

# Effects of conversion of natural forest to plantations, traditional agroforestry and cultivated lands on carbon sequestration and maintenance of soil quality in Gambo district, Southern Ethiopia

Virkingen av å dyrke opp skogsområder for omlegging til plantasjedrift, tradisjonell agroforestry og jordbruk på karbonlagring og jordkvalitet i Gambo distrikt, Sør-Etiopia

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Ambachew Demessie Wele  
Ås UMB 03.12.2009



# Effects of conversion of natural forest to plantations, traditional agroforestry and cultivated lands on carbon sequestration and maintenance of soil quality in Gambo district, Southern Ethiopia

## Abstract

Clearing and conversion of natural forest to short rotation plantation, traditional agroforestry, crop and grazing land uses are rampant in Ethiopia. The unabated deforestation and the eventual reduction in soil productivity and desertification are threats of major importance in the country. Poor land cover, over grazing and mismanagement of agricultural lands strongly contribute to the loss of carbon pool, soil organic matter and many essential nutrients for plant growth that may lead to reduction in soil carbon sequestration. The land use types in Gambo district, Southern Ethiopia, in which this study was undertaken, are natural forest, short rotation plantations, crop lands and traditional agroforestry systems (scattered trees in farm lands, various types of home gardens). Little is known about the state of carbon and nitrogen stocks, soil quality (the soil physical and chemical properties, such as infiltration, soil moisture characteristics, bulk density, CEC, pH etc) for all of these land use types in the study area. However, an understanding of the various land use types and traditional management practices at local level is crucial, to identify systems suitable for sustainable land productivity and carbon sequestration. Therefore, this study was carried out to (i) investigate the changes (loss or gains) in the concentration and stocks of soil organic carbon (SOC), nitrogen (N) and their distribution along 1m depth in soils under the chronosequences of 12, 20, 30, 40 and 50 years after conversion of the natural forest to traditional agroforestry and cultivated lands (ii) assess the effect of conversion of the pristine vegetation to short rotation plantations on the state of SOC, N and soil bulk density (iii) investigate the litter production and “in situ” decomposition rate and residence time of the detritus material of the commonly planted “broad leaved” *Eucalyptus* and coniferous short rotation plantation species and (iv) evaluate the effect of plantation species on key soil chemical and physical properties (e.g. bulk density (BD) pore volume, moisture retention and infiltration) and thus on soil quality in Gambo district, Southern Ethiopia. Soil profile samples were collected at 10, 20, 40, 60, and 100 cm depth intervals and the SOC, N and BD were assessed. Biomass of trees was determined by non destructive method, while that of bushes, shrubs and herbs was by destructive methods. The production of litter and the subsequent decomposition rate were studied on broad leaved (*Eucalyptus globulus*, *Eucalyptus camaldulensis*, *Eucalyptus saligna*) and coniferous species (*Juniperus procera*, *Cupressus lusitanica*, and *Pinus patula*) and compared with leaf litter fall from the adjacent natural forest. The litter fall was recorded by litter traps and the decomposition rate was studied by nylon net bag technique.

The results showed that the greater proportion of SOC and N was concentrated in 0 to 20 cm depth and that their concentration in agroforestry (AF) and farm (F) land uses was significantly lower than that in the natural forest (NF). Soils in traditional agroforestry land use showed a trend of higher SOC stocks in all chronosequences compared with those in the corresponding cultivated lands. But these differences apart from few exceptions were not statistically significant. The loss of SOC stock under the chronosequence of 12 to 50 years of AF and F land uses ranged from 2.8 to 9.9 kg m<sup>-2</sup> or 12 to 43 % of the stock under the natural forest. The rate of SOC loss under AF<sub>12</sub> was 0.62 kg m<sup>-2</sup> yr<sup>-1</sup> and that under AF<sub>50</sub> was 0.09 kg m<sup>-2</sup> yr<sup>-1</sup>. The corresponding values for farm land were 0.66 and 0.13 kg m<sup>-2</sup> yr<sup>-1</sup>. The rate of

N loss also declined with time under both land uses, for example, from 0.028 kg m<sup>-2</sup> yr<sup>-1</sup> for AF<sub>12</sub> to 0.001 kg m<sup>-2</sup> yr<sup>-1</sup> for AF<sub>50</sub>.

Soils under *Juniperus procera* showed higher SOC and N in 0-10 cm depths than the other plantations but were only significantly different from that in *E.globulus*. The percent loss of SOC of soils in plantations established on cultivated lands ranged from 47 % under *P. patuala* to 66 % under *E.globulus* compared to that in the natural forest. The corresponding percent loss of SOC in plantations established on primary forest land ranged from 33 % in *J.procera* to 45 % in *C.lusitanica* in 22-29 years time. The SOC loses of similar depth in traditional agroforestry and farm lands of age chronosequences ranged from 49 % in AF<sub>40</sub> to 69 % in F<sub>50</sub>. As compared to F<sub>50</sub>, the net gain of SOC in plantations established on cultivated lands was 22 % in *Pinus patula* 9 % in *E.camaldulensis* and 2 % in *E.globulus*. No evidence of significant difference on SOC and N distribution among plantations was observed below 10 cm depth with few exceptions. The soils under plantations showed 133.62 to 213.73 Mg ha<sup>-1</sup> or 59.1 to 94.5 % SOC, 230.4 to 497.3 Mg ha<sup>-1</sup> or 6.9 to 14.9 % total biomass carbon (TBC) and 420.37 to 672.80 Mg ha<sup>-1</sup> or 12.5 to 20.0 % C-pool of that under the natural forest. Despite the differences are non significant, the N stock under *Juniperus procera* was the highest, while the lowest stock was under *Eucalyptus globulus* and *Cupressus lusitanica*.

Litter production under broad leaved plantation species and natural forest (ranging from 8.7 to 11.5 Mg ha<sup>-1</sup> yr<sup>-1</sup>) was significantly higher (P<0.05) than that under coniferous species (ranging from 4.4 to 6.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>). The average concentration of C and N in fresh matured leaves (fully expanded but before leaf senescence) was higher than in litter fall, implying that both C and N were either sorbed in the plant system or lost during the litter fall period and these losses varied from 2.9 to 22.3 % for C and 11.8 to 53 % for N. The data on decomposition study showed that the residual litter mass declined with time for all species despite that the weight loss was variable at the different times of the study period. The amount of N which potentially returned to the soil through the litter fall was higher in natural Forest, *Juniperus procera* and *Cupressus lusitanica* than in *Eucalyptus saligna*, *Eucalyptus camaldulensis* *Eucalyptus globulus* and *Pinus patula*. The annual dry matter decay constant (k) varied from 0.07 month<sup>-1</sup> in *Pinus patula* to 0.12 month<sup>-1</sup> in *Eucalyptus saligna*. The half-time (t<sub>0.5</sub>) decay ranged from 6.0 for *Eucalyptus saligna* to 9.7 months for *Pinus patula*. The results suggest that the decomposition rate in *Pinus patula* was relatively lower than the other species and the litter production under broad leaved *Eucalyptus* was comparatively higher to that in coniferous species.

No significant difference was observed on air volume, water volume (% at -10 kPa matric potential), or available water under plantation species. However, significantly higher BD and significantly lower pore volume and infiltration rate were observed under plantations established on cultivated lands than those on forest soils. Water volume (% at -1500 kPa matric potential) in soils under *Juniperus procera* and natural forest was significantly higher than in those of the other plantations. Exchangeable cations decreased with depth with the exception of Ca<sup>2+</sup> under *E.globulus* and *E. camaldulensis* that showed the opposite trend. The concentrations of exchangeable Ca<sup>2+</sup> and Mg<sup>2+</sup> under plantations were lower, and that of K<sup>+</sup> was higher than that under the natural forest. The soil in plantations on previously cultivated lands had soil quality index below the base line value, while those established on undisturbed forest soil, with the exception of *E. saligna*, were above that value.

Despite the differences of SOC stocks among agroforestry and farm lands are negligible, the obtained results indicate that traditional agroforestry systems has a potential of sequestering

more SOC stock provided that better management is practiced and trees with proven multipurpose functions are integrated in all agricultural landscapes. The higher litter fall under broad leaved plantation suggest that the input for C sequestration and nutrient recycling in the soil is high under *Eucalyptus* species and this potential can be exploited to, restore, maintain and sequester SOC given that the rotation period is prolonged. In general, natural forest should be protected from further conversion to other land uses to maintain healthy ecosystem functions. Nevertheless, plantations can be considered over farm lands as good option for sequestration of C and N when mitigation of the increasing atmospheric CO<sub>2</sub> in combination with the sustenance of land productivity is the main quest of land management.

**Key words:** Biomass, carbon sequestration, chronosequences, deforestation, litter fall, natural forest, plantation species, soil organic carbon and traditional agroforestry





# **Virkingen av å dyrke opp skogsområder for omlegging til plantasjedrift, tradisjonell agroforestry og jordbruk på karbonlagring og jordkvalitet i Gambo distrikt, Sør-Etiopia.**

## **Sammendrag**

Avskoging og omlegging av naturlig vegetasjon til andre dyrkingsformål fører til ødeleggelse av jordarealer i Etiopia. Hogst og omlegging fra skog til plantasjer med korte vekstomløp, tradisjonell agroforestry, jordbruk med beiting og intensive plantedyrking skjer mer og mer i Etiopia. Avskoging, reduksjon i jordas dyrkingspotensiale og forørkning er vesentlige trusler i landet. Tynt plantedekke, overbeiting og dårlig jordbruksdrift bidrar sterkt til tap av karbon, reduksjon i innhold av organisk materiale og tap av flere viktige plantenæringsstoffer. Arealbruken i Gambo distrikt, Sør-Etiopia hvor denne studien ble utført, er naturlig skog, plantasjer med kort vekstomløp, jordbruk og agroforestry (dyrking mellom etablerte tre som står igjen på dyrka arealet samt ulike typer småskala hagebruk). Det er lite kunnskap om utvikling av karbon- og nitrogenhusholdningen, jordkvaliteten (fysiske og kjemiske egenskaper som infiltrasjon, jordas fuktighetskarakteristikk, jordtetthet, CEC, pH osv) for alle typer dyrkingsformål i undersøkelsesområdet. Ikke desto mindre er kunnskap om de ulike dyrkingssystemene og tradisjonell jordarbeidingspraksis på lokalnivå avgjørende for å kunne identifisere bærekraftige systemer for produktivitet og karbonlagring.

Denne studien er utført for å (i) undersøke endringene (reduksjon eller økning) i konsentrasjon og lagring av organisk karbon i jord (SOC-soil organic carbon) og nitrogen (N) og fordeling av disse på 1 m dybde i perioder på 12, 20, 30, 40 og 50 år etter omlegging fra opprinnelig skog til tradisjonell agroforestry og dyrket jord under datidens bønders praksis for bruk av planterester (ii) beregne effekten av omlegging fra opprinnelig vegetasjon til plantedyrking i korte omløp på tilstanden til SOC, N og jordtetthet (iii) undersøke strøproduksjon og "in-situ" nedbrytningshastighet og varighet av nedbrytningsmateriale fra vanlige plantede "løvtrær" eukalyptus, bartrær og arter fra korte vekstomløp og (iv) undersøke effekten av kulturvekster på viktige jordkjemiske og -fysiske egenskaper (f. eks. jordtetthet, porevolum, fuktighetskarakteristikk og infiltrasjon) og da også jordkvaliteten i Gambo District i det sørlige Etiopia. Det ble tatt ut jordprøver fra 10, 20, 40, 60, og 100 cm dybdeintervaller fra 1 m dype jordprofiler for alle dyrkingssystemer, og total karbon (TC), SOC, TN og jordtetthet ble bestemt. Biomassen til trær ble bestemt med ikke-destruktive metoder, mens biomasse til busker, kratt og urter ble bestemt med destruktive metoder. Produksjon av strø og påfølgende nedbrytningshastighet ble undersøkt for løvtrær (*Eucalyptus globulus*, *Eucalyptus camaldulensis*, *Eucalyptus saligna*) og bartreartene (*Juniperus procera*, *Cupressus lusitanica*, *Pinus patula*) og sammenlignet med strø fra den tilstøtende naturlige skogen. Strøproduksjonen ble registrert ved hjelp av strøfeller, mens nedbrytningshastigheten ble undersøkt med nylonnettpose-teknikk.

Resultatene viste at den største delen av SOC og N var konsentrert i 0-20 cm dybde, og at konsentrasjonen av disse var signifikant lavere i agroforestry og på dyrkede arealer (jordbruk) enn under den naturlige skogen. Jord som har vært i tradisjonell agroforestry-bruk viste gjennomgående høyere SOC i alle periodene sammenlignet med tilsvarende dyrkede arealer. Tap av SOC-lagre i periodene 12 til 50 år med agroforestry (AF) og jordbruk (F) varierte fra 2,8 til 9,9 kg m<sup>-2</sup> eller 12 til 43 % av lagrene under naturlig skog (NF). Hastigheten på SOC-tap under AF<sub>12</sub> var 0,62 kg m<sup>-2</sup> år<sup>-1</sup> og under AF<sub>50</sub> 0,09 kg m<sup>-2</sup> år<sup>-1</sup>. De tilsvarende verdiene fra dyrkede arealer var 0,66 og 0,13 kg m<sup>-2</sup> år<sup>-1</sup>. Hastigheten for N-tap

gikk også ned over tid for begge dyrkingssystemer, for eksempel, fra 0,028 kg m<sup>-2</sup> år<sup>-1</sup> for AF<sub>12</sub> til 0,001 kg m<sup>-2</sup> år<sup>-1</sup> for AF<sub>50</sub>.

Jord under *Juniperus procera* akkumulerte mer organisk karbon og nitrogen i alle dybdene enn under andre plantebestand, men var bare signifikant forskjellig fra *E. globulus*. Tap I present av SOC i jord under plantasje etablert på dyrka areal varierte fra 47 % for *P. patula* til 66 % for *E. globulus* sammenlignet med naturlig skog. Korresponderende tap av SOC under plantasje etablert på areal fra naturlig skog varierte fra 33 % for *J. procera* til 45 % for *C. lusitanica* over en periode av 22-29 år. For tilsvarende dybde varierte tapet av SOC under tradisjonell agroforestry og på dyrka jord over tid fra 49 % for AF<sub>40</sub> til 69 % for F<sub>50</sub>. Sammenlignet med F<sub>50</sub> så var netto økning i SOC under plantasje etablert på tidligere dyrka jord 22 % for *Pinus patula*, 9 % i *E. camaldulensis* og 2 % i *E. globulus*. Med få unntak så ble det ikke påvist signifikant forskjell i SOC og N distribusjon mellom plantebestander i dybder under 10 cm. Jord under plantasje viste 133.62 til 213.73 Mg ha<sup>-1</sup> eller 59,1 til 94,5 % SOC, 230,4 to 497,3 Mg ha<sup>-1</sup> eller 6,9 til 14,9 % total karbon i biomasse (TBC) og 420,37 to 672,80 Mg ha<sup>-1</sup> eller 12,5 til 20,0 % lagret C sammenlignet med det en finner under naturlig skog. Til tross for at forskjellene ikke er signifikante så var nitrogen lagret under *Juniperus procera* høyest mens det var lavest under *Eucalyptus globulus* og *Cupressus lusitanica*

Strøproduksjon under løvtrebestand og naturlig skog (fra 8,7 til 11,5 Mg ha<sup>-1</sup> år<sup>-1</sup>) var signifikant høyere (P<0.05) enn under bartrærne (fra 4,4 til 6,0 Mg ha<sup>-1</sup> år<sup>-1</sup>). Gjennomsnittlig C- og N-konsentrasjon i ferske, modne blad var høyere enn i strø. Dette indikerer at både C og N gikk tapt under bladfellingsperioden og at disse tapene varierte fra 2,9 til 22,3 % for C og 11,8 til 53 % for N. Den resterende strømmassen ble redusert over tid for alle artene. Mengden N som potensielt returnerte til jorden med strø var høyere i naturlig skog, *Juniperus procera* og *Cupressus lusitanica* sammenlignet med *Eucalyptus saligna*, *Eucalyptus camaldulensis*, *Eucalyptus globulus* og *Pinus patula*. Den årlige tørrstoffnedbrytningskonstanten (k) varierte fra 0,07 måned<sup>-1</sup> i *Pinus patula* til 0,12 i *Juniperus procera*. Halveringstiden (t<sub>0,5</sub>) for nedbryting strakte seg fra 6,0 for *Pinus patula* til 9,7 måneder for *Pinus patula*. Resultatene antyder at nedbrytningshastigheten for *Pinus patula* var relativt langsommere enn for de andre artene og at strøproduksjonen under bredbladet eukalyptus var relativt høyere enn for bartreartene.

Ingen signifikant forskjell ble observert i luft- og vanninnhold (% ved -10 kPa matrikspotensiale), eller tilgjengelig vannlager under de ulike plantebestandene. Det ble imidlertid registrert signifikant høyere jordtetthet og signifikant lavere porevolum og infiltrasjonshastighet under plantebestand på dyrkede arealer enn i uforstyrret skogsjord. Vanninnhold (% ved -1500 kPa matrikspotensiale) i jord under *Juniperus procera* og naturlig skog var signifikant høyere enn under andre plantebestand. Utbyttbare kationer minket med dybde, med unntak av Ca<sup>2+</sup> under *E. globulus* og *E. camaldulensis* som viste motsatt trend. Konsentrasjonen av utbyttbar Ca<sup>2+</sup> og Mg<sup>2+</sup> under plantede bestand var lavere, og av K<sup>+</sup> høyere enn den under den naturlige skogen. Jorda under plantebestand på tidligere dyrkede arealer hadde en jordkvalitetsindeks som var lavere enn grunnverdiene, mens ved etablering på uforstyrret skogsjord, med unntak av *E. saligna*, var høyere enn denne verdien.

Resultatene som er framkommet indikerer at tradisjonell agroforestry har et høyere potensiale for karbonlagring, forutsatt at dyrkingsmetoder forbedres og at trær med kjente, egnede egenskaper og funksjoner integreres i alle jordbruksarealer. Den høyere

strøproduksjonen under bredbladet beplantning antyder at tilført C for lagring og resirkulering av næringsstoff i jorda er høy under *Eucalyptus* arter og at dette potensialet kan utnyttes til å restaurere, vedlikeholde og lagre organisk C, forutsatt at rotasjonsperioden er forlenget. Generelt bør naturlig skog vernes mot omlegging til annet bruk for å opprettholde gode økologiske funksjoner. Derimot kan plantasjer betraktes som et bedre alternativ enn jordbruk for sekvenstrering av karbon og nitrogen som tiltak mot et økende innhold av CO<sub>2</sub> i atmosfæren og for å ta vare på jordas dyrkingspotensial

Nøkkelord: Biomasse, karbonlagring, tidsperioder, avskoging, strøproduksjon, naturlig skog, plantebestand, organisk karbon i jord og tradisjonell agroforestry.



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- Paper I. Wele, D. Ambachew, Singh, B. R., Lal, R. 2009. Soil carbon and nitrogen stocks under chronosequence of cultivated and traditional agroforestry land use in Gambo District, Southern Ethiopia. *Soil Science Society of American Journal* (Submitted)
- Paper II. Wele, D. Ambachew, Singh, B. R., Lal, R. 2009. Soil Carbon and Nitrogen Stocks under Plantations in Gambo District, Southern Ethiopia. *Journal of Sustainable Forestry* (in press)
- Paper III. Wele, D. Ambachew, Singh, B. R., Lal, R. Strand, L.T. 2009. Litter all and litter decomposition under eucalyptus and coniferous plantations in Gambo District, Southern Ethiopia. *Nutrient Cycling in Agroecosystems* (submitted).
- Paper IV. Wele, D. Ambachew, Singh, B. R., Lal, R. Børresen T. 2009 Effect of Eucalyptus and Coniferous Plantations on Soil Properties and Quality in Gambo District, Southern Ethiopia. *Journal of Sustainable Forestry* (submitted)

## 1. Introduction

### 1.1 General Background

Global warming caused by the emission of greenhouse gases (GHGs), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), has become principal human concern in recent years. Next to fossil fuel combustion, conversion of natural forests and peat land ecosystems to farm and other land uses is some of the major sources of the emission of GHGs (Batjes, 1999; Kirby and Potvin, 2007). Deforestation influences the CO<sub>2</sub> level in the atmosphere through the addition of the net release of CO<sub>2</sub> because trees are estimated to resynthesize 10 to 20 times more C per unit area than land under crops or pastures and by the release of C stored in the biota following deforestation, burning, and decomposition (Revelle, 2002; Macyk and Richens, 2002).

Afforestation of agricultural soils and management of forest plantations can enhance SOC stock through C sequestration (Lal, 2005). Agroforestry systems can also potentially be used as an alternative for economically sound and environmentally friendly land use approach (Wang and Feng, 1995; Pandey, 2002; Oelbermann et al., 2005; Lal, 2004a; Nair et al., 2007). Deliberately integrating trees with crop and animal production systems offer a promising avenue for C storage and GHGs emission reduction in several of the managed global terrestrial ecosystems (Nair et al., 2009). The C sequestration potential of agroforestry systems is estimated to be between 12 and 228 Mg C ha<sup>-1</sup> (Albrecht and Kandji, 2003; Dixon, 1995)

Anthropogenic disturbances of both natural and managed ecosystems can cause changes in ecosystem structure and function and potentially alter biogeochemical cycling and overall sustainability of ecosystems (Wali et al., 1999). The soil forming factors, notably climate as well as the local biological activity in which man is often a dominant factor, control the amount of soil organic matter (SOM) that corresponds with equilibrium conditions in certain natural or agro-ecosystems (Batjes, 1999). In disequilibrium due to some disturbance of which particularly human induced ones are most common, the SOC content of the soil may fall below the potential level. The increase in CO<sub>2</sub> in the atmosphere can be mitigated in the short run by sequestering C through best management practices (BMPs) including; minimum tillage, improved fallow, increasing crop growth through fertilizer application, reclamation of degraded lands, afforestation, agroforestry practices etc (Lal, 2004b).

### 1.2 Land degradation in Ethiopia

Ethiopia is a country with topographic features dominated by rugged mountains that are cut by river valleys and deep gorges, flat-topped plateau, undulating hills and lowland plains (Yirdaw, 2002). The highlands constitute more than 44% of the total area of the country (FAO, 1984) and montane forests are the main constituents of the natural vegetation of which dry afro-montane forests form the largest part (Demel, 1996). In the dry montane forests (at altitudes from 1500-2700 m) of Ethiopia, *Juniperus procera* and *Olea europaea* ssp. *Cuspidata* are the typical dominant species (Yirdaw, 2002). As the precipitation increases the montane forests characteristically contain a mixture of *Podocarpus falcatus*, *Aningeria adolfi-friedericii* and other broad-leaved species in the canopy (Friis, 1992).

The highlands of Ethiopia, in contrast to most mountain systems outside Africa, are very suitable for human inhabitation (Hawando, 1997; Yirdaw, 2002). As a result, 88% of the population, 95% of the cropped land (Hurni, 1988) and 60% of the livestock are concentrated in these highlands that put the native forests under immense pressure.

Deforestation had started as early as 2000 years ago in Ethiopia (Yirdaw, 2002). However, the disappearance of forests has been drastic during the past hundred years, but a maximum in deforestation rate was reached in the 1950s and early 1960s (Pohjonen and Pukkala, 1990). The remnant natural forests in the central and northern highlands are found only as isolated small patches at inaccessible locations and around the numerous churches and burial grounds (Yirdaw, 2002; Wassie et al., 2003). It is also estimated that open savannah type of woodlands dominated by *Acacia* species cover more than 20 million hectares (M ha). Nationally, the conservative deforestation rate of natural forests is estimated to be 0.16 to 0.20 M ha yr<sup>-1</sup> and the natural forest cover is believed to have decreased from 16 % in the 1950s to about 2.8 % in 1980s (EFAP, 1994).

The growing demand of the ever-increasing population for grazing and arable land, fuel wood and construction material is the major factor contributing to deforestation and the subsequent result of low productivity of land in Ethiopian highlands (Mekonnen, 1999; Bishaw, 2003). The demand for forest product is still growing and as a result the remnant forests are under high pressure of massive deforestation in the country. At present, because of deforestation much of the highlands are covered with wooded grasslands in which secondary tree species like *Acacia abyssinica*, *Acacia negrii* and *Acacia pilispina* occur (Friis, 1992).

### **1.3 Loss of biodiversity**

Severe deforestation has threatened the extinction of the wide range of Ethiopian flora (Tolera et al., 2008). Endemism is particularly high in the afroalpine vegetation zone and in the dry montane forest and grassland complex of the plateau (Tilahun et al., 1996). As a result of deforestation, Ethiopia's forests and woodlands have been declining both in size and species richness (Yirdaw, 2002). Due to the continuing encroachment, it is highly probable that the present fragmented forests in the highlands are much more impoverished in terms of floristic diversity than the forests, which once occupied the same site. The number of species and intraspecific genetic diversity in fragmented forests will diminish over time after isolation owing to a variety of factors, such as inbreeding and genetic drift (Turner and Corlett, 1996). For such reasons, some of the remnant tree species in the northern and central highlands are endangered, since they are found as isolated individuals. The problem of deforestation continued and the pressure increased on the remnant forests that are located in the southwestern and southeastern highlands that include the study area.

### **1.4 Soil erosion**

Current rates of soil erosion documented in Ethiopia range from 16–300 Mg ha<sup>-1</sup> yr<sup>-1</sup> (Hurni, 1988). Hawando (1997) noted that the SOM loss associated with the removal of surface soil ranges from 15 to 1000 kg ha<sup>-1</sup> yr<sup>-1</sup> which amounts to 1.17 to 78 Tg of SOM yr<sup>-1</sup> from 78 M ha of cultivated and grazing lands. The loss of soil nitrogen ranged from 0.39 to 5.07 Tg yr<sup>-1</sup> and that of phosphorus ranged from 1.17 to 11.7 Tg yr<sup>-1</sup>.

The wide spread practices of burning dung and crop residues for fuel, deforestation, cultivation on steep slopes as well as poor farming practices particularly in the areas practicing cereal mono-culture farming system, increase the susceptibility of the land resources to erosion in dry sub humid and semi-arid areas (Hawando, 1997).



## **1.5 Deforestation and conversion of the natural forest into cultivated lands in Gambo district (The study site)**

Gambo district is the area where one of the few relic natural forests is located. Extensive deforestation, overgrazing and conversion of this forest into arable land are rampant (Ashagrie et al., 2005; Solomon et al., 2002a; Lemenih and Itanna, 2004). Remnant trees deliberately left from the clearance of the wood land and natural forest are scattered all over the agricultural lands (Appendix A, Plate I and II). Such scattered trees in farm lands represent the local traditional (park land type of) agroforestry systems prominent in the study area. The tree species deliberately maintained in the traditional agroforestry systems are mostly those endangered species that are prone to selective removal by encroachers from the adjacent natural forest. While such conserved species supply litter input that may enhance soil productivity through sustenance of SOC, they will also likely serve as seed source for the rehabilitation of their habitat. Crops are grown during the rainy season in both the traditional agroforestry and farm lands without trees. After harvest, farmers remove crop residue by burning or transporting it to their home for various uses (Appendix A, Plate III and IV).

## **1.6 Soil carbon and nitrogen turnover in agricultural and forest soils**

The accumulation and turnover of SOM is a major factor in soil fertility and ecosystem functioning and determines whether soils are sinks or sources of C in the global Cycle (Feller and Beare, 1997; Post and Kwon, 2000; Feller et al., 2001). Land use, soil type, climate and vegetation are the drivers of SOM dynamics (Feller and Beare, 1997). Otherwise under similar conditions, land use management controls the ability of soils to be either a source or a sink of SOM and nutrients. For example, the conversion of natural vegetation to cultivated land results in very rapid declines in SOM (Mann, 1986; Post and Mann, 1990; Davidson and Ackerman, 1993). Much of the loss in SOC can be attributed to reduced inputs of organic matter, increased decomposability of crop residues, and tillage effects that decrease the amount of physical protection to decomposition (Mann, 1986; Post and Kwon, 2000; Vesterdal et al., 2002). On the other hand, a change in land use from agriculture to forestry is replacing the annual cycle of cultivating and harvesting crops by the much longer forest cycle (Vesterdal et al., 2002). This enables the production of a larger biomass and reduces the degree of soil disturbance. The residence time of SOM in less disturbed soils varies between 20 and 40 years for the tropical areas and between 40 and 70 years for the temperate ones, with some SOM pools very labile (<1 year) and others more passive (>100 years) in deep horizons (Feller et al., 2001).

Highly productive woody crops will add substantial C to soil, both above- and below-ground, but with all other factors kept constant, this depends on the native vegetation type (Ovington and Heitkamp, 1960; Lal, 2005) which, in turn are influenced by geologic parent material or managed plantation forest species. In managed forests, within 2–3 years after plantation establishment, mulching by leaf litter and lack of cultivation will slow decomposition and further help retain SOC pool (Grigal and Berguson, 1998). Decomposition accounts for the transformation of nearly as much C as does photosynthesis and is carried out primarily by bacteria and fungi (Berg and McLaugherty, 2008). The SOM decomposition is responsible for huge amount of the CO<sub>2</sub> returned to the atmosphere. Decomposition is also responsible for the formation of humic substances that contribute to increased soil fertility and long storage of C. It is closely tied to nutrient cycling and is essential for the release of organically bound nutrients (Berg and McLaugherty, 2008).

Substantial fraction (often 30 % to 50 % or more) of the energy and carbon annually fixed in forests is contributed to the forest floor as litter fall (mostly) leaves (Ovington and Heitkamp, 1960). Because of this and since litter fall is generally related to the quantity of photosynthetic machinery in the system, it is an interesting index of ecosystem productivity (Olson, 1963).

### **1.7 Factors controlling the dynamics of soil organic matter**

In terrestrial ecosystems, the amount of C in soil is usually greater than the amount in living vegetation. The SOM is represented by plant, animal and microbial residues in all stages of decomposition (Oades, 1988; Post and Kwon, 2000). The C content of the soil depends on both the rate of input of plant litter and its rate of decomposition. Nevertheless, the C sequestration occurs more slowly in soil than in biomass, but C stored in soils would be more resistant than C stored in biomass to sudden changes in forest management. Many organic compounds in the soil are intimately associated with inorganic soil particles (Post and Kwon, 2000). Soil type effects on the SOM turnover are most often ascribed directly to differences in soil clay content (Schjønning et al., 1999). Clay is assumed to protect OM against decomposition and some of the mechanisms proposed to explain stabilization of SOC are adsorption of organics onto surfaces of clays or formation of organic-clay complexes (Oades, 1988) and entrapment of organic particles in aggregates (Van Veen and Kuikman, 1990). The formation of stable soil aggregates is influenced by mineralogy, texture, land use management and the quality and quantity of organic matter inputs. These factors interact to determine the relationships between SOM content and water stable aggregation (WSA) and are highly dependant on clay content (Feller and Beare, 1997). Stable aggregates may enhance the physical protection of SOM against losses due either to mineralization or detachability and erosion (Feller and Beare, 1997). Parent material with high base status and or the presence of substantial content of Al and Fe oxides has a positive influence on stabilizing SOM. This includes soils with andic properties (Zunino et al., 1982; Percival et al., 2000). Base rich materials contain more clay and SOM than soils formed under similar conditions from acidic soil materials (Oades, 1988).

## **2. Rationale of the study**

The sequestration of C which involves the capturing and securely storing of CO<sub>2</sub> emitted from the global energy system or from other sources, is considered as a means to mitigate climatic change, maintain biological diversity, combat desertification, improve soil and water quality, decrease plant nutrient loss, reduce soil erosion, increase water conservation, provide better wild life habitats and restore degraded habitats (Mermut and Eswaran, 2001; Mermut, 2003).

Natural forests, plantation forests, agroforestry and crop lands play a significant role in the terrestrial C cycling and this may affect global climatic change. As noted by Mermut and Eswaran (2001), two fundamental approaches can be followed for sequestering C. These include (i) conserving and maintaining ecosystems so that C stock and sequestration can be maintained (increase the residence time of SOC) and (ii) restoring and rehabilitating ecosystems to increase C sequestration beyond the current levels via experimental manipulation.

The major land uses in Ethiopia include cereal and perennial crops, rangeland, traditional agroforestry, plantation forestry and natural forest systems. To predict dynamics of C fluxes and storage and the changes in soil quality under alternative management

regimes, the soil physical and chemical properties, the baseline C pool and the sequestration potential of different land use systems should be well known. This strategy requires an understanding of the various land use types and traditional management practices at local levels to identify systems suitable for sustainable land productivity and carbon sequestration. However, in Gambo district, Southern Ethiopia, very few of such studies have been conducted to assess the status of soil quality and the C sequestration potential of alternative land use systems under the prevailing environmental and management conditions and hence this study was undertaken.

### 3. Objectives

- 1) Investigate the soil C and N stocks under the chronosequence of cultivated and traditional agroforestry land uses (Paper I)
- 2) Compare the soil C and N stocks under different species of tree plantations established on primary forest and previously cultivated lands (Paper II)
- 3) Assess litter fall and litter decomposition under *Eucalyptus* and coniferous plantations established on primary and previously cultivated lands (Paper III) and
- 4) Evaluate the effect of *Eucalyptus* and coniferous plantations on soil properties and soil quality (Paper IV)

### 4. Materials and methods

#### 4.1 Study area

The study was conducted on three sites namely, Ashoka, Leye and Beseko, which are close or adjacent to the natural forest in Gambo district, Southern Ethiopia that covers an area positioned on the lower fringe of the western escarpment of the south eastern highlands (Fig.1).

Ashoka, Leye and Beseko sites lie within 7°17'N and 7°20'N and 38°48'E and 38°49'E, at about 240 km south east of Addis Ababa. The altitude ranges from 2137 to 2215 meters above sea level (m a.s.l), and the slope from 4 to 11 %. Rainfall is bimodal with mean annual precipitation of 973 mm, most of it falling from July to September (Fig.2). Temperature ranged between the mean monthly maximum of 26.6 °C and mean monthly minimum of 10.4°C across the study area for the period from 1999 to 2007.

The species dominant in the under story vegetation are: *Lannea schimperi* (A.Rich.) Engl. *Rytigynia neglecta* (Hiern) Robbins, *Maytenus arbutifolia* (Hochst.ex A.Rich.) Wilezek, *Bersama abyssinica* Fres and *Psydrax schimperiana* (A. Rich). The most abundant herb in the forest floor is *Hypoestes furkaolii* (Vahl.)R. Br. The traditional agroforestry system is unique and differs from most of the conventional ones. The species of woody perennials distributed in the agricultural landscape are remnant trees deliberately left during the conversion process of the natural forest to cultivated lands (Table 1).

Table 1. Location of soil sampling pits (1m depth) and vegetation characteristics in Agroforestry and farm land uses at experimental sites of Leye and Ashoka

Site	Land use	Age (Years)	Tree species agroforestry systems	D <sub>1.3</sub> (cm)	H (M)	Plot No	Elevation (m.a.s.l)	Coordinate of soil sampling pits		Slope %
								Longitude	Latitude	
Ashoka	Agroforestry	12	<i>P. falcatus</i>	212	42.2	1	2205	07°17.515'N	038°48.245' E	11
			<i>P. africana</i>	134	41.1	2	2208	07°17.508'N	038°48.234' E	11
			<i>P. africana</i>	120	36.2	3	2212	07°17.498'N	038°48.241' E	11
			<i>P. africana</i>	116	35.7	4	2203	07°17.506'N	038°48.252' E	11
Ashoka	Agroforestry	20	<i>P. africana</i>	105	27.0					
			<i>F. sure</i>	115	12.6	1	2178	07°18.062'N	038°48.309' E	8
			<i>F. sure</i>	103	12.6	2	2183	07°18.055'N	038°48.299' E	8
			<i>C. macrostachyus</i>	103	30.6	3	2181	07°18.047'N	038°48.314' E	8
			<i>C. macrostachyus</i>	98	12.6	4	2187	07°18.056'N	038°48.317' E	8
			<i>C. macrostachyus</i>	88	16.8					
			<i>C. macrostachyus</i>	84	13.8					
			<i>C. macrostachyus</i>	80	18.0					
			<i>C. macrostachyus</i>	74	25.2					
			<i>C. macrostachyus</i>	66	25.0					
Ashoka	Agroforestry	30	<i>C. macrostachyus</i>	65	26.8					
			<i>S. abyssinica</i>	129	20.0	1	2177	07°18.116'N	038°48.441' E	6
			<i>P. africana</i>	112	29.4	2	2182	07°18.092'N	038°48.436' E	6
			<i>P. falcatus</i>	86	24.6	3	2179	07°18.093'N	038°48.448' E	6
			<i>P. africana</i>	72	20.8	4	2159	07°18.104'N	038°48.444' E	6
Beseko	Agroforestry	40	<i>P. falcatus</i>	60	20.5					
			<i>P. falcatus</i>	133	30.9	1	2149	07°19.990'N	038°49.317' E	7
			<i>P. falcatus</i>	130	30.6	2	2151	07°19.983'N	038°49.305' E	7
			<i>P. falcatus</i>	124	32.7	3	2157	07°19.969'N	038°49.316' E	7
			<i>P. falcatus</i>	124	22.6	4	2166	07°19.980'N	038°49.327' E	7
			<i>P. falcatus</i>	121	34.8					
			<i>P. falcatus</i>	101	31.8					
Leye	Agroforestry	50	<i>P. falcatus</i>	98	29.4					
			<i>P. falcatus</i>	94	28.3					
			<i>P. falcatus</i>	232	53.1	1	2163	07°18.782'N	038°48.791' E	8
			<i>P. falcatus</i>	200	40.2	2	2168	07°18.756'N	038°48.774' E	8
			<i>P. falcatus</i>			3	2165	07°18.745'N	038°48.787' E	8
Ashoka	Farm	12	<i>P. falcatus</i>			4	2167	07°18.766'N	038°48.801' E	8
					1	2205	07°17.533'N	038°48.244' E	11	
					2	2209	07°17.530'N	038°48.236' E	11	
					3	2215	07°17.522'N	038°48.242' E	11	
Ashoka	Farm	20			4	2207	07°17.526'N	038°48.250' E	11	
					1	2182	07°18.005'N	038°48.326' E	4	
					2	2190	07°17.992'N	038°48.319' E	4	
					3	2185	07°17.983'N	038°48.331' E	4	
Ashoka	Farm	30			4	2184	07°17.991'N	038°48.337' E	4	
					1	2181	07°18.067'N	038°48.442' E	6	
					2	2176	07°18.064'N	038°48.434' E	6	
					3	2175	07°18.055'N	038°48.438' E	6	
Beseko	Farm	40			4	2186	07°18.061'N	038°48.444' E	6	
					1	2139	07°20.063'N	038°49.167' E	6	
					2	2137	07°20.064'N	038°49.157' E	6	
					3	2137	07°20.050'N	038°49.156' E	6	
Leye	Farm	50			4	2139	07°20.050'N	038°49.168' E	6	
					1	2159	07°18.750'N	038°48.734' E	9	
					2	2158	07°18.741'N	038°48.729' E	9	
					3	2163	07°18.733'N	038°48.738' E	9	
				4	2157	07°18.743'N	038°48.744' E	9		

Where D1.3 = Diameter at breast height  
H = Height

The dominant species of the upper storey in the natural vegetation of Bseko, Leye and Ashoka are *Podocarpus falcatus* Thunb.ex Mirb., *Croton macrostachys* Hochst.ex Rich., *Prunus africana* (Hook.F.) Kalkm., *Schefflera abyssinica* (Hochst. Ex A. Rich) Harms., *Syzygium guineense* (Willd.) DC and *Ficus sure* (Forsk.).

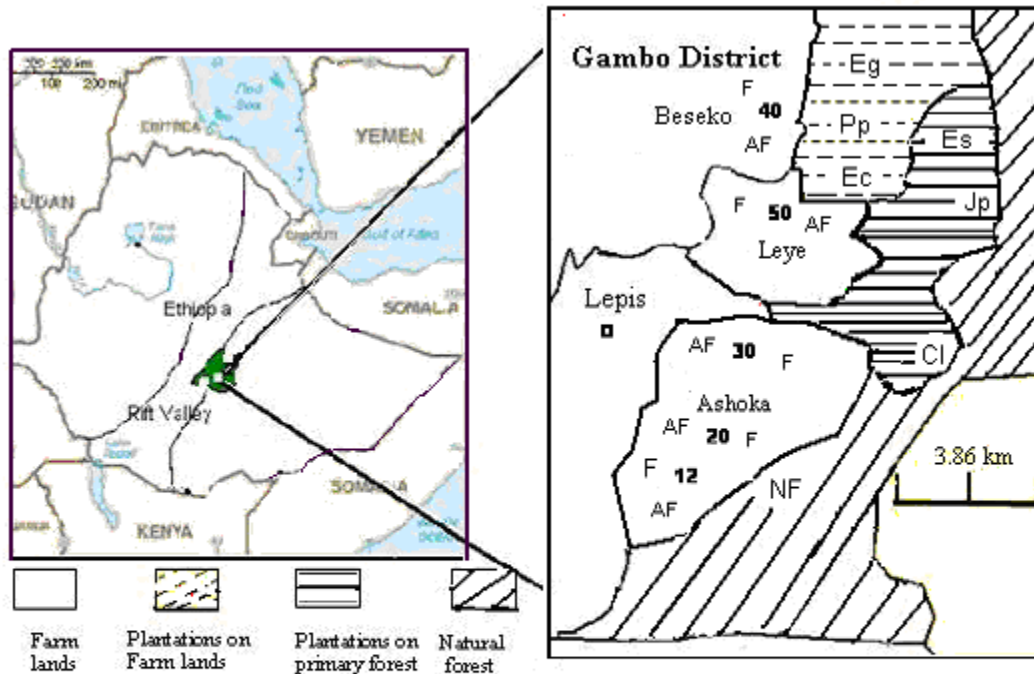


Fig.1. Map showing the sites of the natural forest, the chronosequence of agroforestry and farm land uses in Gambo district, southern Ethiopia. Where: AF = agroforestry, F = farm lands of age chronosequences from 12-50 years, Eg = *E. globulus*, Pp = *P. patula*, Ec = *E. camaldulensis*, Es = *E. saligna*, Jp = *J. procera*, Cl = *C. lusitanica* and NF = natural forest.

These include most of the tree species of the upper storey vegetation under the natural forest such as *Podocarpus falcatus*, *Prunus africana*, *Croton macrostachys*, *Schefflera abyssinica*, *Syzygium guineense* and *Ficus sure*. In the study area, soft wood trees (*Podocarpus falcatus*) and hard woods such as, *Prunus africana*, and *Syzygium guineense* are the most vulnerable species that encroachers are selectively removing from the natural forest. In the traditional agroforestry land use these trees are managed for their multipurpose functions such as production of leaf litter for soil nutrient recycling, fuel wood, fence, timber for construction material, lumber products for sale. Most of them are semi deciduous such as *Ficus sure* and shed a lot of litter during the off season (Appendix A, Plate I and II). The most prominent crops grown in the cultivated fields of the area are maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.) and potato (*Solanum tuberosum* Linnaeus). Most of the crop straw or stalk are often removed or heaped and burned several weeks before the field preparation for the next growing season.

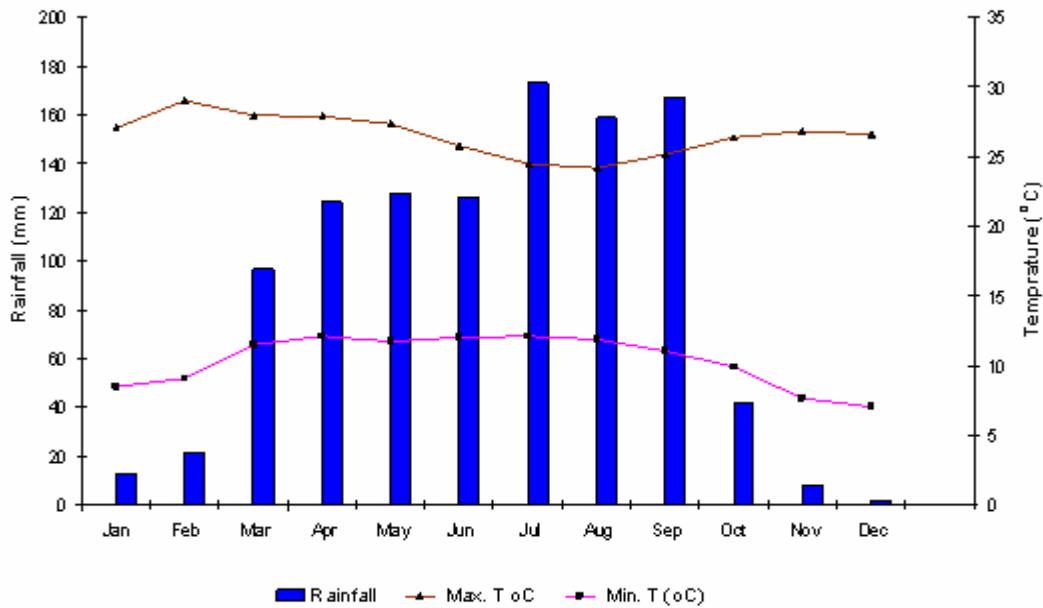


Fig. 2. Mean monthly rainfall (mm), and mean monthly maximum and minimum temperature (°C) for the period 1999 – 2007.

Source: National Meteorological service agency, Addis Ababa, 2008

*Eucalyptus* and coniferous species are commonly used for plantations in Gambo district and include *Eucalyptus globulus* (Labill), *Eucalyptus camaldulensis* (Dehnh), *Eucalyptus saligna* (Smith) and *Cupressus lusitanica* (Mill), *Pinus patula* (Schiede & Deppe) and *Juniperus procera* (Hochst), respectively. The soil parent materials of Gambo district are of volcanic origin, principally trachytes and basalts with ignimbrites and pumices (Appendix A, Plate VI) at the rift valley floor (Solomon et al., 2002). The escarpment extends from about 2100 m to 3200 m a.s.l. and the plain descends gradually to the rift valley lakes at about 1600 m a.s.l. The soils of Leye and Ashoka are classified as Andic Paleustalfs in which the profiles have a thick argillic horizon and some andic soil material in the upper soil layers (Soil Survey Staff, 1999). The particle size distribution and selected soil chemical characteristics from three unreplicated profiles of the study site are presented in Table 2.

The *J. procera*, *C. lusitanica* and *E. saligna* plantations were established after clearing the primary forest land in 1978, 1982 and 1985, respectively, and those of the *E. globulus*, *E. camaldulensis* and *P. patula* were all established in 1985 on previously cultivated lands for 16 years. The coniferous species were harvested in 25-year rotation periods; but the *Eucalyptus* species were managed as coppice and were harvested every 7 to 10 years based on the type of product needed. *J. procera* has never been harvested since its establishment, but it was subjected to silvicultural operations like access pruning, 2<sup>nd</sup> high pruning and 2<sup>nd</sup> thinning. During harvest, the logs are hauled off the site to the processing center while the branches are collected for fire wood, leaving behind the leaf biomass, the undergrowth and the stump of the trees.

## 4.2 The study approach

The soil C reservoir is dynamic and is sensitive to climate and human disturbance (Lemma, 2006). Hence, studies geared towards evaluating changes following land use conversion require long period of time and careful consideration of methods to provide credible results. To this effect the following major approaches are frequently used to study the dynamics of soil C stocks of ecosystems.

1) Temporal monitoring of C pool based on permanent sample plots laid out in statistically sound design: Under this approach experimental manipulation of structural and/or functional components of entire ecosystems is possible (Bakker et al., 1996). Such studies provide means to test hypothesis and results illuminate fundamental mechanisms at the ecosystem level (Likens and Cowan Jr, 1992). But this approach heavily relies on the length of the observation period (Bakker et al., 1996). Moreover, Likens and Cowan Jr (1992) argued that experimental manipulations of entire ecosystems often are very expensive in terms of human effort and financial cost. Also it is critical to have a reference system against which experimental results can be compared. A reference system is particularly valuable for assessing natural and temporal variability during long-term experiments. Strict control systems are difficult, if not impossible, to establish because of the inherent complexity and variability of natural ecosystems (Likens, 1985). Nevertheless, lack of such permanent plots established to monitor the C dynamics like the case in Ethiopia is also one of the difficulties encountered when such assessment are needed to be done.

2) Spatial analogue and chronosequence methods: The spatial analogue method involves spatial sampling on sites of different land uses but operating within a similar environment and on similar soil types (Lemenih, 2004).

The chronosequence method is a synchronized spatial sampling from neighboring sites of different ages managed on similar soils, and under similar climatic conditions and management practices (Lemenih, 2004; Yemefack et al., 2006; Awiti et al., 2008). Chronosequence or spatial analogue methods have the danger of confounding time with possible spatial variability, and assume that all measured differences reflect the effects of time or management and not inherent spatial variability (Lemenih, 2004). Despite these limitations the approach is still in use (e.g Goor and Thiry, 2004; Lemenih, 2004; Awiti et al., 2008). A major advantage of these techniques is that they provide data on long-term changes in soil, plant or other ecosystem components within a reasonable time. This approach was used for Paper I, with the assumption that parameters of interest for all sites studied would be similar to the condition prior to the conversion of native forest to agroforestry and cereal mono-cropping system.

3) Comparative studies of diverse ecosystems (also called cross-system studies) are an attempt to elucidate fundamental processes, and currently are becoming more common (Pace and Cole, 1994). Studies that use comparisons between existing land use types provide more timely results, but are subject to the risk of confounding effects due to natural spatial variation. Results provided by cross-system studies may be more revealing relative to *general* ecosystem processes, at least from a research efficiency point of view, than those from detailed studies of an individual ecosystem (e.g. Caraco et al. (1993). On the other hand, in-depth and sustained studies at individual sites not only provide the data to be compared, but also the perspective about the status of ecosystem development for the site. Considerations of history and developmental stage of ecosystems being compared are critical to success (Likens and Cowan Jr, 1992).

Table 2. Soil characteristics of three selected profiles at Leye and Ashoka sites

Sites	Horizon	Depth (cm)	pH(H <sub>2</sub> O) 1:2.5	BD (gm <sup>-3</sup> )	Particle Size			Textural class	SOC %	CEC cmol (+) kg <sup>-1</sup>	BS %	Oxalate Extraction					Phosphate		
					Sand %	Silt %	Clay %					Alox %	Feox %	Siox %	Fedih (%)	Alp (%)	Melanic index	retention %	Allophane %
Leye	1A	5	7.6	0.9	44	37.3	18.7	L	4.65	40.8	99.8	0.21	0.64	0.11	0.64	0.06	1.84	39.4	0.65
Jp	1A2	10	6.9	0.9	54	33.3	12.7	SL	9.5	55.8	99.9	0.23	0.55	0.09	0.55	0.09	1.90	37.7	0.58
	1A3	25	7.8	1.0	38	31.3	30.7	CL	2.16	32.5	99.8	0.19	0.64	0.13	0.64	0.20	1.73	38.4	0.53
	AB	85	5.8	1.1	20	31.3	48.7	C	1.73	18.5	99.6	0.21	1.18	0.10	1.18	0.98	1.67	43.8	0.16
	Bt1	125	5.1	1.2	22	19.3	58.7	C	1.16	23.9	66.3	0.19	1.06	0.09	1.06	1.40	1.71	43.0	0.09
	Bt2	300	5.1	ND	12	19.3	68.7	C	0.94	22.9	71.3	0.20	1.03	0.07	1.03	2.51	1.75	43.5	0.04
Ashoka	1A	9	7.5	0.7	34	31.3	34.7	CL	2.12	25.1	99.3	0.18	0.76	0.13	0.76	0.34	1.56	33.1	0.42
NF	E	18	7.8	0.9	55.3	21.3	23.4	SCL	0.83	16.2	98.9	0.16	0.62	0.10	0.62	0.17	1.68	26.7	0.40
	2A	40	7.6	1.1	37.3	29.3	33.4	CL	1.64	22.2	99.7	0.17	0.86	0.11	0.86	0.22	1.61	35.9	0.43
	AB	85	7.5	1.2	27.3	35.3	37.4	CL	1.12	20.4	97.8	0.16	0.85	0.11	0.85	0.76	1.62	33.6	0.20
	B	210	7.4	1.3	21.3	11.3	67.4	C	0.7	20.9	93.8	0.19	0.89	0.11	0.89	2.01	1.90	39.7	0.10
Ashoka	1Ap	15	6.5	1.0	49.3	35.3	15.4	L	3.5	31.9	90.4	0.17	0.63	0.09	0.63	0.07	1.80	24.7	0.49
AF <sub>30</sub>	2A1	35	6.6	1.0	47.3	31.3	21.4	C	2.01	20.1	86.6	0.19	0.86	0.09	0.86	0.11	1.63	32.8	0.46
	3Bt1	90	5.3	1.0	21.3	11.3	67.4	C	1.15	16.5	63.9	0.24	1.22	0.06	1.22	1.68	1.80	48.4	0.04
	3Bt2	160	5.1	1.1	23.3	11.3	65.4	C	0.57	16.2	46.1	0.25	1.31	0.06	1.31	2.89	1.88	51.9	0.02
	4BC	180	4.7	1.2	37.3	13.3	49.4	C	0.32	17.0	23.5	0.24	0.82	0.07	0.82	1.69	1.88	53.9	0.05

Where: BD =Bulk density, BS = Base saturation, L=loam, SL =Silt loam, CL= Clay loam, C =Clay, SCL =Silt clay loam, Jp= *Juniperus procera*, AF = A groforestry ,NF =Natural forest  
 $Al_{ox}$ ,  $Fe_{ox}$  and  $Si_{ox}$  = Acid oxalate extractable Fe, Al, Si, Alp =Pyrophosphate extractable Al, p = phosphate retention (Blakemore et al., 1987), % Allophane =  $100(\% Si_o / (23.4-5.1x))$  where  $x = (Al_o - Al_p) / Si_o$  representing the atomic ratio of Al and Si in allophane. Melanic index (extracted in 0.5% NaOH and 0.1% superfloc) =K450/K520 Where 450nm and 520nm are wavelength (Honna et al., 1988). Melanicindex  $\leq 1.70$  is used in conjunction with other properties (color, thickness and organic C content) to define the melanic epipedon in Soil Taxonomy and the melanic horizon in the World Reference Base (1995).



A comparative approach has been frequently used when data on SOC and soil nutrients prior to land use conversion are not available (Lemenih, 2004). This approach was used for the study (Paper II & IV) by collecting samples in four replicates from each land use.

Nevertheless, it would have been better to collect data from a number of replicates with less number of land uses to enhance the strength of statistical power to generate credible results. For this study, we opted to use four replicates and included all relevant land uses (as four replicates in field studies are commonly practiced and are appropriate for statistical comparison as well) to generate comprehensive information about the status of carbon stock.

Table 3. Location of soil sampling pits (1m depth) and vegetation characteristics at Leye and Ashoka sites

Site	Land use	Age (Years)	Plot No	Elevation (m.a.s.l)	Coordinate		Slope %	Previous land use
					Longitude	Latitude		
Leye 1	<i>J. procera</i>	29	1	2209	07018.886 N	038049.219 E	18	PF
			2	2199	07018.863 N	038049.210 E	18	PF
			3	2184	07018.858 N	038049.231 E	18	PF
			4	2219	07018.878 N	038049.236 E	18	PF
			5	2205	07018.870 N	038049.225 E	18	PF
Leye 2	<i>E. camaldulensis</i>	22	1	2174	07018.990 N	038048.978 E	9	FL
			2	2176	07018.992 N	038048.972 E	9	FL
			3	2184	07018.954 N	038048.983 E	9	FL
			4	2188	07018.975 N	038048.992 E	9	FL
			5	2177	07018.173 N	038048.975 E	9	FL
Leye 3	<i>P. patula</i>	22	1	2175	07019.072 N	038048.945 E	7	FL
			2	2147	07019.065 N	038048.920 E	7	FL
			3	2167	07019.053 N	038048.943 E	7	FL
			4	2195	07019.075 N	038048.956 E	7	FL
			5	2176	07019.063 N	038048.921 E	7	FL
Leye 4	<i>E. globulus</i>	22	1	2159	07019.233 N	038048.912 E	3	FL
			2	2147	07019.222 N	038048.908 E	3	FL
			3	2165	07019.200 N	038048.911 E	3	FL
			4	2159	07019.214 N	038048.931 E	3	FL
			5	2134	07019.216 N	038048.916 E	3	FL
Leye 5	<i>E. saligna</i>	30	1	2183	07019.204 N	038048.981 E	9	PF
			2	2160	07019.178 N	038048.963 E	9	PF
			3	2167	07019.163 N	038048.986 E	9	PF
			4	2183	07019.187 N	038048.002 E	9	PF
			5	2153	07019.185 N	038048.992 E	9	PF
Ashoka	<i>C. lusitanica</i>	25	1	2210	07018.023 N	038048.931 E	17	PF
			2	2208	07018.009 N	038048.914 E	17	PF
			3	2221	07018.920 N	038048.872 E	17	PF
			4	2284	07018.005 N	038048.946 E	17	PF
			5	2294	07018.039 N	038048.930 E	17	PF
Ashoka	Natural forest		1	2207	07017.549 N	038048.456 E	6	NF
			2	2197	07017.529 N	038048.455 E	6	NF
			3	2230	07017.513 N	038048.452 E	6	NF
			4	2232	07017.537 N	038048.455 E	6	NF
			5	2212	07017.527 N	038048.457 E	6	NF

Where : PF= Primary forest land      FL      Previously farm land      NF      Natural forest

The six species included in the study were the most used for small and large scale plantation in both government and small scale private holdings in the country including the study area and they were located under similar soil and climatic conditions. Information about the effect of these species on the sequestration of C and N and their influence on soil productivity for the study area was not fully available. We decided to include all of the six species in this study with the assumption that the knowledge acquired will be useful for landscape planning when varying tree plantations are introduced in degraded areas for rehabilitation or restoration of ecosystems in the country. We tried to minimize the risk of confounding effects of both methods used through careful selection of sites with similar slope, topography, altitude, soil type and proximity to the reference natural forest (Fig.1, Table 1 and Table 3).

A field experiment was also carried out to study the litter supply and decomposition (Paper III). For this study the environmental variables like temperature and moisture that strongly influence decomposition were not regulated and the results obtained may vary from those possibly generated under laboratory conditions. The mass loss data were fitted with single exponential model. There are several mathematical formulae that describe litter decomposition such as asymptotic, single exponential, double exponential and triple exponential (Berg and McClaugherty, 2008). These models are categorized into the following three major groups to describe litter decomposition (Moorehead et al., 1996).

- 1) Some models are empirical and most of these are statistically based for example, regression models relate parameters in a system. These models are useful for identifying or indicating the strength of the hypothesized relationships, but can not, by themselves, reveal causality. Empirical models are often useful for interpolation, but their use often limited to the range of data for which they were developed. Extrapolation, however, alluring can be misleading.
- 2) Mechanistic models are another general class of models and are often analytical in nature, using a system of equations to describe complex process. Such models have proven very useful for gaining insight into ecosystem behavior, and for developing and testing general theories.
- 3) Simulation models are created to simulate the behavior of a system, in a way that allows researchers to manipulate initial conditions or other aspects of the model to investigate potential outcomes. Simulation models may use a combination of mechanistic and empirical components.

One of the challenges of decomposition models is the large number of factors that influence the rates and patterns of decomposition. Thus, a single model or a relatively simple approach would not likely give a generally applicable description of the decomposition process. Factors that influence decomposition can be highly interactive, variable, and even hard to measure. The factors include microbial growth, climate, variation in weather between years and different levels of nutrients and lignin (Berg and McClaugherty, 2008).

Different types of models may be used for the same data set and the fit of theoretical to observed data will give different levels of statistical significance. However, the utility of a given model as a predictor is dependent not only on a statistical significance of the fit, but also on the causal relationships that form the basis of specific model. One point in choosing a model is how far the decomposition pattern will be described. The technique of measuring litter decomposition as mass loss may allow the decomposition to be followed until approximately 60-70 % mass loss or until the process has come to a halt.

In general, data sets that covers only small of accumulated mass loss fit well to the single exponential model (Berg and McClaugherty, 2008). Likewise, small data sets with a low number of measured values can often be described using a single exponential equation.

This approach was used to fit the data for this study (Paper III, Table 4). In contrast, data sets that are sufficient to test for asymptotic functions have a set of conditions. Thus a data set with a low number of mass – loss values is not likely to give a significant limit value (asymptote). The simple linear decay function is not universally applicable to the decay of organic matter though it often provides an excellent first approximation especially during early stages of decay. Unfortunately, neither the total biomass nor the constituent nutrients for decaying organic matter follow this simple function well enough to make it predictive (Berg and McClaugherty, 2008).

To determine the soil quality index (Paper IV) an integrated approach was followed. Soil productivity (quality) is not a static feature. It changes constantly and its direction is determined by the interplay between physical, chemical, biological and anthropogenic process (Smaling et al., 1997). The choice for the approach was therefore initiated with the assumption that different nutrients have different roles in sustaining soil productivity and a combination of soil properties provide a better indication of soil quality than single soil property parameters such as SOC, N, P, K etc (Masto et al., 2007; Fu et al., 2004).

### **4.3 Soil and plant sampling**

Plantations, chronosequences of agroforestry and cultivated lands were selected within an area of minimum soil and climatic differences in the study sites of Ashoka, Leye and Beseko in Gambo district, Southern Ethiopia. Sites which are located close or adjacent to each other and confined area for sampling were chosen from native climax natural forest (NF), plantations, traditional agroforestry system (AF) and cultivated lands (F) to avoid the confounding effect of large soil variation. The traditional agroforestry and cultivated lands were in the chronosequence of 12, 20, 30, 40 and 50 years since their conversion from the natural forest. The chronosequence approach adopted in this study has also been used by other investigators (Sa et al., 2001; Turner et al., 2005; Liao et al., 2006). The NF at Ashoka was taken as a reference land use.

The sampling design followed was a pseudo complete randomized design (CRD) and soil samples for the analysis of SOC, total N, physical and chemical properties were collected in four replicates from all land use types. Details are provided in (Paper I, Paper II and Paper IV). Biomass of trees was determined by a non-destructive method, while that of bushes, shrubs and herbs was by destructive methods (Paper II). The production of litter and the subsequent decomposition rate were studied on broad leaved *Eucalyptus* (*E. globulus*, *E. camaldulensis*, and *E. saligna*) and coniferous species (*J. procera*, *C. lusitanica*, and *P. patula*) and the results obtained were compared to that of the adjacent natural forest. The litter fall was recorded by litter traps and the decomposition rate was studied by nylon net bag technique (Paper III). Pondered falling head infiltration measurement (Paper IV) was conducted in triplicates close to the soil sampling pits at each plantation and natural forest site. The measurements were carried out using double ring infiltrometers following the procedures described in Landon (1984).

#### 4.4 Soil and plant analysis

The pH was determined by a potentiometric method (Kim, 2005). The concentrations of total N were measured using a LECO CHN-1000 Carbon and Nitrogen Analyzer. The SOM was analyzed using titrimetric method (Walkley and Black, 1934). The SOC was obtained by dividing the SOM concentration by a factor of 1.724 (Kim, 2005). The exchangeable cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{H}^+$ ) were determined by ammonium acetate extraction (Schollenberger and Simon, 1945) and available P by Bray II as described in Kim (2005).

#### 4.5 Measurements and calculations

##### 4.5.1 Carbon stock

The SOC stock ( $\text{Mg ha}^{-1}$ ) for each sampling depth was calculated using the following relationship as given by Ellert et al., (2001) and Wairiu and Lal, (2003):

$$\text{SOC stock (Mg ha}^{-1}\text{)} = C_{\text{conc}} * \text{BD} * T * 10000 \text{m}^2 \text{ ha}^{-1} * 0.001 \text{ Mg kg}^{-1} \text{ CF}_{\text{coarse}} \quad (1)$$

Where:  $C_{\text{conc}}$  = Carbon concentration ( $\text{kg Mg}^{-1}$ ),  $\text{BD}$  = bulk density ( $\text{Mg m}^{-3}$ )  
 $T$  = depth or thickness of the soil layer (m),  $\text{CF}$  = correction factor  $(1 - (\text{Gravel \%} + \text{Stone \%}) / 100)$

The stock was also calculated using equivalent mass by adjusting the thickness of the soil as described by Ellert et al., (2001) to correct error that may be introduced due to variation in bulk density and the results were compared with the stocks calculated by equation (1).

$$M_{\text{soil}} = \text{BD} * T * 10000 \text{m}^2 \text{ ha}^{-1} \quad (2)$$

Where:  $M_{\text{soil}}$  = soil mass per unit area ( $\text{Mg ha}^{-1}$ )

$$T_{\text{add}} = (M_{\text{soil, equiv}} - M_{\text{soil, layer}}) * 0.0001 \text{ ha m}^{-2} / \text{BD}_{\text{subsurface}} \quad (3)$$

Where:  $T_{\text{add}}$  = additional thickness of sub surface layer required to attain the equivalent soil mass (m)

$M_{\text{soil, equiv}}$  = equivalent soil mass = mass of heaviest soil at each 1m depth ( $\text{Mg ha}^{-1}$ )

$\text{BD}_{\text{subsurface}}$  = bulk density of subsurface layer ( $\text{Mg m}^{-3}$ )

The allophane content of three selected profiles of 3m depth was calculated according to Mezota and Van Reeuwijk (1989) using equation (4):

$$\% \text{ allophane} = 100 (\% \text{ Si}_o / (23.4 - 5.1x)) \quad (4)$$

With  $x = (\text{Al}_o - \text{Al}_p) / \text{Si}_o$  representing the atomic ratio of Al and Si in allophane

Total stock of N ( $\text{Mg ha}^{-1}$ ) for each sampling depth was also computed using the equations as for SOC. The total SOC and N stocks were calculated by adding the stock of each depth (up to 1m). The change in the rate of SOC stocks over time was computed by subtracting the stocks of chronosequence of AF and F land uses from that of NF and dividing it by the number of years of the chronosequence (Paper I and paper II).

#### 4.5.2 Biomass Carbon

The biomass of plantation and natural forest was computed using the following equations:

$$Wb = v * Wd * 10000 \text{ m}^2 \text{ ha}^{-1} \quad (5)$$

$$v = \pi d^2 / 4 * h * fq \quad (6)$$

Where:  $Wb$  = wood biomass of a tree ( $\text{Mg ha}^{-1}$ ),  $Wd$  = wood density ( $\text{Mg m}^{-3}$ ),  $\pi = 3.14$ ,  $v$  = solid wood volume ( $\text{m}^3$ ),  $h$  = tree height (m) and  $fq$  = absolute form quotient (Paper II)

$Fq$  = mid-diameter /d.b.h (Chaturvedi and Khanna, 1982)

#### 4.5.3 Mass loss and decay constant

The leaf mass loss, decomposition rate and decomposition rate constants ( $k$ ) were computed as described in Olsen (1963) using the following equations (Paper III):

$$\% \text{ Mass Loss} = (X_0 - X_t) / X_0 * 100 \quad (7)$$

Where  $X_t$  is the mass of litter at time  $t$ , and  $X_0$  is the initial litter mass at time zero:

The leaf litter decomposition rate constants ( $k$ ) were calculated using the negative single exponential equation:

$$kt = - \ln (X_t / X_0) \quad (8)$$

$$X_t = X_0 = \exp^{-kt} \quad (9)$$

Where  $k$  is the decomposition constant ( $\text{month}^{-1}$ ), and  $X_t$  and  $X_0$  are the same as above

#### 4.5.4 Soil Quality

Taking into account the assumption that different nutrients have different roles in maintaining soil quality, soil quality index (SQI) was developed and calculated by selecting soil factor values using a correlation matrix where their weight vector was obtained from each principal component analysis (PCA), as in the following equation (Fu et al., 2004; Awasthi et al., 2005):

$$SQI = \sum_{i=1}^n W_i * Q(X_i) \quad (10)$$

Where: SQI is soil quality index,  $W_i$  is the weight vector  $i$  soil quality factor,  $Q(X_i)$  is membership value of each soil quality factor (Paper IV).

The values of  $Q(X_i)$  were calculated according to Fu et al., (2004) and Awasthi et al., (2005) by ascending and descending functions using the following equations:

$$Q(X_i) = ((X_{ij}) - (X_i)_{\min}) / ((X_i)_{\max} - (X_i)_{\min}) \quad (11)$$

$$Q(X_i) = ((X_i)_{\max} - (X_i)) / ((X_i)_{\max} - (X_i)_{\min}) \quad (12)$$

$$(W_i) = C_i / \sum_{i=1}^n (C_i) \quad (13)$$

Where  $C_i$  is the component capacity score coefficient of  $i$  soil factor obtained and calculated from principal component analysis.

#### 4.6 Statistical Analysis

The data obtained were analyzed using SAS software (SAS Inc.2003).The variables such as SOC, total N and their distribution in each of the 1m depth interval and soil quality were subjected to one way analysis of variance using the general linear model procedures of SAS (Paper I, II, III, IV). Multiple comparison of means for each class variable was carried out using the Student-Newman-Keuls (SNK) test at  $\alpha = 0.05$ .

### 5. Results and Discussions

#### 5.1 Key soil physical properties

##### 5.1.1 Soil bulk density

The BD in the surface soil layer of 10 cm depth under traditional agroforestry and cultivated land uses ranging from 0.93 to 1.12 Mg m<sup>-3</sup> for AF<sub>12</sub> and F<sub>30</sub> respectively did not differ significantly. But it was significantly lower under the natural forest than that under both land uses of all chronosequences (Paper I, Table 3). Under plantations it ranged from 0.6 Mg m<sup>-3</sup> for *Cupressus lusitanica* to 1.4 Mg m<sup>-3</sup> for *Pinus patula* (Paper II, Table 3). Generally the BD in soils under plantations established on cultivated lands tends to be higher than those under plantations established on undisturbed soils. The soils under *Pinus patula* and *Eucalyptus globulus* showed a significantly higher BD ( $p < 0.05$ ). Similar results were reported by Bewket and Stroosnijder (2003), who concluded that soil BD under *Eucalyptus*, was higher than soils under natural forest, cultivated lands and grazing lands at Chemoga watershed of Blue Nile basin, Ethiopia. The higher BD in soils under cultivated and traditional agroforestry land uses can be attributed to frequent tillage that tends to break soil aggregates and result in compaction. Forest soils usually have lower BD than agricultural soils (Murty, 2002). But the significantly higher soil BD under plantations established on previously cultivated lands compared to those plantations established on undisturbed soils indicates that the period requiring rehabilitation of the disturbed soil was not long enough.

### 5.1.2 Infiltration

The steady state infiltration (the relatively constant infiltration rate) observed in 4-6 hrs time after initiation and the infiltration rate under *C.lusitanica* was significantly higher than at other plantations ( $p<0.05$ ). Nevertheless, the average infiltration rate observed for soils under coniferous plantations established on primary forest land tends to be higher compared to that under plantations established on previously cultivated lands according to expectations from BD values (Paper IV, Table 2).

No significant difference was observed between the antecedent moisture content of soils under all plantation land uses (Paper IV, Table 2). The values for steady state infiltration were  $3.7 \text{ cm hr}^{-1}$  and  $26.7 \text{ cm hr}^{-1}$  for *E. globulus* and *C. lusitanica* respectively.

The surface soil layers of 0-15 cm depth under *C. lusitanica* were sandy clay to clay loam of pumice nature. The higher value of infiltration at steady state of soils under this species may be attributed to larger pore volume of the capillaries which may be consistent with Poiseuille's law that relates the rate of flow to the fourth power of capillary radius (Hillel, 1982). In addition to this, some preferential flow through bio-pores may occur such as root channels and earthworm burrows with radius  $>1 \text{ mm}$  (Brady and Weil, 2004). The lower value of both average infiltration and steady state infiltration for soils under plantations established on previously cultivated lands may indicate that the effect of disturbance of soil due to plowing decades ago still persists. The reduced infiltration capacity in disturbed soils is consistent with the observation made by others (Bharati et al., 2002; Tuli et al., 2005; Yimer et al., 2008).

### 5.1.3 Soil moisture characteristic curves and pore volume

The percent volume of water content at -1500 kPa matric potential across the different plantation species differed significantly ( $p<0001$ ). The volumetric water content at -1500 kPa matric potential under all plantation species was significantly lower than that observed under the natural forest (Paper IV, Table 2). Similarly, the water content under *J. procera* was significantly higher than that under those of the other plantation species. The difference observed in the percent volume of water content of soils at -1500 kPa matric potential within plantations established on the previously cultivated lands was not significant but it tended to be lower than that in plantations established on primary forest land. Neither volume of water at -10 kPa matric potential and available water capacity (AWC %) of all plantations including the natural forest showed any significant differences. However, pore volume of soils under plantation species varied significantly ( $p<0.0029$ ). The coniferous plantation established on primary forest land showed a significantly higher pore volume than those established on previously cultivated lands vis-à-vis to BD values (Paper IV, Table 2).

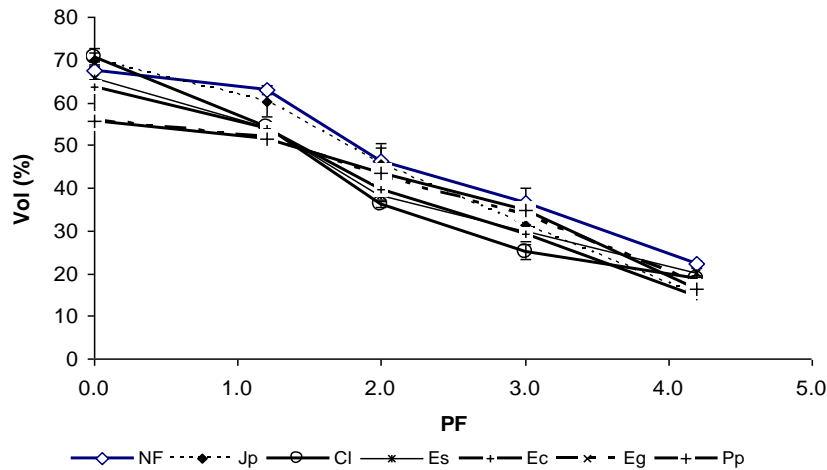


Fig.3. Moisture characteristics curve of soils under natural forest (NF), *J. procera* (Jp), *C. lusitanica* (Cl), *E. saligna* (Es), *E. camaldulensis* (Ec), *E. globulus* (Eg), *P. patula* (Pp).

However, such significant difference in soils within plantations established on previously cultivated lands or within those established on primary forest lands were not observed. The volume of water at -1500 kPa matric potential ranged from 14.6 % under *E. camaldulensis* to 22.3 % under the natural forest (Fig.3). The observed range of water volume of water at -1500 kPa matric potential is consistent with the range reported by Hikmatullah, (1999) for the properties and classification of andisols developed from volcanic ash in the Tondano area, North Sulawesi.

## 5.2 Soil chemical properties

### 5.2.1 Soil chemical Characteristics (exchangeable cations ( $K^+$ , $Ca^{2+}$ , $Mg^{2+}$ and $Na^+$ ))

The  $Ca^{2+}$  concentration of soils in the 0-10 cm depth under *E. camaldulensis* and *E. globulus* (both established on cultivated lands) was significantly lower than that under the natural forest only ( $p < 0.05$ ). In the 40-60 cm soil depth, the  $Ca^{2+}$  concentration under *P. patula* was only significantly higher than that under *C. lusitanica*. (Paper IV, Table 3). No such significant difference was observed in the 10-20 and 20-40 cm depths.  $Ca^{2+}$  and  $Mg^{2+}$  decreased with depth in most plantation and natural forest sites with the exception that under *E. camaldulensis* and *E. globulus*. The soil under *E. camaldulensis* showed significantly higher  $Na^+$  concentration than that under *P. patula*, *E. saligna* and *C. lusitanica*. The overall concentration of  $Na^+$  under plantations established on previously cultivated lands tends to be higher than that under plantations established on primary forest lands (Paper IV, Table 3).

Soils under all land use types (plantation and natural forest) did not show any significant difference in  $K^+$  concentration in the 0-10 cm and 40-60 cm depths. However, soils under *P. patula* exhibit significantly higher  $K^+$  concentration than any of the land uses in the 10 to 20 cm depth ( $P < 0.05$ ). For the same depth, the  $K^+$  concentration in soils under *E. camaldulensis* was also significantly higher than that of under the natural forest. But in the 20 to 40 cm depth  $K^+$  under *P. patula* was only significantly higher than that under the natural forest (Paper IV, Table 3).



The CEC in the surface layers (0-10 cm depth) did not significantly differ under either plantations or natural forest. But in the 10-20 cm depth, the CEC of soils under *E. globulus* was significantly lower than that under *P. patula*, *E. saligna*, *J. procera* and natural forest ( $p < 0.05$ ). In the 20-40 cm depth, the CEC of soils under *E. globulus* was only significantly lower than that under the natural forest (Paper IV, Table 3).

Soil chemical indicators are used mostly in the context of nutrient relations and may therefore be referred to as “indices of nutrient supply” (Schoenholtz et al., 2000a). This study showed that the exchangeable  $\text{Ca}^{2+}$  in soils under *Pinus patula*, *E. saligna*, *C. lusitanica*, *J. procera* and natural forest decreased with depth, while it increased in soils under *E. globulus* and *E. camaldulensis*. The results are also consistent with those reported for the soils of Bale Mountains, Ethiopia (Yimer et al., 2006). The distribution of  $\text{K}^+$  along the 0-60 cm depth was in descending order with the highest accumulation at the 0-10 cm depth in all land use types. The lower  $\text{K}^+$  concentration in the sub surface horizon may be attributed to root absorption. Soil  $\text{K}^+$  is involved in water relations, charge balance, and osmotic pressure in cells and across membranes, which explains its high mobility in plants (Havlin et al., 2009). The higher concentration of  $\text{K}^+$  in the surface horizon of 0-10 cm depth, however, may be due to its release from the decomposed detritus material continuously supplied from plantation species (Palm and Sanchez, 1990). In contrast to  $\text{K}^+$  distribution,  $\text{Mg}^{2+}$  was in ascending order with the highest concentration being in the lower 60 cm depth across the land use types, which may be the result of leaching from the surface horizon or weathering of the parent material (Paper IV, Table 3).

### 5.3 Depth wise distribution of C and N in different land uses

The SOC and N under all land uses investigated invariably decreased progressively with increasing depth. The distribution of SOC or other nutrients with depth is affected by a number of interacting processes such as biological cycling, leaching, soil erosion, weathering of minerals, atmospheric deposition, application of fertilizers etc. The trend of decreasing concentration of SOC and N in soils under all plantations including the natural forest was similar to those under the traditional agroforestry and cultivated land uses of all chronosequences (Paper I Fig 4 and Paper II, Fig 2). Significant difference was observed only in the surface layers of 0 to 10 cm depth ( $p < 0.05$ ). The lack of significant difference in SOC and N concentration below 10 cm depth in all land uses support the assumption that the sites studied had similar soil type prior to the conversion of the relic natural forest to agroforestry and cereal mono-cropping system (Table 4). However, the SOC in soils under the natural forest was significantly higher than that under the remaining land uses. In soils under *J. procera* SOC was significantly higher than that under *E. globulus*. For both SOC and N their concentration tends to be lower on plantations established on cultivated soils than those plantations established on primary forest soils (Table 4).

The surface soil layers where the organic materials were added through leaf fall or crop residues were also supplemented by the greater proportion of the roots litter confined in the shallow depth. However, the SOC, and soil N concentration was higher under the reference natural forest than in either agroforestry or farmlands (Table 4). This may be explained by the continuous litter input from diverse vegetation community and little or no soil perturbation in the functioning of the ecosystem.

Table 4 a. Soil organic carbon distribution under all land uses in Gambo district, Southern Ethiopia

Land uses	Soil organic carbon (%)									
	Depth (cm)									
	10	20	40		60	100				
NF	9.7	(1.20) a	3	(0.24) a	1.8	(0.16) abc	1.3	(0.10) abc	1.1	(0.05) a
Jp	6.5	(0.91) b	2.6	(0.60) a	1.8	(0.20) abc	1.4	(0.19) abc	0.9	(0.10) ab
Es	5.6	(0.51) bc	2.4	(0.18) ab	1.7	(0.08) abc	1.1	(0.05) abc	0.8	(0.10) ab
Cl	5.4	(0.65) bcd	1.8	(0.17) ab	1	(0.05) c	0.8	(0.04) c	0.8	(0.06) ab
Pp	5.1	(0.62) bcd	2.8	(0.25) a	2.3	(0.33) a	1.6	(0.21) ab	0.8	(0.09) ab
AF40	4.9	(0.19) bcd	2.7	(0.22) ab	1.7	(0.17) abc	1.3	(0.25) abc	1.1	(0.23) a
AF12	4.7	(0.39) bcd	2.1	(0.26) ab	1.4	(0.06) bc	1	(0.04) abc	0.7	(0.04) ab
F40	4.5	(0.08) bcd	2.5	(0.11) a	1.7	(0.08) abc	1.1	(0.10) abc	0.7	(0.15) ab
AF20	4.2	(0.20) cd	2	(0.30) ab	1.7	(0.08) abc	0.9	(0.05) c	0.6	(0.04) ab
F12	4.1	(0.04) cd	1.9	(0.23) ab	1.4	(0.12) bc	1	(0.13) abc	0.7	(0.03) ab
F20	4	(0.14) cd	1.3	(0.37) b	1.4	(0.09) bc	0.9	(0.12) bc	0.5	(0.09) b
Ec	3.9	(0.12) cd	3.1	(0.16) a	2.2	(0.25) abc	1.5	(0.12) abc	0.8	(0.07) ab
AF30	3.9	(0.05) cd	2.2	(0.29) ab	1.5	(0.15) bc	0.8	(0.08) c	0.7	(0.04) ab
F30	3.4	(0.30) cd	1.9	(0.22) ab	1.4	(0.26) bc	0.9	(0.10) c	0.6	(0.06) ab
Eg	3.2	(0.19) cd	2.5	(0.14) ab	2.1	(0.22) abc	1.6	(0.27) a	1	(0.13) a
AF50	3.2	(0.08) cd	2.7	(0.32) a	1.9	(0.21) abc	1.1	(0.07) abc	1	(0.11) a
F50	3	(0.22) d	2.3	(0.12) ab	1.4	(0.14) bc	1.1	(0.07) abc	0.9	(0.08) ab

Table 4 b. Total soil Nitrogen distribution under all land uses in Gambo district, Southern Ethiopia

Land uses	Total Soil Nitrogen (%)									
	10	20	40		60	100				
NF	0.9	(0.14) a	0.3	(0.04) a	0.1	(0.02) abc	0.1	(0.01) a	0.1	(0.01) a
Jp	0.8	(0.12) ab	0.3	(0.10) a	0.2	(0.02) abc	0.1	(0.02) a	0.1	(0.00) a
Es	0.6	(0.06) bcd	0.2	(0.02) a	0.1	(0.01) c	0.1	(0.00) a	0.1	(0.01) a
Cl	0.7	(0.08) bc	0.2	(0.03) a	0.1	(0.01) bc	0.1	(0.00) a	0.1	(0.00) a
Pp	0.5	(0.04) cde	0.3	(0.03) a	0.2	(0.04) a	0.1	(0.01) a	0.1	(0.01) a
AF40	0.5	(0.03) cde	0.3	(0.03) a	0.2	(0.02) abc	0.1	(0.04) a	0.1	(0.05) a
AF12	0.5	(0.04) cde	0.2	(0.03) a	0.1	(0.00) c	0.1	(0.00) a	0.1	(0.00) a
F40	0.5	(0.02) cde	0.3	(0.06) a	0.1	(0.01) bc	0.1	(0.00) a	0.1	(0.01) a
AF20	0.4	(0.01) cde	0.2	(0.01) a	0.1	(0.01) c	0.1	(0.00) a	0.1	(0.01) a
F12	0.5	(0.01) cde	0.2	(0.03) a	0.1	(0.01) c	0.1	(0.01) a	0.1	(0.00) a
F20	0.4	(0.01) cde	0.2	(0.03) a	0.1	(0.01) c	0.1	(0.01) a	0.1	(0.00) a
Ec	0.4	(0.00) ed	0.3	(0.02) a	0.2	(0.02) ab	0.1	(0.01) a	0.1	(0.00) a
AF30	0.4	(0.02) cde	0.2	(0.03) a	0.1	(0.01) abc	0.1	(0.00) a	0.1	(0.00) a
F30	0.4	(0.04) ed	0.2	(0.01) a	0.1	(0.01) abc	0.1	(0.01) a	0.1	(0.02) a
Eg	0.3	(0.01) e	0.2	(0.01) a	0.2	(0.02) abc	0.1	(0.01) a	0.1	(0.01) a
AF50	0.3	(0.01) e	0.2	(0.04) a	0.2	(0.02) abc	0.1	(0.01) a	0.1	(0.00) a
F50	0.3	(0.02) e	0.2	(0.02) a	0.1	(0.01) c	0.1	(0.01) a	0.1	(0.00) a

Means followed by the same letter(s) in columns are not significantly different ( $P < 0.05$ ).  $n=4$

NF	Natural forest	Es	E.saligna	AF	Agroforestry of 12 to 50 years of chronosequences
Jp	J.procera	Cl	C.lusitanica	F	Farm lands of 12 to 50 years of chronosequences
		Pp	P.patula		

This trend of SOC distribution was also found in several other studies (Godsey et al., 2007; Awasthi et al., 2005; Jimqnez et al., 2007). Such pattern of SOC and N accumulation in

the surface soils relative to the sub-surface soil layers is also attributed to reduced rate of soil erosion (Erskine et al., 2002) and lower temperature under the canopy of the closed forest (Kirschbaum, 1995; Chapin et al., 2002).

## **5.4 Soil organic carbon and nitrogen stock**

### **5.4.1 SOC and N stocks under AF and F land uses of chronosequences**

The SOC stocks under agroforestry tends to be higher than those under the chronosequences of farm lands ( $P < 0.05$ ). The N stock under NF was higher than all other chronosequences under AF and F land uses (Paper I, Table 5). Also the average value of N stocks under chronosequences of AF was significantly higher than only to that of under the chronosequences of F<sub>20</sub>. The stocks of SOC decreased in the 12 to 30 years of chronosequence and tended to increase in the 30 to 40 years in which the increase was negligible from 40 to 50 years of age in both AF and F land uses. This suggests that with time SOC stabilized or a new equilibrium was attained in the 40 to 50 years of age. When forest is cleared for new agricultural land, a considerable amount of C is lost to the atmosphere because the decay rate of SOC is one order of magnitude higher under agriculture than under forest. However, each soil has a C carrying capacity, i.e. an equilibrium C content depending on the nature of vegetation and climatic conditions (Gupta and Rao, 1994). Land use change disturbs the equilibrium between C inflows and outflows in soil until a new equilibrium is eventually reached in the new system (Guo and Gifford, 2002). The clearance of forests and the subsequent tillage practice affects the proper soil function as a carbon sink by (i) the dwindling supply of litter that would compensate the amount decomposed and (ii) the reducing capacity of the soil to physically protect SOC from decomposition due to the destruction of soil aggregates (iii) enhancing leaching and translocation as dissolved organic carbon (DOC) or particulate organic carbon (POC) and accelerated erosion by water runoff or wind (Post and Kwon, 2000; Lal, 2002).

### **5.4.1 SOC, N stocks and C pool under short rotation plantations**

The data suggest that the C and N stocks under *P.patula* and natural forest was only significantly higher than that under *C.lusitanica* ( $p < 0.05$ ). The N stock under *J. procera* tends to be higher compared to the other plantations and natural forest but the difference was not statistically significant (Fig.5). The lower SOC and N stock under *C.lusitanica* may be partly ascribed to the lower clay content in the upper most layers of the soil profile where the larger portion of the SOC and N stock is most often accumulated (Paper II, Table 2). Clay is assumed to protect SOM against decomposition and stabilize SOC through adsorption of organics onto the surfaces of clays or organic complexes (Oades, 1988) and entrapment of organic particles in aggregates (Van Veen and Kuikman, 1990). Also, the *Cupressus* plantation was at the harvesting stage that may negatively influence the quantity and quality of the stand's litter production capability. This was manifested by the lower detritus mass and the corresponding SOC and N concentration along the depth. Hence, this condition among others, like the density of plant population and topography, may have negatively influenced the SOC and N stocks under *C.lusitanica* compared to the reference and the other plantation species.

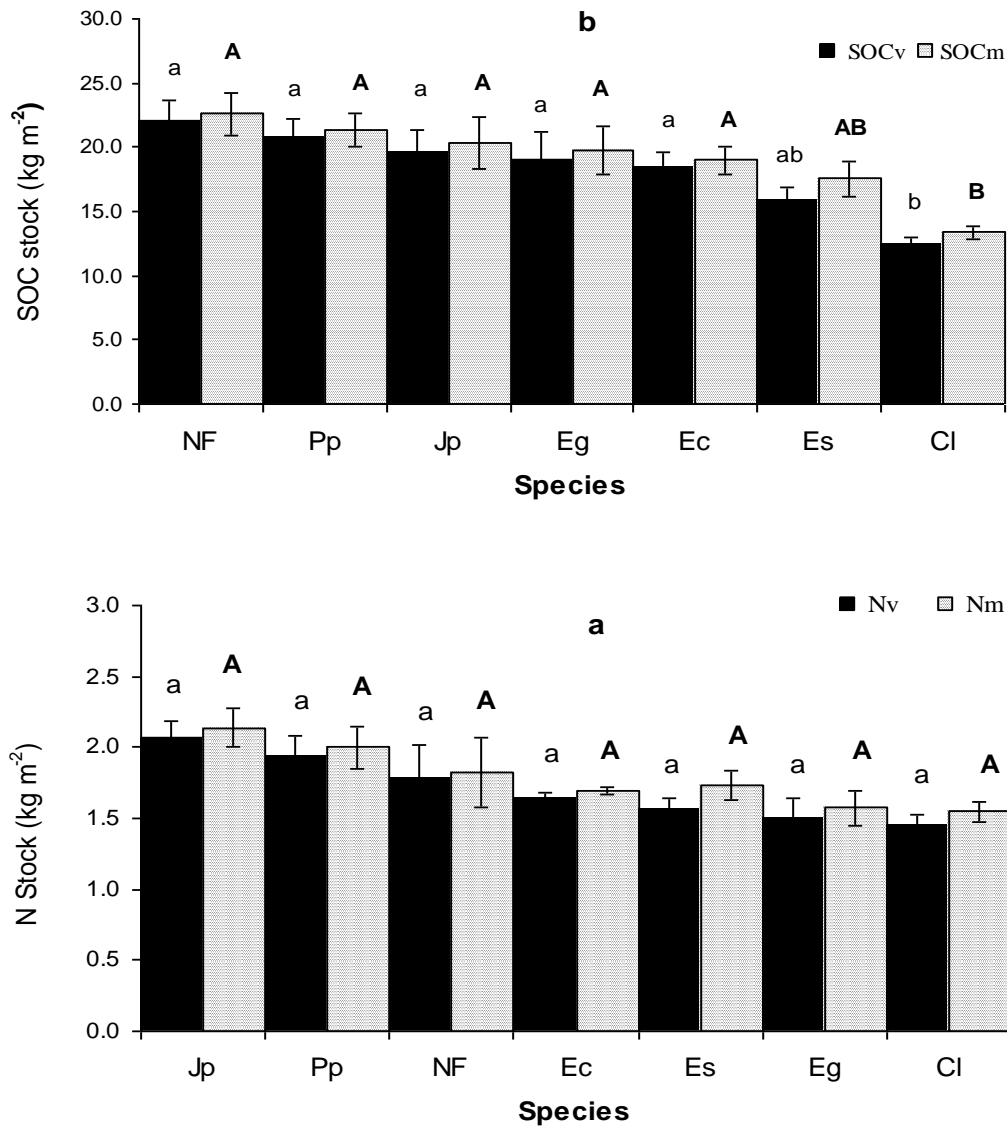


Fig.5. a) Stocks of soil organic carbon (SOC) and b) N under natural forest and plantations Means followed by the same letter(s) are not significantly different ( $P < 0.05$ ), Natural Forest (NF), *J. procera*, (*Jp*), *C. lusitanica* (*Cl*), *E. saligna* (*Es*), *E. camaldulensis* (*Ec*), *E. globulus* (*Eg*), *P. patula* (*Pp*)

Despite no significant difference existed in the C and N stocks among plantations (excluding *C. lusitanica*), there is a tendency that the coniferous species (*P. patula* and *J. procera*) accrue more stocks compared to the *Eucalyptus* species. The minor difference in the age of plantation and the mode of plantation establishment (on disturbed natural forest and on previously cultivated lands) showed little effect on the accrual of C and N stocks. The interaction between species category and land use history was not statistically significant and thus the difference may be explained by the inherent characteristics of species, site to site variability of soil physical and chemical properties and the management practices involved. The result was consistent with that reported by Vesterdal et al. (2002). They found that *Quercus robur* sequestered 2 Mg C ha<sup>-1</sup>, and *Picea abies* sequestered approximately 9 Mg C ha<sup>-1</sup> in forest floors in over 29 years, while the adjacent 200-year-old plantation sequestered 81 Mg C ha<sup>-1</sup> after establishment of these species on arable land.

Generally, the establishment of plantations on either the disturbed or previously cultivated land had reduced the tree and total biomass carbon and nitrogen compared to the reference natural forest.

The total biomass carbon (TBC) and total biomass nitrogen (TBN) under the Natural Forest were significantly higher than those under plantation stands (Paper II, Table 4). The TBC under the Natural Forest was nearly 6-14 folds higher than that under plantations, while the corresponding difference for TBN varied from 14 to 30 fold (Paper II, Table 4). However, no such statistically significant difference in the TBC stock among plantation species was observed (Paper II, Table 4). The total organic carbon pool (SOC + TBC) and the total N pool (soil N + TBN) under plantation species was significantly lower compared to that under the Natural Forest ( $P < 0.05$ ). The total nitrogen pools among plantations were not significantly different (Paper II, Table 4). Overall, plantations sequester significantly higher C and N stock compared to farm lands in accordance with our expectation (Fig.6). The higher accretion of SOC and N in plantations may be explained by higher litter input and little or no soil disturbance compared to farm lands.

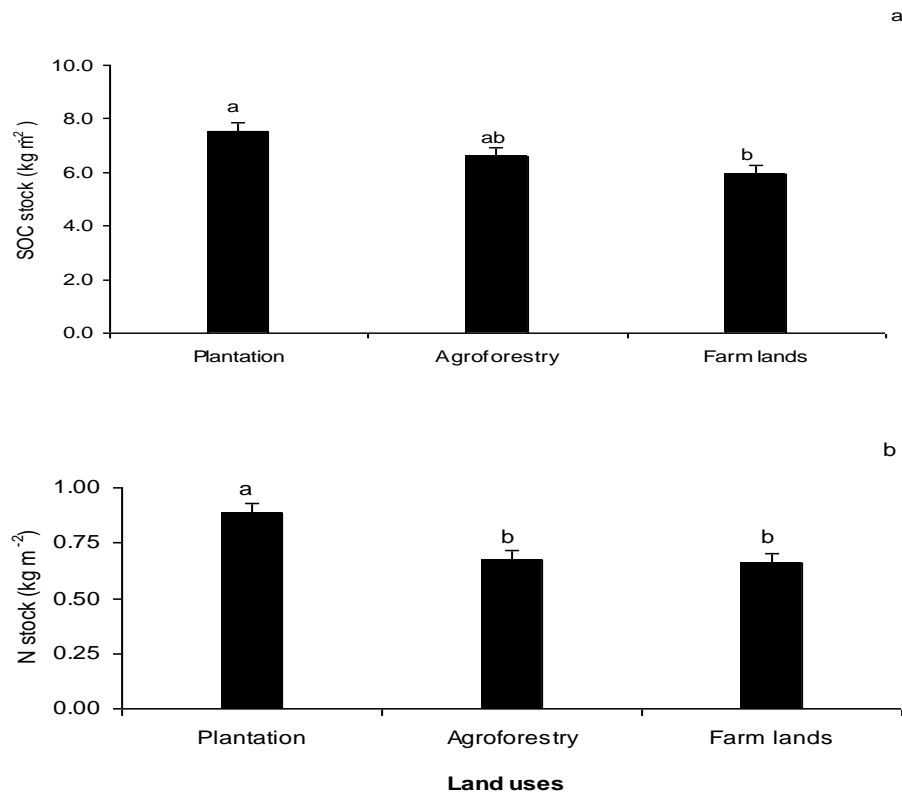


Fig. 6. Total soil organic carbon (a) and nitrogen (b) stock of 0-20 cm depth under plantations agroforestry, and farm land uses ( $p < 0.05$ ).

#### 5.4.3 Rate of SOC and N losses in soils under the chronosequences of AF and F land uses

Conversion of the relict natural forest into AF and F land uses caused decline in SOC, and N stocks in all age chronosequences. The SOC stock under F and AF land uses of 12, 20 and 30 years of cultivation was 13.1 to 15.6 kg m<sup>-2</sup> or 32 to 43 % of that under the natural forest (Paper I, Table 5).

The maximum SOC loss of 9.9 kg m<sup>-2</sup> or 43 % was observed under F<sub>20</sub> while the minimum of 2.8 kg m<sup>-2</sup> or 12 % under AF<sub>40</sub> (Paper I, Table 5). Similar to the loss in SOC stocks under AF and F land uses, losses observed for N in all chronosequences of these land uses ranged from 0.02 to 0.51 kg m<sup>-2</sup> or 1 to 28 %. However, the N stock under AF<sub>40</sub> land uses increased by 0.33 kg m<sup>-2</sup> or about 18 % compared to NF.

Generally, the rate of loss of SOC is very rapid right after cutting NF and it stabilizes between 20 and 30 years with a negligibly small increase in the later chronosequences of 40 to 50 years. The rate of SOC loss was lower under AF (0.07 to 0.62 kg m<sup>-2</sup> yr<sup>-1</sup>) than under F (0.13 to 0.7 kg m<sup>-2</sup> yr<sup>-1</sup>).

Similar to SOC, the loss of N also declined with time and was 0.028 kg m<sup>-2</sup> yr<sup>-1</sup> under AF<sub>12</sub> compared with 0.003 kg m<sup>-2</sup> yr<sup>-1</sup> at AF<sub>50</sub>. The corresponding rate of loss for farmlands was 0.034 and 0.007 kg m<sup>-2</sup> yr<sup>-1</sup>. The difference in the SOC stock among most of the age chronosequences of AF and F land uses is not significant. Despite this the SOC under AF tends to be higher than the corresponding F land uses (Fig. 7).

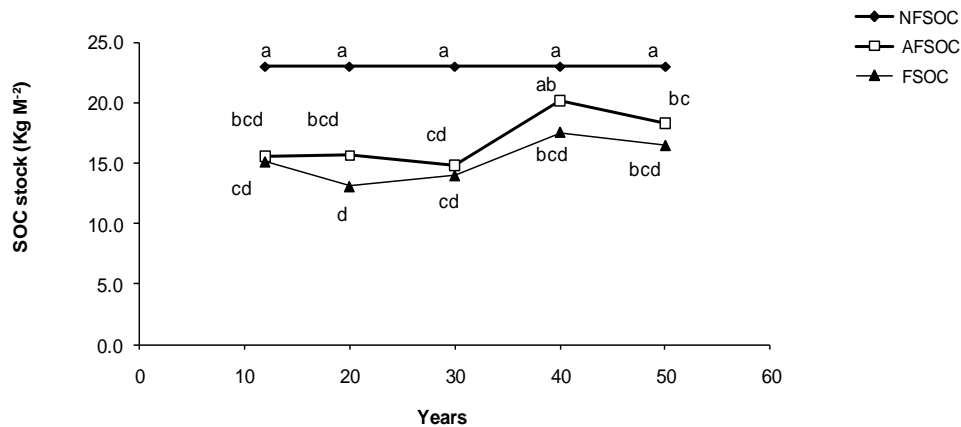


Fig.7. Total SOC stock to 1 m depth in the chronosequences of agroforestry (AF) and farm (F) land uses, Means followed by the same lower case letter(s) between AF and F land uses under different age chronosequences are not significantly different at (P <0.05)

## 5.5 Litter fall dynamics and carbon turnover

### 5.5.1 Litter fall (temporal and annual production)

The average annual litter fall for *Eucalyptus* species (*E. saligna*, *E. camaldulensis* and *E. globulus*), and natural forest (ranging from 8.7 to 11.5 Mg ha<sup>-1</sup> yr<sup>-1</sup>) was significantly higher (P<0.05) compared to that under coniferous species (*C. lusitanica*, *J. procera* and *P.patula*), ranging from 4.4 to 6.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>. No such statistically significant difference was observed within *Eucalyptus* or coniferous species (Fig.8). Yang et al. (2004) observed that mean annual total litter fall varied from 5.47 Mg ha<sup>-1</sup> for *Cunninghamia lanceolata* to 11.01 Mg ha<sup>-1</sup> for natural forest at Fujian, in subtropical China showing values similar to those found in this study. The integrated contribution of the diverse component species in natural forest may explain the higher litter fall as compared to pure plantation stands.

Plants differ in their ability to capture resources and in their influence on ecosystem processes (Russell et al. 2004), and hence, diverse natural vegetation and or mixed plantation produce higher annual litter mass than pure stand crops (Binkley et al. 1992; Lian and Zhang 1998; Parrotta 1999; Yang et al. 2004; Wang et al. 2007). In such case, managing plantations

as mixed stand could mimic the function of natural forest systems and produce higher litter mass and better nutrient recycling. For example, Wang et al. (2007) reported that the mean annual litter production was significantly higher (24 %) in the mixed than the monoculture *Cunninghamia lanceolata*.

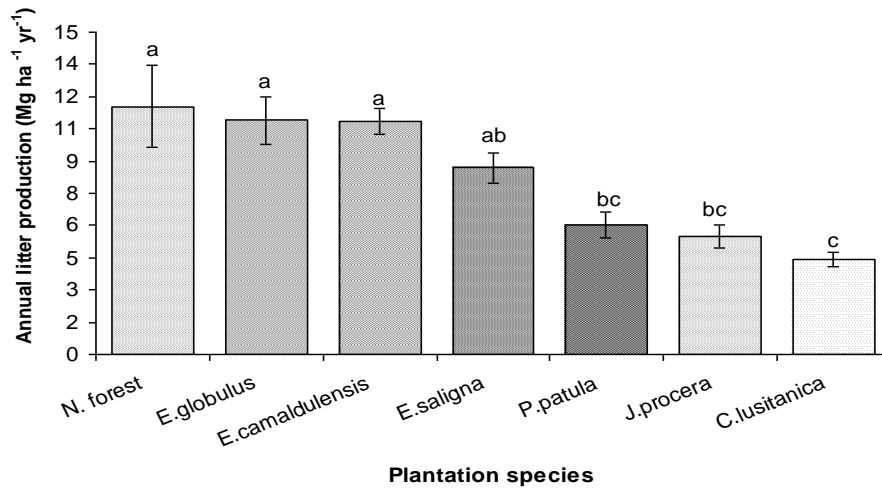


Fig.8. Annual litter production under plantations and natural forest. Means followed by the same lower case letters are not significantly different ( $p < 0.05$ ,  $n = 3$ ).

### 5.5.2 Temporal variation of litter fall

The litter fall under plantations and natural forest also showed temporal variation (Fig.9). The highest peak of litter production was observed in June for *J. procera* and natural forest, September/November for *E. saligna* and *E. globulus*, November/January for *P. patula* and *E. camaldulensis* and January/March for *C. lusitanica* (Fig.9).

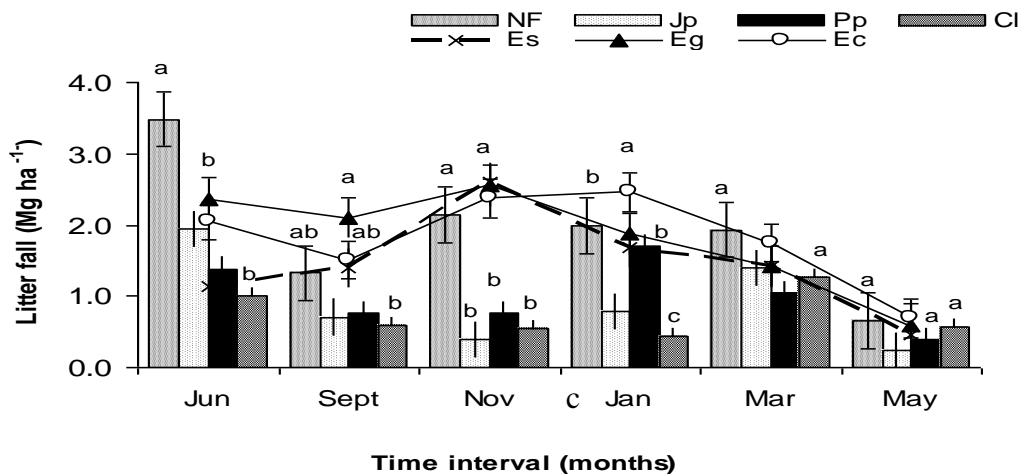


Fig.9. Periodic (two months interval) litter under and natural forest (NF), *J. procera* (Jp), *P. patula* (Pp), *C. lusitanica* (Cl), *E. saligna* (Es), *E. globulus* (Eg) and *E. camaldulensis* (Ec). Conifers species are shown by bars and *Eucalyptus* are shown by line graphs. Means followed by the same letter among species do not differ significantly ( $P < 0.05$ ).

The litter fall under *E. globulus* and *E. camaldulensis* did not show such large variations from April to March, and those of *Eucalyptus* and natural forest were almost consistent throughout the year

The intensity and the powerful swaying wind that usually occurs before the onset of the heavy rainfall events from July to September (Fig.2) may cause the largest accumulation of litter under all plantations and natural forest during April/June period. A similar pattern of litter fall was also obtained by Lisanework and Michelsen (1994) for the Central Highlands of Ethiopia and else where by Jackson (1978) for the tropical rain forest in Australia. The litter production of the natural forest and *Eucalyptus* species showed little variation from September 2007 to March 2008, while such a consistent rhythm was not seen under coniferous species.

Several studies have documented the seasonal variation of litter production (Spain 1984; Martinez-Yrizar and Sarukhan 1990; Wang et al. 2007). They found that for most of the species, the peak rates of litter fall usually occurs during the dry season (Wright and Cornejo 1990), but for some species, litter fall is maximum during the period of greatest precipitation and high temperature (Jackson, 1978).

### 5.5.3 Carbon and Nitrogen in litter fall

The average concentration of C and N in fresh matured leaf ranged from 47.1 to 54.8 % for C and from 1.3 to 2.5 % for N. The corresponding values for litter fall were from 39.0 to 49.3 % for C and from 0.7 to 1.8 % for N (Paper III, Table 2). This trend implies that both C and N were lost during the litter fall period, and these losses varied from 2.9 to 22.3 % for C and 11.8 to 53.0 % for N. The losses may partly be explained due to recycling of nutrients to other parts of the plant during leaf senescence (Gan and Amasino, 1997) or due to decomposition between the time of falling and collection of the samples from the litter traps (Berg and McLaugherty, 2008). In general, the loss of C from *J. procera* and *C. lusitanica* was higher than those of other plantations, and that of under the natural forest was the lowest. The variation of C loss within *Eucalyptus* species was lower than the within coniferous species. However, almost all *Eucalyptus* species showed higher N loss during leaf maturing than coniferous or natural forest species (Paper III, Table 2).

### 5.5.4 Litter decomposition

The residual litter mass in the bags declined exponentially for all plantation species and natural forest (Fig.10). The remaining mass of litter varied between species and between sampling time ( $P < 0.05$ ). In the first 3 months, remaining litter mass for *C.lusitanica* and *P. patula* was significantly higher than that of *E. camaldulensis* and *E. saligna* (Fig.10). At 6 months time, the remaining litter mass of *E. saligna* was significantly lower than *P. patula* only. At 9 months, the remaining litter mass of *C. lusitanica* was significantly lower than *P. patula* only (Fig.10).

Generally, the remaining litter mass under *P. patula*, *E. globulus* and natural forest was consistently higher compared to the other species investigated in the study periods. The single exponential model showed a good fit for all leaf litter of all plantation species (Paper III, Table 4).

The decay rate coefficient ( $k$ ) of all species ranged from  $0.07 \text{ month}^{-1}$  for *P. patula* to  $0.12 \text{ month}^{-1}$  for *E.saligna*, while the half-life decay period ranged from 6.0 to 9.7 months. The decomposition of *Eucalyptus* species in general tended to be faster than coniferous species. On the top of factors variability that control decomposition such as moisture, temperature etc, the fast initial and the subsequent slower rates of decomposition at later time intervals could be due to a higher initial content of water soluble materials, simple substrate and the breakdown of litter by decomposers, especially the micro flora (Songwe et al. 1995) and the higher loss of these easily degradable and labile fractions during the early decomposition phase (Berg and



Tamm 1991; Sundarapandian and Swamy 1999; Jamaludheen and Kumar 1999; Ribeiro et al. 2002; Yang et al. 2004; Huang et al. 2007).

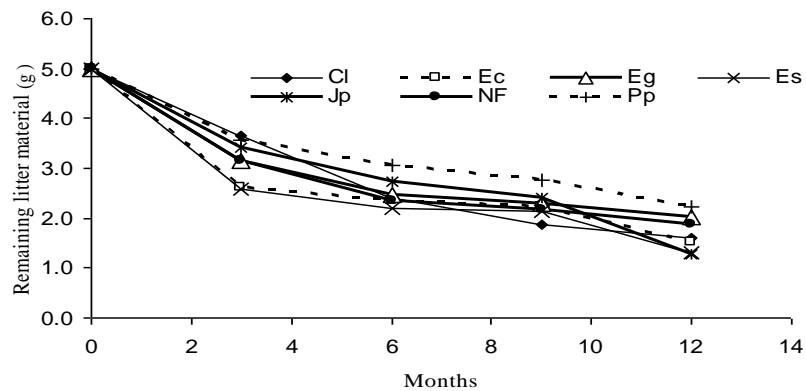


Fig.10. Litter mass remaining in litter bags at various time intervals under *C.lusitanica* (Cl), *E. globulus* (Eg), *E. camaldulensis* (Ec), *E. saligna* (Es), *P.patula* (Pp), *J. procera* (Jp) and natural forest (NF)

Nevertheless, the relatively slower decay rates at later stages may be due to the decrease of the substrate quality as a result of the removal of the labile C and the accumulation of recalcitrant matter in the residual litter mass (Berg and Tamm 1991; Ribeiro et al. 2002). These observations may explain the trend of decomposition observed in the present study. In addition to this, the slow down of decomposition in the 6 and 9 months interval may be explained due to draught (Fig. 2).

However, the data obtained in our study may have been explained better if the decomposition process was observed with narrower time intervals, the study period extended and in situ site moisture and temperature data were collected and included as factors in the analysis.

### 5.5.5 Carbon and nitrogen in the remaining litter mass

The C concentration in the remaining litter mass did not differ significantly between species across the sampling time intervals ( $P > 0.05$ ). However, the N concentration of the remaining litter mass varied at all times ( $P < 0.05$ ). After 6 months, N concentration in the residual litter of *E. saligna* was significantly higher than that of *C. lusitanica*, *E. globulus* and *P. patula* (Paper III, Table 5).

The N concentration in residual litter of *J. procera* and natural forest was also significantly higher than that of *E. globulus* and *Pinus patula*. After 9 months time, N in the remaining litter of *E. saligna*, *J. procera* and natural forest was significantly higher than that of *C. lusitanica*, *E. globulus* and *P. patula*. The N in the remaining litter of *E. camaldulensis* was significantly higher than that of *E. globulus* and *P. patula* ( $P < 0.05$ ). At 12 months time, the N concentration of *E. saligna* was significantly higher than that of *E. globulus* and *P. patula* (Paper III, Table 5).

The 6<sup>th</sup> and 9 months time interval was the off season characterized with little rainfall and this may explain the relatively slowing rate of decomposition. The seasonal changes in moisture, temperature, relative humidity affects the decomposition processes (Kim et al. 2005). Differences in the substrate qualities between species (for example the content of lignin and nutrient composition of the litter) may also influence the rate of decomposition.

Lower N concentration and higher C:N ratio in *P. patula* and *E. globulus* seem to have delayed the decomposition as compared to, for example, natural forest (Paper III, Table 3). Relatively, increase in N content was found in the bagged litter than in the initial amount in both broad leaved *Eucalyptus* and coniferous species, leading to lower C:N ratio during the decaying period. The observed trend is consistent to that reported by Ribeiro et al. (2002) for leaf litter in *E. globulus* and Guo & Sims (1999) for short-term *Eucalyptus* rotation in New Zealand. The decay rate constant in *P.patula* was significantly lower than *E.globulus*, *J.procera*, *C.lusitanica*, *E.camaldulensis*, *E.saligna* and natural forest. However, no such significant difference was observed between the decay rate constant values among the rest of plantation species including the natural forest. But the decay rate constant showed that the litter mass in *E. saligna* and *E. camaldulensis*, *C.lusitanica*, *J. procera*, relatively disappeared faster than the other species.

## 5.6 Soil quality

The iterated PCA analysis showed that the first three PCs with eigen values > 1 explain 79 % of the variability. The final PCA based selection of soil property variables for soil quality indexes (SQIs) were air volume at -10 kPa matric potential (fa), exchangeable potassium (K<sup>+</sup>), pH, infiltration rate (IR), SOC, available phosphorus (av.P), AWC and BD. The weighted eigen values of these soil property variables ranged from 0.09 to 0.14 (Fig.11A).

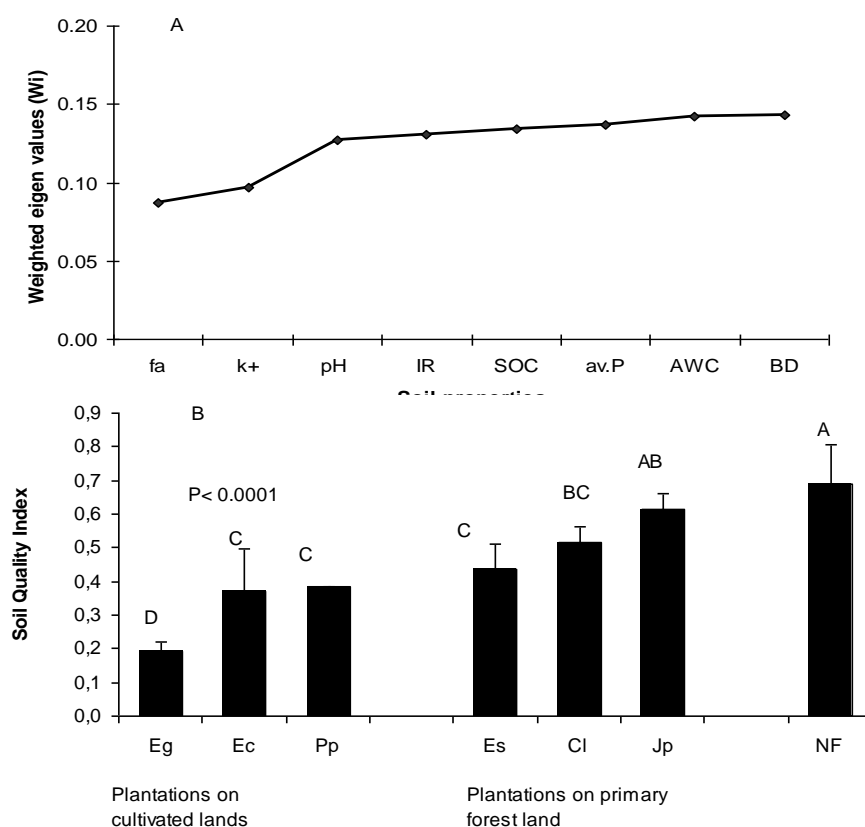


Fig.11. A) Weighted vector  $w_i$  of soil quality factors, air volume (fa), Potassium (k<sup>+</sup>), soil acidity (pH), infiltration rate (IR), soil organic carbon (SOC), available P (av.P), available water capacity (AWC) and soil bulk density (BD) and B) Soil quality index (SQIs) under Plantation land uses where Eg=*E.globulus*, Ec=*E. camaldulensis*, Pp=*P. patula*, Es=*E. saligna*; Cl= *C. lusitanica*, Jp=*J. procera* and NF=natural forest. Means followed by the same upper case letter among species do not differ significantly ( $P < 0.05$ ).

The SQI under all plantation species except *J. procera* (*Jp*) was significantly lower compared to that under natural forest (NF) ( $p < 0.0001$ ). Similarly the SQI under *J. procera* was significantly higher than those of the other plantation species, except to that under *C. lusitanica* (*Cl*) (Fig.11B). But, significant difference was not observed in the SQIs among *C. lusitanica*, *E. saligna* (*Es*), *P. patula* (*Pp*) and *E. camaldulensis* (*Ec*). The SQI of soil under *E. globulus* (*Eg*) was significantly lower compared to those of the other plantations species (Fig.11B). Moreover, significant difference in SQI was observed on a species genera basis among the coniferous, *Eucalyptus* and the natural forest groups ( $p < 0.0001$ ).

The SQI of soils under *Eucalyptus* species was lower than those under coniferous plantations. This trend may be ascribed to the fast growing nature of the *Eucalyptus* species that may intensively absorb soil nutrients as well as the frequent harvest and transportation of woody material out of the system. The whole tree harvesting together with the short harvest cycles, often with leaves intact, results in a nutrient depletion that is far greater than for conventional forest harvests (Heilman and Norby, 1998).

Within *Eucalyptus* species, *E. globulus* and *E. camaldulensis* had lower value of SQI than any of the other plantations. This trend may be attributed to their management as coppice harvested in short periods of time usually in every 7-10 years depending on the size of the woody material needed. On the other hand, the higher value of SQI under *E. saligna* compared to *E. globulus* and *E. camaldulensis* could be attributed to the difference in their mode of establishment and rotation period. *E. saligna* was established on undisturbed primary forest lands and was not harvested since its establishment.

Soil nutrients are accumulated and recycled through the addition of litter from the standing plantation crops. However, the accrual of soil quality variables such as SOC via detritus material is a slow process, and one way of achieving it is by less intense harvest through prolonged rotation periods. Conversion of crop land to forest plantation land use implies that the annual cycle of cultivating and harvesting crops is replaced by a much longer forest cycle (Six et al., 2000; Vesterdal et al., 2002). Such management has probably enabled the accumulation of more biomass under *E. saligna* established on the undisturbed soil and the prolonged rotation period relative to the coppice management in which the *E. globulus* and *E. camaldulensis* have endured.

In cultivated lands, the soil nutrients were exhausted by crops and the disturbance of soil physical parameters may also take longer to be restored, thus making the effect of *E. globulus* and *E. camaldulensis* slower (Post and Kwon, 2000b). Tillage, in addition to mixing and turning the soil, disrupts aggregates and exposes organo-mineral surfaces otherwise inaccessible to decomposers (Post and Kwon, 2000b). Under such management, continuously cultivated lands depleted 80-96 % of the initial forest derived SOC in sand, while depleting 73-85 % of SOC from the silt fraction of Wushwush and Munessa, Ethiopia (Solomon et al., 2002).

## **5.7 Conclusions, recommendations and research perspectives**

Conversion of natural forest to plantations, cultivated and traditional agroforestry land uses and the subsequent residue management had negatively influenced the SOC and N in the study area. Larger proportion of SOC and N was invariably concentrated in the upper 0 to 20 cm soil depth but the concentration in this layer of all land uses was significantly lower than that under the natural forest. The higher concentration of SOC and N in the upper 0-20 cm soil depth, the decline with depth and lack of significant difference in SOC and N content in sub soils between different land use types, implies that in particular the upper 30 cm of soils may

provide conclusive information about the effect of land uses on these parameters. Thus we recommend that 30 cm depth sampling is enough to assess differences between land uses on SOC and N stocks.

The loss of SOC in both agroforestry and farmlands was many fold higher in the early chronosequence of 12 and 20 years than in the later chronosequences of 40 and 50 years. The relatively higher SOC stocks and lower rate of SOC loss in agroforestry suggest that integrating more trees with proven multipurpose functions and increasing the application of the crop residue input in all agricultural lands may have a higher potential of sequestering SOC.

Among plantations, *J. procera* (the native species) and *P. patula* sequestered higher SOC than *Eucalyptus* species. Nevertheless, the accretion of SOC and N stocks in *Eucalyptus* was not that low given the shorter rotation cycle. The notion that *Eucalyptus* species lead to soil degradation by nutrient and water mining do not seem to hold true under the soil and climatic conditions of the study area.

The input of detritus material under plantations was far better than those in the traditional agroforestry and cultivated lands. Moreover, the broad leaved *Eucalyptus* short-term rotation crops exhibit higher annual litter production than coniferous species. The rate of decomposition with the exception of *P.patula* was fast for the plantation species and for natural forest for the investigated one-year period. The addition of nutrients to the soil through decomposition of litter is crucial especially where application of fertilizers is limited to sustain soil productivity as is the case in the study area. Hence, the higher litter production and the subsequent faster rate of decomposition are qualities to consider during the selection of species for short-term rotation crops. The higher annual litter production under *Eucalyptus* species and the higher accretion rate of SOC under *P.patula* and *J. procera* should be taken into account during species selection for plantation establishment. Thus we recommend that *J.procera* and *P.patula* are good candidates for plantation establishment on forest cleared and degraded lands. Over all plantation soils sequester more SOC than farm lands. However, since SOC pools are highest, the relic natural forests should be protected from further conversion to other land uses to maintain large SOC stocks and healthy ecosystem functions. Moreover, plantations are better than farm lands in sequestration of C and N when mitigation of the increasing atmospheric CO<sub>2</sub> in combination with sustenance of land productivity is the main quest of land management

In general, the results of this study indicate that the degraded soil physical and chemical properties under plantations established on cultivated lands did not recover to their original state, and they were consistently inferior to those of soils under plantation stands established on undisturbed forest soils. The value of soil quality below the baseline scoring function of soil properties under plantations established on previously cultivated lands indicate that the period required for rehabilitation of the disturbed soil was not long enough. Plantations, especially *Eucalyptus* species, are managed as coppice harvested in every 7 to 10 years. Such short rotation period will not allow accumulation of SOC and other soil chemical nutrients to the level required to have high soil quality. Similarly, the sites under plantations established on undisturbed forest soils showed lower SQI compared to that under the natural forest and the same was true for plantations, except *J. procera* established on primary undisturbed forest soil. Thus the data support the conclusion that proper selection and management of species and prolonging the rotation period would increase and sustain soil quality.

This study has revealed the changes of SOC and total N due to changes in land uses. But the data obtained could not be related to yield parameters that may help farmers adopt best management practices (BMPs) to sustain their farm productivity while at the same time sequestering carbon to offset carbon emission. Therefore, it will be of paramount importance to carry out research through manipulative experiments on application of crop residue, judicious

fertilizer use, and plantation management practices. Such effort will generate information that can best be utilised for the improvement of the existing farm management to sustain and increase productivity of their farms through increased sequestration of SOC and N. Such strategy may lead to increased soil and crop productivity on one hand and mitigation of climate change through biosequestration (soil and vegetation) of atmospheric CO<sub>2</sub> on the other. The study conducted on litter fall and decomposition was only for one year period. To obtain more reliable data on litter fall, its decomposition and SOC dynamics, the study should be conducted for longer period of time with more native species included. In addition to SOC and N turnover assessment as done in this study, future studies must also involve the dynamics of other nutrients such as phosphorus, K<sup>+</sup> Ca<sup>+2</sup> and Mg<sup>+2</sup> (essential components for both C sequestration and soil productivity). The experiment should be done simultaneously in controlled laboratory and field conditions to better understand the decomposition processes involved. Although the rate of SOC loss is calculated in this study, it is rather a cumulative loss over longer period of time and may not give the true picture of the losses and gains occurring for short time intervals as changes often are non linear under field conditions.

## 6 References

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## 7. Appendix A



**Plate I: Podocarpus dominated traditional system  
Agroforestry system adjacent to NF**



**Plate II : Ficus dominated traditional agro forestry  
Nearby the study sites**



**Plate III: Maize stalk transported away from farm  
lands**



**Plate IV: Wheat straw ready to be transported away fro the  
farm**





**Plate V: Natural Forest that stretches from Besko to Leye and Ashoka sites**



**Plate VI: Volcanic ash (pumice soil) along the sides of Awassa Shashemene highway, Southern Ethiopia**



**Plate VII: The native species of *J.procera* plantation on primary forest land and litter trap and litter bag Decomposition study plots**



**Plate VIII: *E.camaldulensis* on previously cultivated land with very poor undergrowth**





**Soil carbon and nitrogen stocks under chronosequence of cultivated and traditional agroforestry land use in Gambo District, Southern Ethiopia**

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# Soil carbon and nitrogen stocks under chronosequence of cultivated and traditional agroforestry land use in Gambo District, Southern Ethiopia

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## Abstract

Conversion of forests to cultivated lands and traditional agroforestry systems may lead to loss of SOC and N stocks. This study was conducted on soils with the age chronosequences of 12, 20, 30, 40, 50 years of cultivated farm (F), agroforestry (AF) and the adjacent natural forest (NF) lands. We studied the changes in the concentration and stocks of soil organic carbon SOC, total N and their distribution in the soil profile of an Andic Paleustalfs in Gambo District, Southern Ethiopia. Soil samples were collected at 10, 20, 40, 60, 100 cm depth interval from pits of 1m depth from all land use types and they were analyzed for SOC and N. The results showed that the greater proportion of SOC and N was concentrated in 0 to 20 cm depth and that their concentration in AF and F land uses was significantly lower than that under the natural forest (NF). Soils in traditional agroforestry land use showed a trend of higher SOC stocks in all chronosequences than those under the corresponding cultivated lands. The loss of SOC stock under the chronosequence of 12 to 50 years of AF and F land uses ranged from 2.8 to 9.9 kg m<sup>-2</sup> or 12 to 43 % of the stock under the NF. The rate of SOC loss under AF<sub>12</sub> was 0.62 kg m<sup>-2</sup> yr<sup>-1</sup> and 0.09 kg m<sup>-2</sup> yr<sup>-1</sup> under AF<sub>50</sub>. The corresponding values for farm lands were 0.66 and 0.13 kg m<sup>-2</sup> yr<sup>-1</sup>. The rate of N loss also declined with time under both land uses, for example, from 0.028 kg m<sup>-2</sup> yr<sup>-1</sup> at AF<sub>12</sub> to 0.001 kg m<sup>-2</sup> yr<sup>-1</sup> at AF<sub>50</sub>. The results suggest that the losses of SOC and N stocks tends to be higher in farm lands than in agroforestry but in both land uses stocks increased with increasing chronosequences of 12 to 50 years.

**Keywords:** Soil organic carbon soil nitrogen; natural forest; farm land, agroforestry; carbon stocks, soil profile

## Introduction

Global warming caused by the emission of greenhouse gases (GHGs), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), has become one of the main human concerns in recent years. One of the major sources of the emission of GHGs is the conversion of natural forests and peat land ecosystems to farm and other land uses (Kirby

and Potvin, 2007). The effect of elevated CO<sub>2</sub> in the atmosphere in the short run can be mitigated by , sequestering carbon (C) through best management practices (BMPs), including conservation tillage, improved fallow, increasing crop growth through fertilizer application, reclamation of degraded soils, agroforestry practices; reducing erosion damage through effective biological and physical control measures (Lal et al., 2007).

In agricultural landscapes, agroforestry systems can be used as an alternative for economically sound and environmentally friendly land use approach. The C sequestration potential of agroforestry systems is estimated to be between 12 and 228 Mg C ha<sup>-1</sup> (Albrecht and Kandji, 2003; Dixon, 1995). As reported by Takimoto et al. (2008) in the study of an agroforestry systems (traditional parkland systems with *Faidherbia albida* and *Vitellaria paradoxa* as the dominant tree species, live fence, fodder banks and an abandoned previously cultivated land) in the West African Sahel, biomass C stock ranged from 0.7 to 54.0 Mg C ha<sup>-1</sup> and total C stock (biomass C + soil C, into 1m depth) from 28.7 to 87.3 Mg C ha<sup>-1</sup>, in which a major portion of the total amount of C in the system is stored in the soil. The traditional park land agroforestry systems had relatively larger C stock than the other systems for this particular study. Sequestering C in soils is a 'win-win' proposition. Not only it removes excess CO<sub>2</sub> from the air per-se, but also improves soils by augmenting organic matter, energy and nutrient source of biota (Janzen, 2006). Paustian et al., (1997) argued that agricultural soils have a significant CO<sub>2</sub> sink capacity provided that judicious management of farm land is practiced. Loss of SOC in cultivated soils can be reduced by proper use of crop residue in farmlands. The input of residues from agricultural products is essential to increase SOC concentration that will enhance the soil quality in arable lands (Paustian et al., 1997; Duiker and Lal, 2000; Loveland and Webb, 2003).

In Gambo district, Southern Ethiopia, extensive deforestation, overgrazing and conversion of natural ecosystem into arable land are rampant (Ashagrie et al., 2005; Solomon et al., 2002a; Lemenih and Itanna, 2004). Remnant trees deliberately left from the clearance of the woodland and natural forest are scattered all over the agricultural lands, which is called the traditional (park land type) agroforestry (AF) system. This is a unique system that differs from most of the conventional agroforestry systems in configuration, mode of establishment and management. Crops are grown during the rainy season in both the traditional agroforestry and farmland systems. After harvest, farmers either burn the crop residues or transport it to their home for various uses. This type of residue management does not permit the replenishment of depleted organic matter (OM) and thus can lead to decline in soil quality (Yimer et al., 2007; Blanco-Canqui and Lal, 2007). Some studies have demonstrated that *Acacia* woodland soil sequestered 40.3 Mg C ha<sup>-1</sup> and 5.3 Mg N ha<sup>-1</sup> under the semiarid environment in the rift valley of Ethiopia, while *Podocarpus falacatus* forest soil under humid condition sequestered 234.6 Mg C ha<sup>-1</sup> and 20.2 Mg N ha<sup>-1</sup>, which was significantly higher than soil C and total N stocks in cropland soils (Yimer et al,2007; Lemenih and Itanna, 2004; Solomon et al., 2002b).

However, information on classified quantitative data regarding changes in soil C and N stocks following the clearance of natural forest to either agroforestry or farm land are rare, if not nonexistent in Gambo district, Southern Ethiopia. Furthermore, chronosequential long-term changes (12-50 years) in C and N stocks in soils and soil profiles under different land use changes are lacking not only in Ethiopia but in the whole of sub Saharan region. It is hypothesized that traditional agroforestry systems increases SOC and N stocks in different chronosequential long term changes compared to the treeless cultivated lands. Therefore, the objectives of the study were: (i) to investigate the changes (loss or gains) in the concentration and stocks of SOC and N in soils under the

chronosequences of 12, 20, 30, 40 and 50 years after conversion of natural forest to agroforestry and cultivated lands under the prevailing farmer's crop residue management practice, (ii) to study the distribution of SOC and N in the soil profile (1 m depth) of different land use systems.

## Material and Methods

### Description of the study site

The study was conducted at three sites namely, Ashoka, Leye and Beseko, which are adjacent to the natural forest in Gambo district, Southern Ethiopia that covers an area positioned on the lower fringe of the western escarpment of the southeastern highlands (Fig.1). Ashoka, Leye and Beseko sites lie within 7°17'N and 7°20'N and 38°48'E 38°49'E, at about 240 km southeast of Addis Ababa. The altitude ranges from 2137 to 2215 m a.s.l, and the slope from 4 to 11%.

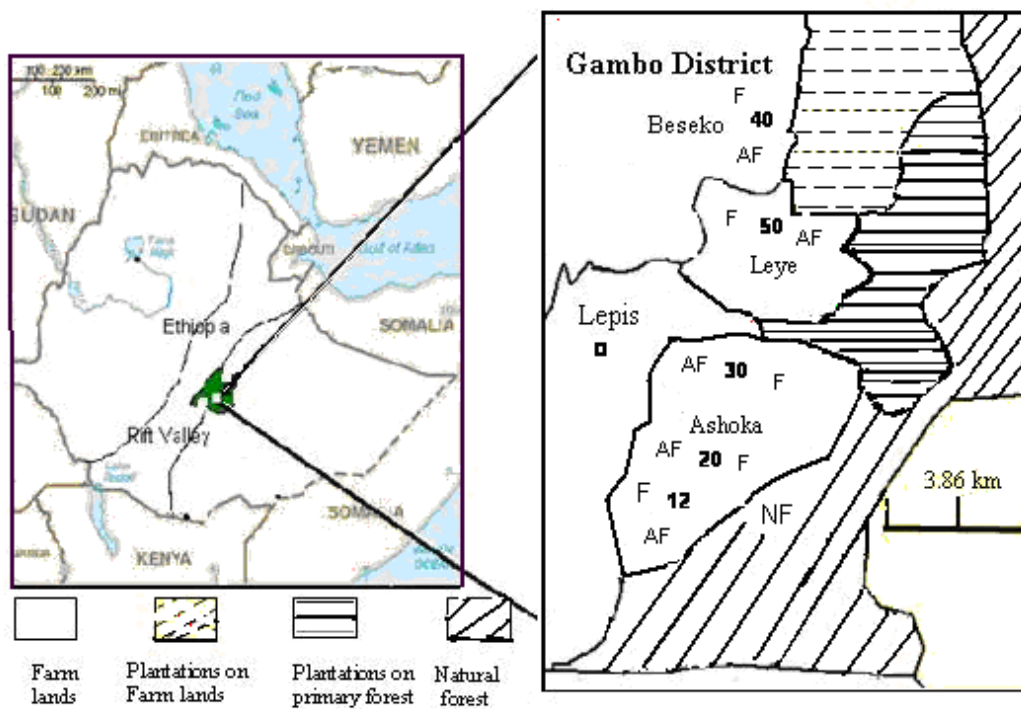


Fig.1. Map showing the sites of the natural forest, the chronosequence of agroforestry and farm land uses in Gambo district, southern Ethiopia. Where: AF = agroforestry, F = farm lands of age chronosequences from 12-50 years, Eg =E.globulus, Pp =P.patula, Ec = E.camaldulensis, Es = E. saligna, Jp = J.procera, Cl. C.lusitanica and NF = natural forest.

Rainfall is bimodal with mean annual precipitation of 973 mm, most of it falling from July to September (Fig.2). Temperature ranges between the mean annual maximum of 26.6 °C and mean of 10.4°C across the study area for the period from 1999 to 2007(Fig 2).

The dominant species of the upper storey vegetation in the natural forest and agricultural landscapes of Bseko, Leye and Ashoka are *Podocarpus falcatus* Thunb.ex Mirb., *Croton macrostachys* Hochst.ex Rich., *Prunus africana* (Hook.F.) Kalkm, *Schefflera abyssinica* (Hochst. Ex A. Rich) Harms., *Syzygium guineense* (Willd.) DC and *Ficus sure*

(Forsk). Moreover, the dominant species in the under story vegetation of the natural forest are: *Lansea schimperi* (A.Rich.) Engl. *Rytigynia neglecta* (Hiern) Robyns, *Maytenus arbutifolia* (Hochst.ex A.Rich.) Wilezek, *Bersama abyssinica* Fres, and *Psydrax schimperiana* (A. Rich). The most abundant herb in the forest floor is *Hypoestes furskaolii* (Vahl.)R. Br.

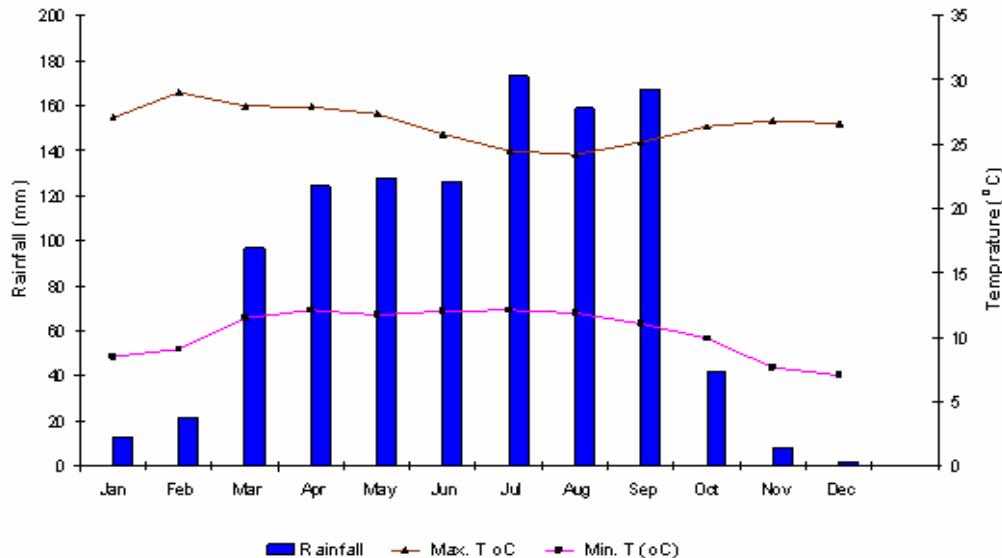


Fig. 2. Mean monthly rainfall (mm), and mean monthly maximum and minimum temperature (°C) for the period 1999 – 2007.

Source: National Meteorological service agency, Addis Ababa, 2008

The species of woody perennials distributed in the agricultural landscape (Table 1) are managed for their multipurpose functions such as production of leaf litter for soil nutrient recycling, fuel wood, fence, timber for construction material, and lumber products for sale. Most of them are semi deciduous and shed a lot of litter during the off season. The most prominent crops grown in the cultivated fields of the area are maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.) and potato (*Solanum tuberosum* Linnaeus). Most of the crop residues are often removed or heaped and burned several weeks before the field preparation for the next growing season.

The soil parent materials of Gambo District are of volcanic origin, principally trachytes and basalts with ignimbrites and pumices at the rift valley floor (Solomon et al., 2002a). The escarpment extends from about 2100 to 3200 m a.s.l and the plain descends gradually to the rift valley lakes at about 1600 m a.s.l. The soils of Leye and Ashoka are classified as Andic Paleustalfs in which the profiles have a thick argillic horizon and some Andic soil material in the upper soil layers (Soil Survey staff, 1999).

Table 1. Location of soil sampling pits (1m depth) and vegetation characteristics in Agroforestry and farm land uses at Leye and Ashoka sites

Site	Land use	Age (Years)	Tree species in AF land use	D <sub>1.3</sub> (cm)	H (M)	Plot No	Elevation (m.a.s.l)	Coordinate of soil sampling pits		Slope %		
								Longitude	Latitude			
Ashoka	Agroforestry	12	<i>P. falcatus</i>	212	42.2	1	2205	07°17.515'N	038°48.245'E	11		
			<i>P. africana</i>	134	41.1	2	2208	07°17.508'N	038°48.234'E	11		
			<i>P. africana</i>	120	36.2	3	2212	07°17.498'N	038°48.241'E	11		
			<i>P. africana</i>	116	35.7	4	2203	07°17.506'N	038°48.252'E	11		
			<i>P. africana</i>	105	27.0							
Ashoka	Agroforestry	20	<i>F. sure</i>	115	12.6	1	2178	07°18.062'N	038°48.309'E	8		
			<i>F. sure</i>	103	12.6	2	2183	07°18.055'N	038°48.299'E	8		
			<i>C. macrostachyus</i>	103	30.6	3	2181	07°18.047'N	038°48.314'E	8		
			<i>C. macrostachyus</i>	98	12.6	4	2187	07°18.056'N	038°48.317'E	8		
			<i>C. macrostachyus</i>	88	16.8							
			<i>C. macrostachyus</i>	84	13.8							
			<i>C. macrostachyus</i>	80	18.0							
			<i>C. macrostachyus</i>	74	25.2							
			<i>C. macrostachyus</i>	66	25.0							
			<i>C. macrostachyus</i>	65	26.8							
Ashoka	Agroforestry	30	<i>S. abyssinica</i>	129	20.0	1	2177	07°18.116'N	038°48.441'E	6		
			<i>P. africana</i>	112	29.4	2	2182	07°18.092'N	038°48.436'E	6		
			<i>P. falcatus</i>	86	24.6	3	2179	07°18.093'N	038°48.448'E	6		
			<i>P. africana</i>	72	20.8	4	2159	07°18.104'N	038°48.444'E	6		
			<i>P. falcatus</i>	60	20.5							
Beseko	Agroforestry	40	<i>P. falcatus</i>	133	30.9	1	2149	07°19.990'N	038°49.317'E	7		
			<i>P. falcatus</i>	130	30.6	2	2151	07°19.983'N	038°49.305'E	7		
			<i>P. falcatus</i>	124	32.7	3	2157	07°19.969'N	038°49.316'E	7		
			<i>P. falcatus</i>	124	22.6	4	2166	07°19.980'N	038°49.327'E	7		
			<i>P. falcatus</i>	121	34.8							
			<i>P. falcatus</i>	101	31.8							
			<i>P. falcatus</i>	98	29.4							
Leye	Agroforestry	50	<i>P. falcatus</i>	94	28.3							
			<i>P. falcatus</i>	232	53.1	1	2163	07°18.782'N	038°48.791'E	8		
			<i>P. falcatus</i>	200	40.2	2	2168	07°18.756'N	038°48.774'E	8		
						3	2165	07°18.745'N	038°48.787'E	8		
						4	2167	07°18.766'N	038°48.801'E	8		
			Ashoka	Farm	12			1	2205	07°17.533'N	038°48.244'E	11
								2	2209	07°17.530'N	038°48.236'E	11
								3	2215	07°17.522'N	038°48.242'E	11
		4				2207	07°17.526'N	038°48.250'E	11			
		1				2182	07°18.005'N	038°48.326'E	4			
Ashoka	Farm	20			2	2190	07°17.992'N	038°48.319'E	4			
					3	2185	07°17.983'N	038°48.331'E	4			
					4	2184	07°17.991'N	038°48.337'E	4			
					1	2181	07°18.067'N	038°48.442'E	6			
Ashoka	Farm	30			2	2176	07°18.064'N	038°48.434'E	6			
					3	2175	07°18.055'N	038°48.438'E	6			
					4	2186	07°18.061'N	038°48.444'E	6			
					1	2139	07°20.063'N	038°49.167'E	6			
Beseko	Farm	40			2	2137	07°20.064'N	038°49.157'E	6			
					3	2137	07°20.050'N	038°49.156'E	6			
					4	2139	07°20.050'N	038°49.168'E	6			
					1	2159	07°18.750'N	038°48.734'E	9			
Leye	Farm	50			2	2158	07°18.741'N	038°48.729'E	9			
					3	2163	07°18.733'N	038°48.738'E	9			
					4	2157	07°18.743'N	038°48.744'E	9			

Where D1.3 = Diameter at breast height  
H = Height  
AF = Traditional agroforestry system

## Soil sampling and analysis

Due to lack of permanent plots for monitoring temporal changes in C and N stocks at the study sites, spatial analogue and chronosequence approach was used for soil sampling in the designated land use systems. Ashoka, Leye and Beseko study sites are located adjacent to each other and have chronosequence of agroforestry and cultivated lands within an area of minimum soil and climatic differences. The confined area for soil sampling from native climax natural forest (NF), traditional agroforestry system (AF) and cultivated lands (F) was chosen to avoid confounding effect of large soil variation. The chronosequence approach adopted in this study has also been used by other investigators (Sa et al., 2001; Turner et al., 2005; Liao et al., 2006). The chronosequences of AF and F land uses were of 12, 20, 30, 40 and 50 years since their conversion from the natural forest. The natural forest at Ashoka was site taken as the reference land use.

The sampling design followed was a pseudo complete randomized design (CRD) with four replicates as presented in Table 1. For each land use and replications, a soil profile of 1x1x1 m was dug and soil samples were collected from 0-10, 10-20, 20-40, 40-60, 60-100 cm depth increments. These samples were air dried, ground and passed through a 2mm sieve prior to analysis. Such processed samples were then analyzed for their physical and chemical properties.

Separate core samples were drawn from the same profile and from the same depth increments for bulk density (BD) determination. This was achieved by forcing manually a sharp edged steel cylinder (3.7 cm high and 5.8 cm in diameter) into the soil (Kim, 2005). The same core sampler was used one at a time and the soil from it was transferred into a plastic bag after each time of sampling. In all, 200 core samples were collected. Soil samples were then oven dried at 105 °C for  $\geq 24$  hrs and weighed using electronic balance. The dry soil was then crushed and passed through 2 mm sieve for making correction in soil bulk density for gravel content. The pH was determined by potentiometric method (Kim, 2005). The concentrations of N were measured using a LECO CHN-1000 Carbon and Nitrogen Analyzer. Soil organic matter (SOM) was analyzed using titrimetric method (Walkley and Black, 1934). The SOC was obtained by dividing the SOM concentration by a factor of 1.724 (Kim, 2005).

## Measurements and calculations

The SOC stock ( $\text{Mg ha}^{-1}$ ) for each sampled depth was calculated using the following relationship as given by Ellert et al., (2001) and Wairiu and Lal, (2003):

$$\text{SOC stock (Mg ha}^{-1}\text{)} = C_{\text{conc.}} \cdot \text{BD} \cdot T \cdot 10000 \text{ m}^2 \text{ ha}^{-1} \cdot 0.001 \text{ Mgkg}^{-1} \cdot \text{CF}_{\text{coarse}} \quad (1)$$

Where:  $C_{\text{conc.}}$  = Carbon concentration ( $\text{kg Mg}^{-1}$ ),  $\text{BD}$  = bulk density ( $\text{Mg m}^{-3}$ )  
 $T$  = depth thickness (m),  $\text{CF}$  = correction factor  $(1 - (\text{Gravel \%} + \text{Stone \%}) / 100)$

The SOC stock was also calculated using equivalent soil mass by adjusting the thickness of the soil as described by Ellert et al., (2001), to correct error that may be introduced due to variation in bulk density. The results obtained with equation 2 were compared with the stock calculated by equation (1).

The soil mass was calculated using equation (2) and thickness of the soil depths were adjusted using equation (3).



$$M_{\text{soil}} = \text{BD} * T * 10000 \text{m}^2 \text{ ha}^{-1} \quad (2)$$

Where:  $M_{\text{soil}}$  = soil mass per unit area ( $\text{Mg ha}^{-1}$ )

$$T_{\text{add}} = (M_{\text{soil, equiv}} - M_{\text{soil, layer}}) * 0.0001 \text{ ha m}^{-2} / \text{BD subsurface} \quad (3)$$

Where:  $T_{\text{add}}$  = additional thickness of sub surface layer required to attain the equivalent soil mass (m)

$M_{\text{soil, equiv}}$  = equivalent soil mass = mass of heaviest soil layer at each 1m depth ( $\text{Mg ha}^{-1}$ )

BD subsurface = bulk density of subsurface layer ( $\text{Mg m}^{-3}$ )

Allophane contents of three selected profiles of 3m depth was calculated according to Mizota and Van Reeuwijk (1989)

$$\% \text{ allophane} = 100(\% \text{ Si}_o / (23.4 - 5.1x)) \quad (4)$$

Where  $x = (\text{Al}_o - \text{Al}_p) / \text{Si}_o$  representing the atomic ratio of Al and Si in allophane

$\text{Al}_o$  = oxalate extractable Al,  $\text{Al}_p$  = pyrophosphate extractable Al

Total stock of N ( $\text{Mg ha}^{-1}$ ) for each sampling depth was also computed using the equations as for SOC stock. The total soil SOC and N stocks were calculated by adding the stock of each depth (to 1m). The change in the rate of SOC stocks over time was computed by subtracting the stocks of chronosequence of AF and F land uses from that of NF and dividing it by the number of years of the chronosequence.

### Statistical Analysis

The data obtained were analyzed using SAS software (SAS Inc.2003). The effect of land uses on SOC and N and their distribution in each of the 1m depth interval were subjected to one way analysis of variance using the general linear model procedures of SAS. Multiple comparison of means for each class variable was carried out using the Student-Newman-Keuls (SNK) test at  $\alpha = 0.05$ .

### Results

The physical and chemical soil characteristics of three selected profiles under *Juniperus procera* (Jp), AF<sub>30</sub> and natural forest (NF) are shown in Table 2. The clay content of the surface soils under AF<sub>30</sub> and NF tends to be higher than that under the *J. procera* plantation. But the CEC allophane and SOC in the surface layers of 0-10 cm depth tends to be higher in soils under *J. procera* compared to those of both AF<sub>30</sub> and the natural forest. Despite that the clay content tends to be higher in the surface soils under AF<sub>30</sub>, The SOC content of the surface soil under AF<sub>30</sub> also tends to be lower compared to that under the NF. The 3m profiles under all land uses were not replicated and that of the natural forest was located relatively in the open space within.

Table 2. Soil characteristics of three selected profiles at Leye and Ashoka sites

Sites	Horizon	Depth (cm)	pH(H <sub>2</sub> O) 1:2.5	Particle Size				Textural class	SOC %	CEC cmol (+) kg <sup>-1</sup>	BS %	Oxalate Extraction					P		
				BD (gm <sup>-3</sup> )	Sand %	Silt %	Clay %					Alox %	Feox %	Siox %	Fedih (%)	Alp (%)	Melanic index	retention %	Allophane %
Leye	1A	5	7.6	0.9	44	37.3	18.7	L	4.65	40.8	99.8	0.21	0.64	0.11	0.64	0.06	1.84	39.4	0.65
Jp	1A2	10	6.9	0.9	54	33.3	12.7	SL	9.5	55.8	99.9	0.23	0.55	0.09	0.55	0.09	1.90	37.7	0.58
	1A3	25	7.8	1.0	38	31.3	30.7	CL	2.16	32.5	99.8	0.19	0.64	0.13	0.64	0.20	1.73	38.4	0.53
	AB	85	5.8	1.1	20	31.3	48.7	C	1.73	18.5	99.6	0.21	1.18	0.10	1.18	0.98	1.67	43.8	0.16
	Bt1	125	5.1	1.2	22	19.3	58.7	C	1.16	23.9	66.3	0.19	1.06	0.09	1.06	1.40	1.71	43.0	0.09
	Bt2	300	5.1	ND	12	19.3	68.7	C	0.94	22.9	71.3	0.20	1.03	0.07	1.03	2.51	1.75	43.5	0.04
Ashoka	1A	9	7.5	0.7	34	31.3	34.7	CL	2.12	25.1	99.3	0.18	0.76	0.13	0.76	0.34	1.56	33.1	0.42
NF	E	18	7.8	0.9	55.3	21.3	23.4	SCL	0.83	16.2	98.9	0.16	0.62	0.10	0.62	0.17	1.68	26.7	0.40
	2A	40	7.6	1.1	37.3	29.3	33.4	CL	1.64	22.2	99.7	0.17	0.86	0.11	0.86	0.22	1.61	35.9	0.43
	AB	85	7.5	1.2	27.3	35.3	37.4	CL	1.12	20.4	97.8	0.16	0.85	0.11	0.85	0.76	1.62	33.6	0.20
	B	210	7.4	1.3	21.3	11.3	67.4	C	0.7	20.9	93.8	0.19	0.89	0.11	0.89	2.01	1.90	39.7	0.10
Ashoka	1Ap	15	6.5	1.0	49.3	35.3	15.4	L	3.5	31.9	90.4	0.17	0.63	0.09	0.63	0.07	1.80	24.7	0.49
AF <sub>30</sub>	2A1	35	6.6	1.0	47.3	31.3	21.4	C	2.01	20.1	86.6	0.19	0.86	0.09	0.86	0.11	1.63	32.8	0.46
	3Bt1	90	5.3	1.0	21.3	11.3	67.4	C	1.15	16.5	63.9	0.24	1.22	0.06	1.22	1.68	1.80	48.4	0.04
	3Bt2	160	5.1	1.1	23.3	11.3	65.4	C	0.57	16.2	46.1	0.25	1.31	0.06	1.31	2.89	1.88	51.9	0.02
	4BC	180	4.7	1.2	37.3	13.3	49.4	C	0.32	17.0	23.5	0.24	0.82	0.07	0.82	1.69	1.88	53.9	0.05

Where: BD =Bulk density, BS = Base saturation, L=loam, SL =Silt loam, CL= Clay loam, C =Clay, SCL =Silt clay loam, Jp= *Juniperus procera*, AF = agroforestry ,NF =natural forest  
 $Al_{ox}$ ,  $Fe_{ox}$  and  $Si_{ox}$  = Acid oxalate extractable Fe, Al, Si, Alp =Pyrophosphate extractable Al, P = phosphate retention (Blakemore et al., 1987), % Allophane =  $100(\% Si_o / (23.4-5.1x))$  where  $x = (Al_o-Al_p)/Si_o$  representing the atomic ratio of Al and Si in allophane. Melanic index (extracted in 0.5% NaOH and 0.1% superfloc) =K450/K520 Where 450nm and 520nm are wavelength (Honina et al., 1988). Melanicindex  $\leq 1.70$  is used in conjunction with other properties (color, thickness and organic C content) to define the melanic epipedon in Soil Taxonomy and the melanic horizon in the World Reference Base (1995).

## **Soil pH and bulk density under the chronosequences of agroforestry and cultivated lands**

Soil pH was lower in the surface 0-10 cm depth and increased invariably in all land uses in the subsurface layers from 10-100 cm depth. Relatively the pH values in the surface soil layers under NF, F<sub>40</sub>, AF<sub>40</sub>, F<sub>50</sub> and AF<sub>50</sub> was higher than the remaining land uses (Table 3).

BD in the 0-10 cm depth under NF was significantly lower than the corresponding depths under other land use types ( $P < 0.05$ ). In 10-20 cm, BD was significantly higher in soils under F<sub>50</sub> compared to most of the other land uses (Table 3) and in 20 to 40 cm depth the BD under AF<sub>50</sub> and F<sub>50</sub> was only significantly higher than that under AF<sub>40</sub>. Apart from few exceptions at 100 cm depth, no significant variations in BD was observed below 40 cm depth (Table 3). In general, BD increased progressively with increase in depth under all land use types.

## **Distribution of SOC and N in soil profile (0-100 cm depth) under chronosequences of agroforestry and cultivated lands**

In the surface layers of 0-10 cm depth, SOC under NF was significantly higher than that under the chronosequence of 12, 20, 30, 40 and 50 yrs of F and AF land uses ( $P < 0.0001$ ). The SOC concentration under NF was as high as 9.7 % and was higher by 4.8 % than that under AF<sub>40</sub> and by 6.7 % than that under F<sub>50</sub> land use. There was no significant difference in SOC among age chronosequences under F and AF land uses (Fig 3 and 4).

In the 10-20 cm depth, SOC concentration under F<sub>20</sub> was significantly lower than that under NF, AF<sub>40</sub>, AF<sub>50</sub> and F<sub>40</sub> ( $P < 0.0024$ ). The SOC concentration did not differ among the remaining land uses of age chronosequences (Fig 3 and 4).

In the 20-40 and 40-60 cm depths, the SOC did not differ significantly ( $P > 0.05$ ) among land uses. In the 60-100 cm depth, the SOC under NF was significantly higher than that under F<sub>30</sub>, and F<sub>20</sub> ( $P < 0.0027$ ) and that of AF<sub>40</sub> and AF<sub>50</sub> was only significantly higher than the SOC concentration of soils under F<sub>20</sub>. The SOC concentration among other land uses was not significantly different (Fig 3 and 4).

Similarly the N concentration in the surface layers of 0-10 cm depth under NF was significantly higher than that under the age chronosequences of 12, 20, 30, 40 and 50 years of F and AF land uses ( $P < 0.0001$ ).

The order of N under the chronosequence of F and AF land uses in the 0-10 cm depth was F<sub>12</sub> > AF<sub>12</sub> > F<sub>40</sub> > AF<sub>40</sub> > AF<sub>20</sub> > F<sub>20</sub> > AF<sub>30</sub> > F<sub>30</sub> > AF<sub>50</sub> > F<sub>50</sub>, but the N concentration under F<sub>12</sub> and AF<sub>12</sub> was the lowest in the 10-20 cm depth (Table 4). No significant difference in N concentration was observed in soils under all land uses below 10 cm depth (Table 4).

## **SOC and N stocks (1 m depth) under agroforestry and farm land uses**

The SOC stock under land uses of all age chronosequences with the exception of AF<sub>40</sub>, was significantly lower than that of under the NF. The SOC stock under AF<sub>40</sub> also was higher than that of under AF<sub>30</sub>, F<sub>12</sub>, F<sub>20</sub> and F<sub>30</sub> ( $P < 0.05$ ). The SOC stock under AF<sub>50</sub> was only significantly higher than that of F<sub>20</sub> (Table 5). But there was no significant difference observed in the SOC stock under the chronosequence of AF<sub>40</sub> and F<sub>50</sub> land uses. The differences in the SOC stocks under the remaining land uses were also not statistically significant.

Table 3. Mean soil pH and bulk density ( $\text{Mgm}^{-3}$ ) in the 0 -100 cm mineral soil under natural forest and the chronosequence of agroforestry and farm land uses

Depth	NF	AF12	AF20	AF30	AF40	AF50	F12	F20	F30	F40	F50
<u>pH-H<sub>2</sub>O (1:2.5)</u>											
10	6.4 (0.23) a	5.8 (0.05) ab	5.8 (0.10) ab	5.9 (0.19) ab	6.1 (0.06) ab	6.0 (0.14) ab	5.7 (0.03) b	5.8 (0.14) ab	5.8 (0.06) ab	6.3 (0.20) ab	6.0 (0.05) ab
20	6.7 (0.13) a	6.0 (0.11) b	6.0 (0.08) b	6.1 (0.18) b	6.3 (0.03) b	6.1 (0.13) b	6.1 (0.06) b	6.2 (0.08) b	6.0 (0.10) b	6.4 (0.11) ab	6.2 (0.02) b
40	6.5 (0.33) a	6.2 (0.18) a	6.0 (0.13) a	6.3 (0.16) a	6.5 (0.05) a	6.3 (0.17) a	6.1 (0.28) a	6.4 (0.06) a	6.2 (0.13) a	6.6 (0.12) a	6.5 (0.02) a
60	6.5 (0.44) a	6.1 (0.24) a	6.0 (0.25) a	6.3 (0.22) a	6.4 (0.25) a	6.4 (0.20) a	6.0 (0.29) a	6.4 (0.09) a	6.3 (0.15) a	6.5 (0.16) a	6.6 (0.09) a
100	6.6 (0.51)a	6.0 (0.24)a	6.0 (0.30)a	6.7 (0.54)a	6.6 (0.32)a	6.4 (0.28)a	5.8 (0.30)a	6.3 (0.12)a	6.4 (0.18)a	6.3 (0.19)a	6.5 (0.19)a
<u>Bulk density (<math>\text{Mgm}^{-3}</math>)</u>											
10	0.72 (0.09) b	0.93 (0.02) a	1.09 (0.07) a	0.98 (0.05) a	1.07 (0.03) a	0.96 (0.01) a	0.94 (0.02) a	0.99 (0.02) a	1.12 (0.04) a	1.04 (0.01) a	1.07 (0.08) a
20	0.89 (0.04) b	0.91 (0.02) b	1.04 (0.01) ab	1.05 (0.03) ab	0.98 (0.01) b	1.03 (0.04) ab	0.89 (0.05) b	0.93 (0.08) b	1.07 (0.02) ab	1.06 (0.01) ab	1.18 (0.06) a
40	1.11 (0.02) ab	1.07 (0.04) ab	1.04 (0.04) ab	1.03 (0.03) ab	0.94 (0.01) b	1.15 (0.01) a	1.05 (0.08) ab	1.06 (0.07) ab	1.02 (0.03) ab	1.14 (0.04) a	1.20 (0.01) a
60	1.18 (0.07) a	1.24 (0.03) a	1.27 (0.01) a	1.15 (0.05) a	1.05 (0.03) a	1.21 (0.04) a	1.18 (0.09) a	1.22 (0.03) a	1.17 (0.06) a	1.18 (0.03) a	1.19 (0.01) a
100	1.25 (0.02) a	1.34 (0.01) a	1.30 (0.02) a	1.22 (0.00) a	1.11 (0.05) b	1.10 (0.01) b	1.29 (0.03) a	1.32 (0.03) a	1.22 (0.01) a	1.24 (0.04) a	1.09 (0.03) b

Note: Means followed by the same letter (s) in row under NF, AF and F are not significantly different ( $p = 0.05$ ), Values in parenthesis indicate standard errors of the mean (pH  $n=4$  and Pb  $n=3$ )  
 AF = Agroforestry land use system of 12, 20, 30, 40, 50 years since the conversion of natural forest, F = Farm land of 12, 20, 30, 40, 50 years since the conversion of the natural forest

In general, the absolute value of SOC stock under all age chronosequences of AF tended to be higher, than that of the corresponding age chronosequences of F land uses although, most of the differences are not statistically significant. This trend suggests that AF has a greater C sequestration potential than F land uses after conversion from the natural forest.

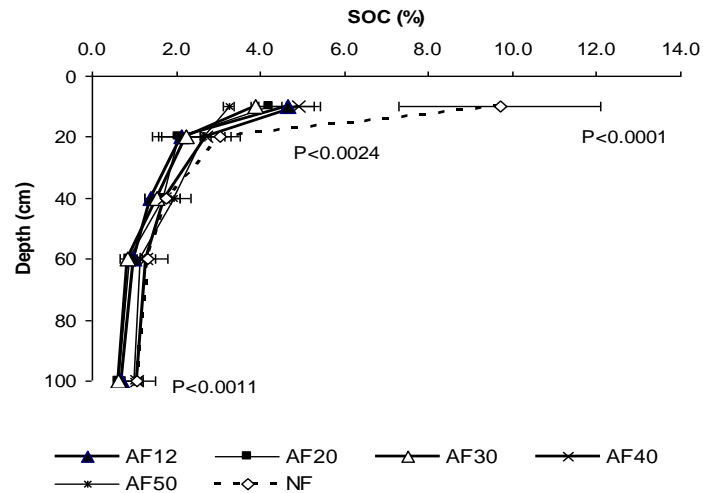


Fig.3. Vertical distribution of SOC in 1m depth under natural forest (NF) and the chronosequences of agroforestry land use. Error bars represent standard errors (n=4), NF= Natural forest, AF =Agroforestry land use of 12, 20, 30, 40, 50 years of age since conversion of natural forest,

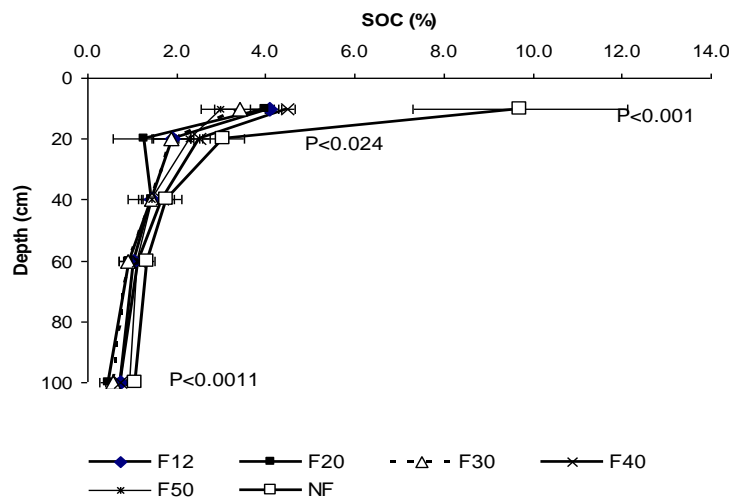


Fig.4. Vertical distribution of SOC in 1m depth under natural forest NF and the chronosequences of farmland land use. Error bars represent standard errors (n = 4), NF= Natural forest, F= Farm land of 12, 20, 30, 40, 50 years of age since the conversion of natural forest

The N stock under AF<sub>40</sub> was significantly higher only than that of under AF<sub>20</sub> (P <0.05). The N stocks under the remaining land uses of all age chronosequences was not significantly different (Table 5). The SOC stocks increased at 40 and 50 years of age chronosequences compared to the 12 to 30 years of age chronosequences. The result suggests that with time a new equilibrium in SOC sequestration was attained in both systems but the equilibrium stock of SOC after 50 years was higher under AF than under F land uses (Fig 5).

Table 4. Distribution of total nitrogen along the depth of 1m in natural forest ,agroforestry and Farm land uses of age Chronosequences

Depth	NF	Total Nitrogen (%)																				
		AF12		AF20		AF30		AF40		AF50		F12		F20		F30		F40		F50		
10	0.90	(0.14) a	0.50	(0.04) b	0.43	(0.02) b	0.43	(0.02) b	0.48	(0.05) b	0.30	(0.00) b	0.50	(0.00) b	0.43	(0.02) b	0.38	(0.05) b	0.50	(0.00) b	0.28	(0.03) b
20	0.28	(0.05) a	0.18	(0.05) a	0.20	(0.00) a	0.28	(0.02) a	0.25	(0.03) a	0.23	(0.05) a	0.15	(0.03) a	0.20	(0.04) a	0.23	(0.03) a	0.28	(0.08) a	0.23	(0.03) a
40	0.15	(0.03) a	0.10	(0.00) a	0.10	(0.00) a	0.15	(0.03) a	0.15	(0.03) a	0.15	(0.03) a	0.10	(0.00) a	0.10	(0.00) a	0.18	(0.03) a	0.13	(0.03) a	0.10	(0.00) a
60	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a	0.13	(0.05) a	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a
100	0.08	(0.03) a	0.10	(0.00) a	0.10	(0.00) a	0.10	(0.00) a	0.13	(0.05) a	0.10	(0.00) a	0.10	(0.00) a	0.08	(0.03) a	0.08	(0.03) a	0.10	(0.00) a	0.10	(0.00) a

Means followed by the same lower case letter(s) in row are not significantly different ( $p < 0.05$ ), AF= Agroforestry land use system of 12, 20, 30,40,50 years duration since conversion of natural forest, F= Farm land of 12, 20,30,40,50 years duration since the conversion of the natural forest, values in parenthesis represents standard error (n=4)

Table 5. Soil organic carbon and N stocks (1 m depth) and the rate of change under the chronosequences of agroforestry and farm land uses

Lu	SOCv by Volume (kg m <sup>-2</sup> )		Rate of loss(kg m <sup>-2</sup> )	SOCm by equivalent soil mass (kg m <sup>-2</sup> )		Rate of loss (kg m <sup>-2</sup> y <sup>-1</sup> )	Nv by volume (kg m <sup>-2</sup> )		Rate of loss (kg m <sup>-2</sup> y <sup>-1</sup> )	Nm by equivalent soil Mass (kg m <sup>-2</sup> )		Rate of loss (Mg ha <sup>-1</sup> y <sup>-1</sup> )
NF	22.10	(1.58) a	0.00	22.97	(1.53) a	0.00	1.78	(0.24) a	0.000	1.84	(0.25) ab	0.000
AF12	15.43	(0.54) bc	0.56	15.57	(0.59) bcd	0.62	1.49	(0.07) a	0.024	1.51	(0.07) ab	0.028
AF20	15.60	(0.38) bc	0.33	15.64	(0.40) bcd	0.37	1.56	(0.06) a	0.011	1.57	(0.06) ab	0.014
AF30	14.31	(0.75) bc	0.26	14.83	(0.87) cd	0.27	1.48	(0.08) a	0.010	1.54	(0.09) ab	0.010
AF40	18.58	(1.61) b	0.09	20.15	(1.88) ab	0.07	1.95	(0.33) a	-0.004	2.17	(0.40) a	-0.008
AF50	17.39	(1.11) bc	0.09	18.30	(1.08) bc	0.09	1.60	(0.09) a	0.004	1.69	(0.08) ab	0.003
F12	14.72	(0.82) bc	0.61	15.11	(0.82) cd	0.66	1.39	(0.05) a	0.033	1.43	(0.06) ab	0.034
F20	12.96	(0.67) c	0.46	13.08	(0.65) d	0.49	1.31	(0.08) a	0.023	1.33	(0.07) b	0.025
F30	13.66	(1.05) c	0.28	13.98	(1.08) cd	0.30	1.60	(0.16) a	0.006	1.65	(0.18) ab	0.006
F40	17.27	(1.10) bc	0.12	17.54	(1.23) bcd	0.14	1.79	(0.12) a	0.000	1.82	(0.13) ab	0.001
F50	15.90	(0.93) bc	0.12	16.45	(0.87) bcd	0.13	1.44	(0.08) a	0.007	1.49	(0.08) ab	0.007

Means followed by the same letter (s) in columns with stocks under NF, AF and F land uses are not significantly different ( $P < 0.05$ ), Values in parenthesis indicate standard errors of the mean, n=4. Lu= Land use, NF= natural forest, AF =agroforestry land use of 12,20,30,40,50 years of age since conversion of natural forest, F= Farm land of 12, 20,30,40,50 years of age since the conversion of natural forest, SOCv = Soil organic carbon stock calculated by soil volume, SOCm =Soil organic carbon stock calculated by equivalent soil mass, Nv = Nitrogen stock calculated by soil volume, Nm = Nitrogen stock calculated by equivalent soil mass

## Rate of losses of SOC and TN stocks after conversion of NF to AF and F land uses

Conversion of the relict NF into arable land use caused decline in SOC, and N stocks for all chronosequences of AF and F land uses. The SOC stock in F and AF land uses of 12, 20 and 30 years of cultivation was 13.1 to 15.6 kg m<sup>-2</sup> or 32 to 43 % lower than NF (Table 5), while the corresponding decline under the chronosequence of 40 and 50 years of both land uses ranged from 2.8 to 6.5 kg m<sup>-2</sup> or 12 % to 28 %.

Over all the loss of SOC stock under the age chronosequence of 12, 20, 30, 40 and 50 years of F and AF land uses ranged from 2.8 to 9.9 kg m<sup>-2</sup> or 12 % to 43 % (Table 5). The maximum SOC loss of 9.9 kg m<sup>-2</sup> or 43 % was observed under F<sub>20</sub> while the minimum of 2.8 kg m<sup>-2</sup> or 12 % under AF<sub>40</sub> (Table 5). Similar to the loss of SOC stocks under AF and F land uses, losses observed for N in all chronosequences of these land uses ranged from 0.02 to 0.51 kg m<sup>-2</sup> or 1 % to 28 %. However, the N stock under AF<sub>40</sub> land uses increased by 0.33 kg m<sup>-2</sup> or about 18 % compared to NF.

Generally, the rate of loss of SOC stocks was higher for the first 12 to 20 years but was in a progressive decline that approached to a steady state after 40 to 50 years under both land uses of age chronosequences (Table 5).

The rate of SOC loss was lower under AF (0.07 to 0.62 kg m<sup>-2</sup> yr<sup>-1</sup>) than that of under F land use (0.13 to 0.7 kg m<sup>-2</sup> yr<sup>-1</sup>). Similar to SOC stocks, the rate of loss of N stock also declined with time and was 0.028 kg m<sup>-2</sup> yr<sup>-1</sup> under AF<sub>12</sub> compared with 0.003 kg m<sup>-2</sup> yr<sup>-1</sup> under AF<sub>50</sub>. The corresponding rates of loss for F lands were 0.034 and 0.007 kg m<sup>-2</sup> yr<sup>-1</sup> (Table 5).

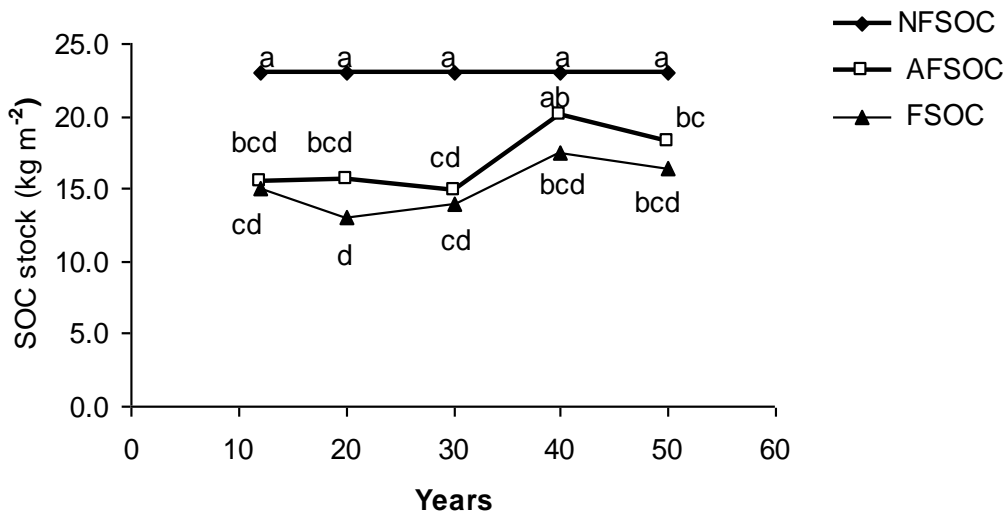


Fig.5. Total SOC stock of 1 m depth in the chronosequences of agroforestry (AF) and farm (F) land uses, Means followed by the same lower case letter(s) are not significantly different at (P < 0.05)

## Discussion

### Soil pH and bulk density under the chronosequences of agroforestry and farm lands

The lower soil pH in the upper 0-10 cm layer may be explained due to the relatively higher amount of OM compared to the lower depth of soil. The pH of the land uses was negatively correlated with SOC (p < 0.000). The result is consistent to that reported by Abbasi and Rasool (2005) that OM was negatively correlated with soil pH in the hilly

area of Rawalakot Azad Jammu and Kashmir (Pakistan). Mulugeta et al. (2005) have also documented similar result for the near by the study site at Lepis, Southern Ethiopia.).

Higher BD in the upper layer of AF and F land uses as compared to NF may be attributed to lower SOC content and soil compaction caused by cultivation practices in the F land use (Murty et al., 2002). Loss of SOC caused by conversion of NF to F land use can lead to higher BD and the situation can become worse by continuous cultivation.

### **Distribution of SOC, and TN in soil profile (0-100 cm) under the chronosequence of agroforestry and cultivated lands**

The results of this study indicate that the distribution of SOC, and N under all land uses decreased consistently with increasing soil depth. The largest concentration of SOC and N stocks was in the upper 0-10 and 10-20 cm depths. The distribution of SOC or other nutrients with depth is affected by a number of interacting processes such as biological cycling, leaching, soil erosion, weathering of minerals, atmospheric deposition, application of fertilizers etc. In the present study, most of the OM added through leaf fall or crop residues were retained in the upper layers of the soil and also the greater proportion of roots was confined to the top layers of the soil. Secondly, the transport of dissolved organic carbon (DOC) to sub-soil can also be limited in this environment as evapotranspiration exceeds the precipitation in most months of the year (Hawando, 1997). Lemenih and Itanna (2004) pointed out that in the Rift valley of Ethiopia, 50% of soil C was retained in the upper 20cm of the soil while in humid and cool region an even distribution of SOC is observed throughout the profile. Similar results were also reported by Lemenih et al., (2005) in the nearby site to the study area and by Awasthi et al., (2005) in the Mardi watershed of Nepal. For example, Lemenih et al., (2005) also reported that in the vertical profiles, the difference in soil C and N concentrations were mostly confined to the upper 0-10 and 10-20 cm soil depths.

The concentrations of SOC, and N were higher under the reference NF than under either AF or F land uses, probably due to the continuous litter input from diverse vegetation community and little or no soil perturbation due to human interference in the functioning of the ecosystem. This trend of soil C distribution was also observed in several other studies (Godsey et al., 2007; Awasthi et al., 2005; Jimenez et al., 2007). In general the SOM concentration in the cultivated soils is less protected than that in the uncultivated soils (Fu et al., 2004). Soil mixing due to tillage and increase in soil temperature due to soil exposure and the enhanced biological activity may lead to accelerated decomposition of SOM.

The higher concentration of the SOC under AF<sub>40</sub>, and AF<sub>50</sub> may be explained by the litter and crop residue input from relatively larger population of trees and the frequently grown wheat crop. In most of the other F and AF land uses, the sorghum and maize stalks are either burnt in place or are removed for use in the house holds. Such management during land preparation process suggests that the input of crop residues is minimal and not adequate to replace the depleted SOC during the growing period. The low return of crop residues can adversely affect soil physical and chemical properties (Blanco-Canqui and Lal, 2008), and reduce agronomic productivity.

The data presented suggest that in the case of AF land use, the number of tree population alone is not the sole cause for the accrual of SOC. For example; the largest number of tree population under AF<sub>20</sub> did not influence the magnitude of SOC concentration. Despite the difference being statistically not significant, the SOC concentration of the soil under AF<sub>20</sub> was lower compared to that under NF, AF<sub>40</sub>, and AF<sub>50</sub> F<sub>40</sub> F<sub>50</sub> AF<sub>30</sub> and AF<sub>12</sub>. This trend of SOC accrual may be attributed to the quality and quantity of litter input which in turn depends on the age of the trees and the species used. Soil type also influence organic



matter turnover due to differences in soil clay content (Schjønning et al., 1999). Clay is assumed to protect OM against decomposition and some of the mechanisms proposed to explain stabilization of SOC are adsorption of organics onto surfaces of clays or organic complexes (Oades, 1988) and entrapment of organic particles in aggregates (Van Veen and Kuikman, 1990). Parent material with high base status and or the presence of substantial content of Al and Fe oxides has also positive influence on stabilizing SOM (Zunino et al., 1982; Percival et al., 2000). Nevertheless, in three selected soil profiles, the clay content of the surface soil under AF<sub>30</sub> and NF tends to be higher than that under the *J. procera* plantation established on undisturbed soil. On the other hand the SOC and allophane content of the surface soils under *J. procera* was relatively higher than that under AF<sub>30</sub> and NF land uses. However, the SOC concentration in the surface soil under the natural forest also tended to be higher than that of under AF<sub>30</sub> land use. As reported by Feller et al., (2001) for a given texture, allophanic soils exhibited higher SOC concentrations than the LAC and HAC for Lesser Antilles soils. But the allophanic content of soils in the study site represented by these three land uses was negligible.

Hence, the data suggest that higher concentration of SOC and N in the upper soil layers under NF, F and AF land use systems is influenced by the addition of litter from the trees and vegetation in the case of NF and AF systems, and the addition of crop residue and root biomass from crops grown every season in both AF and cereal based mono cropping systems.

### **SOC and N stocks (1 m depth) under agroforestry and farm land**

The results of this study show that the conversion of the NF into AF and F land uses resulted in significantly lower SOC and N stocks (Table 3), but the decline in these stocks was lower in AF than in F land use for all age chronosequences. When NF is cleared for new agricultural land, considerable amount of C in vegetation is lost to the atmosphere because the decay rate of SOC is by an order of magnitude under F than under NF. However, each soil has a C sink (storage) capacity, i.e. an equilibrium C content depending on the nature of vegetation and climatic conditions (Gupta and Rao, 1994). But the equilibrium between C inflows and outflows in soil is disturbed by land use change until a new equilibrium is eventually reached in the new system (Guo and Gifford, 2002). The clearance of forests and the subsequent tillage practices affect soil C sink capacity by: (1) the dwindling supply of litter that would compensate the amount decomposed, (2) the declining capacity of the soil to physically protect SOC from decomposition due to the destruction of soil aggregates and (3) the enhanced leaching and translocation as dissolved organic carbon (DOC) or particulate organic C (POC) and accelerated erosion by water runoff or wind (Post and Kwon, 2000; Lal, 2002).

In cultivated soils of small land holders such as in the study region, the amount of crop residues returned to the soil is only a small portion of the total amount produced. Even if the crop residue is fully returned to the soil, it may not balance the quantity and quality of litter supply that would increase the SOC to its potential level as it used to be before the conversion of the NF. This trend may be partly due to high rate of mineralization (Singh and Lal, 2001) and partly because of the less diverse and lack of continuous input from crops (Elberling et al., 2003). Most of cultivated soils in the Midwestern USA have lost 25-40 Mg C ha<sup>-1</sup>, and their SOC content is below the potential levels (Lal, 2002). In the present study however, the traditional AF practiced by small holders showed consistently increasing trend of SOC stocks in all chronosequences than the corresponding age chronosequences of F lands (Fig.5) because trees in traditional AF systems supply litter and trap and recycle leached nutrients. Thus, AF systems may also lead to lower decay rate due to change in microclimate caused by the tree shading. Similar to the present study

Takimoto et al. (2008) also reported that the traditional park land AF systems in the West African Sahel had relatively larger C stock than those in other land use systems.

Rate of loss in AF and F land uses tended to be higher for the first 12 to 20 years due to lower supply of organic litter and higher decomposition rate in open cultivated soils. However, the rate of loss decreased with increase in number of years in the age chronosequence. In the 40 to 50 years of age, the rate of loss was nearly constant indicating a quasi equilibrium for the prevailing management and cropping system (Table 3). The rate of SOC loss was 4-6 fold lower in the chronosequence of 50 years age than in that of 12 years age. However, in all chronosequences the rates of loss of SOC tended to be higher in F lands than AF land uses (Table 3). The total N stock did not show any significant variations among all land uses, perhaps because farmers applied chemical fertilizer in their cultivated soils and hence the loss of N through mineralization was compensated through such management practices.

## **Conclusion**

Conversion of natural forest to cultivated and traditional agroforestry land uses and the subsequent residue management negatively influenced the SOC and N stocks in the study area. Relatively, larger proportion of SOC and N was concentrated in the upper 0 to 20 cm soil depth. In this layer of soil under both AF and F land uses, the concentrations of SOC and N were significantly lower than that under the natural forest. Traditional agroforestry practiced by small holders tends to accrue higher SOC stocks in all age chronosequences than those of the corresponding farm lands and also the rate of loss in the former land use was lower than that in the latter. The rate of loss of SOC in both agroforestry and cultivated land uses was many folds higher in the younger age chronosequence of 12 and 20 years than in the age chronosequences of 40 and 50 years. The higher absolute value of SOC stocks and lower rate of SOC loss in agorforestry suggest that integrating trees in farm lands may lead to sequester more carbon and nitrogen stocks than the corresponding mono cropped farm lands. This trend implies that while the productivity of the soil is better sustained, the traditional agroforestry system plays an important role as a strategy to offset carbon emissions. Furthermore, traditional agroforestry system also provides a habitat to endangered species that are otherwise selectively encroached from the near by natural forest and hence serving as a gene bank that is strategically important to restoring the degraded forest ecosystem. Nevertheless, increasing more trees with proven multipurpose functions and improving the application of the residue input in all agricultural lands can enhance the potential of sequestering SOC while improving and sustaining productivity.

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## **Soil carbon and nitrogen stocks under plantations in Gambo district, Southern Ethiopia**

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# Soil carbon and nitrogen stocks under plantations in Gambo district, southern Ethiopia

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## Abstract

*The effect of six plantation species in comparison to natural forest on soil organic carbon (SOC) and total nitrogen (N) stocks, depth wise distribution, biomass carbon (BC) and nitrogen was investigated on an Andic paleudalfs soil in Gambo district, Southern Ethiopia. The soil organic carbon, nitrogen and bulk density were determined from samples taken in 4 replicates from 10, 20, 40, 60, and 100 cm depth at each site. Similarly, the biomass carbon and nitrogen of the plantation species and understory vegetation were also determined by destructive and non destructive methods. The SOC and N were concentrated in the 0-10 cm depth and decreased progressively to 1 m depth. Next to the natural forest, Juniperus procera accrued higher SOC and N in 0 -10 cm depth than the corresponding plantations. No evidence of significant difference on soil organic carbon and total nitrogen distribution among plantations was observed below 10 cm depth with the exception of minor irregularities. The plantations accrue from 133.62 to 213.73 Mg ha<sup>-1</sup> or 59.1 to 94.5 % SOC, 230.4 to 497.3 Mg ha<sup>-1</sup> or 6.9 to 14.9 % TBC and 420.37 to 672.80 Mg ha<sup>-1</sup> or 12.5 to 20.0 % total C-pool of that under the natural forest. Apart from C.lusitanica, the SOC stock sequestered in soils under plantations and natural forest did not exhibit difference of any statistical significance but was in the order of NF > P.patula > J.procera > E.globulus > E.camaldulensis > E.saligna > C.lusitanica. No significant nitrogen stock difference was seen but the absolute value obtained under J. procera and Pinus patula was the highest, while the lowest was under and C.lusitanica. It implies that SOC and N can be sequestered restored or maintained under plantations through extended rotation period and careful selection of species such as P.patula and J.procera as the loss seen is negligible compared to that of the natural forest.*

**Key words:** Soil organic carbon (SOC); soil nitrogen (N); natural forest (NF); total biomass carbon (TBC); plantation forest, Ethiopia

## Introduction

Land use changes, particularly conversion of natural forests into other land uses contribute to anthropogenic carbon (C) emission (Kirby and Potvin, 2007) and hence degradation of the physical, chemical and biological qualities of soils. Deforestation is the major factor contributing to land degradation by erosion agents (Teketay, 2001).



In many tropical regions, environmental degradation through clearing of native forest is proceeding at an unprecedented rate impacting prospects for maintaining the soil quality and conservation of biological diversity (Parrotta, 1992; Vagen et al., 2005).

Soil C loss may be elevated due to changes in the balance between biomass production and decomposition impacted by deforestation. Decrease in plant productivity may lead to loss of soil fertility through erosion, reduction in soil C sequestration, and increase in net emission of GHGs. Conversely, if proper and sustainable use of forest resources is practiced, C sequestration will be enhanced and the potential to decrease the rate of enrichment of atmospheric concentration of CO<sub>2</sub> may be promoted (Resh et al., 2002; Malmer, 1996). The drastic environmental effect of deforestation, explicitly loss of soil organic carbon (SOC), total nitrogen (N), soil fertility and decline of ecosystem functions, in general can be reversed by rehabilitation of the degraded lands through reforestation and/or allow the natural process of regeneration to take its course by reducing the anthropological perturbation on the already affected lands. Basically, when reforestation through plantation is the choice to rehabilitate degraded lands, meet the demand for wood products, sequester C, and to improve an overall ecosystem function, then the choice of plant material mostly leans towards those exotic species that are easy to manage in nurseries and are fast growing once they are planted in the field. Montagnini and Nair (2004) argued that *Eucalyptus*, *Acacia*, *Pinus* and other coniferous species are the main medium-rotation utility species, and there is a strong variation in the C sequestration potential among them.

Nevertheless, irrespective of the forest type (plantation or natural) their capacity to sequester C depends on complex interactions of climate, soil type, management, characteristics and composition of the species (Paul et al., 2002; Lal, 2005). In highly fertile and productive soils the species richness and diversity is higher compared to soils that have lost their intrinsic value through unchecked degradation (Sollins, 1998). Under similar soil and environmental characteristics, soil C as well as above and below ground biomass accumulation vary due to the influence of diverse plant species occupying the habitat. Chen (2006) reported that tree C storage varies for stands with the same species richness while Montagnini and Porras (1998) argued that it increases with increasing tree species diversity. There is also a dilemma that pure stand fast growing plantations such as *Eucalyptus* species can exhaust soil nutrients that may lead to the decline of site productivity. On the other hand, research findings have shown that some *Eucalyptus* species grow better and produced higher biomass under prolonged water deficit compared to the indigenous species in Ethiopia (Gindaba et al., 2005).

In Ethiopia, like many of the tropical regions, deforestation is very common in the larger portion of the country (Allen and Barnes, 1985). A very high and still growing demand for grazing and arable land, fuel wood and construction material is the major factor contributing to severe deforestation (Senbeta et al., 2002; Darkoh, 1998; Taddese, 2001; Wubet et al., 2003) and as a result, the native forest resource is severely reduced. This raises a serious concern that the remnant native forests will disappear if such trend continues unabated. The scanty supply of forest products and the decline of soil productivity through accelerated soil erosion necessitated restoration of degraded lands and to this effect forest tree plantations were started in the 1960's in many parts of the country, mainly with exotic tree species (Amare et al., 1990). In Gambo District of Munessa-Shashemene area, plantations were established by clearing the *Podocarpus falcatus* (Thunb.) R. Br. ex Mirb) and *Hagenia abyssinica* (Bruce) J.F. Gmel.) dominated natural forest (Betre et al., 2000). In the study sites of Leye and Ashoka, of Gambo District exotic coniferous (*Cupressus lusitanica* (Mill.), *Pinus patula* (Schiede & Deppe)) and *Eucalyptus* species (*Eucalyptus camaldulensis* (Dehnh.), *Eucalyptus globules* (Labill.) and *Eucalyptus saligna* (Smith)) were planted during establishment.

*Juniperus procera* (Hochst. Ex Endl.), the only indigenous coniferous species plantation, was also established in 1978 on primary forest land. The *E. camaldulensis* and *E. globulus* plantations were established on previously cultivated for 16 years, while the remaining species were planted on primary forest land after clearing the natural forest where dominant trees were selectively removed for lumber production (hereafter, primary forest).

In such perspective, the turnover of soil and biomass C and N is not well understood. Limenih et al. (2005) investigated the changes of soil C and N stocks under *C.lusitanica* and *E. saligna* stand, which was established on previously cultivated land in a nearby site of the study area. However, our knowledge about the C and N turnover of the entire plantation species found in the study area in their respective mode of plantation (on cultivated lands and on primary forest) is very limited. Little is known about the status and the eventual contribution to the losses or gains of SOC and N of the lower story vegetation under those extensively used plantation species. Furthermore, the performance of the indigenous coniferous species (*J. procera*) to sequester C at equal time footing with those exotic plantation species commonly used in the study area has not yet been investigated.

It was hypothesized that the short rotation plantation species established on previously cultivated lands restore C and N stocks lost due to conversion of the pristine vegetation. Therefore, this study investigated the soil and vegetation pools of C and N, the loss of SOC and N under land use change and their distribution in the soil profile (to 1 m depth) under the extensively used five exotic and one indigenous plantation species of the study site.

## **Material and methods**

### **Description of the study site**

The study was conducted at Leye and Ashoka, sites in Gambo district which are part of the Munessa Shashemene forest area of southern Ethiopia (Fig 1). It covers the area positioned on the lower fringe of the western escarpment of the southeastern highlands. Leye and Ashoka sites lie within 7°17'N and 7°19'N and 38°48'E 38°49'E. The altitude ranges from 2134 to 2294 m a.s.l, and the slope from 3 to 18 %. Rainfall is bimodal with mean annual precipitation of 973 mm, most of it falling from July to September. Temperature ranges between the maximum of 26.6 °C and minimum of 10.4 °C across the study area for the period from 1999 to 2007. The *J. procera*, *C.lusitanica* and *E. saligna* plantations were established after clearing the primary forest land in 1978, 1982 and 1985, respectively, and those of the *E. globulus*, *E. camaldulensis* and *P. patula* were all established in 1985 on previously cultivated lands for 16 years. The coniferous species were harvested in 25-year rotation periods; but the *Eucalyptus* species were managed as coppice and were harvested every 7 to 10 years based on the type of product needed. *J. procera*, has never been harvested since its establishment, but it was subjected to silvicultural operations like access pruning, 2<sup>nd</sup> high pruning and 2<sup>nd</sup> thinning. During harvest, the logs are hauled off the site to the processing center while the branches are collected for fire wood, leaving behind the leaf biomass, the undergrowth and the stump of the trees.

The soil parent materials of the Munessa area are of volcanic origin, principally trachytes and basalts with ignimbrites and pumices at the Rift Valley floor (Solomon et al., 2002). The soils of Leye and Ashoka are reddish in color, freely drained and of medium to heavy texture. They are characterized by a thick argillic horizon and some andic soil material in the upper soil layers and were classified as Andic Paleudalf (Soil Survey staff, 1999).

## Soil sampling and analysis

Plantation species that were approximately similar in age but varied in their mode of establishment (on primary forest lands and on previously cultivated lands) and located adjacent to each other were selected for this study. The native climax natural forest (NF) at Ashoka, located nearby the plantations, was taken as a reference land use. Data on site location, altitude, slope, dominant vegetation, and C and N concentrations in the biomass of the vegetation are presented in Table 1.

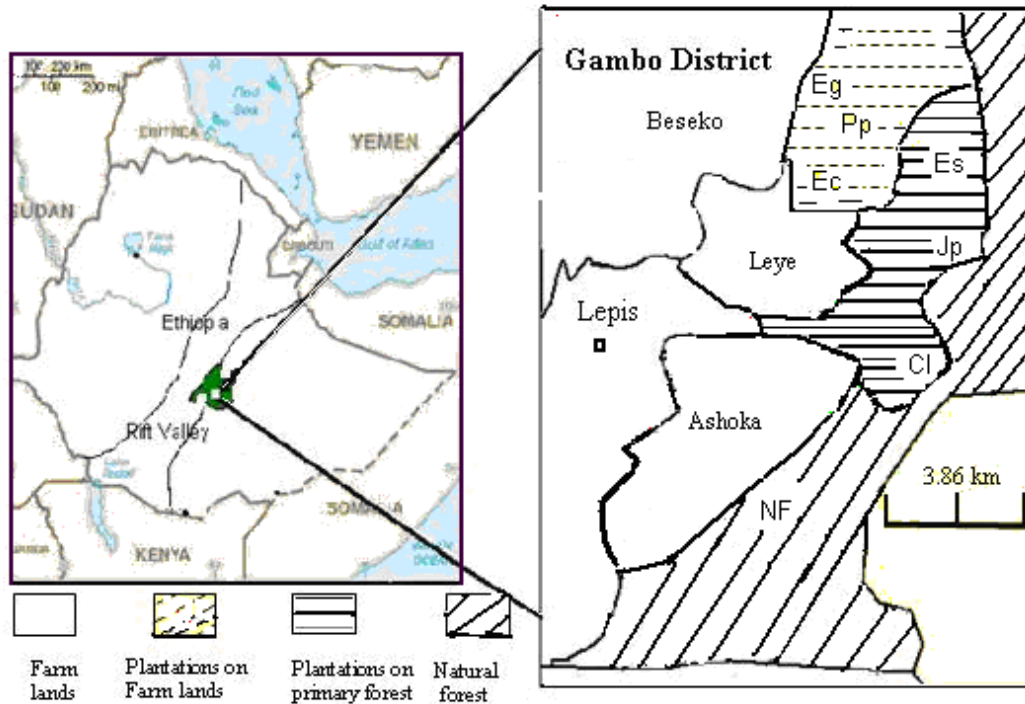


Fig.1. Map of Gambo district, southern Ethiopia showing the plantation and natural forest sites. Where: Eg = *E. globulus*, Pp = *P. patula*, Ec = *E. camaldulensis*, Es = *E. saligna*, Jp = *J. procera*, Cl = *C. lusitanica* and NF = natural forest

The sampling design followed was Pseudo complete randomized design (CRD) with four replicates. At each plantation site, a main plot of 20x20 m in four replicates was demarcated to assess tree stands. From the main plots, sub plots of 5x5 m were assigned to assess the lower story woody vegetation. For the determination of the herb and litter biomass and also for bulk soil and core sampling purposes, sub-sub plots of 1x1 m were demarcated in each sub plot of 5x5 m. In the main plot (20x20 m), the diameter of upper storey trees was measured using diameter tape while height was measured using Suunto Clinometers PM-5. In sub plots (for the lower story woody vegetation) and sub-sub plots (for undergrowth non woody vegetation), a destructive sampling technique was applied. The total woody vegetation in the sub plot (5x5 m) and the total herb and litter biomass within 1x1 m was collected for the above ground biomass determination of the site.

At each 1x1 m plot, a pit of 1x1x1 m was dug for each replicate; soil samples were collected at 0-10, 10-20, 20-40, 40-60, 60-100 cm depth increments. The collected soil samples were air dried ground and passed through a 2-mm sieve. These samples were analyzed for their physical and chemical properties. In addition to these pits, a bigger pit, up to a depth of 2-3 m, was dug in the centre of the larger 1-ha block in each land use type and was subjected to profile description. During the soil sampling or profile description processes, presence of carbonates was explored using HCl. The coordinates of the point

sampling spots were recorded using Garmin GPS (Table 1). Sampling was done in December 2007 soon after the rainfall season.

Separate core samples (97.8 cm<sup>3</sup>) were drawn from the same pits up to a depth increment of 1 m for determination (BD). The soil samples were then oven dried at 105 °C for ≥24 hrs and weighed. The dry soil was then crushed and passed through a 2-mm sieve for the possible correction of percentage gravel and stone for the BD determination of the soil sample.

The physical and chemical properties of soils were determined by the methods described below. Texture was measured by the hydrometer method and the pH was determined by potentiometer method (Kim, 2005). The concentrations of total N were measured using a LECO CHN-1000 Carbon and Nitrogen Analyzer. Soil organic matter (SOM) was analyzed using titrimetric method (Walkley and Black, 1934). The SOC was then obtained by dividing the soil organic matter concentration by a factor of 1.724 (Kim, 2005).

### Measurements and calculations

The SOC stock (Mg ha<sup>-1</sup>) in each depth was calculated by the following equation as described in Ellert et al., (2001) and Wairiu and Lal (2003):

$$\text{SOC stock (Mg ha}^{-1}\text{)} = C_{\text{conc}} \cdot \text{BD} \cdot T \cdot 10000 \text{ m}^2 \text{ ha}^{-1} \cdot 0.0001 \text{ Mg kg}^{-1} \cdot \text{CF}_{\text{coarse}} \quad (1)$$

Where:  $C_{\text{conc}}$  = Carbon concentration (kg Mg<sup>-1</sup>), BD = bulk density (Mg m<sup>-3</sup>)  
 T = depth thickness (m), CF = correction factor (1 - (Gravel % + Stone %) / 100)

The stock was also calculated using equivalent soil mass by adjusting the thickness of the soil as described by Ellert et al., (2001), to correct error that may be introduced due to variation in BD and compared the results with the stock calculated by equation (1). The soil mass was calculated using equation (2) and thickness of the soil depths were adjusted using equation (3).

$$M_{\text{soil}} = \text{BD} \cdot T \cdot 10000 \text{ m}^2 \text{ ha}^{-1} \quad (2)$$

Where:  $M_{\text{soil}}$  = soil mass per unit area (Mg ha<sup>-1</sup>)

$$T_{\text{add}} = (M_{\text{soil, equiv}} - M_{\text{soil, layer}}) \cdot 0.0001 \text{ ha m}^{-2} / \text{BD}_{\text{subsurface}} \quad (3)$$

Where:  $T_{\text{add}}$  = additional thickness of sub surface layer required to attain the equivalent soil mass (m)

$M_{\text{soil, equiv}}$  = equivalent soil mass = mass of heaviest soil at each 1m depth (Mg ha<sup>-1</sup>)

BD subsurface = bulk density of subsurface layer (Mg m<sup>-3</sup>)

The same equations were also used for the calculation of N stock in each depth (Mg ha<sup>-1</sup>). The SOC and N stocks for the profile (1 m) were calculated by adding the stock of each depth. The rate of change SOC and N stock over time was computed by subtracting the stocks of plantation stands from that of natural forest and dividing it by the number of years since the plantations were established.

### Biomass sampling and calculations

Discs were taken using a power saw at different stem heights from a number of harvested trees that represent those exotic and indigenous species managed extensively in the plantation sites. The disc samples were oven dried at 70 °C and weighed for their dry weight determination.

The volume ( $m^3$ ) of each disc was computed using the equation  $\Pi d^2/4 * T$  (where  $T$  = Thickness of the disc (m) and  $d$  = diameter of the disc (m)) and the density of wood ( $Wd$ ,  $Mg\ m^{-3}$ ) was determined through multiplying the volume by the dry weight of the disc.

The under story vegetation biomass was determined by completely removing bushes and herbs from the sub and sub-sub plots and, after weighing and recording the total fresh weight, a small sample of known fresh weight was oven dried at  $70\ ^\circ C$  for  $\geq 48$  hrs until constant weight was obtained. The total dry mater of understory vegetation was then calculated. The oven-dried samples of litter, herb, and shrub and bush biomass were crushed using a grinding mill. The samples were analyzed for their total C and N concentrations by a LECO CHN-1000 Carbon and Nitrogen Analyzer. The biomass of plantation and natural forest was computed using the following equations:

$$Wb = v * Wd * 10000 \quad (4)$$

$$v = \Pi d^2/4 * h * fq \quad (5)$$

Where:  $Wb$  = wood biomass of a tree ( $Mg\ ha^{-1}$ ),  $Wd$  = wood density ( $Mg\ m^{-3}$ ),  $\Pi=3.14$ ,  $v$  = solid wood volume ( $m^3$ ),  $h$  = tree height (m) and  $fq$  = absolute form factor (Chaturvedi and Khanna, 1982).

$$fq = \text{mid-diameter}/d.b.h$$

Where: mid-diameter = diameter in the mid-height of a tree

## Statistical analysis

The effects of plantation species on depth wise distribution of SOC, total N, soil and vegetation C and N stocks and other parameters were subjected to one way analysis of variance using the general linear model procedures of SAS (SAS Inc., 2003). The identity link function  $Y = \mu + \alpha_i + e_{ij}$  was used with the assumption that the data was from a normal distribution and the error terms are independent and normally distributed. Multiple comparison of means for each class variable was carried out using the Student-Newman-Keuls (SNK) test at  $\alpha = 0.05$ .

## Results

### Important vegetation and soil characteristics under different plantations

The number of trees  $ha^{-1}$  under plantations varied considerably (Table 1). This was probably attributed to thinning operations, self thinning, timing of planting, and the mode of harvesting as described under methods. The concentration of C and N in the biomass of the tree species among plantations and the natural forest varied in the order of  $J. procera > P. patula > C. lusitanica > E. camaldulensis > E. globulus > E. saligna$  for C and in the order of  $E. camaldulensis > J. procera > C. lusitanica > P. patula = E. globulus > E. saligna$  for N (Table 1).

Table 1. Site locations and vegetation characteristics at Leye and Ashoka study sites

Sites	Location		Elevation (m a.s.l.)		Species	Age (year)	No. of trees per ha	Biomass	
	Longitude	Latitude	Min	Max				C (%)	N (%)
Leye	07°18' 886"N	038°49'219"E	2184	2219	<i>J. procera</i>	29	425	51.58	0.24
Leye	07°18' 990"N	038°48'978"E	2174	2188	<i>E. camaldulensis</i>	22	500	49.64	0.26
Leye	07°19' 072"N	038°48'945"E	2147	2195	<i>P. patula</i>	22	625	51.12	0.16
Leye	07°19' 233"N	038°48'912"E	2134	2165	<i>E. globulus</i>	22	600	49.19	0.16
Leye	07°19' 204"N	038°48'981"E	2153	2183	<i>E. saligna</i>	30	750	48.65	0.15
Ashoka	07°18' 023"N	038°48'931"E	2208	2294	<i>C. lusitanica</i>	25	450	50.87	0.17
Ashoka	07°17'513"N	38°48'452"E	2197	2232	Natural forest			50.87	0.17

The NF is represented by the dominant species (*Podocarpus falcatus*) and the concentration of C & N in the biomass is similar to *C. lusitanica*. The texture of the top surface soil layer (0-20 cm) varied from clay loam (CL) to sandy clay loam (SCL) under NF, from sandy loam (SL) to loam (L) under *C.lusitanica*, *J. procera* and *E. saligna* and from clay loam (CL) to clay (C) under *E. camaldulensis*, *P. patula*, and *E. globulus*.

Table 2. Particle size and textural classes of the profiles in plantation and natural forest sites

Site	Species	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class
Leye1	<i>J. procera</i>	5	44.0	37.3	18.7	L
		10	54.0	33.3	12.7	SL
		25	38.0	31.3	30.7	CL
		85	20.0	31.3	48.7	C
		125	22.0	19.3	58.7	C
		300	12.0	19.3	68.7	C
Leye 2	<i>E. camaldulensis</i>	60	26.0	37.3	36.7	CL
		130	16.0	17.3	66.7	C
		300	16.0	15.3	68.7	C
Leye 3	<i>P.patula</i>	65	20.0	27.3	52.7	C
		105	16.0	15.3	68.7	C
		300	16.0	13.3	70.7	C
Leye 4	<i>E.globulus</i>	20	30.0	33.3	36.7	CL
		60	22.0	21.3	56.7	C
		145	18.0	11.3	70.7	C
		190	22.0	9.3	68.7	C
		300	30.0	15.3	54.7	C
Leye 5	<i>E.saligna</i>	20	46.0	35.3	18.7	L
		75	22.0	17.3	60.7	C
		120	20.0	15.3	64.7	C
		180	24.0	13.3	62.7	C
		225	36.0	13.3	50.7	C
Ashoka	<i>C.lusitanica</i>	10	66.0	23.3	10.7	CL
		15	76.0	15.3	8.7	SL
		40	54.0	23.3	22.7	SCL
		80	30.0	11.3	58.7	C
		150	26.0	11.3	62.7	C
		225	32.0	13.3	54.7	C
Ashoka	Natural forest	300	44.0	29.3	26.7	CL
		15	34.0	31.3	34.7	CL
		35	55.3	21.3	23.4	SCL
		90	37.3	29.3	33.4	CL
		160	27.3	35.3	37.4	CL
		180	21.3	11.3	67.4	C
C	= clay	CL	= clay loam	SL	Sandy clay	
L	= loam	SCL	= sandy clay loam			

The clay content in the upper soil depth (0-20 cm) tends to be low under the plantations of *J. procera*, *E. saligna* and *C.lusitanica* and it tends to be higher under *P. patula*, *E. camaldulensis* and *E. globulus* compared to the corresponding depths under NF (Table 2).The texture of the soil layers below 40 cm depth varied from CL to C. The data

also showed that the clay content of the top soil layer (0-20 cm) under the NF was 1.9 to 3.2 times higher than that under plantations established on disturbed forest, but lower by 1.1 to 1.5 times than the plantations established on previously cultivated lands. Generally, the clay content of the soil increased progressively with increasing depth irrespective of the plantation types.

The soil pH under the NF was significantly higher in all depths compared to that under plantations. However, no such significant and consistent differences in soil pH under plantation species were observed apart from few minor exceptions. For example, in the 10-20 cm depth, soil pH under *E. saligna* and *J. procera* was significantly higher ( $p < 0.05$ ) compared to that under *E. camaldulensis* and *E. globulus* plantations (Table 3).

Table 3. Mean soil pH and bulk density in the 0-100 cm mineral soil under natural and plantation forests

Depth (cm)	Plantation species						
	NF	Cl	Jp	Es	Eg	Pp	Ec
	pH-H <sub>2</sub> O(1:2.5)						
10	6.4 ± 0.23 a	5.4 ± 0.14 bc	5.9 ± 0.14 b	5.5 ± 0.11 bc	5.1 ± 0.20 c	5.6 ± 0.15 bc	5.5 ± 0.13 bc
20	6.7 ± 0.13 a	5.5 ± 0.26 cde	6.2 ± 0.14 b	5.9 ± 0.16 bc	5.0 ± 0.16 e	5.8 ± 0.12 bcd	5.3 ± 0.10 ed
40	6.5 ± 0.33 a	5.4 ± 0.30 b	6.1 ± 0.14 ab	5.9 ± 0.34 ab	5.1 ± 0.15 b	6.0 ± 0.11 ab	5.5 ± 0.14 b
60	6.5 ± 0.44 a	5.1 ± 0.16 b	6.1 ± 0.14 ab	5.5 ± 0.24 b	5.2 ± 0.19 b	6.1 ± 0.11 ab	5.6 ± 0.13 b
100	6.5 ± 0.51 a	5.1 ± 0.07 c	5.8 ± 0.14 abc	5.4 ± 0.12 bc	5.5 ± 0.17 abc	6.2 ± 0.15 ab	5.8 ± 0.06 abc
	Bulk density (Mg m <sup>-3</sup> )						
10	0.72 (0.06) d	0.6 (0.06)d	0.9 (0.08)c	0.9 (0.05)c	1.2 (0.05)b	1.4 (0.05)a	1.1 (0.02)bc
20	0.89 (0.03)a	0.9 (0.07)a	0.9 (0.03)a	1.0 (0.05)a	1.0 (0.03)a	0.9 (0.03)a	1.0 (0.03)a
40	1.11 (0.02)a	1.1 (0.11)a	1.0 (0.02)a	0.9 (0.02)a	1.1 (0.07)a	1.0 (0.03)a	1.0 (0.05)a
60	1.18 (0.05)a	1.1 (0.04)a	1.1 (0.07)a	1.0 (0.02)a	1.0 (0.08)a	1.0 (0.06)a	1.1 (0.07)a
100	1.25 (0.02)a	1.1 (0.05)a	1.2 (0.08)a	1.0 (0.07)a	1.1 (0.04)a	1.1 (0.08)a	1.2 (0.04)a

Mean followed by the same letter(s) in rows are not significantly different ( $P < 0.05$ )

NF = Natural forest  
 Cl = *C. lusitanica*  
 Jp = *J. procera*  
 Es = *E. saligna*

Eg = *E. globulus*  
 Pp = *P. patula*  
 Ec = *E. camaldulensis*

In the 20-40 cm depth, the soil pH under NF showed the highest significant difference than *E. camaldulensis*, *C. lusitanica*, and *E. globulus* plantations. The significant difference of soil pH between plantation species and NF were observed only in the upper 0-40 cm depths (Table 3). Under *Eucalyptus* species the pH tended to be lower than that under coniferous plantations (*J. procera* and *P. patula*), but higher than that under *C. lusitanica*. In general, excluding minor exceptions, the pH under natural forest and the plantation species showed an increasing trend with increasing soil depth.

Significantly lower soil BD was observed under *C. lusitanica* and NF compared to that under the remaining plantation species in the 0-10 cm depth ( $P < 0.0001$ ). The BD observed under *P. patula* was significantly higher than all plantation and natural forest land uses. Next to *P. patula* the higher BD was seen in soils under *E. globulus*, which was significantly higher than the remaining plantations with the exception of that under *E. camaldulensis*.

In the upper 0-10 cm depth, BD of soils under *Pinus patula* and *E. globulus* was significantly higher than that under the remaining plantations and NF ( $P < 0.0001$ ). No significant difference in BD was observed in soils under NF and plantation species below 10 cm depth (Table 3). In general, the BD 0-10 cm depth under plantations established on cultivated lands was significantly higher than that under plantations established on primary forest lands and it increased progressively increasing depth in all cases up to 1m depth.

## Distribution of SOC and N in soil profile (1 m depth) under plantations and natural forest

The SOC in the 0-10 cm depth under plantation was significantly lower than that under NF ( $P < 0.0001$ ). No significant difference in SOC under plantation species was observed except that *J. procera* differed significantly than that under *E. globulus* (Fig 2). In the 10-100 cm depth, no significant difference of SOC concentration was observed among NF and plantations excluding that of *C. lusitanica*, which is significantly lower than all of the other species in the 20-60 cm depth. The SOC under plantation species in the 0-20 cm depth was lower than NF, but in all depths from 20 to 60 cm, it tended to be higher under plantation species than NF, with minor exceptions within and below the 60 cm depth.

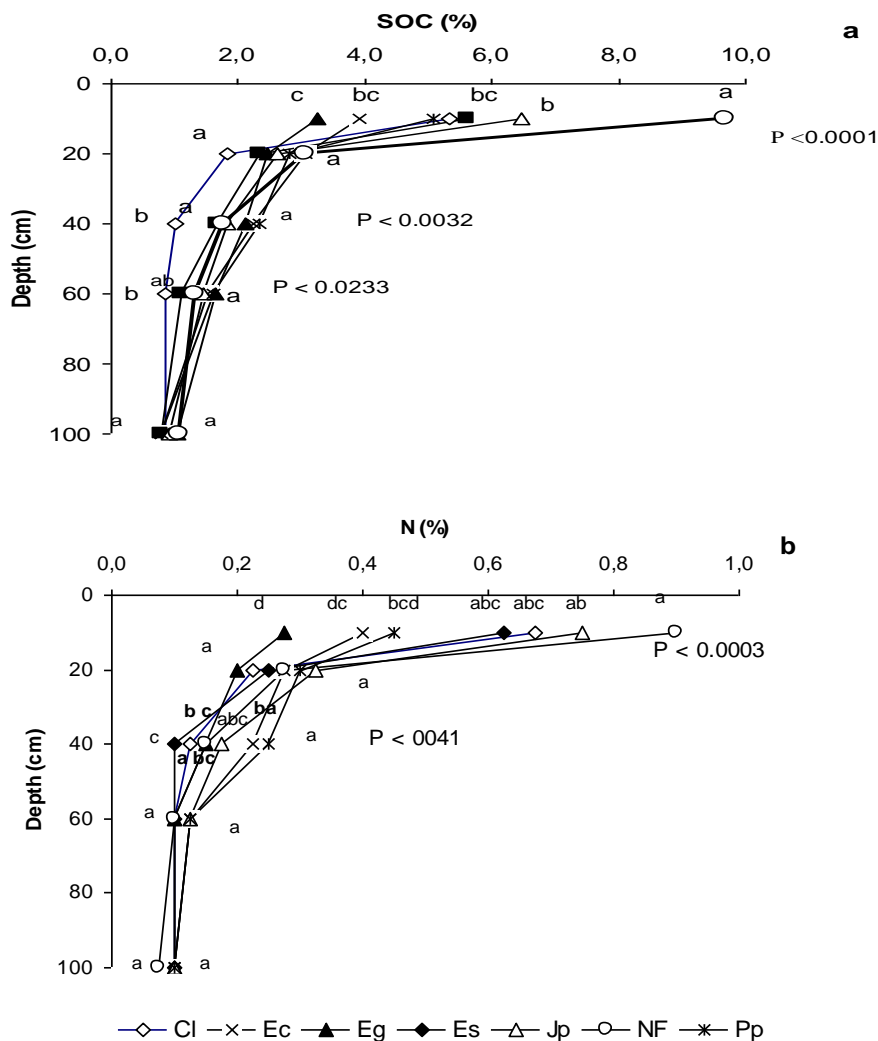


Fig.2. Distribution of soil organic carbon (SOC) (a) and total nitrogen (N) (b) along 1m depth under natural forest and plantations. Mean followed by the same letter (s) are not significantly different ( $P < 0.05$ ) Natural Forest (NF), *J. procera* (Jp), *C. lusitanica* (Cl), *E. saligna* (Es), *E. camaldulensis* (Ec), *E. globulus* (Eg), *P. patula* (Pp)

Total N in the 0-10 cm depth, under *P. patula*, *E. camaldulensis* and *E. globulus* plantations established on previously cultivated lands was significantly lower than that under NF ( $P < 0.0001$ ), but N under *J. procera*, *C. lusitanica* and *E. saligna* plantations, established on primary forest lands, did not differ significantly with that of under the NF.



Among plantation species, N under *J. procera* was significantly higher than that under *E. camaldulensis* and *E. globulus*, while, that under *C.lusitanica* and *E. saligna* showed a significant difference to that of under *E. globulus* (Fig. 2).

In the depths from 20-100 cm, no significant difference in N concentration was observed between plantation species and NF or among plantation species themselves. However, there were a few minor exceptions to this fact. For example, in the 20-40 cm depth, N under *P. patula* was significantly different from that under *C.lusitanica* and *E. saligna*. Also, the N values under *E. camaldulensis* differed significantly from that under *E. saligna*, but no such significant difference was observed between the other plantation species (Fig. 2)

Generally, the data showed a decreasing trend of SOC and N concentrations from the surface down to 1 m depth. The larger portion of the SOC and N concentrations was confined in the upper 0-20 cm depth invariably under all sites.

### **Soil organic carbon and nitrogen stocks (1m depth) under plantations and natural forest**

The SOC stock under all plantation land uses did not show significant difference apart from that of *C.lusitanica* (Figure 3), which was significantly lower than that of under the NF ( $P<0.05$ ). The N stock under *J. procera* was higher compared to plantations and the reference NF soils, but this difference was not statistically significant (Fig.3). Moreover, the absolute value of SOC and N stocks calculated by soil mass equivalent equation tends to be slightly higher compared to that calculated by soil volume basis but the statistical significance of the means tends to be tantamount.

The tree biomass C (TRC) and N (TRN) under plantation species was significantly lower compared to that under NF ( $P<0.05$ ). But both TRC and TRN among plantation species did not differ significantly (Table 4). The understory biomass C (UVBC) under NF was significantly higher compared to all plantations. Similarly next to the NF the UVBC under *C.lusitanica* was significantly higher compared to that under *P. patula*, *J. procera*, *E. globulus* and *E. camaldulensis* ( $P<0.05$ ). The UVBC under *E. saligna* was also significantly higher than that under *E. camaldulensis* and that under *P.patula* was significantly higher than that under *E. camaldulensis* (Table 4). Moreover, the litter biomass C (LC) under the Natural Forest was significantly higher only to that under *C.lusitanica* ( $P<0.05$ ). But no such significant difference was observed in the litter C stock of the remaining plantations (Table 4).

The under storey biomass N (UVBN) under *C.lusitanica* and NF was significantly higher than that under the rest of plantations ( $P<0.05$ ). The litter biomass N (LN) under the NF was also significantly different from that under plantations ( $P<0.05$ ). But the LN under plantations did not show any significant difference similar to LC explained above (Table 4).

The total biomass C (TBC) and total biomass N (TBN) under the NF were significantly higher than that under plantation stands ( $P<0.05$ ). The TBC under the NF was nearly 2-3 folds higher than that under plantations, while the corresponding difference for TBN varied from 7 to 10 fold. However, no such statistically significant difference in the TBC stock among plantation species was observed (Table 4). The magnitude of TBC under plantations was in the order of *E. globulus* > *E. saligna* > *C.lusitanica* > *J. procera* > *E. camaldulensis* > *P. patula* and that of TBN was *J. procera* > *E. globulus* > *E. camaldulensis* > *E. saligna* > *P. patula* > *C.lusitanica*.

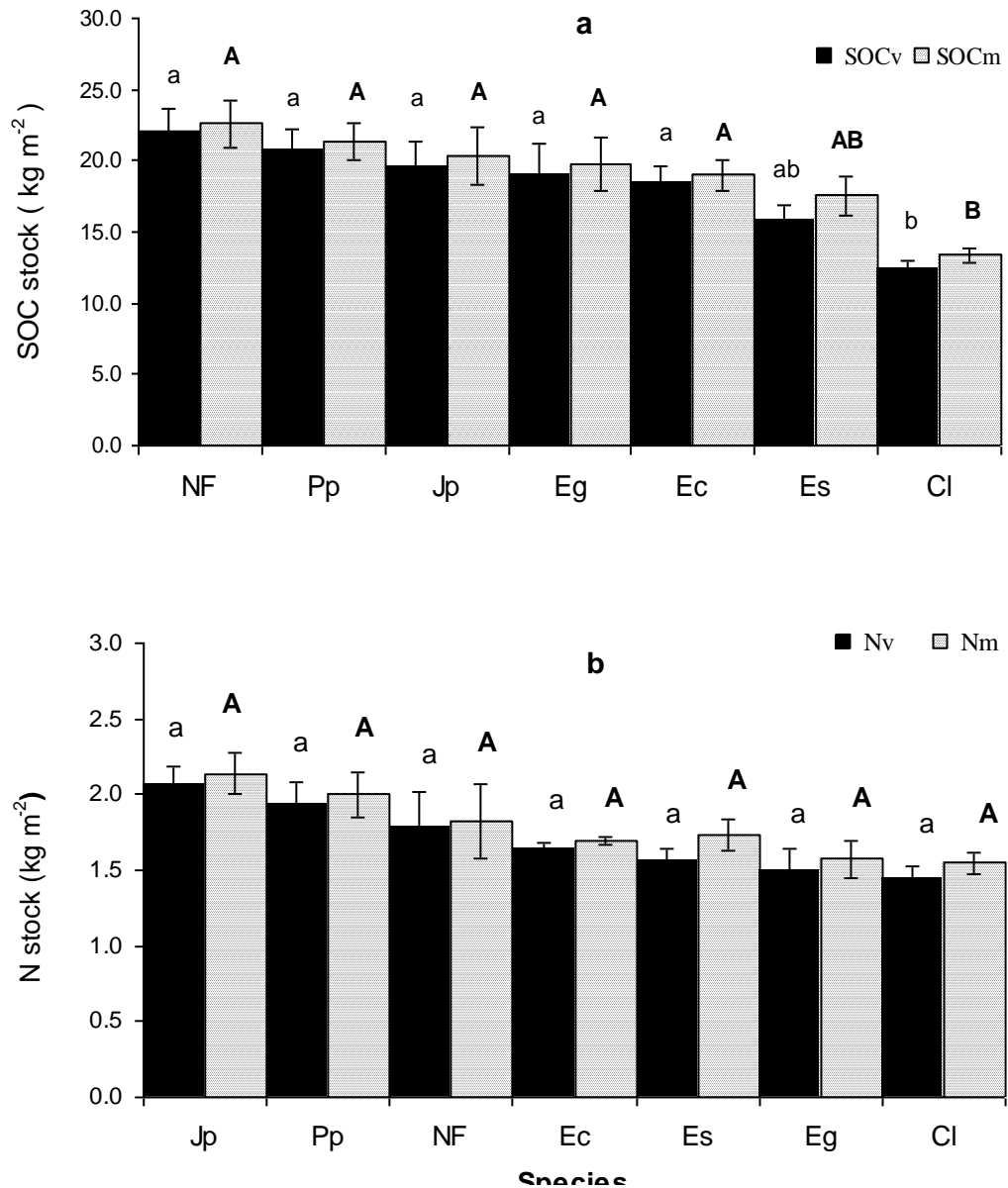


Fig.3. Stocks of soil organic carbon (a) and soil nitrogen under plantations and natural forest land uses. Where SOC= of soil organic carbon (a) and N = total nitrogen (b) under natural forest and plantations, Means followed by the same letter(s) are not significantly different ( $P < 0.05$ ), SOCv = Soil organic carbon stock by volume, SOCm = Soil organic carbon stock by equivalent mass, Nv = Total nitrogen by volume, Nm = Total nitrogen by mass equivalent, NF = natural forest, Jp = *J.procera*, Cl = *C.lusitanica*, Es = *E.saligna*, Ec = *E. camaldulensis*, Eg = *E.globulus* and Pp= *P.patula*

The total organic C pool (SOC + TBC) and the total N pool (soil nitrogen + biomass nitrogen) under plantation species was significantly lower compared to that under the NF ( $P < 0.05$ ). No significant difference was seen in the C and N pools among plantations (Table 4).

Table 4. The upper and lower story vegetation biomass carbon and nitrogen stocks under the natural and plantation forests

	NF	CI	Jp	Es	Ec	Pp	Eg
	<u>Biomass Carbon Stock (Mg ha<sup>-1</sup>)</u>						
Stock							
SOC	226.1 (16.83) a	133.62 (5.12) b	203.42 (20.30) a	198.2 (18.76) a	189.68 (10.4) a	213.7 (13.1) a	175.5 (13.62) ab
TRC	3325.93 (637.23) a	281.67 (31.67) b	323.17 (77.62) b	317.58 (37.87) b	281.32 (72.29) b	226.61 (46.8) b	493.16 (106.01) b
UVBC	4.93 (0.66) a	3.71 (0.67) a	0.94 (0.12) bc	2.05 (0.40) b	0.15 (0.02) bc	1.72 (0.5) bc	0.51 (0.11) bc
LC	6.03 (2.10) a	1.35 (0.46) b	2.91 (0.36) ab	2.91 (0.30) ab	3.91 (0.43) ab	2.07 (0.5) ab	3.67 (0.57) ab
TBC	3336.89 (638.77) a	286.74 (31.03) b	327.02 (77.64) b	322.53 (38.06) b	285.38 (71.99) b	230.40 (46.5) b	497.33 (106.09) b
C pool	3363.00 (655.59) a	420.37 (36.14) b	530.44 (97.94) b	520.72 (56.82) b	475.06 (82.43) b	444.13 (59.6) b	672.80 (119.70) b
	<u>Biomass Nitrogen Stock (Mg ha<sup>-1</sup>)</u>						
TN	18.23 (2.50) a	15.47 (0.74) a	21.38 (1.31) a	15.73 (1.24) a	16.97 (0.23) a	19.98 (1.51) a	17.27 (1.03) a
TRN	24.12 (4.05) a	0.94 (0.11) b	1.50 (0.36) b	0.98 (0.12) b	1.47 (0.38) b	0.71 (0.15) b	1.60 (0.34) b
UVBN	0.09 (0.01) a	0.11 (0.02) a	0.03 (0.00) b	0.03 (0.01) b	0.00 (0.00) b	0.03 (0.00) b	0.01 (0.00) b
LN	0.05 (0.02) a	0.00 (0.00) b	0.01 (0.00) b	0.01 (0.00) b	0.02 (0.00) b	0.01 (0.00) b	0.01 (0.00) b
TBN	24.26 (4.07) a	1.05 (0.09) b	1.54 (0.36) b	1.02 (0.12) b	1.50 (0.38) b	0.74 (0.14) b	1.63 (0.34) b
<b>N pool</b>	42.49 (6.57) a	16.53 (0.83) b	22.93 (1.68) b	16.75 (1.36) b	18.47 (0.61) b	20.73 (1.65) b	18.89 (1.38) b

Means followed by the same litter(s) in rows are not significantly different (P<0.05), Values in parenthesis represent standard errors (n=4)

NF	natural forest	Pp	<i>P. patula</i>	UVBC	Under story vegetation biomass carbon	LN	Litter biomass nitrogen
CI	<i>C. lusitanica</i>	Eg	<i>E. globulus</i>	LC	Litter biomass carbon	UVBN	Under story vegetation biomass <b>nitrogen</b>
Jp	<i>J. procera</i>	SOC	Soil organic carbon	TBC	Total biomass carbon	TBN	Total biomass nitrogen
Es	<i>E. salinga</i>	TN	Total soil nitrogen	C-pool	Soil organic carbon + total biomass carbon	N-pool	Soil nitrogen + total biomass nitrogen
Ec	<i>E.camaldulensis</i>	TRC	Tree biomass carbon				

## Discussion

### Important soil characteristics

The soil texture analyzed from unreplicated profiles (of 2-3m depth) shows variations across plantation and NF sites. Since the depth of the upper layer in the profiles varied considerably (Table 2), it is difficult to compare the results with that of the depth intervals from which the soil sample was collected within plantation and the NF sites. There is, however, some tendency for lower clay content in the upper layer under plantations established on previously cultivated soils than those established on disturbed forest lands. Loss of clay content through soil erosion and leaching on previously cultivated (Celik, 2005; Erskine et al., 2002) and disturbed forest lands (Islam and Weil, 2000) caused by the exposure of surface soils during the vegetation clearance (Edeso et al., 1999; Limbrey, 1978) could explain these variations

Soil pH under plantation species was significantly lower than that under NF, which could be attributed to either leaching of cations during land preparation and establishment or there could be lower supply of cations from the monoculture plantations as compared to diverse vegetation species under NF. Plantations acidify the soil by accumulating basic cations in the forest biomass, increasing production of organic acids from decomposing litter and increasing leaching cations by organic acids (Nsabimana et al., 2008). The presence of organic acids that have major role in soil acidification mainly in surface soil horizon is a direct effect of the continuous litter supply of the vegetation. Betre et al. (2000) reported that native forest had significantly ( $P < 0.05$ ) higher pH than the plantation of *C.lusitanica*, *P.patula* and *Eucalyptus* species in Ethiopia which is consistent to the result obtained in this study. Also among plantation species, *Eucalyptus* species showed lower pH than coniferous (*J.procera* or *P.patula* species). Soil pH beneath *Eucalyptus* plantations has also been shown to decline from 5.9 to 5.0 in 8 years in Hawaii (Rhoades and Binkley, 1996). Under *Eucalyptus* plantations in India, soil pH was lower because soils under such plantations are subjected more to the action of environmental factors, where the oblong shape of the canopy leads the rain to form big drops of through fall and enhance leaching of cations and hence lower pH (Balagoplan et al., 1991). The lowest pH under conifer species *P.patula* may be attributed to the acidifying effect caused by low molecular organic acids produced in the litter of softwood species, which inhibit the rate of decomposition (Lundgren, 1978).

### Distribution of SOC and N (1m depth) under plantations and natural forest

The results of the study showed that the SOC and N under NF and plantations were invariably higher in the top 0-20 cm soil depth and decreased consistently downward to the 1 m depth. The results are consistent with those reported for the nearby site by Lemenih et al., (2005) and elsewhere by Christopher et al., (2009); Russell et al.,(2007). For example, in the nearby site of the study area, Lemenih (2005) reported that the larger portion of C and N was confined to the 0-10 cm and 10-20 cm depths. Similarly, as described by Christopher (2009), the SOC and N concentrations were more in the surface 0-5 cm no-till soil than under conventional tillage in the Midwestern United States. Also, Russell et al., (2007) argued that the larger portion of SOC and N was accumulated in the upper 0-15 cm soil layer following the planting of trees in an abandoned pasture at La Selva Biological Station, Costa Rica. The higher SOC and N in the upper layers relative to the lower depth is attributed to the

continuous supply of litter, reduced rate of disturbance, little erosion impact (Erskine et al., 2002) and lower temperature under the canopy of the closed forest (Kirschbaum, 1995) that may reduce decomposition favoring an increase in residence time of SOM. Temperature affects directly by promoting microbial activity and indirectly by altering soil moisture and the quantity and quality of OM inputs to the soil (Chapin et al., 2002). Relatively large-sized OM, such as certain roots or litter, may resist degradation even if labile in nature due to a restricted surface area for microbial attack (Carter and Stewart, 1996). The conditions conducive to rapid decomposition and mineralization that can be accompanied by hydrologic factors responsible for removing soil organic nutrients (Qualls, 2000) include soil moisture and good aeration (about 60 % of pore spaces filled with water) and warm temperature (25 to 35 °C) and near neutral pH (Brady and Weil, 2004). However, this study indicates that the pH varied from 5.1 under *E.globulus* to 6.4 under NF, which was slightly acidic in the upper soil layer of 0-10 cm depth that may limit biochemical degradation of OM through the activity of microorganisms.

The data showed that the SOC and N concentration under the natural forest was higher compared to the plantations. This can be explained by the contribution of the more diverse components of the vegetation, the relatively neutral soil pH and the non existence of soil disturbance under the NF compared to the pure stands of plantations that endure human interference. The decreased concentration of SOC and N in the lower layers of the 1-m profile in both land uses (plantation and NF) can be explained by the reduced leaching and erosion in the forest floor. The plantation or the NF floor is well shielded by the mulch that is continuously supplied with considerable amounts of litter and the closed canopy of the plantations and the vegetation in the NF. Nevertheless, our data revealed that the NF was superior in both understory vegetation stock and litter biomass that may effectively intercept the through fall and reduce its effect in leaching the dissolved C to a deeper depth and eventually removing it from the ecosystem. Also, adsorption is more likely responsible for maintaining DOC substrate concentrations in the mineral soil and preventing its loss into streams (Qualls and Haines, 1992).

### **SOC and N stocks under plantations and natural forest**

The results of this study show that the stocks under plantations were significantly lower than those under the NF. Soils under *C.lusitanica* exhibit the lowest stocks compared to the reference as well as the remaining plantation species. The lower stock under *C.lusitanica* may be partly ascribed to the lower clay content in the upper most layers of the soil profile where the larger portion of the SOC and N stock is most often accumulated. Clay is assumed to protect OM against decomposition and stabilize SOC through adsorption of organics onto surfaces of clays or organic complexes (Oades, 1988) and entrapment of organic particles in aggregates (Van Veen and Kuikman, 1990). Also, the *Cupressus* plantation was at the harvesting stage where the mature age has negatively influenced the quantity and quality of the stand's litter production capability. This was manifested by the lower detritus mass and the corresponding SOC and N concentration along the depth. Hence, this phenomenon among others, like age and topography, may have negatively influenced the SOC and N stocks under *C.lusitanica* to be the lowest compared to the reference and the other plantation species. Despite no significant difference existed in the C and N stocks among plantations (excluding *C.lusitanica*), there is a tendency that the coniferous species (*P. patula* and *J. procera*) accrue more stocks compared to the *Eucalyptus* species. The minor difference in the age of plantation and the mode of plantation establishment (on disturbed NF and on previously cultivated lands) showed little effect on the accrual of C and

N stocks. The interaction between species and land use history was not statistically significant and thus the difference may be explained by the inherent characteristics of species, site to site variability of soil physical and chemical properties and the management practices involved. The result was consistent with that reported by Vesterdal et al. (2002). They found that *Quercus robur* sequestered 2 Mg C ha<sup>-1</sup>, *Picea abies* sequestered approximately 9 Mg C ha<sup>-1</sup> in forest floors over 29 years, after establishment of these species on arable land.

The establishment of plantations on either the disturbed or previously cultivated land had reduced the tree and total biomass C and N compared to the reference NF. This may be due to the difference in the species combination and higher age of trees under the NF relative to the younger age and pure stands of plantations. However, all plantations, excluding *C.lusitanica*, sequestered more SOC than agroforestry and farm land of 30 years of cultivation (Wele et al., 2009). Our finding showed that the understory vegetation biomass C and N under the reference NF and *C.lusitanica* plantation was higher than the remaining plantations. The higher understory vegetation biomass C under *C.lusitanica* was attributed to the effect of thinning operations that reduce the number of trees with the aim of providing enough growing space before harvest. This had resulted in wide openings in the canopy similar to that of the NF that favors the growing of the understory vegetation. However, the understory biomass N under the remaining plantations was small, and hence its contribution to the C and N stocks is negligible. In addition to this, the plantations varied in their litter biomass under the forest floor, the largest being under the NF. Litter biomass becomes lower as trees mature, and this, coupled with the smaller number of trees ha<sup>-1</sup> at *C.lusitanica* stand, may explain the lower SOC stock underneath.

## Conclusion

The conversion of the NF to plantations reduced the SOC and N stocks. But the difference in the stocks among plantation species was not statistically significant. The results show that *P. patula* and *J. procera* (the native species) sequestered higher SOC stock than *Eucalyptus* and *C.lusitanica* plantations. Nevertheless, the negative effect of *Eucalyptus* species on the accrual of SOC and N stocks was not that high given the shorter rotation cycle. The concentration of SOC and N was highest in the 0-10 cm depth and decreased consistently to 1m depth at all sites. Among the plantation species, the SOC and N under *J. procera* tended to be higher in the 0-10 cm depth than the other plantation species. However, the differences in SOC and N distribution among plantation species below 10 cm depth were only minor. *J. procera* has never been harvested since establishment and the rotation cycle for *P.patula* and *C.lusitanica* was 25 years while that of *Eucalyptus* species was at every 7 to 10 years for the study area. It suggests that SOC and N can be sequestered, restored or maintained through extended rotation cycle and through careful selection of species such as *P.patula* and *Juniperus procera* for plantation establishment as the losses seen are negligible when compared to that of the reference NF.

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**Litter fall and litter decomposition under eucalyptus and coniferous plantations in Gambo district, Southern Ethiopia**

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Nutrient Cycling in Agroecosystem (Submitted)



# Litter fall and litter decomposition under eucalyptus and coniferous plantations in Gambo district, Southern Ethiopia

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## Abstract

Litter fall and its decomposition rate, play an important role in nutrient recycling, carbon (C) budgeting and in sustaining soil productivity under short rotation plantations and natural forest (NF). The above ground litter production and the subsequent decomposition rate were studied on commonly planted “broad leaved” *Eucalyptus* (*Eucalyptus globulus*, *Eucalyptus camaldulensis*, *Eucalyptus saligna*) and coniferous (*Juniperus procera*, *Cupressus lusitanica*, *Pinus patula*) plantation species and compared with the adjacent broad leaved NF. The production of litter was recorded by litter traps and the decomposition rate was studied by nylon net bag technique. Litter production under broad leaved plantation species and NF (ranging from 8.7 to 11.5 Mg ha<sup>-1</sup> yr<sup>-1</sup>) was significantly higher ( $P < 0.05$ ) than that under coniferous species (ranging from 4.4 to 6.0 Mg ha<sup>-1</sup> yr<sup>-1</sup>). The average concentration of carbon (C) and nitrogen (N) in fresh mature leaves was higher than in litter fall, implying that both C and N were either sorbed in the plant system or lost through decomposition, leaching or erosion during the litter fall period and these losses varied from 2.9 to 22.3 % for C and 11.8 to 53 % for N. The amount of N, which potentially returned to the soil through the litter fall, tends to be higher in NF, *Juniperus procera* and *Cupressus lusitanica* than in *Eucalyptus saligna*, *Eucalyptus camaldulensis*, *Eucalyptus globulus* and *Pinus patula*. The data on decomposition study showed that the residual litter mass in the litter bag declined with time for all species even though it varied at the different time intervals of the year possibly due to the variability of moisture and temperature. The annual dry matter decay constant (k) varied from 0.07 month<sup>-1</sup> in *Pinus patula* to 0.12 month<sup>-1</sup> in *Eucalyptus saligna*. The half-time ( $t_{0.5}$ ) decay ranged from 6.0 for *Eucalyptus saligna* to 9.7 months for *Pinus patula*. The results suggest that the decomposition rate in *Pinus patula* was relatively lower than the other species and the litter production under broad leaved *Eucalyptus* was comparatively higher to that in coniferous species. Over all the litter decomposition is fast for all species. The higher litter production and its relative faster rate of decomposition is a positive aspect to be considered during species selection for the restoration of degraded habitats given that other judicious management practices such as prolonging the rotation period are adhered.

**Key words:** Broad leaved species; carbon budgeting; nutrient recycling; rotation period, species diversity, soil fertility, sustainability

## Introduction

The quantity and quality of litter production and the decomposition process play an important role in soil fertility in terms of nutrient cycling, C budgeting and formation of soil organic matter (SOM) under plantations where part or all of the biomass accumulated during the production period is hauled out of the site after harvest. Under such circumstances, it is likely that continuous cropping with short rotation crops may result in nutrient depletion and deterioration of physical and biochemical activity of the soil (Parrotta 1999; Fisher; Binkley 2000 and Wang et al. 2007). Litter fall is the major pathway for the return of organic matter to the soil (Ewel 1976; Vitousek et al. 1995) from plant components through decomposition cycle. In the forest floor, it acts as an input and output system of nutrients (Das and Ramakrishnan 1985) and the rates at which forest litter falls and subsequently decays regulate energy flow, primary productivity and nutrient cycling in forest ecosystems (Olson 1963; Waring and Schlesinger 1985). Changes in the amount of (SOC) in the soil are the result of differences between additions and losses (Greenland and Nye 1959; Esser and Lieth 1989; Swift and Anderson 1989). As an insulating layer, litter protects the soil from extreme changes in moisture and temperature, intercepts thorough fall, and improves infiltration (Das and Ramakrishnan 1985; Lemma et al. 2007). It is also a principal source of energy for the saprobiota of the forest floor and soil (Spain 1984).

When natural forests (NF) are replaced by monoculture plantations, the forest species diversity decreases, the total litter fall gets reduced and eventually the pattern of nutrient release through decomposition changes (Lisanework and Michelsen 1994; Wang et al. 2007; Pandey et al. 2007). Moreover, litter fall under some species also exhibit periodic characteristics. In sites with severe dry seasons, deposition of litter on the forest floor increases and decomposition rate decreases resulting in an accumulation of litter at the soil surface. But, decomposition and mass reduction starts at the onset of moist conditions during wet season, (Proctor 1983; Swift and Anderson 1989). Hence, climatic seasonality characterized by alternating wet and dry periods plays a vital role in regulating the rate of decomposition (Tripathi and Singh 1992).

In Gambo district, Ethiopia, exotic and indigenous species of plantations were established as part of satisfying the acute demand for fuel wood and construction material. The litter production and nutrient release of the decomposing detritus material for some of these species was studied by Lisanework & Michelsen (1994) at Menagesha State Forest on the gentle slope of Mt Wuchacha in central highlands of Ethiopia. The total annual fine litter production was found to be in the order of *Cupressus lusitanica* < *Eucalyptus globulus* < *Pinus patula* < *Juniperus procera*. On the other hand, Lemma et al. (2007) reported that SOC storage under *Cupressus lusitanica* was larger than that under *Pinus patula* and *Eucalyptus grandis* due to higher total litter input at Belete Forest located in the southwestern highlands of Ethiopia. Therefore, the conflicting and varied results presented in the studies described above warrant additional research to record litter fall and characterize the turnover of SOC and N under major plantation species in the region which are influenced by local environmental and management factors. Also, the replacement of NF with exotic plantation species may lead to lower litter production and poor nutrient release resulting in soil productivity decline in the long run. Information on these aspects under tropical conditions as found in Ethiopia is rather scanty. Therefore, the objectives of this study were to: (i) assess the annual and seasonal variations in litter fall production under different plantation species and NF, (ii) investigate the “in situ” decomposition rate and residence time of the detritus material and (iii) estimate the seasonal and annual

changes in C and N concentration in the litter fall and decomposing fine litter materials of the commonly planted “broad leaved” *Eucalyptus* and coniferous plantation species.

## Material and methods

### Description of the study site

The study was conducted at Leye and Ashoka, plantation sites of Gambo District, southern Ethiopia (Fig. 1). Leye and Ashoka sites lie within 7°17'N and 7°19'N and 38°48'E and 38°49'E. The altitude ranges from 2134 to 2294 m a.s.l, and the slope from 3 to 18 %.

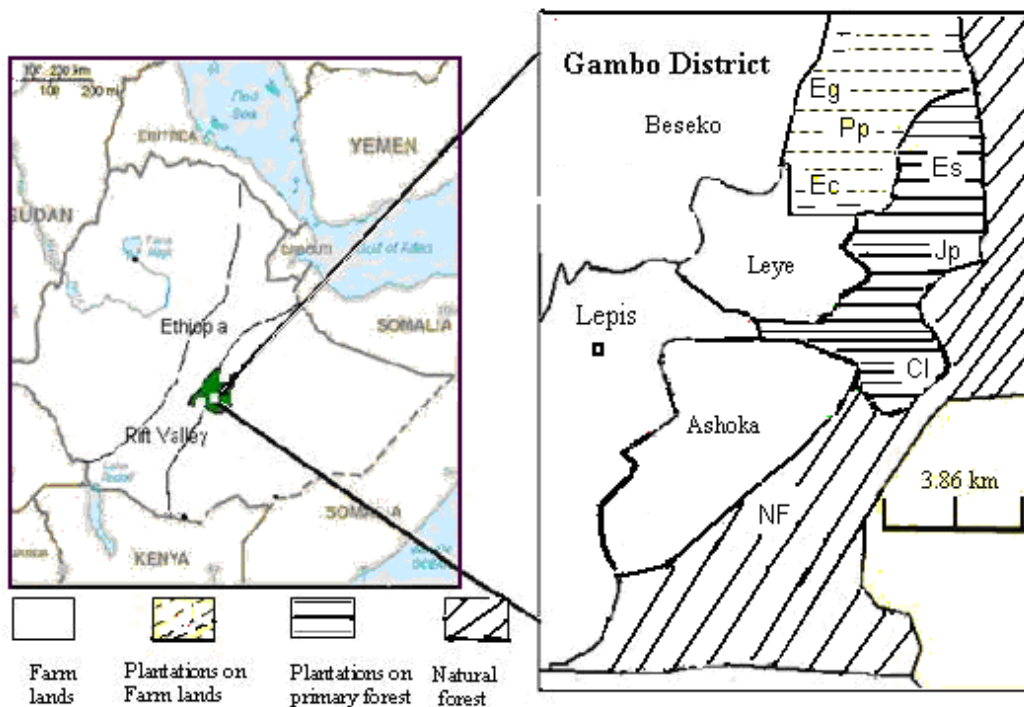


Fig.1. Map of Gambo district, southern Ethiopia showing the plantation and natural forest sites. Where: Eg = *E. globulus*, Pp = *P. patula*, Ec = *E. camaldulensis*, Es = *E. saligna*, Jp = *J. procera*, Cl = *C. lusitanica* and NF = natural forest

Rainfall is bimodal with mean annual precipitation of 973 mm, most of it falling from July to September. Temperature ranges between the maximum of 26.6 °C and minimum of 10.4 °C across the study area for the period from 1999 to 2007 (Fig. 2).

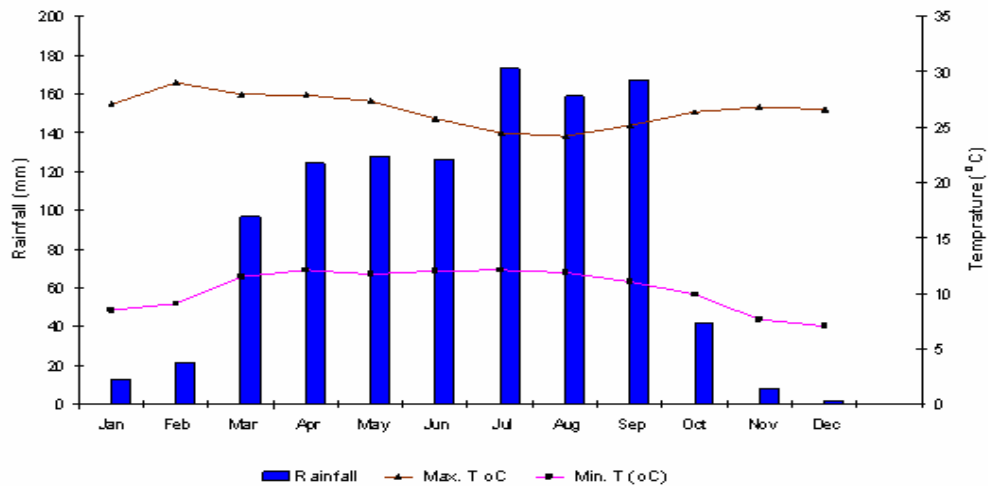


Fig. 2. Mean monthly rainfall (mm), and mean monthly maximum and minimum temperature (°C) for the period 1999 – 2007.

Source: National Meteorological service agency, Addis Ababa, 2008

The rain fall and temperature data was obtained from the nearby meteorological station and no such data were collected in situ experimental plots or specific to the study sites. The vegetation and soil characteristics of the sites that also include the natural forest area are presented in Table 1.

Table 1. Site locations and vegetation characteristics at Leye and Ashoka study sites

Sites	Location		Elevation (m a.s.l.)		Species	Age (year)	No. of trees per ha	Biomass	
	Longitude	Latitude	Min	Max				C (%)	N (%)
Leye	07°18' 886"N	038°49'219"E	2184	2219	<i>J. procera</i>	29	425	51.58	0.24
Leye	07°18' 990"N	038°48'978"E	2174	2188	<i>E. camaldulensis</i>	22	500	49.64	0.26
Leye	07°19' 072"N	038°48'945"E	2147	2195	<i>P. patula</i>	22	625	51.12	0.16
Leye	07°19' 233"N	038°48'912"E	2134	2165	<i>E. globulus</i>	22	600	49.19	0.16
Leye	07°19' 204"N	038°48'981"E	2153	2183	<i>E. saligna</i>	30	750	48.65	0.15
Ashoka	07°18' 023"N	038°48'931"E	2208	2294	<i>C. lusitanica</i>	25	450	50.87	0.17
Ashoka	07°17'513"N	38°48'452"E	2197	2232	natural forest			50.87	0.17

## Litter collection

For this study, "broad leaved" species (*Eucalyptus saligna* (Smith), *Eucalyptus camaldulensis* (Dehnh.), *Eucalyptus globules* (Labill.)) and coniferous species (*Cupressus lusitanica* (Mill.), *Pinus patula* (Schiede & Deppe) and *Juniperus procera* (Hochst. Ex Endl)) were selected. The plantation species were approximately of similar age (22-30 years old) and were located adjacent to each other (Fig.1). The native climax NF at Ashoka, located nearby the plantations, was taken as a reference land use. Litter fall traps of 1m x 1m wooden frame were placed under each plantation species in 8 replicates at four main plots of 20 x 20 m. A perforated polythene plastic sheet was placed on the surface soil

underneath the wooden frame traps. Fifty-six such traps were installed under six plantation species and the NF.

Litter fall which primarily consists of leafy materials (but the possibility for some inclusions of twigs and small woody fractions can not be ruled out) was collected at every 2-months interval for a period of 1 year during April 2007 to June 2008.

In this study litter implies only the above ground leafy materials. The litter mass was determined by recording the total weight of litter collected and by oven drying a small sample of known weight at 70 °C for  $\geq 48$  hrs for dry weight calculations. The mean litter fall was computed on a unit area basis for each interval and species. Then oven-dried samples of litter were crushed using a grinding mill and were analyzed for their total C and N concentrations by a LECO CHN-1000 Carbon and Nitrogen Analyzer.

### **Litter decomposition**

A leaf decomposition experiment using standard litterbag techniques ( Bocock and Gilbert 1957; Olson 1963; Anderson and Swift 1983; Paul and Clark 1989; Anderson and Ingram 1989; Esser and Lieth 1989 ) was conducted for a period of 1 year from July 2007 to June 2008. Mature fresh leaf samples from all plantation species and natural forest were collected in July 2007 from various species of trees located in the similar areas where the litter fall traps were installed. Thus, the samples collected from the diverse vegetation in the NF were bulked with equal proportion and were used as reference material for comparison with the decomposition rate of leaf substrate in plantation species. Such collected samples were first air dried under shade for a period of one week and later on they were oven dried at 70 °C until constant weight was achieved. Five grams of oven-dried leaf samples were then placed in 1-mm size nylon-mesh bags and nailed on the forest floor close to the litter fall trap. A total of 224 litter bags in 8 replicates for each of the 7 species and 4 decay periods (3, 6, 9, 12 months) were installed. The litter bags were collected at 3-month intervals and transported to the laboratory and cleaned of ingrown roots, if any, and brushed free of foreign materials. The litter bag was then emptied onto a paper bag and oven dried at 70 °C to constant weight. The oven-dried litter mass was weighed and recorded for further analysis. Due to damages inflicted by wild animals, only 4 out of 8 replicates were recovered by the end of the experiment. The oven-dried samples of litter were crushed using a grinding mill and were analyzed for their total C and N concentrations by a LECO CHN-1000 Carbon and Nitrogen Analyzer.

### **Measurements and calculations**

The leaf mass loss, decomposition rate and decomposition rate constants (k) were computed using the following equations as described by Olsen (1963):

$$\% \text{ Mass Loss} = (X_0 - X_t) / X_0 * 100 \quad (1)$$

Where  $X_t$  is the mass of litter at time t, and  $X_0$  is the initial litter mass at time zero:

$$\% \text{ Mass Remaining in the litter bag} = 100 - \% \text{ Mass Loss} \quad (2)$$

The leaf litter decomposition rate constants (k) were calculated using the negative single exponential equation:



$$kt = - \ln X_t / X_0 \quad (3)$$

Where  $k$  is the decomposition constant ( $\text{month}^{-1}$ ), and  $X_t$  and  $X_0$  are the same as above,  $t$  is decomposition time (in years). Mean residence time ( $R_t$ ) of leaf litter in each treatment was estimated by the inverse of  $k$  calculated (Waring and Schlesinger 1985):

$$R_t = 1/k \quad (4)$$

Half-life periods  $t(0.5)$  of decomposing litter samples was estimated from  $k$  values using equation (5):

$$t(0.5) = \ln(0.5) / (-k) = -0.693 / (-k) \quad (5)$$

Nutrient loss and/or resorption for the litter fall were estimated using equation developed by (Huang et al. 2007):

$$\text{Nutrient loss (\%)} = ((G-L)/G)*100 \quad (6)$$

Where  $G$  is the initial nutrient concentration in mature green leaves and  $L$  is the concentration of nutrients in the litter fall.

## Statistical Analysis

The data on litter fall, C and N concentration were subjected to one way analysis of variance using general linear model procedures of SAS (SAS Inc. 2003). The treatment comparison of means for each class variable was carried out using the Student-Newman-Keuls (SNK) test at  $\alpha = 0.05$ . Residual litter mass remaining in the litter bags and their C and N concentrations were analyzed statistically using the same method as for litter fall.

## Results and discussion

### Litter fall

The average annual litter fall for *Eucalyptus* species (*E. saligna*, *E. camaldulensis*, and *E. globulus*) and natural forest (ranging from 8.7 to 11.5  $\text{Mg ha}^{-1} \text{ yr}^{-1}$ ) was significantly higher ( $P < 0.05$ ) compared to that under coniferous species (*C. lusitanica*, *J. procera* and *P. patula*), ranging from 4.4, to 6.0  $\text{Mg ha}^{-1} \text{ yr}^{-1}$ . No such statistically significant difference was observed within *Eucalyptus* or coniferous species (Fig.3). Yang et al. (2004) observed that mean annual total litter fall varied from 5.47  $\text{Mg ha}^{-1}$  for *Cunninghamia lanceolata* to 11.01  $\text{Mg ha}^{-1}$  for natural forest at Fujian, in subtropical China showing the values similar to those found in this study. The higher annual litter production under the NF compared to the pure stand plantations may be explained by the diverse nature of the vegetation. Plants differ in their ability to capture resources and their influence on ecosystem process (Russell et al. 2004), and hence, diverse natural vegetation and or mixed plantation produce higher annual litter mass than pure stand crops (Binkley et al. 1992; Lian and Zhang 1998; Parrotta 1999; Yang et al. 2004; Wang et al. 2007). In such case, managing plantations as

mixed stand could mimic the function of NF systems and produce higher litter mass and better nutrient recycling. For example, Wang et al. (2007) reported that the mean annual litter production was significantly higher (24 %) in the mixed than the monoculture *Cunninghamia lanceolata*.

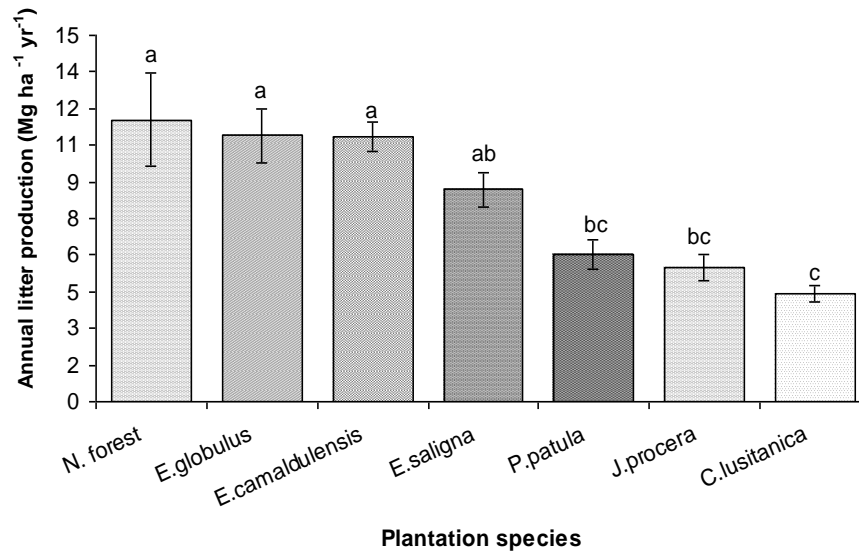


Fig. 3. Annual litter production under plantations and Natural Forest. Means followed by the same letters are not significantly different ( $p < 0.05$ ,  $n = 4$ ).

Higher above ground and below ground litter mass production are one of the major factors for SOC accumulation. The higher litter production and the subsequent faster litter decomposition of *Eucalyptus saligna*, *Eucalyptus camaldulensis* and *E. globulus* implies a better nutrient recycling under broad leaved *Eucalyptus species*. In addition to higher production of litter, some *Eucalyptus* species also has an ameliorative effect despite many argues that it exhausts soil nutrient due to its quick growth. For example Mishra et al., (2003) reported that *Eucalyptus tereticornis* improved the physical and chemical properties of a sodic soil in India by lowering the soil pH, electrical conductivity (EC) and exchangeable sodium percentage (ESP) and by increasing the SOC, total N, available P and exchangeable cations.

### Temporal variation of litter fall

The litter fall under plantations and NF also showed temporal variation (Fig.4). The highest peak of litter production was observed in April/June for *J. procera* and NF, September/November for *E. saligna* and *E.globulus*, November/ January for *P. patula* and *E. camaldulensis* and January/March for *C. lusitanica* (Fig.4).The litter fall under *E. globulus* and *E.camaldulensis* did not show such large variations from April to March and those of *Eucalyptus* and natural forest was almost consistent throughout the year.

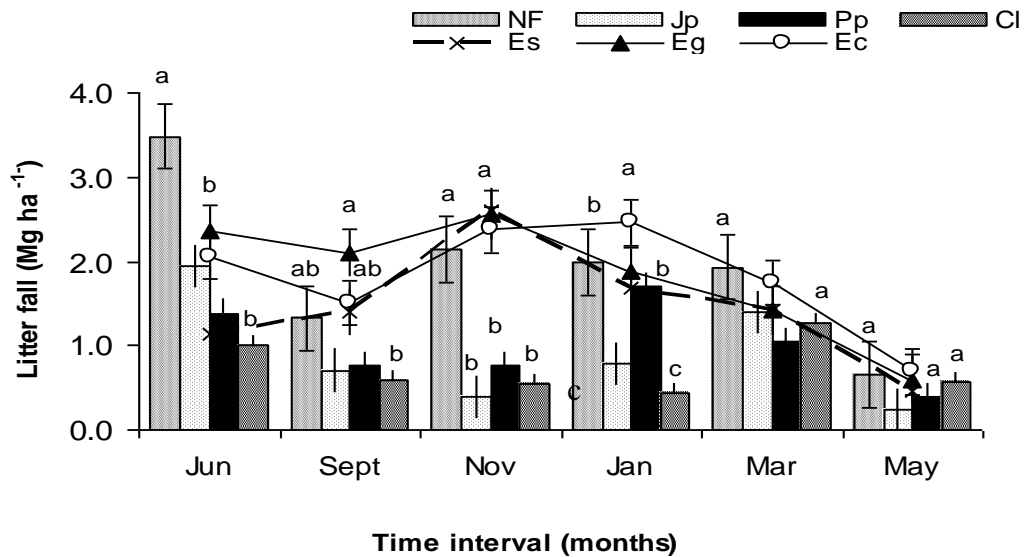


Fig.4. Periodic (two months interval) litter under and Natural Forest (NF), *J.procera* (Jp), *P.patula* (Pp), *C.lusitanica* (Cl), *E.saligna* (Es), *E.globulus* (Eg) and *E.camaldulensis* (Ec). Conifers are shown by bars and *Eucalyptus* are shown by line graphs. Means followed by the same letter do not differ significantly among species ( $P < 0.05$ ).

The intensity and the powerful swaying wind that usually occurs before the onset of the heavy rainfall event from July to September (Fig.2) may have caused dead hanging leaves to shake off which leads to the largest accumulation of litter fall under all plantations and the natural forest at this time of the year compared to that on March to May time interval. A similar pattern of litter fall was also obtained by Lisanevork and Michelsen (1994) for the Central Highlands of Ethiopia and elsewhere by Jackson (1978) for the tropical rain forest in Australia. The litter production of the NF and *Eucalyptus* species showed little variation from September 2007 to March 2008, while such a consistent rhythm was not seen under coniferous species

Nevertheless, the periodical pattern of the litter fall showed that the litter production under the NF and *Eucalyptus* species was higher, and that of coniferous species was lower, compared to that reported by Lisanevork & Michelsen (1994) at Menagesha State Forest in the central highland of Ethiopia. Several studies have documented the seasonal variation of litter production (Spain 1984; Martinez-Yrizar and Sarukhan 1990; Wang et al. 2007), and they found that for most of the species, the peak rates of litter fall usually occurs during the dry season (Wright and Cornejo 1990), but for some species, litter fall is maximum during the period of greatest precipitation and high temperature (Jackson 1978).

### Carbon and nitrogen concentration in litter fall

The average concentration of C and N in freshly matured leaf ranged from 47.1 to 54.8 % for C and from 1.3 to 2.5 % for N. The corresponding values for litter fall were from 39.0 to 49.3 % for C and from 0.7 to 1.8 % for N (Table 2). This implies that both C and N were lost and /or resorbed in other plant parts during the litter fall period. These losses varied from 2.9 to 22.3 % for C and 11.8 to 53.0 % for N. The losses may partly be explained due to recycling of nutrients to other parts of the plant during leaf senescence (Gan and Amasino, 1997) or due to decomposition between the time of falling and collection of the samples from the litter traps (Berg and McClaugherty, 2008).

In general, the loss of litter C under *J. procera* and *C. lusitanica* was higher than those of other plantations, and that of NF was the lowest. The variation of C loss within *Eucalyptus* species was lower than between coniferous species. However, almost all *Eucalyptus* species showed higher N loss during leaf maturing than coniferous or NF species (Table 2).

### Temporal variation in C and N concentration in litter fall

Periodic variations in C and N concentration and C:N ratio of the litter fall were observed under the plantations and the NF ( $P < 0.05$ ). In April/June and July /September, the litter C concentration under plantations and natural forest did not differ significantly, but in November/January that under *E. globulus* was significantly higher than that under *C. lusitanica*, *E. camaldulensis*, *J. procera* and NF. The remaining plantation species also showed significant variations. For example, in the same period, the litter C concentration under *C.lusitanica* was significantly higher compared to that under *J. procera* and NF, while that of *E.camaldulensis* was higher than *J.procera* and NF. In the March/May time interval, the C concentration of litter under *E. globulus* was only significantly higher than that under *J.procera* and NF (Table 3).

Table 2. Carbon & N concentration in green leaf and in litter and the loss of C and N during the litter fall under plantations and NF.

Species	Green leaf (GL)			Litter (L)		Loss = 1-(L/GL)*100		
	C	N (%)	C:N	C (%)	N (%)	C:N	C (%)	N (%)
NF	47.1	2.5	19.1	45.8 a	1.8 a	25.6 d	2.9	27.6
Cl	51.1	1.3	37.9	44.4 a	1.2 bc	37.3 c	13.1	11.8
Pp	50.3	1.3	37.8	46.2 a	0.7 d	64.8 a	8.1	46.4
Jp	50.2	1.9	26.4	39.0 b	1.4 b	28.1 d	22.3	27.0
Eg	54.8	1.3	43.2	49.3 a	0.7 d	68.0 a	10.1	42.9
Es	53.1	2.0	26.1	47.3 a	1.0 cd	49.5 b	11.0	53.0
Ec	51.7	1.8	29.0	46.7 a	0.9 cd	49.3 b	9.7	46.8

Values for green leaves are from bulked samples and therefore statistics are not provided. Means followed by the same letters in a column are not significantly different ( $p < 0.05$ ,  $n = 3$ ).

NF	Natural forest	Jp	<i>J. procera</i>	Ec	<i>E.camaldulensis</i>
Cl	<i>C. lusitanica</i>	Eg	<i>E. globulus</i>		
Pp	<i>P. patula</i>	Es	<i>E. saligna</i>		

There was no temporal variation among C concentrations of litter under *E. globulus*, *P. patula* and *E. saligna* plantations throughout the study period. However, from June to September (intense rainfall period), C concentration of litter under, *J. procera*, *E. camaldulensis*, *C. lusitanica* and NF was lower than the litter C concentration in March/May time interval. In these period of time the C concentration of litter under *J. procera* and NF, was significantly lower compared to the rest of the plantation species. The low C concentration under *E. globulus*, *P. patula* and *E. saligna* during the intense rainfall period may be caused by higher removal of DOC (Fisher and Binkley 2000).

Variation was also observed in the N concentration between species across the study period. For example, N concentration in the litter fall under *J.* plantation in the June

to January time interval tends to be higher than those of the other plantations but was lower than that of the NF ( $P < 0.05$ ). With only few exceptions, the N concentration in the litter under NF tends to be significantly higher than that under plantation species throughout the study period. Also the N concentration in *J. procera* litter was higher than the other plantation species, but a significant difference was seen only compared to that of *E. globulus* (in the June/September), *P. patula* (from June to May) and all *Eucalyptus* plantations (from November to March) time intervals (Table 3).

The C:N of the litter under plantation species showed temporal variation throughout the time intervals of the study period ( $P < 0.05$ ). The litter fall under *P. patula* and *E. globulus* showed higher C:N ratio in most of the study period ( $P < 0.05$ ) compared to the remaining species. Lower N concentration in the litter fall under these species may be responsible for high C:N ratio observed under these species. The NF, *J. procera* and *C. lusitanica* showed consistently lower litter C:N ratio throughout the study period. This may be attributed to the inherent characteristics of the species for N concentration in their litter and the difference in intra site variation. For example, Ribeiro et al., (2002) reported a similar pattern of C:N ratio variation in the initial leaf substrate for *E. globulus* grown under a different water and nutrient regime in Central Portugal.

Table 3. Carbon and nitrogen concentration and C:N ratio in litter fall at different time intervals

Species	Time interval in months			
	April/June 2007	July / September	November/January	March /May 2008
	<b>Carbon (%)</b>			
Natural Forest	45.3 a	45.6 a	46.0 e	46.1 b
<i>C. lusitanica</i>	35.9 a	40.6 a	50.3 bc	50.7 ab
<i>P. patula</i>	38.9 a	47.5 a	51.4 ab	47.0 ab
<i>J. procera</i>	31.5 a	35.7 a	47.8 d	41.1 c
<i>E. globulus</i>	46.2 a	46.8 a	52.1 a	52.0 a
<i>E. saligna</i>	46.4 a	42.6 a	51.4 ab	48.7 ab
<i>E.camaldulensis</i>	44.2 a	44.8 a	49.4 c	48.4 ab
	<b>Nitrogen (%)</b>			
natural Forest	1.98 a	1.97 a	1.67 a	1.55 ab
<i>C. lusitanica</i>	0.91 bc	1.16 bc	1.22 b	1.46 abc
<i>P. patula</i>	0.81 bc	0.76 c	0.45 c	0.83 c
<i>J. procera</i>	1.14 b	1.53 ab	1.27 b	1.61 a
<i>E. globulus</i>	0.53 c	0.75 c	0.71 c	0.9 bc
<i>E. saligna</i>	0.83 bc	1.1 bc	0.72 c	1.18 abc
<i>E. camaldulensis</i>	0.87 bc	0.99 bc	0.81 c	1.12 abc
	<b>C:N ratio</b>			
natural Forest	23.49 e	23.4 c	28.67 c	32.42 b
<i>C. lusitanica</i>	39.93 d	34.75 bc	41.22 c	34.85 b
<i>P. patula</i>	47.72 c	62.76 a	114.37 a	57.94a
<i>J. procera</i>	26.98 e	23.33 c	37.74 c	25.7 b
<i>E. globulus</i>	86.8 a	62.45 a	73.68 b	57.48 a
<i>E.saligna</i>	56.15 b	41.6 b	71.52 b	41.72 ab
<i>E. camaldulensis</i>	51.16 bc	46.19 b	62.55 b	45.76 ab

Means followed by the same letters in a column are not significantly different ( $p < 0.05$ ,  $n = 3$ ).

## Litter decomposition

The residual litter mass in the bags at each sampling time (in months) declined exponentially for all plantation species and NF (Fig.5). At the first three months, the weight of remaining litter material reduced sharply but it was minimal in the six and nine months time interval. The weight loss increased again during the beginning of the twelve months time. The first three months (July, August and September) and twelve months intervals were the rainfall season and the sufficient soil moisture may explain the sharp decline in weight of the remaining litter material during these periods (Fig.5). The corresponding minimal weight loss of the remaining litter material in the six to nine months may be attributed to insufficient soil moisture available, which is characterized by low rain fall events and their eventual distribution throughout the study site (Fig.2) However, under this study, in situ temperature and moisture data from study site was lacking to be included as a factor in the analysis.

The remaining mass of litter varied between species within and between sampling time ( $P < 0.05$ ). In the first 3 months, remaining litter mass for *C. lusitanica* and *P. patula* was significantly higher than that of *E. camaldulensis* and *E. saligna* (Fig.5). At 6 months time, the remaining litter mass of *E. saligna* was significantly lower than *P. patula*. At 9 months, the remaining litter mass of *C. lusitanica* was significantly lower than *P. patula* only (Fig.5).

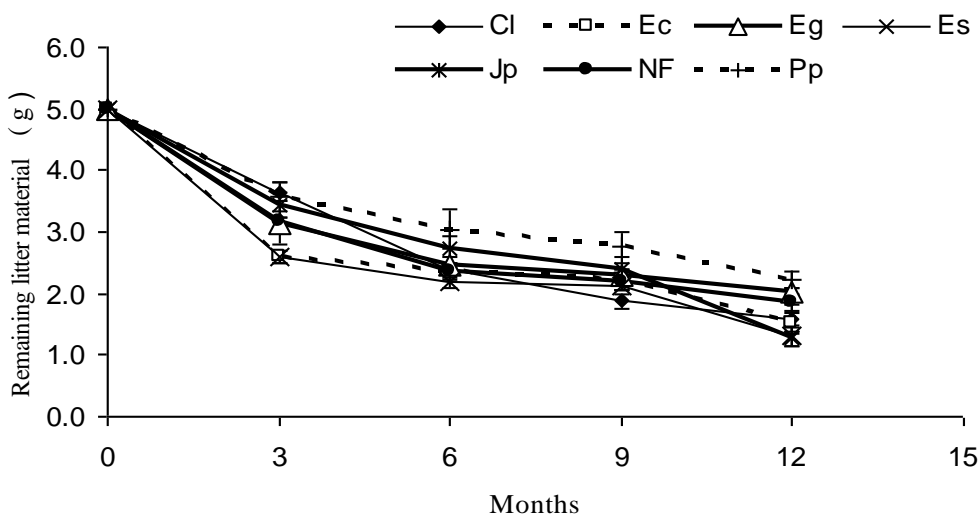


Fig.5. Litter mass remaining in litter bags at various time intervals under *C.lusitanica* (Cl), *E. camaldulensis* (Ec), *E. globules* (Eg), *E. saligna* (Es), *J.procera* (Jp), Natural forest (NF) and *Pinus patula* (Pp),

At 12 months time, the residual litter of the *Pinus patula* was significantly higher compared to almost all other plantation species. Generally, the remaining litter mass under *P. patula*, *E. globulus* and NF was consistently higher compared to the other species investigated in the study periods.

The decay rate coefficient ( $k$ ) and half-life ( $t_{0.5}$ ) decay periods of decomposing leaf litter samples are presented in Table 4. The decay rate coefficient ( $k$ ) of all species ranged from 0.07 (*P. patula*) to 0.12 month<sup>-1</sup> (*E. saligna*), while the half-life decay period ranged

from 6 to 9.7 months respectively. The decomposition of *Eucalyptus* species in general tended to be faster than the coniferous species.

Table 4. Litter decay rate coefficient (k), half-life t (0.5) and residence time for different specie

Species	Decay rate constant (k) (Months <sup>-1</sup> )	Y = ae <sup>-kt</sup> R <sup>2</sup>	Half-life t(0.5) (Months)	Residence time (Rt) (Months)
<i>P. patula</i>	0.07 a	0.61	9.7	14.0
<i>E. globulus</i>	0.09 ab	0.53	8.0	11.5
natural forest	0.09 ab	0.52	7.3	10.6
<i>J. procera</i>	0.10 b	0.80	6.7	9.6
<i>C. lusitanica</i>	0.10 b	0.85	6.6	9.6
<i>E. camaldulensis</i>	0.10 b	0.47	6.6	9.5
<i>E. saligna</i>	0.12 b	0.61	6.0	8.7

Means followed by the same letters(s) are not significantly different (p<0.05), n=4.

On the top of variability of other factors controlling decomposition such as moisture, temperature etc., the fast initial and the subsequent lower rates of decomposition at later time intervals could be attributed to a higher initial content of water soluble materials, simple substrate and the breakdown of litter by decomposers, especially the micro flora (Songwe et al. 1995) and the higher loss of these easily degradable and labile fractions during the early decomposition phase (Berg and Tamm 1991; Sundarapandian and Swamy 1999; Jamaludheen and Kumar 1999; Ribeiro et al. 2002; Yang et al. 2004; Huang et al. 2007).

Table 5. Carbon and nitrogen concentration and C:N ratio in the remaining litter mass for under plantations and NF

Months	Carbon (%)						
	NF	Cl	Pp	Jp	Eg	Es	Ec
0	47.1 †	51.1 †	50.3 †	50.2 †	54.8 †	53.1 †	51.7 †
180	45.1 a	45.6 a	49.2 a	43.4 a	53.2 a	51.9 a	46.1 a
270	41.5 a	43.3 a	46.1 a	43.4 a	52.1 a	49.2 a	43.2 a
360	36.1 a	42.0 a	46.2 a	40.2 a	47.2 a	49.4 a	42.7 a
	Nitrogen (%)						
0	2.5 †	1.3 †	1.3 †	1.9 †	1.3 †	2.0 †	1.8 †
180	2.2 ab	1.8 bc	1.5 c	2.1 ab	1.5 c	2.3 a	1.9 abc
270	2.4 a	1.8 bc	1.3 d	2.3 a	1.6 c	2.5 a	2.1 ab
360	2.2 ab	2.0 ab	1.3 c	2.2 ab	1.7 bc	2.5 a	2.2 ab
	C:N Ratio						
0	19.1 †	37.9 †	37.8 †	26.4 †	43.2 †	26.1 †	29.0 †
180	20.9 c	25.7 bc	32.2 ab	20.9 c	36.2 a	22.6 bc	23.9 bc
270	17.6 c	24.4 b	35.3 a	18.6 bc	31.8 a	20.1 bc	21.0 bc
360	16.7 c	21.3 c	36.5 a	18.4 c	27.5 b	19.8 c	19.0 c

Means followed by the same letters in a row are not significantly different at P<0.05

Cl *C. lusitanica* Eg *E. globulus* Jp *J. procera* Pp *P. patula*  
Ec *E. camaldulensis* Es *E. saligna* NF natural forest

† Values of the initial samples were from bulk samples and therefore statistics is not provided

The relatively slower decay rates at later stages may be due to the decrease of the substrate quality as a result of the removal of the labile C and the accumulation of recalcitrant matter in the residual litter mass (Berg and Tamm 1991; Ribeiro et al. 2002). These observations may explain the trend of decomposition observed in the present study.

The data obtained in our investigation may have been explained better had the decomposition process was observed with narrower time intervals, larger number of replicates, longer study period and in situ site moisture and temperature data were collected and included as factors in the analysis.

### **Carbon and nitrogen concentration in the remaining litter mass under plantation and Natural forest**

The C concentration in the remaining litter mass did not differ significantly between species across the sampling time intervals ( $P > 0.05$ ). However, the N concentration and C:N ratio varied at all experimental periods ( $P < 0.05$ ). At around 180 days, N concentration in the residual litter of *E. saligna* was significantly higher than that of *C. lusitanica*, *E. globulus* and *P. patula* (Table 5).

The N concentration in residual litter of *J. procera* and NF was also significantly higher than that of *E. globulus* and *Pinus patula*. Similarly, in 270 days interval, N in the remaining litter of *E. saligna*, *J. procera* and NF was significantly higher than that of *C. lusitanica*, *E. globulus* and *P. patula*. In the same time interval the N in the remaining litter of *E. camaldulensis* was significantly higher than that of *E. globulus* and *P. patula* ( $P < 0.05$ ). After 360 days, the N concentration of *E. saligna* was significantly higher than only to that of *E. globulus* and *P. patula* (Table 5).

The seasonal variation in remaining litter mass within individual species may be explained by changes in moisture, temperature and relative humidity (Kim et al. 2005) as these variables changed during the study period (Fig.2). The nutrient composition and differences in the substrate qualities between species such as lignin content of litter may also influence the observed rate of decomposition. Lower N concentration and higher C:N ratio in *P. patula* and *E. globulus* relatively seem to have delayed the decomposition as compared to, for example, NF (Table 3).

The N retention in the litter relatively showed an increasing trend throughout the study period, and relatively more N was found in the bagged litter than the initial amount in both broad leaved *Eucalyptus* and coniferous species. This may be ascribed to the reduction of C, macro and micro nutrients in the litter on one hand and release of N from colonizing microorganisms that consumed it on the other. The observed trend is consistent to that reported by Ribeiro et al. (2002) for leaf litter in *E. globulus* and Guo & Sims (1999) for short-term *Eucalyptus* rotation in New Zealand. There was no significant difference observed between the decay rate constant values of the investigated species. But the litter mass in *J. procera*, *E. saligna* and *E. camaldulensis* disappeared faster than the other species

The decay rate at the end of the one-year period was in the order of *E. saligna* > *E. camaldulensis* = *C. lusitanica* = *J. procera* > Natural forest = *E. globulus* > *P. patula*. The slightly (but not significantly) faster rate of litter decay in *E. saligna* and *J. procera* can be explained by the higher N concentration or lower C:N ratio of the litter mass. Similarly, the relative rate of litter decomposition was slower under Natural Forest compared to *J. procera*, *E. saligna* and *E. camaldulensis*, which may be attributed to the substrate quality in the litter mixture of the dominant species subjected for the investigation. Lisanevsky & Michelsen (1994) observed that after 24 months of litter bag experiment, the remaining dry weight was significantly higher in NF and the *C. lusitanica* sites than the *E. globulus* and *J. procera*. These observations corroborate well with the results of the present study.

### **Conclusion**

The finding of this study showed that the broad leaved *Eucalyptus* short-term rotation crops exhibit higher annual litter production than coniferous species. The rate of



nutrient release through decomposition is invariably fast for all species including the natural forest for the investigated one-year period. The addition of nutrients to the soil through litter input is crucial especially where application of fertilizers is limited. Hence, the higher litter production and the subsequent faster rate of nutrient release are qualities to be taken into account during the selection of species for short-term rotation crops. Such management may relatively contribute to enhance nutrient recycling through litter fall where the larger part of the biomass is exported out of the plantation site. Therefore the observed higher litter production under broad leaved *Eucalyptus* plantations and its relative faster rate of decomposition is a positive aspect to be considered for plantation establishment or restoration of degraded habitats given that other judicious management practices such as prolonging the rotation period are adhered.

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Effect of *Eucalyptus* and Coniferous Plantations on Soil Properties  
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# Effect of *Eucalyptus* and Coniferous Plantations on Soil Properties and Quality in Gambo district, Southern Ethiopia

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## Abstract

*Plantation establishment using exotic species on disturbed cultivated soils and undisturbed forest soils are common in Gambo district, southern Ethiopia, but their effects on soil properties are not fully known. Therefore, this study was carried out to investigate the major soil physical and chemical properties and to further evaluate the soil quality as affected by these land use changes. Soil samples in triplicates, collected under different plantations, were analyzed for their physical and chemical properties. Based on these soil properties, an integrated soil quality index was determined. The bulk density (BD) varied from 0.72 to 1.14 Mg m<sup>-3</sup> and that of under E.globulus and P.patula established on cultivated soils was significantly higher than those plantations established on undisturbed soils. No significant difference was observed on air volume, water volume (% at -10 kPa matric potential), or available water capacity (AWC) under all plantation species. However, significantly lower pore volume and infiltration rate were observed under plantations established on cultivated lands than those on undisturbed forest soils. Water volume (% at -1500 kPa matric potential) in soils under J.procera and natural forest (NF) was significantly higher than in those of the other plantations. Exchangeable cations decreased with depth with the exception of Ca<sup>2+</sup> under E. globulus and E.camaldulensis that showed the opposite trend. The concentrations of exchangeable Ca<sup>2+</sup> varied from 6.5 to 22.7 cmol kg<sup>-1</sup> and that of under J.procera was significantly higher than those under E. globulus and E. camaldulensis. No significant difference was observed among the other exchangeable cations under any of the plantations. The soil under plantations on previously cultivated lands showed soil quality index below 0.5 (the base line value), while those established on undisturbed forest soil, with the exception of E. saligna, were above that value. The study results suggest that selecting species such as J.procera and prolonging the harvesting period would improve and maintain the quality of soil properties.*

**Key words:** *plantation species, undisturbed forest soil, previously cultivated lands, soil physical and chemical properties, soil quality*

## Introduction

Forest soil properties, including the quantity and quality of soil organic carbon (SOC) stocks, are influenced by the complex interactions of climate, soil type, management and tree species (Lal, 2005; Russell et al., 2007). Trees in the forest vegetation increase the supply of nutrients within the upper surface soil (Buresh and Tian, 1997; Li et al., 2006). The continuous deposition of tree litter underneath the canopy over many decades creates the characteristic surface layers of organic matter (OM) found in the forest areas. The OM on the surface and in the lower layers is maintained by a relatively slow oxidation resulting from lower temperature under the forest canopy (Whalen and Reeburgh, 1996). The soil structure is also maintained since it is shielded and protected from the impact of raindrops by forest canopy and surface organic layers. Studies on water infiltration, water runoff, and sedimentation have also shown that water percolates into forest soils faster than it does in agricultural or abandoned agricultural soils (Eldridge and Freudenberger, 2005).

Land use change, particularly conversion to cultivated land, depletes the SOC stock through enhanced oxidation and deteriorates other physical and chemical characteristics (Lal, 2005). Furthermore, OM and nutrients are annually lost when crops are harvested and the residues are fully or partly collected for household use leading to the deterioration of the soil structure. For example, Evrendilek (2004) reported degradation of soil properties during a 12-year period of cultivation after conversion of grassland into cropland in the Taurus Mountains of the Southern Mediterranean region of Turkey. A poorly managed agricultural soil reduces chemical parameters of soil quality such as SOC and degrades soil physical properties resulting in increased bulk density (BD) and lower rate of infiltration. Decline in soil quality is attributed to the fact that ecologically sensitive components of the forest ecosystem are not able to buffer the effects of agricultural practices (Islam and Weil, 2000) once converted to cultivated lands. Such decline in soil quality may lead to a permanent degradation of land productivity (Juo et al., 1995; Islam et al., 1999). When agricultural land is no longer used for cultivation and allowed to revert to natural vegetation or replanted with perennial vegetation, SOC can accrue by processes that essentially reverse some of the effects responsible for SOC losses and deterioration of physical and chemical properties (Post and Kwon, 2000a).

Soil is a dynamic, living natural body and a key factor in the sustainability of terrestrial ecosystems (Shukla et al., 2004). Sustainable uses depend on soil quality that is explained by the optimum condition of soil physical and chemical properties in relation to specific function (Lal, 2004). Soil quality is broadly defined as the capacity for water retention, C sequestration, plant productivity, waste remediation and other functions, within natural or managed ecosystem boundaries (Schoenholtz et al., 2000b; Doran, 2002; Sa and Lal, 2009). It is a concept based on the premise that management can degrade, stabilize, or improve soil ecosystem functions (Franzluebbers, 2002). Soil quality cannot be measured directly, but it can be inferred by measuring soil attributes, which serve as quality indicators (Brejda and Moorman, 1999). Different soil properties have different roles in maintaining soil quality. Hence, an integrated soil quality index (SQI) based on the weighted contribution of individual soil properties may serve as a better indicator of proper functioning of soil in different land uses. Soil quality and soil health change over time due to natural events or human impacts. The amount of C, N and P stored in the undisturbed soils represent an equilibrium between the input and loss of these elements from climax forests (Chaer et al., 2009), and as such soil health or quality under the undisturbed natural forest ecosystem is considered to be high.

The increasing demand for firewood, timber, pasture, shelter, food crops and the eventual conversion of natural forests to croplands contributed to severe deforestation in sub-Saharan Africa, including Ethiopia. It has resulted in severe reduction of the native forest resources in the Rift Valley and central highlands of the country. The vicious cycle of demand for wood products and productive land to support the needs of the growing population

necessitated the restoration of degraded lands; and to this effect forest tree plantations were started decades ago in many parts of Ethiopia (Amare et al.,1990).

Restoration of vegetation through plantation affects not only the status of vegetation cover but also the soil conditions. Plantation species may differ in a variety of traits, including production of detritus material (Landon, 1984; Montagnini et al., 1993), and in their effect on soil physical and chemical properties. In the context of plantations and short-rotation woody crops, which are functionally and structurally more similar to agronomic systems than the natural forest (NF), their relationships with soil chemical properties (forest productivity, limiting nutrient availability and soil quality) may be available for some target species (Schoenholtz et al., 2000a). In most cases, however, these relationships still need to be verified or established for other species and genera specific to the local environmental conditions where such information are lacking like the case in Ethiopia. The knowledge acquired on the performance of the species used in the plantations will be useful to design the best management practices (BMPs), aimed at improving the soil quality. Therefore, the objectives of this study are to: i) investigate the effect of plantation species on some key soil physical properties (e.g., BD, pore volume, moisture retention and infiltration), ii) assess the changes in chemical properties in surface and subsurface soils under plantation species, and iii) determine the soil quality based on soil properties under selected plantation species.

## Material and methods

### Description of the study site

This study focused on land uses that include different plantation species at Leye and Ashoka sites (7°17'N and 7°19'N and 38°48'E and 38°49'E) of Gambo district, Southern Ethiopia. The altitude ranges from 2134 to 2294 m a.s.l, and the slope from 3 to 18 %. Rainfall is bimodal with mean annual precipitation of 973 mm, most of it falling from July to September. Temperature ranges between the maximum of 26.6 °C and minimum of 10.4 °C across the study area for the period from 1999 to 2007. The vegetation characteristics of the site that also include the natural forest area are presented in Table 1.

Table 1. Site locations and vegetation characteristics at Leye and Ashoka study sites

Sites	Location		Elevation (m a.s.l.)		Species	Age (year)	No. of trees per ha	Biomass Concentration of	
	Longitude	Latitude	Min	Max				C (%)	N (%)
Leye	07°18' 886"N	038°49'219"E	2184	2219	<i>J.procera</i>	29	425	51.58	0.24
Leye	07°18' 990"N	038°48'978"E	2174	2188	<i>E. camaldulensis</i>	22	500	49.64	0.26
Leye	07°19' 072"N	038°48'945"E	2147	2195	<i>P.patula</i>	22	625	51.12	0.16
Leye	07°19' 233"N	038°48'912"E	2134	2165	<i>E. globulus</i>	22	600	49.19	0.16
Leye	07°19' 204"N	038°48'981"E	2153	2183	<i>E. saligna</i>	30	750	48.65	0.15
Ashoka	07°18' 023"N	038°48'931"E	2208	2294	<i>C. lusitanica</i>	25	450	50.87	0.17
Ashoka	07°17'513"N	38°48'452"E	2197	2232	natural forest			50.87	0.17

### Soil sampling and analysis

Soil sampling was done in December 2007, soon after the rainfall season, on sites where plantations are of approximately similar ages (22-30 years). The plantations vary in their mode of establishment, as some were established on primary forest and the others on previously cultivated lands, and were located adjacent to each other (Fig.1). The species planted on previously cultivated lands for 16 years were *Eucalyptus camaldulensis* (Dehnh.),



*Eucalyptus globulus* (Labill.) and *Pinus patula* (Schiede & Deppe). Those species planted on primary forest lands were *Juniperus procera* (Hochst. Ex Endl.), *Cupressus lusitanica* (Mill.) and *Eucalyptus saligna* (Smith).

The native climax NF at Ashoka was taken as the reference land use. The sampling design followed was pseudo complete randomized design (CRD) with three replicates. At all sites, plots of 20x20 m in three replicates were demarcated and pits of 1x1x1 m were dug at each of them. From each pit and each replicate; soil samples were collected at 0-10, 10-20, 20-40, 40-60 cm depth increments. The collected soil samples were air dried, ground and passed through a 2-mm sieve. These samples were analyzed for their physical and chemical properties by the methods described below.

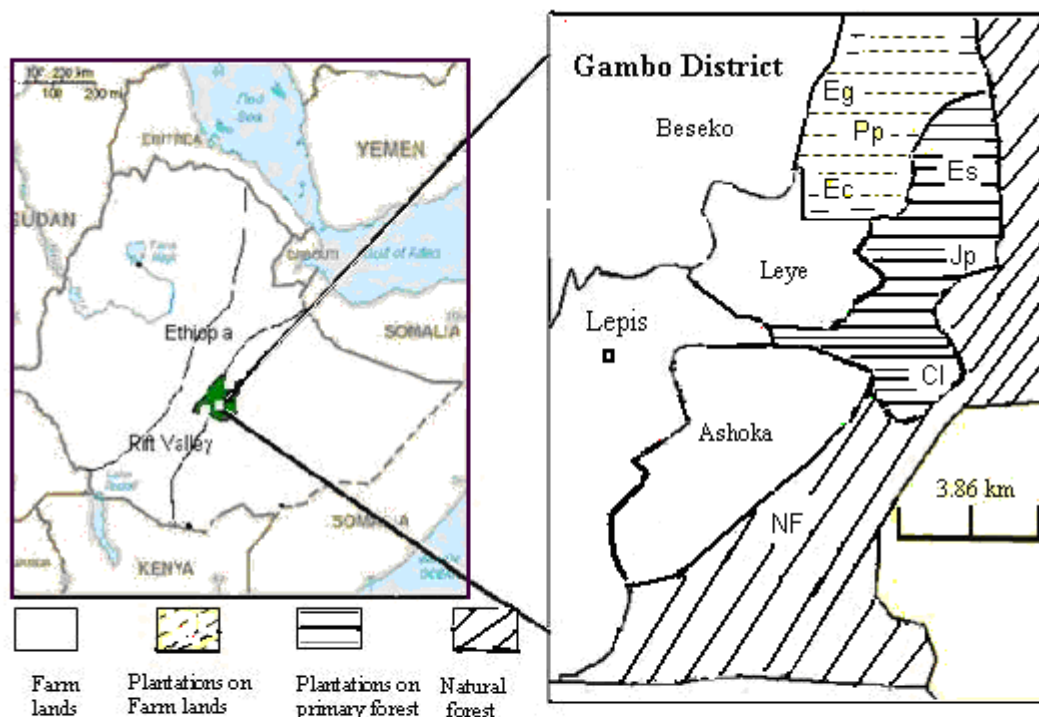


Fig.1. Map of Gambo district, southern Ethiopia showing the plantation and natural forest sites. Where: Eg = *E. globulus*, Pp = *P. patula*, Ec = *E. camaldulensis*, Es = *E. saligna*, Jp = *J. procera*, Cl = *C. lusitanica* and NF = natural forest

The exchangeable cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$   $\text{K}^+$  and  $\text{H}^+$ ) were determined by ammonium acetate extraction (Schollenberger and Simon, 1945) and available P by Bray II as described by Kim, (2005). The CEC was determined by adding all exchangeable  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$   $\text{K}^+$  and  $\text{H}^+$  as described in Kim (2005). The core samples (3.7 cm and a diameter of 5.8 cm high) were drawn from the same profiles and same depths for moisture characteristic determinations. This was achieved by manually forcing a sharp-edged steel cylinder into the soil. For BD determination, another single core sampler was used one at a time and emptied into a plastic bag. The soil samples were then oven dried at 105 °C for  $\geq 24$  hrs and weighed using an electronic balance. The dry soil was then passed through a 2-mm sieve for the possible correction of percentage gravel and stone for the BD of the soil sample.

### Infiltration measurement

Ponded falling head infiltration measurement was conducted in three replicates close to the soil sampling profiles at each plantation and NF site. The measurements were carried out using

double ring infiltrometers following the procedures described in Landon, (1984); Lal and Shukla, (2004). The water in the outer cylinder was kept at approximately the same level as in the inside one to avoid any interaction affecting the inner level. The infiltration test was run until the steady state was reached that extended from 4-5 hrs. Soil samples were taken at the depth of 25 cm to determine the initial moisture content before the infiltration test commenced. The average infiltration rate was calculated by dividing the cumulative infiltration by the time taken since infiltration started, as described in Landon, (1984).

### **Determination of soil water characteristics**

The relative volume fractions of air, water and solids were determined from 100cm<sup>3</sup> undisturbed soil samples (von Nitzsch, 1936). Moisture release characteristics were measured using ceramic pressure plates (Richards, 1947). The air porosity at -10 kPa matric potential was determined with an air picnometer (Torstensson, 1936), and the total porosity was determined as the sum of air porosity and volumetric water content at -10 kPa matric potential. Available water capacity (AWC) was determined by subtracting the volume of water content at -1500 kPa from the volume of water content at 10 kPa matric potential.

### **Assessment of soil quality index**

The approach we followed to develop soil quality index (SQI) was an integrated soil quality assessment based on a combination of soil physical and chemical properties measured in the study area. The procedure was also used by other investigators (Fu et al., 2004; Awasthi et al., 2005; Pang et al., 2006; Masto et al., 2008). The numerical values of physical and chemical properties obtained for the undisturbed NF where soil functioning is at its maximum potential (Warkentin, 1996; Karlen et al., 1997; Arshad and Martin, 2002a), were considered as the optimum. Hence, the SQIs under the NF were taken as a control or reference with which the SQIs of soils under plantation species are compared.

Taking into account the assumption that different nutrients have different roles in maintaining soil quality, SQI was developed and calculated by selecting soil quality indicators from 21 soil physical and chemical properties. Based on the output from correlation matrix and factor analysis, uncorrelated soil variables with higher component loadings were selected and included for the next step of SQI assessment. The weighted average of these selected soil variables was obtained from the output of principal component analysis (PCA) and then, their membership value  $Q(X_i)$  was determined. Such obtained soil quality scores ( $W_i$  and  $Q(X_i)$ ) were finally integrated into SQI as in the following equation (Fu et al., 2004;).

$$SQI = \sum_{i=1}^n W_i * Q(X_i) \quad (1)$$

Where: SQI is soil quality index,  $W_i$  is the weighted vector  $i$  soil quality factor,  $Q(X_i)$  is membership value of each soil quality factor.

The values of  $Q(X_i)$  were calculated by ascending and descending functions by using the following linear equations (Fu et al., 2004; Awasthi et al., 2005).

$$Q(X_i) = (X_{ij} - (X_i)_{min}) / ((X_i)_{max} - (X_i)_{min}) \quad (2)$$

$$Q(X_i) = (X_{max} - X_i) / ((X_i)_{max} - (X_i)_{min}) \quad (3)$$

Where:  $X_{ij}$  is the value of the soil's physical and chemical properties that were selected for the soil quality assessment,  $X_{max}$  and  $X_{min}$  are the maximum and minimum value of soil physical and chemical properties.

Both equations (2 and 3) were applied to determine Q(Xi) and that was used also by other investigators (Fu et al., 2004; 2006; Mastro et al., 2008). Equation (2) was used for “more is better scoring function” while equation (3) for “less is better scoring function”. For soil chemical indicators such as pH, observations were scored as “more is better” up to a threshold value (e.g., pH 4.5-7) then scored as “less is better” above the upper and below the lower threshold value (Liebig et al., 2001; Arshad and Martin, 2002b). The lower threshold value of pH sufficiency curves developed for agricultural soils in the temperate region was 4.5, below which the relative productivity of trees will decline (Schoenholtz et al., 2000a). Other soil physical indicators, such as bulk density (BD), are scored as “less is better” as higher values indicate soil compaction and hence poor soil infiltration and gas exchange that relatively lowers productivity. The combination of both was used for optimum scoring function Q(Xi). The sum of weightings for all soil functions was equal to 1.0.

### **Weights of the indicators**

The contribution or importance of each soil quality factor is usually different and can be indicated by a weighting coefficient. There are many ways to assign the weights for each indicator that includes experience, mathematical statistics or models (Wang and Gong, 1998). Nevertheless for this study we used principal component analysis (PCA).

The weighted average (Wi) for each of the selected soil physical and chemical variables included in the PCAs were determined by equation (4) and used in calculating the SQI according to (Fu et al., 2004; Awasthi et al., 2005).

$$W_i = C_i / \sum_{i=1}^n (C_i) \quad (4)$$

Where: Ci is the component capacity score coefficient of i soil quality factor obtained and calculated from principal component analysis.

### **Statistical analysis**

The data on soil physical and chemical parameters were subjected to one way analysis of variance using general linear model procedures of SAS (SAS Inc., 2003). The statistically significant changes in physical and chemical properties of the soils under plantation forests were detected by multiple comparison of means for each class variable using the Student-Newman-Keuls (SNK) test at  $\alpha = 0.05$ . Data obtained from four soil depths (0-10, 10-20, 20-40 and 40-60 cm) from each plantation and NF site were all considered in the analysis.

To evaluate soil quality, several tests were run including PCA and Pearson’s correlation analysis. Topsoil (0-10 cm) properties of 21 variables (antecedent moisture content infiltration rate at steady state, average infiltration rate, field capacity, percent water content at -1500 kPa matric potential, AWC, air volume at -10 kPa matric potential, pore volume, SOC, N, available phosphorous, pH, EC,  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ ,  $K^+$ ,  $H^+$ , CEC, BS) for 6 plantation species and NF sites were considered for SQI determination. The analysis was carried out using the factor procedure of the software package SPSS. The numbers of components included were determined by taking into account the PCs with eigen values  $> 1$  and those sufficient to explain more than 60 % of the total variability.

## Results

### Soil physical properties

#### Infiltration

The steady state infiltration (the relatively constant infiltration rate) was observed from 4 to 6 hrs time after initiation. The average infiltration rate under *C.lusitanica* was significantly higher than the remaining plantations ( $p<0.05$ ). Nevertheless, the average infiltration rate observed for soils under coniferous plantations established on primarily forest land tends to be higher compared to that under plantations established on previously cultivated lands (Table 2). No significant difference was observed between the antecedent moisture content of soils under all plantation land use types.

#### Moisture characteristics and pore volume

The percent volume of water content at -1500 kPa matric potential across the different plantation species differed significantly ( $p<0001$ ). The volumetric water content at -1500 kPa matric potential under all plantation species was significantly lower than that observed under the natural forest (Table 2). Similarly, the percent volume of water of soils at -1500 kPa matric potential under *J. procera* was significantly higher than that under those of the other plantation species. The difference observed in the percent volume of water content of soils at -1500 kPa matric potential within plantations established on the previously cultivated lands was not significant (Table 2). The volume of water at -1500 kPa matric potential ranged from 14.6 % under *E.camaldulensis* to 22.3 % under the natural forest (Fig.2).

Volume of water (%) at -10 kPa matric potential and available water of all plantations including the natural forest also did not show any significant differences. However, pore volume of soils under plantation species varied significantly ( $p<0.0029$ ). The coniferous plantation established on primary forest land showed a significantly higher pore volume than that established on previously cultivated lands (Table 2). But, such significant difference in soils within plantations established on previously cultivated lands or within those established on primary forest lands were not observed. The BD of soils at 0-10 cm depth under plantations established on cultivated lands was significantly higher compared to those of the corresponding plantations established on primary forest lands ( $P<0002$ ). The BD of soils under *P. patula* and *E. globulus* was significantly higher than those under the remaining plantations and the NF (Table 2). No significant difference was observed in the air volume at -10 kPa matric potential of soils under all plantations and the NF (Table 2). Generally, the quality of soil physical properties under plantations on previously cultivated lands was lower compared to those plantations established on undisturbed primary forest lands.

The SOC and N (both included for soil quality assessment) at 0-10 cm depth under both types of plantations established on previously cultivated and primary forest lands were significantly lower than that under the NF. Further details pertaining to vertical distribution of SOC, N, and pH are presented in (Wele et al., 2009a).

#### Chemical properties (exchangeable cations)

The  $Ca^{+2}$  concentration of soils in the 0-10 cm depth under *E. camaldulensis* and *E. globulus* (both established on cultivated lands) was significantly lower than that under the NF only ( $p<0.05$ ). In the 40-60 cm depth, the  $Ca^{+2}$  concentration under *P. patula* was only significantly higher than that under *C. lusitanica*. No such significant difference was

Table 2. Soil physical properties (0-10 cm depth) under plantation land use types

Data	Eg		Ec		Pp		Es		Cl		Jp		NF	
Antecedent moisture content (%)	19.30	(11.14)a	21.93	(12.66)a	20.40	(11.78)a	20.20	(11.66)a	21.80	(7.07) a	20.83	(3.59) a	26.30	(5.58) a
Infiltration rate at steady state (cm hr <sup>-1</sup> )	3.65	(2.11) b	10.75	(6.21) b	4.81	(2.78) b	6.48	(3.74) b	26.71	(6.23) a	5.47	(0.75) b	10.53	(2.57) b
Infiltration rate (cm hr <sup>-1</sup> )	4.31	(2.49) b	13.76	(7.94) b	8.52	(4.92) b	9.24	(5.34) b	35.97	(7.59) a	20.65	(5.96)ab	25.94	(4.92) ab
Bulk density (Mg m <sup>-3</sup> )	1.14	(0.66)a	0.92	(0.53) ab	1.13	(0.65) a	0.86	(0.50) b	0.72	(0.04) b	0.74	(0.03) b	0.80	(0.05) b
Water volume (% at -10 kPa)	42.72	(24.66) a	41.07	(23.71)a	43.36	(25.03)a	38.37	(22.15)a	36.15	(0.82)a	45.73	(4.77)a	46.10	(3.15)a
Water volume (% at -1500 kPa)	15.84	(9.15)d	16.67	(9.62)cd	16.78	(9.69)cd	17.56	(10.14)cd	18.27	(0.99)c	20.09	(0.77)b	25.17	(0.07)a
Available water capacity (%)	26.88	(15.52)a	24.40	(14.09)a	26.58	(15.34)a	20.81	(12.02)a	17.89	(0.99)a	25.64	(5.24)a	20.93	(3.21)a
Air volume (% at -10 kPa)	13.13	(7.58)a	24.00	(13.86)a	12.40	(7.16)a	27.30	(15.76)a	34.57	(2.77)a	24.20	(6.22)a	21.43	(4.82)a
Pore volume (%)	55.85	(32.25)b	65.07	(37.57)ab	55.76	(32.19)b	65.67	(37.91)ab	70.72	(1.99) a	69.93	(1.68) a	67.53	(2.08)a

Means in a row followed by the same letter do not differ significantly among species (P<0.05). Values in parenthesis represent standard errors=3.

Eg      *E. globulus*                      Es      *E. saligna*                      NF      natural forest  
Ec      *E. camaldulensis*                      Cl      *C. lusitanica*  
Pp      *P. patula*                                      Jp      *J. procera*

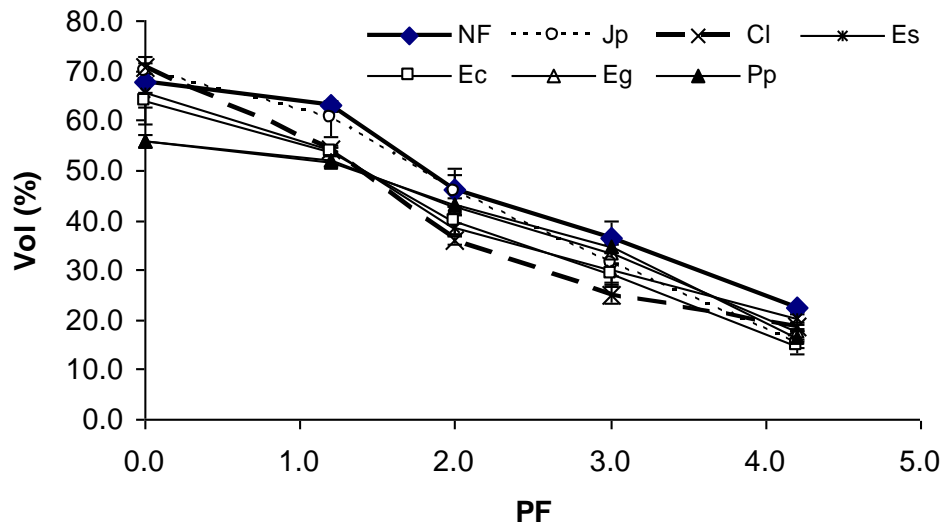


Fig. 2. Water content-matric potential curve of soils under natural forest (NF), *J. procera* (Jp), *C. lusitanica* (Cl), *E. saligna* (Es), *E. camaldulensis* (Ec), *E. globulus* (Eg), *P. patula* (Pp).

observed in the 10-20 and 20-40 cm depths apart from that under *C. lusitanica* was significantly lower than that under *P. patula* in the 60 cm depth ( $P < 0.05$ ). The concentration of  $Mg^{2+}$  did not exhibit variation in the 0-60 cm soil depth. But in the 10-20 cm depth  $Mg^{2+}$  under the Natural forest was significantly higher than plantation land uses. The concentration of both  $Ca^{2+}$  and  $Mg^{2+}$  decreased with depth in most plantation and NF sites with the exception of that under *Eucalyptus camaldulensis* and *E. globulus*. The soil under *E. camaldulensis* showed significantly higher  $Na^+$  concentration than that under *P. patula*, *E. saligna* and *C. lusitanica*. The overall concentration of  $Na^+$  under plantations established on previously cultivated lands tends to be higher than that under plantations established on primary forest lands (Table 3).

Soils under all land use types (plantation and natural forest) did not show any significant difference in  $K^+$  concentration in the 0-10 cm and 40-60 cm depths. However, soils under *P. patula* exhibit significantly higher concentration than any of the land uses in the 10 to 20 cm depth ( $P < 0.05$ ). For the same depth, the  $K^+$  concentration in soils under *E. camaldulensis* was also significantly higher than that of under the natural forest. But in the 20 to 40 cm depth  $K^+$  under *P. patula* was only significantly higher than that under the NF (Table 3).

The CEC in the surface layers (0-10 cm depth) did not significantly differ under either plantations or NF. But in the 10-20 cm depth, the CEC of soils under *E. globulus* was significantly lower than that under *P. patula*, *E. saligna*, *J. procera* and NF ( $p < 0.05$ ). In the 20-40 cm depth, the CEC of soils under *E. globulus* was only significantly lower than that under the NF (Table 3).

The electrical conductivity (EC) of soils under *E. camaldulensis* in the 0-10 cm depth was significantly lower than that under the natural forest ( $P < 0.05$ ). But no such significant difference was observed in the 10-20 cm depth among any plantation land uses including the natural forest (Table 3). The EC of soils under *J. procera* was significantly higher than that under the remaining plantations. A similar trend was also observed in the 40-60 cm depth (Table 3). In the 0-10 cm depth, the exchangeable acidity (H) of soils under *E. camaldulensis* was significantly higher than the rest of land uses including the NF ( $< 0.05$ ).

Table 3. Exchangeable cations and CEC under plantation sites

Variables	Depth (cm)	Species													
		Eg	Ec	Pp	Es	Cl	Jp	NF							
Ca <sup>2+</sup> (cmol kg <sup>-1</sup> )	10	6.5 (0.23) b	6.9 (1.13) b	15.7 (0.85) ab	19.2 (3.25) ab	19.4 (3.34) ab	22.7 (1.96) a	21.4 (6.98) ab							
	20	6.3 (0.68) a	8.0 (0.84) a	14.4 (1.11) a	12.2 (2.34) a	8.1 (2.39) a	14.6 (2.94) a	13.5 (2.38) a							
	40	7.8 (0.65) a	9.3 (0.53) a	13.9 (1.39) a	9.1 (0.90) a	6.9 (1.26) a	12.0 (0.71) a	14.4 (5.10) a							
	60	8.9 (0.36) ab	9.8 (0.42) ab	12.5 (1.13) a	7.6 (0.50) ab	5.3 (0.95) b	10.7 (1.49) ab	10.6 (2.93) ab							
Mg <sup>2+</sup> (cmol kg <sup>-1</sup> )	10	1.7 (0.06) a	1.9 (0.07) a	2.8 (0.14) a	3.5 (0.41) a	2.9 (0.33) a	3.9 (0.30) a	4.1 (1.32) a							
	20	1.3 (0.08) b	1.5 (0.10) b	1.8 (0.13) b	2.4 (0.32) b	1.8 (0.22) b	2.6 (0.55) b	3.6 (0.34) a							
	40	1.5 (0.21) a	2.0 (0.19) a	2.3 (0.34) a	3.3 (1.18) a	3.0 (0.19) a	2.7 (0.10) a	3.6 (0.58) a							
	60	2.0 (0.24) a	2.8 (0.14) a	3.2 (0.30) a	2.6 (0.48) a	3.0 (0.33) a	3.1 (0.21) a	3.7 (0.71) a							
K <sup>+</sup> (cmol kg <sup>-1</sup> )	10	1.4 (0.07) a	1.5 (0.15) a	1.7 (0.21) a	1.0 (0.18) a	1.1 (0.05) a	1.6 (0.24) a	1.8 (0.54) a							
	20	1.1 (0.06) bc	1.2 (0.06) b	1.9 (0.06) a	0.9 (0.23) bc	0.8 (0.19) bc	1.2 (0.13) bc	0.6 (0.11) c							
	40	0.7 (0.09) ab	0.8 (0.15) ab	1.7 (0.37) a	1.0 (0.36) ab	0.4 (0.11) b	1.3 (0.26) ab	0.5 (0.16) b							
	60	0.7 (0.09) a	0.8 (0.09) a	1.3 (0.29) a	1.2 (0.56) a	0.3 (0.10) a	0.7 (0.16) a	0.8 (0.40) a							
Na <sup>+</sup> (cmol kg <sup>-1</sup> )	10	0.1 (0.01) a	0.2 (0.01) a	0.1 (0.01) a	0.1 (0.02) a	0.1 (0.04) a	0.1 (0.04) a	0.1 (0.02) a							
	20	0.1 (0.03) ab	0.2 (0.01) a	0.1 (0.02) b	0.1 (0.02) b	0.1 (0.04) b	0.2 (0.02) ab	0.2 (0.01) ab							
	40	0.1 (0.02) ab	0.2 (0.00) ab	0.1 (0.01) b	0.1 (0.01) b	0.1 (0.03) b	0.1 (0.03) ab	0.2 (0.05) a							
	60	0.2 (0.03) ab	0.2 (0.02) ab	0.1 (0.01) b	0.1 (0.02) b	0.1 (0.03) b	0.2 (0.03) ab	0.2 (0.03) a							
H <sup>+</sup> (cmol kg <sup>-1</sup> )	10	1.9 (0.66) b	8.3 (0.97) a	1.7 (1.19) b	4.7 (2.36) b	3.0 (0.49) b	0.0 (0.00) b	0.4 (0.42) b							
	20	1.5 (0.62) a	4.9 (1.57) a	0.0 (0.00) a	3.2 (1.67) a	3.5 (1.90) a	1.6 (1.60) a	1.7 (1.74) a							
	40	0.8 (0.48) a	2.2 (1.64) a	0.0 (0.00) a	1.3 (1.05) a	5.4 (2.41) a	0.6 (0.56) a	1.6 (1.60) a							
	60	0.0 (0.00) a	1.4 (1.39) a	0.0 (0.00) a	2.6 (1.50) a	5.5 (1.69) a	3.3 (2.05) a	2.0 (2.01) a							
CEC (cmol kg <sup>-1</sup> )	10	11.7 (0.73) a	18.8 (1.17) a	22.0 (1.90) a	28.5 (1.60) a	26.5 (4.07) a	28.2 (2.42) a	27.8 (7.61) a							
	20	10.4 (1.19) b	15.8 (1.63) ab	18.2 (1.13) a	18.8 (1.60) a	14.2 (1.43) ab	20.1 (2.87) a	19.6 (0.65) a							
	40	11.1 (0.73) b	14.5 (1.04) ab	18.0 (0.96) ab	14.7 (1.39) ab	15.8 (1.21) ab	16.7 (0.97) ab	20.4 (4.22) a							
	60	11.7 (0.39) a	14.9 (0.81) a	17.2 (0.80) a	14.0 (1.97) a	14.2 (1.90) a	18.0 (1.12) a	17.3 (1.81) a							
EC (1:2.5 H <sub>2</sub> O, mS cm <sup>-1</sup> )	10	0.2 (0.05) ab	0.1 (0.03) b	0.2 (0.05) ab	0.2 (0.04) ab	0.5 (0.07) a	0.3 (0.03) ab	0.4 (0.13) a							
	20	0.1 (0.02) a	0.1 (0.02) a	0.1 (0.04) a	0.1 (0.01) a	0.1 (0.00) a	0.2 (0.04) a	0.1 (0.02) a							
	40	0.1 (0.02) b	0.0 (0.00) b	0.1 (0.04) b	0.1 (0.02) b	0.1 (0.01) b	0.2 (0.07) a	0.2 (0.02) ab							
	60	0.1 (0.02) ab	0.0 (0.00) b	0.1 (0.05) ab	0.1 (0.03) ab	0.1 (0.01) ab	0.2 (0.06) a	0.2 (0.05) ab							

Means in a row followed by the same letter do not differ significantly among species (P<0.05). values in the parenthesis represent standard errors, n=3.

Eg	<i>E. globulus</i>	Es	<i>E. saligna</i>	NF	Natural Forest
Ec	<i>E. camaldulensis</i>	Cl	<i>C. lusitanica</i>		
Pp	<i>P.patula</i>	Jp	<i>J. procera</i>		

## Soil quality index

The weights of the indicators  $W_i$  and the membership values  $Q(X_i)$  used to assess SQIs reflects the relative soil quality of different land uses. The weighted average value ( $W_i$ ) and the membership values  $Q(X_i)$  for the selected soil properties are shown in Fig. 3A and Table 4 respectively. The iterated PCA analysis showed that the first three PCs with eigen values  $> 1$  explains 79 % of the variability. The final PCA based selection of soil property variables for SQIs were air volume at -10 kPa matric potential (fa), exchangeable potassium ( $K^+$ ), pH, infiltration rate (IR), SOC, available phosphorus (av.P), AWC (%) and BD. The weighted eigen values of these soil property variables ranged from 0.09 to 0.14 (Fig. 3A).

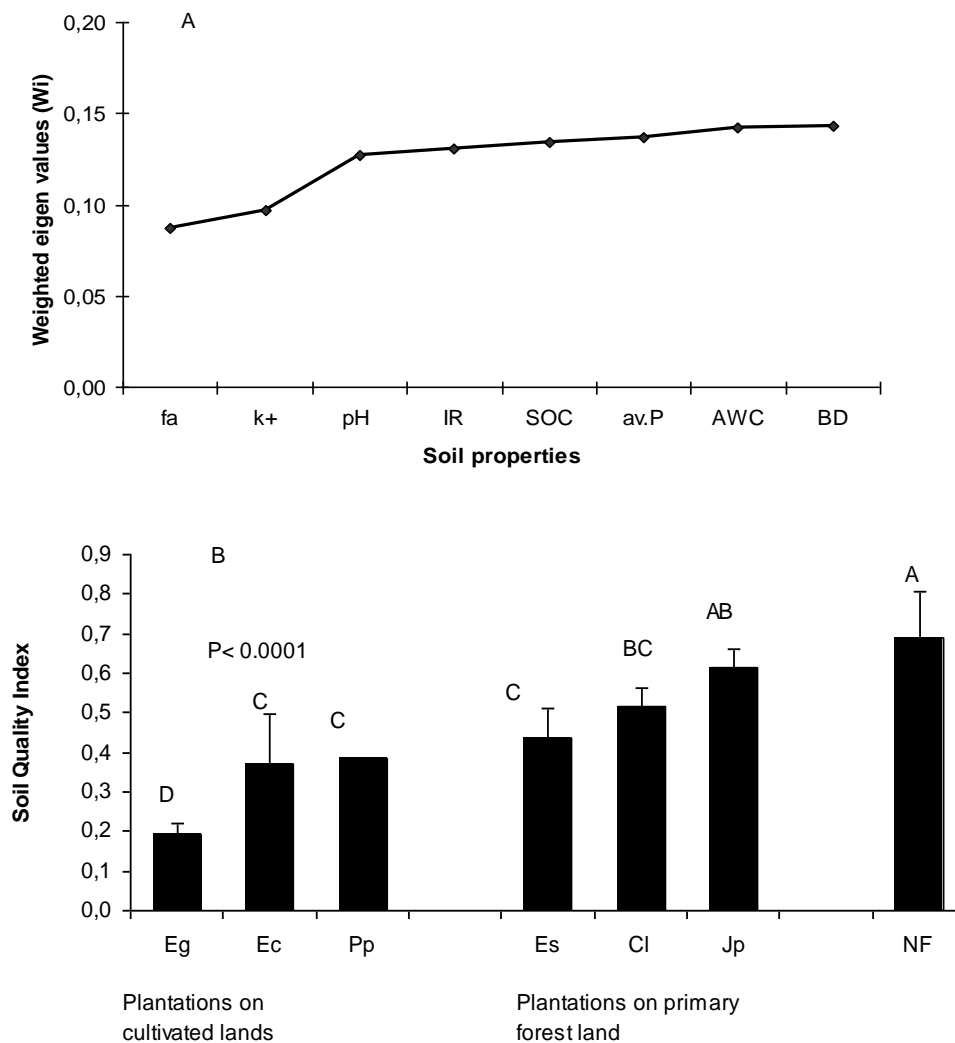


Fig.3. A) Weighted vector  $i$  of soil quality factors, air volume(fa), Potassium ( $k^+$ ),soil acidity (pH),infiltration rate(IR), soil organic carbon (SOC), available P (av.P), available water capacity (AWC) and soil bulk density ( BD) and B) Soil quality index (SQIs) under Plantation land uses where *E.globulus*=Eg, *E. camaldulensis* =Ec, *P. patula* = Pp, *E. saligna* =Ec, *C. lusitanica* = Cl, *J. procera* = Jp and natural forest = NF. Means followed by the same upper case letter do not differ significantly among species ( $P < 0.05$ ).



Table 4. Means and their scoring functions (0-10 cm depth) of the selected SQI soil physical and chemical properties under plantation land use types.

Soil properties	Species													
	Eg		Ec		Pp		Es		Cl		Jp		NF	
K cmol (kg <sup>-1</sup> )	1.42	(0.07)	1.53	(0.15)	1.73	(0.21)	0.98	(0.18)	1.11	(0.05)	1.56	(0.24)	1.83	(0.54)
Linear score function (Q k)	0.37	(0.13)	0.50	(0.14)	0.68	(0.24)	0.44	(0.44)	0.14	(0.10)	0.45	(0.22)	0.69	(0.31)
Available P (cmol kg <sup>-1</sup> )	1.47	(0.32)	1.45	(0.15)	4.12	(0.58)	6.63	(2.20)	5.27	(0.93)	4.64	(0.83)	6.95	(2.75)
Linear score function (Q av.P)	0.03	(0.02)	0.06	(0.06)	0.41	(0.13)	0.69	(0.22)	0.59	(0.23)	0.43	(0.06)	0.62	(0.20)
pH(1:2.5)	5.21	(0.26)	5.48	(0.19)	5.57	(0.19)	5.43	(0.15)	5.46	(0.18)	5.91	(0.11)	6.33	(0.29)
Linear score function (Q pH)	0.14	(0.09)	0.38	(0.12)	0.51	(0.25)	0.15	(0.13)	0.20	(0.13)	0.65	(0.12)	0.94	(0.06)
Soil organic carbon (SOC %)	3.37	(0.20)	3.84	(0.14)	5.60	(0.48)	5.51	(0.71)	5.79	(0.67)	7.03	(1.02)	10.18	(1.55)
Linear score function (Q SOC)	0.00	(0.00)	0.07	(0.01)	0.37	(0.11)	0.39	(0.14)	0.40	(0.14)	0.55	(0.14)	1.00	(0.00)
Bulk density (g cm <sup>-3</sup> )	1.14	(0.06)	0.92	(0.09)	1.13	(0.03)	0.86	(0.06)	0.72	(0.04)	0.74	(0.03)	0.80	(0.05)
Linear score function (Q BD)	0.07	(0.07)	0.57	(0.15)	0.07	(0.07)	0.66	(0.16)	0.92	(0.06)	0.92	(0.08)	0.75	(0.06)
Average infiltration rate (IR) (cm hr <sup>-1</sup> )	4.31	(1.46)	13.76	(6.57)	8.52	(3.57)	9.24	(2.49)	35.97	(7.59)	20.65	(5.96)	25.94	(4.92)
Linear score function (Q IR)	0.04	(0.03)	0.26	(0.14)	0.19	(0.13)	0.21	(0.09)	0.91	(0.09)	0.58	(0.22)	0.72	(0.22)
Available water capacity (AWC %)	26.88	(1.52)	24.40	(3.18)	26.58	(1.47)	20.81	(1.19)	17.89	(0.99)	25.64	(5.24)	20.93	(3.21)
Linear score function (Q AWC)	0.79	(0.17)	0.64	(0.29)	0.77	(0.18)	0.34	(0.15)	0.12	(0.12)	0.61	(0.31)	0.37	(0.32)
Air volume (%) (at -10 kPa)	13.13	(2.67)	24.00	(7.39)	12.40	(1.54)	27.30	(4.11)	34.57	(2.77)	24.20	(6.22)	21.43	(4.82)
Linear score function (Q fa)	0.06	(0.03)	0.55	(0.27)	0.02	(0.02)	0.65	(0.18)	0.88	(0.06)	0.48	(0.28)	0.34	(0.20)

Values in parentheses are the standard errors (n=3)

Eg	<i>E. globulus</i>	Es	<i>E. saligna</i>	NF	Natural forest
Ec	<i>E. camaldulensis</i>	Cl	<i>C. lusitanica</i>		
Pp	<i>P. patula</i>	Jp	<i>J. procera</i>		

The SQI under all plantation species except *J. procera* (*Jp*) was significantly lower compared to that under NF (NF) ( $p < 0.0001$ ). Similarly the SQI under *J. procera* was significantly higher compared to those of the other plantation species, except to that under *C. lusitanica* (Cl) (Figure 3B). But, significant difference was not observed in the SQI of that under *C. lusitanica*, *E. saligna* (Es), *P. patula* (Pp) and *E. camaldulensis* (Ec). The SQI of soil under *E. globulus* (Eg) was significantly lower compared to those of the other plantations species (Figure 3B).

Moreover, significant variation of SQIs was observed on a species genera basis among the coniferous, *Eucalyptus* and the NF groups ( $p < 0.0001$ ). The statistically significant difference was in the order of NF > coniferous species > *Eucalyptus* species (Table 5). Similarly, difference in the SQIs was statistically significant among plantations of different modes of establishment. In this category, the magnitude of the SQIs was in the order of NF > plantations established on primary forest land > plantations established on previously cultivated lands. But, the interaction between species category and land use history was not statistically significant (Table 5).

Table 5. Soil quality index (SQI) by genera and land use history.

<b>By Genera</b>		
Natural	Coniferous	Eucalyptus
0.69067a	0.50456b	0.33267c
<b>Plantation Establishment (land use history)</b>		
Natural	On primarily cultivated land	On previously cultivated land
0.69067a	0.52189b	0.31533c

Means in a row followed by the same letter do not differ significantly among species ( $P < 0.05$ )

## Discussion

### Soil physical properties

The results of this study indicate that the average infiltration rate and infiltration at steady state were higher for soils under plantations established on primary forest land compared to that under plantations established on cultivated lands. The values for steady state infiltration were  $3.7 \text{ cm hr}^{-1}$  and  $26.7 \text{ cm hr}^{-1}$  for *E. globulus* and *C. lusitanica* respectively. The surface soil layers of 0-15 cm depth under *C. lusitanica* were sandy loam to clay loam of pumice nature. The higher value of infiltration at steady state of soils under this species may be attributed to larger pore volume of the capillaries which may be consistent with Poiseuille's law that relates the rate of flow to the fourth power of capillary radius (Hillel, 1982) and some preferential flow through bio-pores such as root channels and earthworm burrows with radius  $> 1 \text{ mm}$  (Brady and Weil, 2004). The lower value of both average infiltration and steady state infiltration for soils under plantations established on previously cultivated lands may indicate that the effect of disturbance of soil due to plowing decades

ago still persists. The reduced infiltration capacity in disturbed soils is consistent with the observation made by others (Bharati et al., 2002;Tuli et al., 2005;Yimer et al., 2008). For example, Tuli et al. (2005) reported that the permeability of both air and water was greatly reduced for the disturbed soil samples, especially for air permeability in soil due to its greater dependency on soil aggregation and structure. On the other hand this study indicates that the percent volume of water at -1500 kPa matric potential in soils under plantations established on primary forest land is higher compared to that established on previously cultivated lands. The observed range of water volume at -1500 kPa matric potential is consistent with the range reported by Hikmatullah, (1999) for the properties and classification of andisols developed from volcanic ash in the Tondano area, North Sulawesi. The soils under eucalyptus plantations and *P. patula* had higher BD compared to those under other plantations and the NF. Similar results were reported by Bewket and Stroosnijder (2003), who concluded that soil BD under *Eucalyptus* was higher than soils under NF, cultivated lands and grazing lands at Chemoga watershed of Blue Nile basin, Ethiopia.

### **Chemical properties (exchangeable cations)**

Soil chemical indicators are used mostly in the context of nutrient relations and may therefore be referred to as “indices of nutrient supply” (Schoenholtz et al., 2000a). This study revealed that the exchangeable  $\text{Ca}^{2+}$  in soils under *Pinus patula*, *E. saligna*, *C. lusitanica*, *J. procera* and NF decreased with depth, while under *E. globulus* and *E. camaldulensis* it increased. The distributional trend of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  along the depth followed the pH distribution for similar depth and sites reported earlier by Wele et al., (2009a). The results are also consistent with those reported for the soils of Bale mountains, Ethiopia (Yimer et al., 2006). The distribution of  $\text{K}^+$  along the 0-60 cm depth was in descending order with the highest accumulation at the 0-10 cm depth in all land use types. The lower  $\text{K}^+$  concentration in the sub surface horizon may be attributed to root absorption. The  $\text{K}^+$  is involved in water relations, charge balance, and osmotic pressure in cells and across membranes, which explains its high mobility in plants (Havlin et al., 2009). The higher concentration of  $\text{K}^+$  in the surface horizon of 0-10 cm depth, however, may be due to its release from the decomposed detritus material continuously supplied from plantation species (Palm and Sanchez, 1990). In contrast to  $\text{K}^+$  distribution,  $\text{Mg}^{2+}$  was in ascending order with the highest concentration being in the lower 60 cm depth across the land use types which may be the result of leaching from the surface horizon or weathering of the parent material.

The concentration of individual exchangeable cations was in the order of  $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$  in all soils under all plantation land use systems including the NF. The magnitude of exchangeable cations of soils under plantations established on previously cultivated lands was lower compared to that established on primary forest lands, which may be due to the soil disturbance resulted from plowing long time ago. The distribution of CEC along the 0 to 60 cm depth was in descending order similar to that of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , the highest values being at the upper surface layer. The mean CEC ( $\text{cmol kg}^{-1}$ ) in the 0-10 cm soil depth ranged from 11.7 in soils under *E. globulus* to 28.5 under *E. saligna*. The decreasing trend with soil depth in all plantations and the NF lands coincides with the depth-wise distribution trend of SOC reported in Wele (2009a). The results are in accord with those reported for similar soils by other researchers (Eshetu et al., 2004;Yimer et al., 2006) in that soils with higher SOC contents have higher CEC and the vice versa.

## The soil quality index

The SQIs under *Eucalyptus* species were lower than those under coniferous plantations. This trend may be ascribed to the fast growing nature of the *Eucalyptus* species that may intensively absorb soil nutrients as well as the frequent harvest and transportation of woody material out of the system. The whole tree harvesting together with the short harvest cycles, often with leaves intact, results in a nutrient depletion that is far greater than for conventional forest harvests (Heilman and Norby, 1998). Within *Eucalyptus* species, *E. globulus* and *E. camaldulensis* had lower value of SQIs than any of other plantations. This trend may be attributed to their management as coppice harvested in short periods of time; every 7-10 years depending on the size of the woody material needed. On the other hand, the higher value of SQI under *E. saligna* compared to *E. globulus* and *E. camaldulensis* could be attributed to the difference in their mode of establishment and rotation period. *Eucalyptus saligna* was established on undisturbed primary forest lands and was not harvested since its establishment. Soil nutrients are accumulated and recycled through the addition of litter from the standing plantation crops. However, the accrual of soil quality variables such as SOC via detritus material is a slow process, and one way of achieving it is by less intense harvest through prolonged rotation periods.

Conversion of crop land to forest plantation land use implies that the annual cycle of cultivating and harvesting crops is replaced by a much longer forest cycle (Six et al., 2000; Vesterdal et al., 2002). Such management has probably enabled the accumulation of more biomass under *E. saligna* established on the undisturbed soil and the prolonged rotation period relative to the coppice management in which the *E. globulus* and *E. camaldulensis* have endured. In cultivated lands, soil nutrients were exhausted by crops and the disturbance of soil physical parameters may also take longer to be restored, thus making the effect of *E. globulus* and *E. camaldulensis* slower (Post and Kwon, 2000b). Tillage, in addition to mixing and turning the soil, disrupts aggregates and exposes organo-mineral surfaces otherwise inaccessible to decomposers (Post and Kwon, 2000b). Under such management, continuously cultivated lands depleted 80-96 % of the initial forest derived SOC in sand, while depleting 73-85 % of SOC from the silt fraction of Wushwush and Munessa, Ethiopia (Solomon et al., 2002).

In contrast to *Eucalyptus* species, coniferous species are harvested after the 25-year rotation cycle, which may relatively allow improvement of soil quality parameters through nutrient recycling by root absorption from the subsoil and by litter fall and decomposition on the surface of the soil. The length of the rotation also reduces the intensity of soil nutrient transport from the site and exposure of the soil to agents of degradation between harvest and restocking. Nevertheless, the soils under plantation species established on previously cultivated lands (*E. globulus*, *E. camaldulensis* and *P. patula*) had lower values of SQIs compared to those established on primary forest lands (*J. procera*, *C. lusitanica* and *E. saligna*). Soils under *J. procera* and *C. lusitanica* established on undisturbed primary forest land showed no sign of degradation since their SQIs are above the base line value (0.5).

## Conclusion

The results of this study indicate that the degraded soil physical and chemical properties under plantations established on cultivated lands did not recover to their original state, and they were consistently inferior to those of soils under plantation stands established on undisturbed forest soils. The value of soil quality below the baseline scoring function of soil properties under plantations established on previously cultivated lands indicate that the period requiring rehabilitation of the disturbed soil was not long enough. Plantations, especially *Eucalyptus* species, are managed as coppice harvested after 7 to 10 years. The short rotation period will not allow accumulation of SOC and other soil chemical nutrients as reflected by the results in this study. On the other hand, the sites under plantations established on undisturbed forest soils had lower SQI compared to that under the NF. In all plantations except *J.procera* established on primary undisturbed forest soil, soil quality decreased as compared to that under NF. Thus the data support the conclusion that proper selection and management of species and prolonging the rotation period would increase and sustain soil quality.

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