element concentration and distribution in above-ground biomass tree components in a *Eucalyptus* plantations chronosequence (Paper II).

iii. Quantify changes in soil physical and chemical properties status along a chronosequence of *Eucalyptus globulus* coppice plantations (Paper III).

iv. Assess the ground flora species composition, diversity and biomass production across a number of *E. globulus* consecutive cutting cycles and coppice-shoot ages (Paper IV).

2 Materials and methods

2.1 Description of the study sites

2.1.1 Location, climate and vegetation

The study area is located at latitudes 9° 05′ - 9°16′ N and longitudes 38° 50′- 39° 05′ E ranging from an elevation of 2300 to 3200 m above sea level (Fig. 2). All the study sites are situated at peri-urban areas of Addis Ababa, and mainly located on the Entoto ridge (max. 3199 meters above sea level) of the Main Ethiopian Rift Escarpment. The ridge marks the northern boundary of Addis Ababa following the Ambo-Kassam, east-west trending major fault. The climate of the study area is characterized by dry sub-humid with bimodal rainy seasons. The short rainy season extends from March to May, and the long rainy season ranges from July to August. According to Ethiopian Meteorological Services Agency (2006), the mean annual rainfall over the last 10 years (1995-2004) was 920 mm. The mean maximum and minimum annual temperature were 24 °C and 12 °C, respectively.

The large area of Entoto, where the major study area is located belongs to the Afromontane forest belt in the central highlands of Ethiopia. Formerly, indigenous trees such as *Juniperus excelsa*, *Olea europea* spp. *Cuspdata*, and *Podocarpus falcutus* were dominantly covering the area. Similar to other parts of Ethiopia, the natural Juniperus-Podocarpus-Olea forest which was once abundant on the Entoto Mountain rapidly vanished due to an over exploitation of the indigenous trees (Pohjonen, 1989). The remnants of Juniperus and Olea trees in the area reflect elements of this vegetation. On steep slope areas woodland was comprised *Dodonea viscosa*, *Rhus abyssinica*, *Celtis krausiana*, *Myrosina africana*, *Erica arborea*, *Acacia abyssinica* and some others. Currently, the dominating species in the area is *Eucalyptus globulus* plantation on which this study focuses.

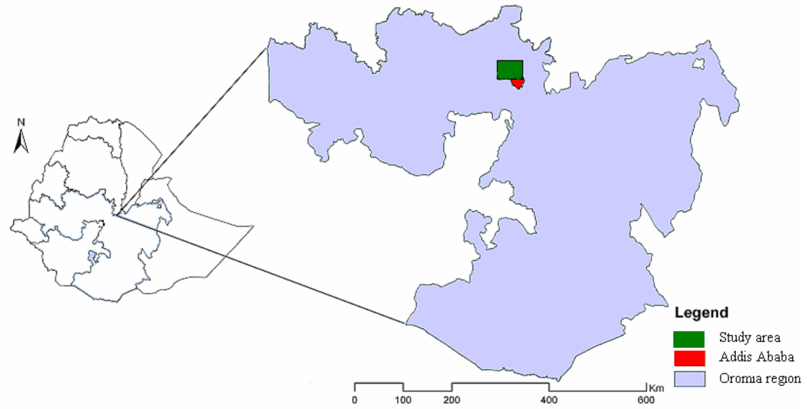


Figure 2. Map of the study area showing the location of the sampled plantations in the central highlands of Ethiopia within the Oromia Regional State and the city of Addis Ababa Administration.

2.1.2 Geology and pedology

The bedrock geology and morphology is very much characterized by complex volcanic stratigraphic successions, tectonic movements in connection to the development of the Great Rift Valley and the erosion between successive lava flows. Prominent volcanic summits surrounding the city are Mount Wuchucha in the west (3385 m a.s.l), Mount Furi (2850 m a.s.l) in the south west and Mount Yerer (3100 m a.s.l) in the southeast. A comprehensive description of the geological setting is given by UNEP/UNESCO/UN-HABITAT/ECA (2003).

According to Girmay & Assefa (1989), the bedrock geology or rocks of this region is characterized by extrusive rocks and pyroclastic sediments formed during the latest 23 million years. A general stratigraphy is represented from the bottom and upward by Alaji basalts, Entoto silicics, Addis Ababa basalts and the Nazareth group followed by Bofa basalts. The northern part of the Addis Ababa region is made up of rhyolotic and trachytic lava flows, ignimbrites and welded tuffs, constituting the Entoto silicics. Welded tuff or welded pumice is a pyroclastic deposit, which has been indurated by the combined action of the heat retained by the particles and the enveloping hot gasses. Steep slopes generally characterize the topography and flat areas with basalt lava plains intercept a rugged terrain.

The variation in the characteristics of soils is very much dependent on the soil forming factors. In this area, especially the complex nature of the volcanic deposits gives rise to a great variability of the parent material for soil formation. However, the dominant parent material in the selected study sites is mainly characterized by basaltic primary minerals. The other factors responsible for soil forming factors are topography, time or maturity in combination with biological activities. The soil development in the study area is mostly due to the chemical weathering of volcanic material enhanced by physical disintegration of the rocks. The weathering products are either in situ, forming residual soils or transported by water and deposited in plain areas. The soils in the central, western and south-western parts of Addis Ababa are formed from weathering of old basaltic and rhyolitic rocks resulting in thick soils. In some places the soil thickness can be more than 10 meters. However, depending on the limited time elapsed since the rock formation, the young basalts and welded tuffs often have given rise to a rather thin soil cover. The texture classes fall within clays and clay loams and the color goes from red to reddish-brown. Depending on the type of parent materials, also black colors are occurring. According to the World Resource Base classification Systems, Andosols, Vertisols, Nitisols, Solonchaks represent the soil types within the region, as well as Solonetzs followed by Cambisols. However, the dominant soil type in the study area is characterized by Haplic Nitisols.

2.2 History of *Eucalyptus* plantations establishment and development

Unlike the other sub-Saharan countries, Ethiopia has a long tradition and experience in plantation forestry. This dates back to the 1890s during the reign of Emperor Menelik II (1890-1914). The existence of Addis-Ababa as a capital was threatened by acute fuelwood shortage, due to over exploitation of natural forests on the surrounding mountains, i.e., Mount Entoto and Wuchucha. To alleviate the acute fuelwood shortage, the Emperor responded by introducing *Eucalyptus* plantations, mainly Blue gum (*Eucalyptus globulus* Labill.) around the city. He ordered the distribution of 100 seedlings to each inhabitant, who was instructed to plant, tend and manage them (Fekerte, 1991; Pohjonen & Pukkala, 1988). It was reported that within six or seven years, people had begun to sell *Eucalyptus* as fuelwood. After realizing the profitability of planting *Eucalyptus*, the landlords took over the management and control of plantations.

Private ownership continued until the 1974 Ethiopian revolution, after which the plantations were confiscated by the state. By that time, some 20,000 hectares of plantations had been established by private owners around Addis Ababa, and currently *Eucalyptus globulus* plantations cover more than 15000 hectares in the surroundings of Addis Ababa.

Eucalyptus globulus grows well at elevations ranging from 1400-3200 meters above sea level (Pohjonen & Pukkala, 1990). After the original seedling establishment, *Eucalyptus globulus* is mainly managed by short rotation coppice system in 5-7 years harvest age over consecutive cutting cycles. Lower cost to regenerate succeeding stands from stump sprout under subsequent rotations has made an appealing coppice management profitable (Greyer et al., 1985). In a coppice system, once the single stem first rotation plantation is harvested, the cut stump re-sprout to provide the second generation crop and then continue for several cycles depending on the vigour of the plants. The sprouting shoots grow rapidly after harvest because the roots have already established access to soil water and nutrients. They usually store large amount of carbohydrates which help to sustain rapid re-growth rates (Steinbeck, 1981).

2.3 Sampling schemes and laboratory analyses

The study was based on a chronosequence approach, i.e. ten *Eucalyptus globulus* monoculture coppice plantations, spanning from two to ten cutting cycles (Table 1), and the study sites were carefully selected for comparable topography, climate, slope inclination and exposition. Several researchers have compared soil physical and chemical changes between different land uses over time (e.g., Moody, 1994; Turner & Lambert, 2000). Chronosequence studies generally use a series of plots in different aged plantations with presumed similar management regimes and environmental conditions. The present study has employed a chronosequence approach to determine the pattern of biomass partitioning and nutrient distribution (Papers I & II), soil property (paper III), and ground flora attribute changes (Paper IV) with increasing total plantation age and coppice-shoot age. The total plantation age and coppice-shoot age were obtained by means of interviews with elderly local people, documentation surveys and recorded compartment information from the archives of forestry enterprises and oral communication with the pertinent staff of forestry technicians at each of the study sites. Since the total plantation and number of cutting cycles are very strongly correlated ($r = 0.998$, $p < 0.001$), here after the number of cutting cycles can be used vis-a-vis the total plantation age, and denoted as N in the text. Coppice-shoot age is defined as the age of current shoots that emerged after the last harvest. The mean harvest age was estimated to be 5 to7 years, which gave a number of cutting cycles from 2 to 10.

2.3.1 Biomass measurements and nutrient content determination - Papers I and II

Depending on stand density four sample plots with 10 x 10 m or 20 x 20 m size were randomly laid out in each plantation and all tree diameters at 5-10 cm above stump height (D) were measured. Seven to eleven tree stems representing the range in D were harvested at each stand to assess tree biomass and nutrient content. Total tree height and stem diameter at different heights were measured and trees separated into leaves, twigs (< 1 cm), branches (1-2 cm), and stem. Bark was peeled off from stemwood samples that were collected as discs. Each component was weighted in the field and sub-samples were transported to the laboratory in plastic bags and were then oven-dried at 70° C to a constant weight. The total oven-dry weight of each component for each component was obtained by applying dry matter content of the sub-samples. Stand biomass on hectare basis was calculated by multiplying average total (or component) biomass of the plots either by 100 (for 10 x 10 m plots) or by 25 (for 20 x 20 m plots).

Plant component samples of all trees were analyzed for total N by a micro-Kjeldahl procedure. Calcium, Mg and K were determined by digesting samples in H_2SO_4 and H_2O_2, and then analyzed by atomic absorption spectrophotometry. The mean element concentration values per tree component were multiplied by their respective mean biomass to determine the amounts of nutrients in the sampled tree components. Mean nutrient values of tree components on per hectare bases were calculated as described in the biomass determination (Paper I).

2.3.2 Soil sampling and chemical analyses - Paper III

Four plots with the size of 10x10 m or 20 x 20 m were randomly laid in each stand. Soil samples were then collected from the ten stands from the upper 30 cm mineral soil. In each plot, four pits were dug at four corners and samples were taken from 0-10 and 10-30 cm soil layers to assess their soil physico-chemical properties. In addition, one pit at the centre of each plot was opened and the soil profile was described according to the FAO guideline for soil profile description (FAO, 1990). Moreover, soil samples were taken in 0-5 sections until 30 cm depth, using a 9 mm stainless corer for each pit and plot, and then bulk density was calculated from the weight of the soil for each of the cores. Before physical and chemical analyses, the soils were dried at 70° C and ground to pass a 2 mm sieve. Determination of soil texture was carried out by the Bouyoucos hydrometer method. Soil reaction (1:2.5 H_2O) was determined using an electronic pH meter with a glass electrode. Available P was extracted with 0.1 M sulphuric acid and measured colorometrically by the ascorbic acid blue method (Olsen et al., 1954). Exchangeable Ca and Mg were measured after extraction using 1 M ammonium acetate at pH 7.0. Concentrations for Ca and Mg in the extracts were analyzed using an atomic absorption spectrophotometer, while K was determined by flame photometry (Black et al., 1965). After extraction with neutral 1N ammonium acetate, total N was determined by the micro-Kjeldahl method (Schnitzer, 1982). Cation exchange capacity (CEC) was estimated titrametrically by distillation of ammonium that was displaced by sodium (Chapman, 1965). Base saturation (%) was computed by dividing the sum of base forming cations (K, Ca and Mg) by the CEC of the soil and multiplied by 100.

The total nutrient stock (g m^{-2}) of soil was calculated according to the following equation:

$$NC = (BD \star C \star SD),$$

where NC is nutrient content (g m^{-2}), BD is soil bulk density (kg m^{-3}), and C is the soil nutrient concentration (g kg^{-1} soil), and SD is the soil depth of a soil layer (m).

Table 1. *Stand characteristics of the sampled* Eucalyptus globulus *plantations in the central highlands of Ethiopia*

Site number	Locality name	Plantation age (year)	Cutting cycles	Coppice-shoot age (year)	Tree density (Stems ha^{-1})	Mean diameter (cm)	Mean height (m)	Stem volume (m^{3} ha^{-1})
1	Entoto	11	2	7	2680	6.7	13.2	65.6
2	Menagesha	13	2	4	6925	4.1	8.9	48.8
3	Entoto (Wore-Genu)	14	2	7	6150	4.8	9.5	61.5
4	Entoto	19	3	5	2768	5.8	8.6	36.3
5	Entoto (Gala-Amba)	37	6	9	9925	5.1	8.5	101.4
6	Entoto (Shinkuro)	40	7	5	2850	6.9	10.9	63.0
7	Holeta	40	7	5	6450	4.4	9.7	55.7
8	Entoto	60	10	1	3225	2.9	5.5	8.0
9	Entoto	60	10	4	2494	4.6	6.6	17.1
10	Entoto	60	10	4	2013	4.9	7.9	18.0

2.3.3 Ground flora sampling and evaluation - IV

To assess the ground flora biomass production and diversity, five *Eucalyptus* stands (Table1, stand numbers 2, 3, 5, 6 and 7) ranging from 2 to 7 cutting cycles were selected and 16 quadrats (1x1 m size each) were randomly placed in each stand. Above-ground field layer biomass from 80 quadrats was clipped, oven dried at 70 ° C, and weighted to 0.1g precession. The Shannon-Wiener diversity index (H') was calculated for each site with the following equations:

$$H' = -\Sigma(P_i \ln P_i) \qquad (1),$$

$$EH = H'/H_{max} \qquad (2),$$

where P_i is the proportion of individuals that species i contributes with to the total, EH is Shannon's equitability of evenness, and H_{max} is the total number of species.

The Shannon-Wiener diversity index expresses species richness and evenness into a single measure (Magurran, 1988) and the has finite ranges between 0 and 1. Species richness is a count of the total number of species per unit area or habitat; whereas species evenness (equitability) is the uniformity of an assemblage of species. To evaluate the relationships of biomass production, vegetation cover and species diversity with the coppice-shoot age and cutting cycles, the Spearman's correlation test was performed.

2.3.4 Nutrient mass flow determination via litter removal

The nutrient export from the sites through litter raking (leaves, twigs and branches), and stem harvest was determined and compared with changes in the soil nutrient pool. The nutrient stock (kg ha^{-1}) was calculated using the multiple regressions of the present study (Papers II & III). Turn over rates of litter for *Eucalyptus globulus* were assumed to have about similar coefficients to other *Eucalyptus* species (Nabuurs & Mohern, 1993; Whitehead & Beadle, 2004). Accordingly, the turnover coefficients: 0.5, 0.5 and 0.05 for leaves, twigs and branches, respectively were used to determine the amount of nutrient stock. Further, the mean plant litter nutrient concentrations reported by Olsson (2004) for *Eucalyptus globulus* plantations in the central highlands of Ethiopia were used to estimate nutrient mass flow via litter removal across a number of cutting cycles. The harvest age per cutting cycles was set to 7 years, and an annual litter removal was calculated according to the following equation:

$$L_S = W_L \star T \star C \qquad (3)$$

In which L_S is the amount of nutrient stock (kg ha^{-1}), W_L is the weight of litter biomass (kg ha^{-1}), T is the turnover rate coefficient, and C is the litter nutrient concentrations (%).

2.4 Statistical data analyses

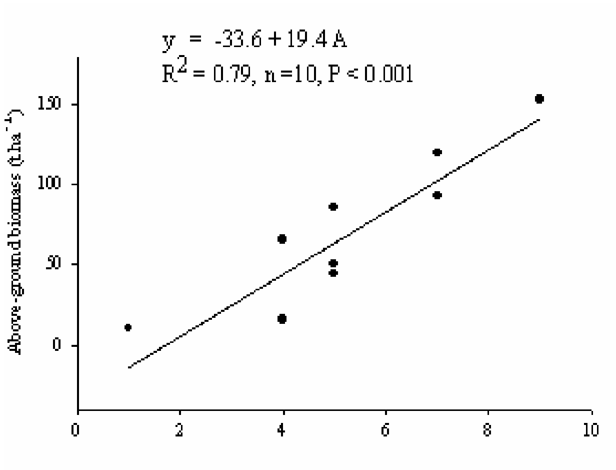
One-way analysis of variance (ANOVA) was conducted for detecting statistically significant differences in biomass partioning and distribution (Paper I), tree nutrient concentrations (Paper II), soil physico-chemical properties (Paper III), and ground flora attributes (Paper IV) across the coppice-shoot age and total plantation age (number of cutting cycles) at 0.05 significance levels. The Spearman's rank correlation was carried out to investigate the relationships between variables as well. Furthermore, to determine the degree of relationship between the total plantation age and number of cutting cycles, a Spearman's correlation was performed. For both variables a very strong correlation was obtained ($r = 0.998$, $p = < 0.001$). Henceforth, the number of cutting cycles unequivocally can be used vis-à-vis the total plantation age. Simple regression and multiple regression analyses were also performed to test the relationships between the measured variables. The selection criteria for the regressions were based on R^2, p-value and standard error of estimates (S.E.E). The significance of the difference in regression slopes between the variables was tested by means of ANOVA and the regressions were selected based on R^2 and p-value. All statistical tests were conducted with Minitab, release 14.1 software. On the other hand, the multiple comparisons of means were evaluated by the SAS statistical program (SAS Institute, 2004).

3 Results and discussion

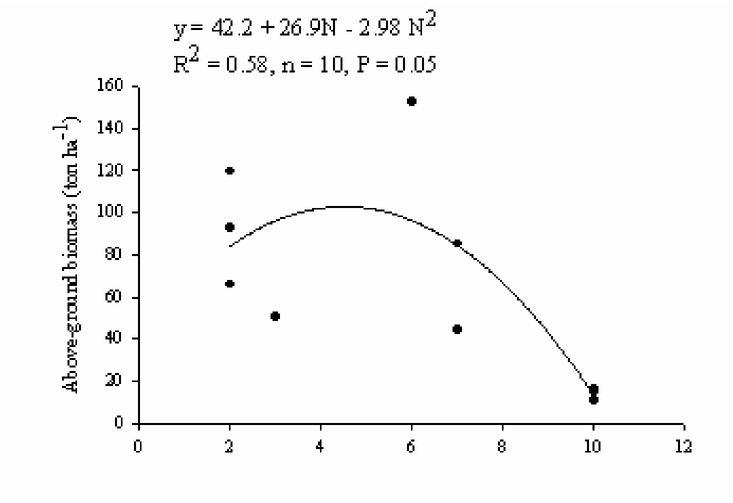
3.1 Temporal dynamics of biomass and nutrient distribution - Papers I and II

3.1.1 Above-ground biomass production across coppice-shoot age and cutting cycles

The total above-ground biomass varied significantly ($r = 0.89$; $p < 0.001$) across coppice-shoot age and ranged from 11 ton ha^{-1} in 1-year-old to 153 ton ha $^{-1}$ in 9 year old coppice-shoot age plantations (Fig. 3a). Stemwood biomass accounted for the largest share (58%) followed by leaves (17%), stembark (11%), twigs (8%) and branches (7%), respectively. Contrary to coppice-shoot age, a general declining biomass pattern was observed ($r = -0.76$; $p = 0.05$) with the total plantation age/ cutting cycles (Fig. 3b). Based on values reported across *Eucalyptus* plantations world wide, the results fall within the lower ranges reported by several authors in Ethiopia and elsewhere (George, 1977; Singh & Sharma, 1981; Pukkala & Pohjonen, 1989; Cromer, 1996; Laclau et al., 2000; Asferachew, 2004; Zerfu 2002; Yamanda et al., 2003). Nevertheless, the mean total above-ground biomass values reported for *Eucalyptus tereticornis (*Mysore Gum*)* varied from 11.9 to 146 t ha^{-1} in the three and nine years old plantations, respectively, in humid regions of India (Rawat & Negi, 2004) is comparable with our results. The low biomass obtained in the present study is presumably attributed to soil nutrient depletion (Paper III), and an elevated stool mortality rate as plantations aged under subsequent rotations. Similar biomass decline patterns have been also observed in several other studies (e.g., Keeves, 1966; Verwijst, 1996; Rubilar et al., 2005). Moreover, intensive litter raking as practiced within the study sites had a profound adverse effect on soil nutrient status. Birkuktayet (2004) reported in agreement with the present results that intensive litter removal had a considerable negative impact on soil physical and chemical soil properties on the north western Ethiopian highlands of *Eucalyptus* plantations.



(a) Coppice-shoot age (year)



(b) Number of cutting cycles

Figure 3. Total above-ground biomass relationships with coppice-shoot age (a) and cutting cycles (b) for *Eucalyptus globulus* plantations, central highlands of Ethiopia. The above-ground biomass values for the two stands of 4-year-old coppice-shoots, and the tenth cutting cycle stands were very close in magnitude, and it was not possible to visualise individual points for the two plantations in the figure.

3.1.2 Nutrient concentrations in above-ground biomass along a chronosequence of *E. globulus* plantations

There were no significant differences for the majority of element concentrations with coppice shoot age (Tables 2 & 3). However, except for P, most nutrients showed a declining trend as the coppice-shoots aged. Processes that may affect concentration changes with coppice age is e.g., first dilution effect where uptake does not match biomass growth, and secondly withdrawal of mobile elements from aging tissues. Decreasing concentrations in *Eucalyptus* and other tree species with age have been reported by several authors (Tandon et al., 1988; Ranger et al., 1994; Laclau et al., 2002; Meerts, 2002; Verdaguer & Ojeda, 2002). The withdrawal of mobile elements from old tissues to new actively growing young tissues has been reported by e.g**.,** Turner & Lambert (1983), and Bell & Ward (1984).

Although the total plantation age did not affect the element concentrations significantly, a general increasing tendency was observed as the number of cutting cycles advanced (Paper II). The plausible explanation for such pattern may be associated with a well developed root system in older plantations. Similarly, higher carbohydrate storage in older plant stump parts compared to shoots grown on younger stumps was demonstrated by Verdaguer & Ojeda (2002) for seeding and resprouting in *Ericacae* stands. In addition, the results reported by Barron et al. (2002) indicated that the trend between the first and second rotation pine plantations had a similar pattern, which was in close agreement with our findings.

The nutrient concentrations of N, P, K, Ca and Mg were substantially different ($p < 0.001$) in the studied tree above-ground components. The concentrations were lower for stemwood and branches than for leaves and twigs in accordance with the general feature of many temperate and some tropical forest species (Helmisaari & Siltala, 1989). Nutrient concentrations differences among tree compartments were probably related to physiological function of different tissues. Furthermore, Rubilar et al. (2005) observed translocations of N, P, K and Mg from old tissues to active organs. Myre & Camire (1994) also noted higher nutrient concentrations in sapwood than heartwood. Regarding the mineral concentration of leaves, the results presented here are similar to those obtained by Mekonnen et al. (2006) on Vertisols of *E. globulus* planatations in Genchi, central Ethiopia. Nevertheless, the mean nutrient concentrations for N and P in the leaves which ranged from 0.79-0.87% and 0.08-0.12% respectively were below the values reported by many authors (Boardman et al., 1997; Benton & Jones, 1998; Laclau et al., 2000). For instance, the report made by Boardman et al. (1997) considers < 1.0% N and < 0.1 P % foliar concentration as deficiency thresh hold values for the Australian *Eucalyptus globulus* plantations. The low foliar nutrient concentrations found in the present study most probably linked to the deficiency of these elements in the soil (Paper III).

Table 2. *Mean (±SE) nutrient concentrations of N, P, K, Ca and Mg (% of dry weight) in above-ground components of* Eucalyptus globulus *coppice plantations with coppice-shoot age (A))*

A	Element	Leaves	Twigs	Branches	Stem bark	Stem wood
1	N	0.79±0.04 a	0.21±0.01 a	0.15±0.02 ab	0.15±0.01 a	0.25±0.194 a
4		0.87±0.04 a	0.18±0.01 a	0.16±0.01 a	0.16±0.01 a	0.07±0.010 b
5		0.81±0.04 a	0.21±0.02 a	0.13±0.01 ab	0.17±0.01 a	0.06±0.006 b
7		0.80±0.03 a	0.21±0.01 a	0.10±0.01 c	0.17±0.01 a	0.05±0.003 b
9		0.79±0.03 a	0.20±0.01 a	0.12±0.01 c	0.15±0.01 a	0.04±0.003 b
1	P	0.08±0.02 b	0.01±0.00 a	0.03±0.00 c	0.04±0.01 b	0.04±0.003 a
4		0.12±0.01 a	0.07±0.01 a	0.06±0.01 a	0.06±0.01 ab	0.03±0.005 a
5		0.11±0.01 ab	0.05±0.00 a	0.04±0.00 bc	0.06±0.00 a	0.04±0.003 a
7		0.11±0.01 ab	0.06±0.01 a	0.04±0.00 bc	0.05±0.00 ab	0.03±0.003 a
9		0.12±0.01 a	0.07±0.01 a	0.05±0.00 ab	0.08±0.01 a	0.10±0.012 b
1	K	1.13±0.11 a	0.71±0.05 a	0.51±0.05 a	0.65±0.04 a	0.27±0.036 a
4		1.09±0.08 a	0.63±0.03 a	0.45±0.03 a	0.49±0.04 ab	0.24±0.018 a
5		0.92±0.06 ab	0.56±0.04 a	0.31±0.03 b	0.40±0.04 bc	0.16±0.013 b
7		0.85±0.06 b	0.54±0.06 a	0.25±0.03 b	0.32±0.03 c	0.13±0.013 b
9		0.95±0.05 a	0.54±0.03 a	0.23±0.04 b	0.54±0.05 c	0.13±0.013 b
1	Ca	2.27±0.31 a	1.17±0.12 a	0.41±0.06 a	1.30±0.05 a	0.12±0.016 a
4		1.94±0.12 a	1.17±0.09 a	0.51±0.06 a	1.33±0.15 a	0.23±0.068 a
5		1.74±0.14 a	1.22±0.10 a	0.42±0.04 a	1.37±0.09 a	0.14±0.013 a
7		1.96±0.17 a	1.15±0.10 a	0.42±0.04 a	1.42±0.11 a	0.13±0.020 a
9		1.74±0.07 a	1.24±0.07 a	0.56±0.06 a	1.32±0.09 a	0.10±0.014 a

Table 3. *(Continued)*.

A	Element	Leaves	Twigs	Branches	Stem bark	Stem wood
1	Mg	0.18±0.02 a	0.06±0.01 a	0.03±0.00 b	0.06±0.00 b	0.02±0.005 b
4		0.21±0.01 a	0.08±0.01 ab	0.06±0.01 ab	0.13±0.01 ab	0.03±0.004 ab
5		0.22±0.01 a	0.11±0.01 a	0.07±0.01 a	0.17±0.02 a	0.04±0.004 a
7		0.21±0.02 a	0.09±0.01 ab	0.04±0.01 ab	0.11±0.01 ab	0.02±0.003 ab
9		0.13±0.00 a	0.06±0.01 ab	0.03±0.00 ab	0.13±0.02 ab	0.02±0.004 b

Means followed by the same letter(s) within each column are not significantly different at the 0.05 level.

3.1.3 Nutrient content in above-ground biomass

The nutrient content (per unit area) in above-ground biomass increased with coppice-shoot age and attained a maximum in the 9-years old shoots in the order of Ca > K > N > Mg > P (Table 3). The main reason for the positive relation between shoot age and nutrient content was the increasing biomass content (Paper I) with shoot age. This increase was big enough to over shade the slight decrease in concentration for some elements. Despite large stemwood biomass, leaves contained by far the largest proportion of nutrients of all the *Eucalyptus* tree above-ground compartments (Paper II). Hence, the supply of leaves/litter in a forest floor may have a considerable impact on soil fertility in a short and long-term basis. In general, the temporal dynamics pattern of nutrient content along with shoot age was consistent with other similar studies reported by Ranger & Colin-Belgrand (1996); Laclau et al. (2000). In contrast, the nutrient content decreased with total plantation age (cutting cycles). The higher nutrient content and biomass in younger plantation age (in fewer numbers of cutting cycles) are in agreement with the published reports by e.g., Keeves (1966), and Powers (1999).

Table 3. *Above-ground biomass (ton ha^{-1}) and nutrient stock (kg ha^{-1}) along the chronosequence of* Eucalyptus globulus *plantations in the central highlands of Ethiopia*

CC	PA	A	DM	N	P	K	Ca	Mg
2	11	7	119.5	242	56.2	321.8	750.8	98.8
2	13	4	65.7	141.7	42.4	288.3	459.0	86.2
2	14	7	92.9	147.4	47.1	279.6	506.7	38.8
3	19	5	50.6	103.3	29.7	181.0	324.5	27.3
6	37	9	152.6	323.1	135.6	569.2	1028.2	86.4
7	40	5	64.8	43.9	32.1	234.9	433.5	72.4
10	60	1	10.6	26.0	4.2	48.8	77.7	6.0
10	60	4	15.4	41.1	9.0	79.8	136.7	9.4

CC = cutting cycles; PA = plantation age (year); A = shoot age (year); and DM represents total above ground biomass.

3.2 Soil physical and chemical properties status along the chronosequence - Paper III

Coppice-shoot age did not show any statistical significant impact on soil bulk density and soil chemical properties. It is particularly interesting that not even the organic C concentration was affected. Possible reasons may be related to complete litter raking practices, small variations in coppice-shoot ages for the sampled stands. For these reasons the organic content in the top soil does not reflect the higher amount of leaf and leaf litter in stands with older shoots. In contrast to this, there was an impact of total plantation age or cutting cycles on soil physical and chemical properties. Soil bulk density in the upper 30 cm increased significantly with number of cutting cycles ($p < 0.05$) and increased by about 40-45 % in the 0-10 and 10-30 cm layers. Most soil nutrient concentrations showed a decline in both the soil layers along the cutting cycles (Table 4). Statistically significant decreases ($p < 0.05$) were obtained for organic carbon, total nitrogen, exchangeable Ca, exchangeable Mg, CEC, and BS (base saturation). Organic C and total N were 30 and 50% higher, respectively, in the second (2N) than in the tenth cutting cycle (10N). The CEC, which in the 0-10 and 10-30 cm soil depths were in the range of 23.9 to 29.2 and 22.5 to 28.6 $cmol_c\ kg^{-1}$ respectively, was strongly and negatively correlated with total plantation age ($p < 0.05$). The base saturation (BS) declined by 9% from the 2N to 7N cutting cycle and 46% from the 2N to the 10N cutting cycle at 0-10 cm depth, and by 13% from the 2N to 7N, and reduced by 45% from the 2N to 10N in 10-30 cm soil layer. On the other hand, cutting cycles had no significant effect on pH, P available and exchangeable K. The insignificant differences for the available P concentration usually presumed to be deficient and its magnitude in most tropical soils is so small, which may be the case in the present study that we did not able to detect substantial variations between cutting cycles.

Most macro soil nutrient content negatively correlated with cutting-cycle number and tended to be positively correlated with coppice-shoot age (Paper III). In fact, number of cutting cycles had stronger effect than coppice-shoot age. The relatively strong impact of cutting cycles and the very marginal impact of coppice-shoot age on nutrient stock were best expressed by the multiple regressions (Paper III). The soil quality decline from generation to generation is most probably due to anthropogenic activities such as repeated whole-tree harvesting and litter raking. Several other studies have reported the impact of human induced disturbance on forest sites (e.g., Pennington et al., 2001;

Biruktayet, 2004; Du Toit, 2003; Jandl et al., 2007). For instance, decreased productivity following slash and litter removal has been observed for various *Eucalyptus* species (Fölster & Khanna, 1997; Merino et al., 2003; Biruktayet, 2004) as well as for radiate pine (Nambiar, 1996; Smith et al., 2000).

Indicators of site quality deterioration over time are declining contents of some nutrients in the soil and higher bulk density (Paper III), lower production (Paper I), and low concentrations of N and P in living tree components (Paper II). It should be particularly stressed that the underlying bedrock is basaltic and hence originally rich in e.g., Ca- and Mg-containing minerals. Nevertheless, a drop in exchangeable Ca and Mg was recorded (Paper II). It seems that N and P are of special importance since their concentrations in leaves are low and they are depleted in soil over time. They may both suffer from the litter raking and in the case of P also by strong immobilisation at secondary iron oxides in the mineral soil.

The most notable changes observed in soils in this study were the increase in soil bulk density and the significant decrease in most soil nutrients. This can be related to number of cutting cycles; and these factors most probably affect tree growth. Soil compaction in conjunction with low organic matter over consecutive cutting cycles presumably reduce water infiltration rate into the top soil profile and enhance surface run-off, all of which may retard forest growth. In concurrence with a similar phenomenon, Taylor and Simlock et al. (2006) found that soil compaction had an adverse impact on plant root growth. Overall the soil nutrient concentration values obtained in the present study are in agreement with other similar studies (Madeira & Pereira, 1990/91; Grove et al., 2001; Zerfu, 2002). However, our results are lower than those reported by Asferachew (2004) on Andosols at Munessa forest plantations, central Ethiopia and by Bernhard-Reversat (1996) in Congolese *Eucalyptus globulus* plantations. The relatively lower values obtained in our study might be attributed to elevated number of cutting cycles, inherent soil fertility differences between the two soil types and complete litter raking practice undergone in *Eucalyptus* plantations within the study area.

Table 4. *Mean (±SE) of soil chemical properties in the 0-10 and 10-30 cm soil depths in second, seventh and tenth- rotations of* Eucalyptus globulus *plantations in the central highlands of Ethiopia*

	Depth	Number of cutting cycles			
Soil property	(cm)	2N (n =4)	7N (n =3)	10N (n = 3)	ANOVA
pH (1:2.5 soil:H_20)	0-10	5.5±0.11	5.4±0.12	5.3±0.03	ns
	10-30	5.6±0.12	5.4±0.09	5.4±0.05	ns
P available (mg kg^{-1})	0-10	2.61±0.40	1.85±0.39	1.63±0.22	ns
	10-30	2.37±0.45	1.16±0.23	1.34±0.19	ns
K exchangeable ($cmol_c$ kg^{-1})	0-10	0.88±0.10	0.76±0.09	0.71±0.15	ns
	10-30	0.69±0.11	0.57±0.08	0.61±0.13	ns
Ca exchangeable ($cmol_c$ kg^{-1})	0-10	9.78±1.94	6.99±1.37	3.37±0.50	★
	10-30	9.92±1.95	6.78±1.60	3.22±0.49	★
Mg exchangeable ($cmol_c$ kg^{-1})	0-10	3.86±0.39	4.10±0.75	2.23±0.21	★
	10-30	3.80±0.44	4.24±0.73	2.30±0.19	★
CEC ($cmol_c$ kg^{-1})	0-10	29.2±1.21	27.7±2.83	23.9±0.73	★
	10-30	28.6±1.29	26.8±1.57	22.1±1.15	★★
Base saturation (%)	0-10	50.5±6.42	46.0±7.26	27.3±2.14	★
	10-30	51.5±7.17	44.6±6.80	28.1±2.25	★
Organic C (%)	0-10	4.00±0.25	2.80±0.20	2.13±0.16	★★★
	10-30	2.96±0.21	2.25±0.17	1.48±0.10	★★★
Total N (%)	0-10	0.26±0.02	0.19±0.02	0.17±0.01	★★★
	10-30	0.23±0.02	0.17±0.01	0.16±0.01	★★★
C:N	0-10	15.5±1.13	16.0±1.99	12.7±0.73	ns
	10-30	13.6±1.09	14.0±1.75	9.69±0.67	ns

★★★ Significant at $p < 0.001$; ★★ significant at $p < 0.01$; ★ significant at $p \leq 0.05$; ns =not significantly different.

3.3 Ground flora composition, diversity and biomass production in consecutive cutting cycles of *E. globulus* plantations - Paper IV

A total of 41 ground flora species belonging to sixteen families were identified and are all listed in Table 2 (Paper IV). Poaceae, Cyperaceae, and Asteracae families were the most common families under the five *Eucalyptus* plantations.

Based on a pair-wise comparison analysis, the mean values of vegetation cover, Shannon's index, species richness, species evenness and biomass differed significantly ($p < 0.05$) between several of the sites (Table 5). At site S2 (Wore Genu), the vegetation cover was 72% and followed the order: Menagesha (S1, 53%) > Gala Amba (S3, 50%) > Shinkuro (S4, 32%) > Holota (S5, 15%). Site 1 had the highest mean Shannon's species diversity ($H' = 1.49 \pm 0.17$), but it didn't show a significant difference between S2 (1.38 ± 0.16) and S3 (1.27 ± 0.17) sites. The mean species richness was the lowest at S2 site in Holota plantation (0.75 ± 0.17) while the plantation at Gala Amba contained the larges species number (3.38 ± 0.39). Mean evenness values (16 quadrats per site) ranged from 0.05 in S5 site to 0.37 in S4 site. At site S1, species evenness was the highest (0.37) while the evenness index at S5 was significantly lowest of all the five sites (Table 5). However, the evenness indices with the mean values: 0.21, 0.22 and 0.25 for sites S3, S2 and S1 respectively were not significantly different.

The results of the regression correlations revealed that most of the measured ground flora attributes (biomass, vegetation cover, Shannon's diversity, species richness, and evenness) were neither coppice-shoot age nor cutting cycle dependent (Table 6). However, some of the measured ground flora variables exhibited a patterned trend along parts of the chronosequence. Except the plantation at Holota, the mean biomass generally showed an increasing trend with coppice-shoot age (Table 6). Mean biomass was 59 g m^{-2} in the 4- year, 67 g m^{-2} in the 5- year at Shunkuro site, 102 g m^{-2} in the 7- year, and 111 g m^{-2} in 9-year-old stands. The mean ground flora biomass at Holota with a 5-year-old stand was exceptionally the lowest of all the studied sites, and amounted to 15 g m^{-2}. The lowest biomass value obtained for this site is in concurrence with the stand's poor soil macronutrient status (Paper III). Albeit the insignificant differences, a general declining trend was found for the ground flora attributes as the number of cutting cycles increased (Table 5). The mean vegetation cover for the second (2N), sixth (6N) and seventh (7N) cycles was 63%, 51% and 23% respectively. This pattern corresponded well to that of the Shannon-Wiener diversity indices and species richness. The mean Shannon-Wiener diversity index declined by 65% from the 2N to the 7N and by 60% from the 6N to the 7N cycle plantations. Stands that had high Shannon's diversity indices contained high mean species richness.

In general, the declining trend of the measured ground flora variables in consecutive cutting cycles, most likely related to resource use competition, soil fertility limitations (Paper III) and site disturbance intensity. For instance, Yirdaw and Luukkanen (2003) have reported a similar pattern and indicated that the second and the fourth rotations had more woody undergrowth species than the new *Eucalyptus* plantation (first rotation stand) in the central highlands of Ethiopia. This is in agreement with our results showing that a higher number of cutting cycles/rotation number gave lower vegetation cover and diversity.

Many authors (Auclair & Goff, 1971; Hanks, 1971; Howard, 1979; Howard & Thomas, 2003) stated that species diversity follows one of four patterns over a successional time scale: (1) increase, (2) decrease, (3) peak at middle succession, or (4) no trend. Despite the few stands measured in the present study, our results do support a decreasing pattern over the consecutive cutting cycles, i.e. vegetation cover, species diversity and richness decreased from a high value in the early cutting cycles and further declined as the number of cutting cycles increased. These patterns in turn imply that consecutive cutting cycles coupled with whole-tree harvesting and site disturbance may alter micro-site environment and overstory canopy architecture. In agreement with this notion, several researchers showed the effect of tree plantations' overstory canopy structure on native woody undergrowth regeneration in Ethiopia and elsewhere (e.g., Parrotta, 1995; Lemenih, 2004; Yirdaw & Luukkanen 2004). For instance, Lemenih (2004) demonstrated the effect of canopy cover and undersory environment of tree plantations on undergrowth species richness, and concluded that stands of plantation species with open canopies could enhance more native woody recolonization than stands with dense canopies in central Ethiopian highlands. In fact, other site factors such as photosynthetically active radiation (PAR) reaching forest floor could have a substantial impact on ground flora regeneration and recolonization in forest plantations. In contrast, an opposite pattern has been reported by Gonard and Romane (2005) after logging chestnut coppice stands in southern France. As a consequence of logging, the clear cut stand (second rotation coppice stands) contained more undergrowth plant species diversity compared to the uncut stands.

In conclusion, part of the decline in species richness over cutting cycles in the present study may be attributed to site disturbance, caused by repeated whole-tree harvest with short rotation cutting cycles. Most likely, recurrent litter raking within the study area could also exacerbate soil nutrient depletion and thereby alter plant cover, biomass and species richness over time. *Eucalyptus* is also alleged to have an allelophatic effect on the understorey vegetation (e.g., Poore & Fries, 1985; Konar & Kushari, 1989).

Table 5. *Mean (±SE) of ground flora cover (%), Shannon-Wiener diversity index (H'), species richness (species number1m^{-2}), species evenness, and biomass (g dry matter m^{-2}), under the five Eucalyptus globulus plantations in the central highlands of Ethiopia*

Site codes	Locality name	PA (yr)	CC	A (yr)	Vegetation cover (%)	Shannon index (H')	Species richness (no. m^{-2})	Evenness	Biomass (g m^{-2})
S1	Menagesha	13	2	4	53.1 ± 8.80 ab	1.49 ± 0.17 a	3.50 ± 0.37 a	0.25 ± 0.03 a	59.4 ± 6.4 a
S2	Wore Genu	14	2	7	71.9 ± 6.78 a	1.38 ± 0.16 a	3.44 ± 0.36 a	0.22 ± 0.03 a	101.9 ±7.9 b
S3	Gala Amba	37	6	9	50.4 ± 8.57 ab	1.27 ± 0.17 a	3.38 ± 0.39 a	0.21 ± 0.03 a	111.3 ±13.9 b
S4	Shinkuro	40	7	5	32.1 ± 6.96 bc	0.90 ± 0.18 b	2.06 ± 0.32 b	0.37 ± 0.04 b	66.9 ± 9.9 ab
S5	Holeta	40	7	5	14.5 ± 6.06 c	0.11 ± 0.07 c	0.75 ± 0.17 c	0.05 ± 0.03 c	15.0 ± 3.7 c

PA = Plantation age (yr); CC = Cutting cycles; and A = Shoot-age (yr). Same letter(s) in a column indicate no significant differences at $p < 0.05$ level.

Table 6. *Correlations (r) between ground flora cover, species richness, Shannon-Wiener diversity index and ground flora biomass with coppice-shoot age and cutting cycles (n=5)*

	Coppice-shoot age (year)		Cutting cycles	
Ground flora variables	r	p-values	r	p-values
Vegetation cover	0.40	0.50	-0.83	0.09
Species richness	0.39	0.52	-0.74	0.16
Shannon diversity index	0.26	0.67	-0.72	0.17
Ground flora biomass	0.77	0.13	-0.35	0.57

3.4 Synthesis of nutrient mass flow by stem harvest and litter raking - Papers I, II and III

The total amount of P lost by litter raking was estimated to be 10% of the total loss through stem harvest and litter raking (Table 7). Corresponding values for K was 27%, N 36%, Mg 42% and Ca 54%. In conclusion, litter raking had strong negative impacts on the nutrient stocks of Ca and Mg and least of P. This is explained by comparatively low concentrations of P in dry litter and high concentrations of Ca and Mg.

For P, Ca, Mg and K, the change in soil stock cannot be compared with the losses since these stocks refer to different fractions of the element, i.e. the soil pool is determined as an extractable fraction which is only a small part of the total soil stock bound to organic matter and minerals. However, the analyses of N refer to total N in both soil and vegetation. The results show that the amount of N lost from the soil pool by far exceeded the losses through uptake in biomass and harvest (Table 7). Factors that may explain the excess loss of N are erosion and leaching, as well as uptake in belowground biomass which was not analysed in this study. It should also be mentioned that we only studied the soil to 30 cm depth and changes in the N stock in deeper soil layers may change the conclusions.

There are several other investigations of the impact of harvesting regimes on soil nutrient pools for *Eucalyptus* and other tree species (Hopmans et al., 1993; Merino et al., 2005). For instance, Merino et al. (2005) reported the impact of different harvesting intensities in fast growing forest plantations in southern Europe. They found high ratios between nutrients exported by harvesting and those available in soil stores, indicating limitations for P, Ca and Mg over the long term basis which is consistent with frequently observed deficiencies in the tropical regions. Waide & Swank (1975), Aber et al. (1978), and Proe & Duch (1994) have highlighted the adverse impact of litter and residue management to soil nutrient pools and sustainability of forest plantations in the tropics and temperate regions. Among others, Proe & Duch (1994) pointed out that retention of harvest residues at the site significantly increased mean tree height growth of Sitka spruce.

Over all, the soil macronutrients, principally C, N, Ca and Mg, varied substantially and declined across a number of cutting cycles. The decline was the greatest particularly after the sixth and seventh cycles. Accompanying the soil fertility decline, the above-ground biomass and the measured ground flora attributes, i.e. field layer vegetation cover, biomass, species richness and diversity showed a declining pattern as well. One reason for these changes and patterns is most likely soil nutrient mining through repetitive whole tree harvesting coupled with frequent site disturbance on short rotations, and complete litter removal without any soil nutrient replenishments. However, other reasons for decreased biomass growth rate may be deteriorating root systems over time and stump mortality. What happens to organic matter, particularly forest litter, appears to be crucially important to the forest ecosystems sustainability for the following three major reasons: (i) the surface litter layer contributes largely to soil erosion reduction; (ii) litter and organic matter represent a significant nutrient store, albeit usually in a dynamic state of litter addition and litter/organic matter re-incorporation; (iii) the litter organic matter and mineral soil interface is the main source of nutrient cycling and microbial activity, and usually has the greatest concentration of fine roots found anywhere in the soil profile. If this significant organic matter is removed and raked continuously it could have a detrimental effect on soil fertility.

Table 7. *Accumulated removal of elements by stem harvest and litter raking and changes in soil nutrient content after 10 cutting cycles*

	Soil changes	Total removal	Stem removal	Litter removal
Element	(kg ha^{-1})	(kg ha^{-1})	%	%
N	-1629	649.1	63.7	36.3
P	-7.2	449.4	90.3	9.7
K	-68.4	1673.2	72.9	27.1
Ca	-166.5	4282.9	46.1	53.9
Mg	-44,1	432.9	57.6	42.4

4 Conclusions and recommendations

Management of extensive *Eucalyptus globulus* plantations in the central highlands of Ethiopia so far has not experienced a fundamental change over decades. Traditional extensive *Eucalyptus* cultivation is still an ongoing activity that includes whole-tree harvesting and litter raking without any fertilizer application over consecutive cutting cycles/rotations. Nevertheless, *Eucalyptus* plantations are increasingly important resources in Ethiopia, and the trend is likely to rise for the foreseeable future. On the other hand, because of their voracious water consumption, high soil nutrient demand and negative impact on understory vegetation, *Eucalyptus* plantations are alleged to have adverse environmental implications and may lead to forest site degradation.

Land degradation is one of the factors which could threaten the resource base of the central highland of *Eucalyptus* plantation's sustainability to provide an ever increasing wood demand for peoples, particularly to 4-5 million inhabitants of Addis Ababa. In an Ethiopian context, the state of knowledge about the temporal changes caused by the *Eucalyptus* chronosequence plantations is insufficient, scanty and poorly understood. In this thesis, we evaluated the effects of cutting cycles and coppice-shoot age on the above-ground biomass production and nutrient distribution (Paper I and II), soil physico-chemical properties (Paper III), and ground flora attributes (Paper IV) temporal changes. Based on the findings from this study, the following conclusions and recommendations were drawn:

4.1 Conclusions

- Above-ground biomass was strongly correlated with the coppice-shoot age. In contrast, there was a significant decline of biomass production with increasing number of cutting cycles. The decline in magnitude was very remarkable particularly after the sixth and seventh cycles.

- The coppice-shoot age had no significant effect on nutrient concentrations of the tree components. However, except for P, they showed a declining trend as the coppice-shoots aged. Similarly, the influence of cutting cycle on tree component's nutrient concentrations was insignificant. Unlike the coppice shoot age, it showed an increasing trend with the nutrient concentrations of biomass components.

- The lowest nutrient concentration was contained in the woody tree components, such as branches and the highest in leaves.

- The soil macronutrients in the top 30 cm soil were highest under the second cutting cycle (2N) stands, followed by 7N and then 10N plantations, indicating that some nutrient deficiency, particularly N, P and K may become a growth limiting factor over the consecutive cutting cycles of *Eucalyptus*. Hence, special emphasis should be given to replenish total N and available P because their concentrations were comparatively low and possibly retard plant growth.

- The observed reductions in biomass production and soil nutrients across cutting cycles are comparable to the previous studies of *Eucalyptus* and other tree species in the tropics and temperate regions.

- Although non significant, results from this study indicate that stands with higher number of cutting cycle contain more species than stands with a fewer cutting cycles. This implies that consecutive cutting cycle under short rotation whole-tree harvesting could have an adverse impact on the ground flora composition and diversity.

From an overall view, it can be concluded that the *Eucalyptus* plantation sites were under the state of a slow degradation process, most likely resulting from whole-tree logging system and the complete litter removal from litter raking, combined with mortality of stumps. This is also consistent with lower amount of nutrients in the soil (Paper III) and lower ground-flora diversity (Paper IV).

4.2 Recommendations

To improve biomass productivity, maintain soil fertility and conserve ground flora diversity in consecutive cutting cycles, an urgent intervention is needed. Such measures could include:

- Harvest *Eucalyptus* plantations on 15-20 years rotations with the maximum of six cutting cycles before any drastic biomass reduction and soil nutrient depletion may take place. This would minimize frequent site disturbance and increase the resilience time for soil fertility amelioration, enhance ground flora regeneration and conservation.

- Limit the cutting-cycle number to between 4 and 6 or change land use before any drastic site quality degradation would occur. This implies a change to a less intensive land use, e.g. slow growing indigenous tree species.

- Adopt harvesting techniques that are conservative of soil nutrients. Thus, it is instructive to discourage whole-tree logging and litter raking which deplete soil nutrients and allow the twigs, leaves of harvested trees that are rich in nutrients, to decompose on the forest floor to help replenish soil nutrients because the systems are sustaining mainly on internal nutrient cycling process. Debarking harvested trees in the plantation will also reduce the drain on soil nutrients. Mixing leguminous tree species with *Eucalyptus* could come as an alternative option as well.

- If the aforementioned measures would not bring satisfactory results, other similar interventions such as fertilization, particularly nitrogen and phosphorous should be applied in the worst scenario for replenishment and maintenance of soil nutrient stock to ensure sustainable management of *Eucalyptus globulus* coppice plantations in the central highlands of Ethiopia. However, improving site fertility and increasing productivity via fertilizer application is costly and beyond the economic capacity of the forestry enterprises with in the study area.

5 Future research direction

- Fine roots of trees and understory vegetation play an important role in the soil carbon and nutrient dynamics. However, there is insufficient quantitative and qualitative information available about their contribution to the carbon and nutrient budgets in the central highlands of *Eucalyptus globulus* plantations. Therefore, research on quantification of fine roots across consecutive cutting cycles/rotations will be required for estimating their role as carbon stores and sources of soil litter input. Also, the physiological basis of coppicing is still not yet well understood. Therefore, future research to evaluate and determine the physiological basis of the effects of multiple cutting cycles in relation to the temporal and spatial root dynamics on soil properties is needed.

- Litter removal is a widely held practice in *Eucalyptus* plantations within the study area. So, further investigation aiming at its impact on soil properties, undergrowth vegetation species richness and diversity is vital.

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