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Forest management options for carbon stock and soil rehabilitation in Chilimo dry afro-montane forest, Ethiopia

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FOREST MANAGEMENT OPTIONS FOR CARBON STOCK AND SOIL REHABILITATION IN CHILIMO DRY AFRO-MONTANE FOREST, ETHIOPIA

Presentada por Mehari Alebachew Tesfaye por optar al grado de doctor por la Universidad de Valladolid

Dirigida por:

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Dr. Felipe Bravo Oviedo

Dedication

This thesis is dedicated to my beloved children
(Kidus Mehari and Yohanan Mehari)

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LIST OF ORIGINAL WORKS

This thesis is based on five original works which are presented in the text with Roman numerals (I, II, III, IV, V) i.e. one published, one accepted with major revision, one submitted and two manuscripts.

I. Tesfaye, A. Mehari, Bravo-Oviedo, A., Bravo, F., Kidane, B., Bekele, K., Sertse, D., 2014. Selection of tree species and soil management for simultaneous fuelwood production and soil rehabilitation in the Ethiopian Central Highlands. Land Degradation & Development (2014). Doi: 10.1002/idr/.2268 (Wiley online library.com).

II. Tesfaye, A. Mehari, Ruiz-Peinado, R., Bravo-Oviedo, A., Bravo, F., 2014. Aboveground biomass equations for sustainable production of fuelwood in a native dry tropical afro-montane forest of Ethiopia. Submitted to Annals of Forest Science, Springer.

III. Tesfaye, A. Mehari, Bravo, F., Ruiz-Peinado, R., Pando, V., Bravo-Oviedo, A., 2015. Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands. Accepted with major revision, Geoderma, Elsevier.

IV. Tesfaye, A. Mehari, Bravo, F., Bravo-Oviedo, A., 2015. Stand density management diagram for Chilimo dry afro-montane forest using species proportion in Central Highlands of Ethiopia. Manuscript.

V. Tesfaye, A. Mehari, Bravo-Oviedo, A., Bravo, F., Herrero, C., 2015. Variation in carbon concentration and wood density for five most commonly grown tree species in Ethiopia. A paper presented on 28th and 29th of January 2015: IX young researchers meeting on conservation and sustainable use of forest systems 2015, Valsaín-Segovia-Spain (Abstract published).

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Abstract

ABSTRACT

Five studies were conducted in Central Highlands of Ethiopia to generate alternative forest management options for carbon stock and soil rehabilitation in Chilimo dry afro-montane forest and adjacent land uses. A screening trial for fuel wood and rehabilitation of degraded lands was performed for four years (2005-2009) using: *Acacia decurrens*, *Acacia saligna*, *Chamaecytisus palmensis*, *Dombeya torrida*, *Eucalyptus globulus*, *Grevillea robusta* and *Hagenia abyssinica* under three soil management: control, manure and manure plus mulch. The experimental design was split plot, species as the main plot and treatments as subplot with three replicates. Data on survival rate, height growth and root collar diamater growth were taken annualy for selection experiment. Composite soil sampling was taken before and after intervension using augering method. Systematic random sampling technique was used for Chilimo natural forest under three forest patches: Chilimo, Gaji and Gallessa. One time inventory was conducted using 35 sampling plots in Chilimo dry afro-montane mixed natural forest and 9 plots in plantation. Both biometric and soil sampling data were collected in these plots. Data required for aboveground biomass equation, carbon concentration and wood density for *Allophyllus abyssinicus*, *Olea europea* ssp. *cuspidiata*, *Olinia rochetiana*, *Scolopia theifolia* and *Ruth glutinosa* were generated using distructive sampling. Soil chemical analyzed for % C, total N, P, K, Ca, Mg, pH and CEC following appropriate procedures. Carbon concentration in the plant samples was estimated using ash method, while volume for wood density was estimated using water displacement method. Biomass equations found in the literature were selected, evaluated and fitted. A species propotion was calculated to develop stand density management diagram for the Chilimo natural forest. A general linear model and general linear mixed model were used for data analysis with SAS software and graphing using R-software. Mean separation was performed using Tukey-Kramer test. Among the six tested tree and one shrub species tested *G. robusta* A. Cunn. Ex R. Br. showed maximum survival (100 %) followed by *H .abyssinica* (Bruce) J.F.Gmel. (93.52 %). *C. palmensis* (Christ.) Hutch and *H. abyssinica* (Bruce) J. F.Gmel were highly improved soil condition. *E. globulus* Labill. and *Acacia* spp presented the highest growth rates and biomass production. The above ground biomass and soil organic carbon and nitrogen stock for the Chilimo natural forest and adjacent land uses were known. Species and site specific above ground biomass equation models were found to be more accurate and reliable than using general equations. Diameter at breast height and total height were found to be the most independent fitting variables to predict the biomass. Consequently, dominant height and quadratic mean diame-

ter were found to be the best endogenous variables for stand density management diagram for Chilimo forest. The major factors affecting carbon and nitrogen concentration in the Chilimo natural forest and adjacent land uses were soil depth, land use type and species. The Chilimo native dry afro-montane forest stores 225.03 Mg C ha^{-1} in 1 m soil depth which can serve as sources of carbon stock for tropical forests. Morethan 80 % of 1 m carbon stock was stored on the first 50 cm soil depth. In addition, native forest stores more carbon (84.4 %, 26.4 %, and 33.7 %) than bare soil, crops and plantations. The carbon concentration found in the plant sample was varied within and among a species, stem position and plant parts. Stem parts stored more carbon (56.98 %) than branch (56.74 %) and leaves parts (54.53 %). *O. europaea* ssp. *cuspidiata* had higher (0.67 g cm^{-3}) wood density than others. *H. abyssinica* (Bruce) J. F. Gmel is recommended for soil rehabilitation, whereas, *G. robusta* A.Cunn. Ex R. Br. can be used for simultaneous fuelwood production and soil rehabilitation. *E. globulus* Labill can be planted for both soil rehabilitation and fuelwood production, although, care should be taken when planting in degraded areas. These forest management options can be applied in similar dry afro-montane forests found in the country.

RESUMEN

Se realizaron cinco estudios en la región Central HighlandEtiopía para generar alternativas de manejo forestal sostenible con los objetivos de secuestro de carbono y rehabilitación de suelos degradados en un bosque seco afro-montano. Se comparótambiénel efecto de cambio usos, en concreto plantaciones y cultivos. El primer estudio (2005-2009) tuvo por objetivo la elección de especies para producción de leñas y recuperación de suelo degradado. Las especies utilizadas fueron*Acacia decurrens, Acacia saligna, Chamaecytisus palmensis, Dombeya torrida, Eucalyptus globulus*, *Grevillea robusta* y *Hagenia abyssinica.* Se probaron tres alternativas de manejo (control, estiércol y abono más mulch). El diseño experimental fue split-plot, las especies formaron la parcela principal y los tratamientos sobre el suelo las subparcelas con tres repeticiones cada una. Los datos sobre tasa de supervivencia, crecimiento en altura y diámetro en el cuello de la raíz se tomaron anualmente. Se tomaron muestras de suelo al principio y al final del experimento. Para desarrollar las alternativas de manejo sostenible en bosques naturales y plantaciones se diseñó un muestreo aleatorio sistemático en el bosque de Chilimo. Se realizó un inventario en 35 parcelas 9 parcelas en plantaciones. Tanto los datos biométricos y de muestreo de suelo se recogieron en todas las parcelas. En el bosque natural se desarrollaron ecuciones de biomasa para estimar la cantidad de carbono almacenado en el suelo. Los datos necesarios para generar ecuaciones de biomasa aérea, concentración de carbono y la densidad de la madera para *A. Allophyllu*s, *Olea europea*. Spp. *cuspidiata*, *Olinia rochetiana*, *Scolopia theifolia* y *Ruth glutinosa* se obtuvieron utilizando un muestreo destructivo. Tamién se realizó une estudio de las propiedades edáficas de los suelos determinando el porcentaje de C, N total, P, K, Ca, Mg, pH y CIC siguiendo procedimientos adecuados. La concentración de carbono de las muestras especies forestales se estimó mediante el método de las cenizas, mientras que el volumen se calculó utilizando el método de desplazamiento de agua. . Dentro del bosque natural se seleccionaron las especies principales para desarrollar un diagrama de manejo de densidad. Un modelo lineal general y un modelo lineal mixto se utilizaron para el análisis de datos con el software SAS y la representación gráfica utilizando R-software. La comparación de medias se realizó mediante la prueba de Tukey-Kramer. Los resultados de los estudios demuestras que, de las seis especies de árboles y un arbusto probados *G. robusta* A. Cunn. Ex R. Br. mostró la máxima supervivencia (100%) seguida de *H .abyssinica* (Bruce) JFGmel. (93,52%). *E. globulus* Labill. y *Acacia* spp presentaron la mayor tasa de crecimiento y la producción de biomasa. *H. abyssinica* (Bruce) JF Gmel se recomienda para la rehabilitación del suelo, mientras que, *G. robusta*

A.Cunn. Ex R. Br. puede ser utilizada simultánea para la producción de leña y la rehabilitación de suelos. *E. globulus* Labill se puede plantar tanto para la rehabilitación del suelo como para la producción de leña, aunque. Los modelos de biomasa aérea específicos de cada especie y sitio fueron más precisos y fiables que las ecuaciones generales. Diámetro a la altura del pecho y altura total resultaron ser las variables independientes que mejor preciden la biomasa aérea. Los principales factores que afectan a la concentración de carbono y nitrógeno en el bosque natural Chilimo y usos de la tierra cercanos fueron la profundidad del suelo, tipo de uso de la tierra y las especies. Los bosques secos afro-montanos nativos de Chilimo almacenan 225.03 Mg C ha^{-1} a 1m de profundidad del suelo, que puede servir como fuentes de carbono de los bosques tropicales. Más de 80% de stock de carbono almacenado hasta 1m de profundidad se concentra en los primeros 50 cm de suelo. Además, el bosque nativo almacenó más carbono (84,4%, 26,4% y 33,7%) que el suelo desnudo, cultivos y plantaciones respectivamente. La altura dominante y el diámetro medio cuadrático resultaron ser las mejores variables endógenas para los diagramas de manejo de densidad del rodal de bosque Chilimo. La concentración de carbono varía dentro y entre especies, así como en la posición del fuste y componentes muestreados. El fuste almacenó más carbono (56,98%) que en las ramas (56,74%) y las hojas (54,53%). *O. europaea* ssp. *cuspidiata* tuvo la mayor (0,67 g cm-3) densidad de la madera entre todas las espcies. La densidad de la madera disminuyó con la altura del fuste. Estas opciones de manejo forestal se pueden aplicar en los bosques afro-montanos secos similares que se encuentran en el país.

Introduction

1. INTRODUCTION

1.1. African forest resources, the case of Ethiopia

According to FAO (2010) the total world forest area is 3.952 billion hectares. Forests and woodlands occupy 675 million hectares (23 %) in Africa, which accounted for (16.8 %) of the global forest cover. Africa's forest and woodlands are classified into: tropical rainforests, tropical moist forests, tropical dry forests, tropical shrubs, tropical mountain forests, subtropical humid forests, subtropical dry forests, subtropical mountain forest and plantations (FAO, 2010). The distribution and species composition of these forests depends on the rainfall pattern and varies along the regions of Africa. Central Africa has the densest forest cover while, Northern Africa have the least forest cover (FAO, 2010). Tropical moist forests are widely found in coastal areas of west Africa and equatorial central Africa, where there is abundant rainfall and low dry season including: Cameroon, Central Africa Republic, Congo, Equatorial Guinea and Gabon. These countries accounted 60 % of the tropical moist forest. However, Mali, Niger, Chad and Sudan (Sahara Desert) in the north and Botswana (Kalahari Desert) in the south (Narendra *et al*., 1994) are widely dominated by deciduous and open woodland and gradually bend to grassland and finally desert. The forests and woodland coverage of eastern Africa is 13 % (UNEP, 2002). Kenya has the largest forest and woodland coverage (30 %) followed by Uganda (21 %). Djibouti has the lowest forest cover (0.3 %) (FAO, 2005). The natural high forest coverage of Ethiopia is 2.7 % but with the inclusion of woodlands and plantation forest the Ethiopian forest coverage is 10 % (Nyssen *et al*., 2004; Moges *et al*., 2010). Planted forest area is 14.8 million hectares and these represent 5 % of the global total (FAO, 2010).

Dry forests cover a spectrum of vegetation types from deciduous forests with a continuous tree canopy to moist savanna, dry deciduous woodlands, dry savannas and dry scrubland. They constitute one of the major terrestrial ecosystems, existing in all developing regions of the world: Africa, Asia and Latin America. Proportionally, they are the most prominent in Africa, where drier forests in all their varieties from the desert margin scrub to closed woodland to deciduous forests-support the most people, livestock and wildlife. Dry forest, woodlands and savanna which surround the major agricultural belt are fairly open and have low productivity. They are, however, the dominant vegetation cover 63 % of the Sub-Saharan African countries (Chidumayo, 2004). According to

CIFOR (2007), dry forests are found in a band across Africa from Senegal in the west making a loop around the Congo basin, to Ethiopia in the east and South Africa in the south.

Forests in Africa provide energy, food, timber and non-wood forest products (NWFPs) and are important contributors to wealth and health of the household at community, national, sub regional and regional levels. Wood fuels are the primary energy sources in Sub-Saharan Africa and over 70 % of the continent population depends on forest resources (AFDB, 2003). Forests and woodlands are also important for combating land degradation, mitigation of climate change, conservation of wet lands, coastal area and freshwater ecosystems. The forests are also contributing 10 % to 70 % of the gross domestic product (GDP) in the Sub-Saharan African countries and from 5.5 to 9.0 % for the Ethiopian economy (FAO, 2010; Mekonnen *et al*., 2012).

However, African forests and trees are seriously threatened by agricultural expansion, commercial harvesting, increasing exploitation of fuelwood and other products and increasing urbanization and industrialization. All these problems are aggravated due to inadequate land use planning, inappropriate agricultural systems and drought.

Although, Africa is not a major emitter of CO_2 and other greenhouse gases from commercial and industrial energy uses, it accounts about 20-30 % of CO_2 emission due to deforestation and land use cover change (IPCC, 2013). To reduce deforestation and land degradation in the country, Ethiopia has been implemented REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and now it is a REDD+ participant country to the Forest Carbon Partnership Facility (FCPF) of the World Bank (Moges and Tenkir, 2014). Even Ethiopia has developed the first carbon project under clean development mechanism (CDM) in Humbo (Welaita) before REDD+. Nowadays, there are regional REDD+ projects like Bale and Keffa biosphere reserve REDD+ projects (Moges and Tenkir, 2014). Chilimo dry afro-montane forest might be also part of the REDD+ project in the future.

Sustainable management of the vast and diverse African natural forest resources is proving to be extremely challenging. In addition, there are only little information on the biophysical aspect of the natural forest, estate and the properting and end use of the various tree species. The existing informations are lower in quality and quantity to make rational decision for sustainable management and utilization of the forest resources in the continent.

1.1.1. Ethiopian forests

Ethiopia occupies the interior of the horn of Africa stretching between 3° and 15 °N and 33° and 48 °E. It covers a total area of 1.13 million km^2 (CSA, 2000) that spands over a wide range of altitude, from 110 m below sea level to over 4600 m above sea level. The presence of wider altitudinal coverage enhances the diversity of climate, topography, soil type and vegetation resources.

Ethiopian is endowed with various landscape types resulted in different agroecological zones and vegetation types of the country. The vegetation types varied from tropical rain forest and cloud forests in the southwest to the desert scrubs in the east and northeast and diversified agroforestry practices and systems in the central highlands (Bongers and Tennigkeit, 2010). The structure and species composition of the natural vegetation types are also diverse due to the presence of wider physiognomic and climatic landscapes in the country. Ethiopia is among the top 25 biodiversity rich countries in the world. More than 7000 species of plants, 240 species of mammals and 845 species of birds are found in the country. Among this 1150 species of plants, 22 species of mammals and 24 species of birds are endemic (Bongers and Tennigkeit, 2010). The vegetation are important for production, protection and conservation functions in the country. They supply most of the wood products (industrial and non-industrial) consumed within the country and diverse non wood forest products (NWFPs) such as: wild coffee, gum, resin, honey, beeswax, herbal medicines and bamboo. They also provide various ecosystem services such as watershed protection, biodiversity conservation and carbon sequestration. The vegetation ecosystem in the Ethiopian plateau and mountains are the sources of a number of great rivers including one of the longest river in the world, Blue Nile and other big rivers in the country such as: Omo, Awash and Wabishebele Rivers.

Generally the natural vegetation types of Ethiopia is classified into 12 different major vegetation types based on altitudinal gradient (Friis *et al*., 2010): (i) Desert and semi-desert shrub land, (ii) *Acacia-Commiphora* woodland and bush land, (iii) Wooded grassland of the Western Gambela region, (iv) *Combretum-Terminalia* woodland and wooded grasslands, (v) Dry evergreen afro-montane forest and grasslands complex, (vi) Moist evergreen afro-montane forest, (vii) transition rainforest, (viii) Ericaceous belt, (ix) Afroalpine vegetation, (x) Riverine vegetation, (xi) Freshwater, lakes, lake shores, marshes, swamps and flood plain vegetation and (xii) Salt-water, lakes, lakes shores, salt marshes and plain vegetation.

The natural high forests of Ethiopian are mainly found in the highlands where annual rainfall distribution and amount is better. The Highlands cover 44 % of the country's total land area accommodate 90 % of total human population, 93 % of the cultivated land and 75 % of the country's livestock population. Dry afro-montane forests and moist afro-montane forests are the dominant vegetation types found in the highlands. However, the dry afro-montane forests are the most dominant one in the central, northern and western Highlands.

The dry afro-montane forests are dominated by both broadleaved and coniferous species such as: *Juniperus procera, Podocarpus falcatus* and *Olea europaea* ssp. *cuspidiata* e.g. Chilimo, Menagesha-Suba, Wefwasha and Munessa-Shashemene forests. While, the moist montane forest are mainly found in the southern and southwestern parts of the country and are dominated by large broadleaved and soft-leaved species such as: *Aningeria adolfi-friendercii, Olea welwitschii, O. hockstetter* and *Croton macrostachys* (Bekele, 1994 and 2003; Woldemariam, 1998; Kelbessa and Soromessa, 2004; Kassa *et al*., 2008; Shumi, 2009) where relatively higher rainfall is found (Bekele, 1994).

Dry evergreen montane forests are very complex vegetation type occurring in areas of relatively high humidity, with limited and unreliable rain and prolonged dry season. During the dry season, temperature increases and day time humidity drops down and water courses either dry up or greatly diminish inflow (Teketay, 1996). Besides, dry afro-montane areas are inhabited by the majority of the Ethiopian population and represent a zone of sedentary cereal based mixed agriculture for centuries.

Man made plantation forests are also another form of forests widely practiced and found in the country. The dominant plantation forests are composed of four genera (*Eucalyptus, Cupressus, Pinus* and *Acacia*). *Eucalyptus* accounts for, the lion's share of the plantation forest in the country (90 %) followed by *Cupressus lusitanica*, *Juniperus procera* and *Pinus* spp, respectively (WBISPP, 2005; Moges *et al*., 2010; Bekele, 2011). *Eucalyptus* is also the first exotic tree species to be formally introduced to Ethiopia by Emperor Minilik II from Australia in 1890s (Pukkala and Ponjonen, 1989 and 1993; Bekele, 2003). Sixty different species of genus of *Eucalyptus* are reported to have been introduced to Ethiopia, but *E. globulus* and *E. camaldulensis* are the most wide spread of all (Lemenih and Kassa, 2014). The area coverage of *Eucalyptus* plantation steadily increased since its introduction, for example it was only 5000 hectares in 1890s (Getahun, 2010) and increased to 896, 240 hectares in 2011 (Bekele, 2011).

1.2. Land degradation and deforestation in Ethiopia

Forests contribute directly to the livelihood of 1.2 billion people living in the developing nations (90 %) from the total population and 38 % of the total energy requirement in these nations is also directly obtained from forest biomass (Sims, 2003).

Historical studies on forests showed that, forest depletion occurred when the society under go economic development, industrialization and urbanization (Rudel *et al*., 2005; Amarcher *et al*., 2009). Deforestation and land degradation are the major environmental problems facing developing countries (Africa, Asia and Latin America) (Amarcher *et al*., 2009). In the 1980s and 1990s, the annual rate of deforestation had averaged 1 % worldwide with deforestation in tropical rainforest averaging 0.6 % (FAO, 2001) and between 1990 and 2000, more than 14.2 million hectares of tropical rainforests disappeared. Deforestation, land degradation and poor forest management reduce carbon storage in forests on the contrary, sustainable management, planting and rehabilitation of degraded lands increase carbon sequestration (FAO, 2010).

Sub-Saharan Africa (SSA) accommodates one of the world’s fastest growing populations and it is significantly affected by land degradation because of deforestation, poor land management and conversion of fragile natural habitats into fields for crops. The forest area in East Africa was reduced by 783,000 hectares between 2000 and 2010: equivalent to an annual loss rate of 1.01 % (FAO, 2011). Shortage of forest products, loss of soil fertility and disruption of the water cycle are followed by poverty, hunger and social unrest in the region (Barrowclough and Ghimire, 1996). This general layout is similar to other tropical and sub-tropical areas and has made restoration of degraded lands as an essential challenge. John *et al*. (1997) identified some of the factors that act as a catalyst of such situation: intensive crop expansion, over-grazing and unsustainable fuel wood harvesting. Wood fuels are also the primary energy sources in Sub-Saharan Africa, accounting for approximately 70 % of total energy use and contributed to directly for deforestation and indirectly to land degradation in these region.

Like wise to other Sub-Saharan African countries Ethiopia faces deforestation and land degradation as the major environmental problems. This is due to reckless cutting of trees and shrubs for fuelwood, charcoal, construction wood, lumber and agricultural land expansion resulted from over population growth in the country. Hence, Ethiopia is one of the most populus country in Africa next to Nigeria with a total population of 90 million by 2015 (Bishaw, 2004; Berhe, 2004; Argaw, 2005; FDRE, 2011). Ethiopia is an agriculturaly based economic country located in eastern Africa.

Agriculture is the backbone of the country, accounted 47 % of the gross domestic product (GDP), 80 % of the employment opportunity and 60 % of the export item (Shiene, 2012). Similarly, 90 % of the total population is using forest biomass for energy (Alem *et al.*, 2010; FDRE, 2011).

Although, the remnants of dry afro-montane forests are found in the Highlands, majority of these forests are deforested due to the above mentioned problems (Lemenih *et al.*, 2008). For example, the annual deforestation rate in the country is estimated to be 150,000 to 200,000 hectares (Tadesse, 2001). Most of the natural forests and wood lands are located in these areas and are converted into bush lands and agricultural lands (Dubale, 2001; Teketay, 2001). Nowadays, in addition to Highlands, deforestation is also continuing in the lowlands due to agricultural expansion by investors and new settlements in these areas. For example from 2000 to 2008, agricultural lands were expanded by about 4 million hectares and 80 % of these new expansions were come from conversion of forest lands, woodlands and shrub lands. The demand is also expected to increase from 15 million hectares in 2008 to 34 million hectares by 2030, respectively (Brown *et al.*, 2010; EDRI, 2010). In addition, new threats such as: Land grabbing, biological invasion and climate change, which contributes to major forest depletion in the lowlands, are also emerged in the country (Tigabu *et al.*, 2014). Due to deforestation, there is acute shortage of fuelwood, charcoal, construction wood, timber and non-wood forest products in addition to disturbed ecosystem services (soil erosion, hydrological imbalance, loss of biodiversity etc…), in both Highlands and lowlands (Lemenih and Kassa, 2014).

Most parts of the soil found in the Highlands are degraded due to lack of vegetation cover and excessive soil erosion, annually 1.5 billion tonnes of top soil is eroded in the country (Tadesse, 2001), 27 million hectares representing approximately 50 % of the highlands are already significantly degraded and 14 million hectares are badly eroded. In two million hectares of the cultivated land, the soil depth is so reduced that the land is no longer able to support any vegetation cover. Fifty four percent of the remaining highlands are highly susceptible to erosion (Asmono *et al.*, 2002). A continental study commissioned by FAO in 38 Sub-Saharan Africa (SSA) countries, including Ethiopia showed that, Ethiopia is among the highest rates of nutrient depletion (Lemma *et al.*, 2006). The soil has become shallow as a result of persistence erosion that has been taking place for centuries (Zerihun, 1999).

Titilola (2008) reported the predominant cause of land degradation and soil erosion is excessive human pressure or poor management of the land specifically overgrazing, over-cultivation of cropland and deforestation. Currently, the seemingly combined objective of restoring vegetation cover and production of fuel wood is a key environmental issue. Besides, restoration of degraded forest lands and woodlands can be paving as other potential opportunity in the future for firewood production where the resources are available. However, a time lag will appears and the allowable harvested volume should be carefully determined in these regard.

Though, relentless efforts have been made to avoid land degradation in the country through tree planting and soil and water conservation measures, the problem is still continuing. Then, species selection for afforestation is crucial as the tree species may affect soil properties differently (Li *et al*., 2012). Other interim management solutions such as physical soil retention structures may be needed prior to establishing vegetation in degraded lands (Yitbarek *et al*., 2012). Exclosures have been identified as a valuable rehabilitation option when the main driver of land degradation is grazing (Mekuria and Aynekulu, 2011) or intense recreational use (Özcan *et al*., 2013). Both measures are expensive for local communities. Effective restoration practices should be based on local perceptions of soil erosion and should include easily available local management options (Kiome and Stocking, 1995). The application of manure has demonstrated to be positively affecting the infiltration capacity of soils and plant production on grazed lands at low cost (Tadesse *et al*., 2003). In addition, mulching can both enhance conditions for plant growth in harsh environments (Blanco-Garcia and Lindig-Cisneros, 2005) and protect topsoil against erosion (Roose and Barthés, 2001). Consequently, the correct selection of plant species and soil management is vital for both fuel wood production and soil rehabilitation (Figure, 1).

In recent years the fuel wood crisis that links deforestation with fuel wood consumption has been discarded as many of the harvest occurs on species growing “outside” the forest (Mahiri and Howorth, 2001). This pattern of fuel wood consumption is improved by householders ‘tree plantations’, where natural forests are scarce (Bewket, 2003). As a consequence, tree planting has emerged as a plausible option to fulfill the fuel wood demand (Lemenih and Bongers, 2010) but there may not be a link between tree planting and fuel wood consumption (Gebreegziabher and van Kooten, 2013). A wide research program is needed to fulfill the lacks of information regarding this issue.

(a). Initial stage (b). Initial stage (C). Land degradation

(d). Land preparation (e). After 1 year : *A. saligna* (f). After 1 year : *A. saligna*

(g). After 2 years: *A. saligna* (h). After 3 years: *G. robusta* (i). After 4 years : *C. palmensis*

Fig. 1: *Images from rehabilitation of degraded lands in the study areas*, *Fig.1 (a), (b), (c), (d), (e), (f)): Showed the status of a degraded land,land preparation ,tree planting and A. saligna after one year,(Fig.1 (g), (h), (i)) : Showed A. saligna, G. robusta and C. palmensis trees after two,three and four years planted under Debrelibanos site, Central Highlands of, Ethiopia.* **Photos by**: Mehari A. Tesfaye (2005-2009) (Debrelibanos, Ethiopia).

1.3. Carbon stock in tropical and Ethiopian forests

Human activities are increasing the stocks of greenhouse gases emitted to the atmosphere. As a result the current level of greenhouse gases in the atmosphere is raised from 280 to 430 ppm, causing the world to warm by more than 0.5 degree celsius and will lead further warming in the future (IPCC, 2013). Different measures are considered to solve the problem and among this, forests fix large amount of carbon in the process of photosynthesis and store it in the form of biomass. Carbon storage in forest ecosystems involves numerous components including biomass carbon and soil carbon (Annissa *et al*., 2013). As more photosynthesis occurs, more CO_2 is converted into biomass, reducing carbon in the atmosphere and sequestering it in plant tissue above and below ground (IPCC, 2003; Gorte, 2009) resulting in growth of different parts (Charon and Rasal, 2010). Biomass production in different forms plays an important role in carbon sequestration in trees (Charon and Rasa, 2012). Aboveground biomass, belowground biomass, deadwood, litter, stumps and humus are the major carbon pools in any forest ecosystem (FAO, 2005; IPPC, 2003 and 2007).

IPCC (2013) reported the global forests cover over 4 billion hectares and contribute around 50 % global greenhouse gas mitigation. The tropical forests spread over 13.76 million km^2 area worldwide accounted about 60 % of the global forest cover and store an estimated 193-229 Pg of carbon in aboveground biomass and recycling 915 Gt of carbon each year, through photosynthesis and net primary production (Brown, 1997; FAO, 2005; Millennium forest resources assessment report, 2005; Baccini *et al*., 2008) or roughly 20 times the annual emission from combustion and land use change (Friedlingstein *et al*., 2010). Tropical rain forests contribute substantially to the global carbon cycle accounting for 40 % terresterial net primary production, 60 % of forest biomass and 27 % of carbon stored in forest soils. Tropical dry forests constitute more than 40 % of all tropical forests, having a net terrestrial primary production of 40 %, stored 60 % carbon and contain half of world species (Mayaux *et al*., 2005; Miles *et al*., 2006; Chidumayo *et al*., 2011). Global climate change will further reduce rainfall intensity and seasonality in the tropics; this has a bigger impact on the livelihood of the people in the tropics including plant and animal species (FAO, 2006). Increament of atmospheric concentrations of CO_2 also affect plant metabolism directly through photosynthesis and this has altered the dynamics of tropical forests (Chidumayo *et al*., 2011). The factors limiting carbon sequestration capacity must be understood to predict the changing role of tropical forests in the global carbon cycle.

Soil is the largest carbon reservoirs of the terrestrial carbon cycle 1500-1550 Gt of organic carbon and soil inorganic carbon approximately 750 Gt both to 1 m depth. About three times more carbon is contained in soils than in the world's vegetation 560 Gt and soils hold double the amount of carbon that is present in the atmosphere 720 Gt (Post *et al* ., 2001; Lal, 2004b). Soils play a key role in the global carbon budget and greenhouse effect and it contains 3.5 % of the earth's carbon reserves, compared with 1.7 % in the atmosphere, 8.9 % in fossil fuels, 1.0 % in biota and 84.9 % in the oceans (Lal, 2004a). Carbon stocked in organic form in soils (SOC) is affected by environmental factors such as topography, parent material or soil depth (Fu *et al*., 2004; Johnson *et al*., 2000). Forest soils are subjected to lower human disturbance than agricultural soils and having lower bulk density than others soils due to the presence of higher organic matter content (Lal, 2005). Forest soils are part of any forest ecosystem and play a vital role in the global carbon cycle (Jabaggy and Jackson, 2000; Rooney, 2013). And, about 40 % of the total SOC of the global soils resides in forest ecosystem (Six and Jastrow, 2002; Baker, 2007).

The national carbon stock of Ethiopia was estimated to be 153 Tg C by Houghton (1998), 867 Tg C by Gibbs *et al*. (2007) and 2.5 Gt of C by Sisay (2010). Consequently, estimation of the natural high forest carbon stock was ranging between 101 Mg C ha^{-1} (Brown, 1997; Moges *et al*., 2010) and 200 Mg C ha^{-1} (Temam, 2010; Tsegaye, 2010). The discrepancy between these values is due to the different methods and tools used for the authors and the variability in soil, topography and forest types. Nevertheless, biomass equations and forest growth models are very scarce for Ethiopian condition, although, there are few works done by some authors (Zerfu, 2002; Embaye *et al*., 2005; Woldeyohannes, 2005; Mamo and Sterba, 2006; Zewdie *et al*., 2009). Thus, localized carbon stocking assessment works should have been made in these regards (IBC, 2005; Moges *et al*., 2010).

Majority of the high forests found in Ethiopia are managed primarily for protection and conservation pupose while commercial utilization is secondary objective, in light of the status of the remaining natural high forests and the national overall objectives, the forestry administration at the Federal level has classified 58 of the most important high forest areas totaling an estimated area of 2 million hectares as National Forest Priority Areas of the country (NFAs). Over two-third of these high forests are heavily disturbed forest and needs appropriate management. The estimated annual height and diameter growth for these forests is very low (Bekele, 2001). In addittion, there are limited informations' how to manage these forests in a sustainable way and to show their importance for climate change mitigation and adaptation (Lemenih and Kassa, 2014). Likewise, the soil carbon and nitrogen stock and concentration both in the forest floor, mineral soil and adjacent land uses are also scanty.

1.4. Chilimo dry afro-montane forest of Ethiopia

Chilimo forest is one of the few remnants of dry afro-montane forest located in Dendi district, Western Shewa zone, Oromia administrative region, Ethiopia. The forest is found 70 km southwest of Addis Ababa. The forest is geographically located at 38° 07′ E to 38° 10′ E and 9° 30′ to 9° 50′ N' longitude, with an altitude range of 2,170-3,054 m above sea level (Figure 3). The mean annual temperature of the area ranges between 15-20 °C and receives a mean annual precipitation of 1,264 mm (Shumi, 2009). Köppen's classification defines the climate of Chilimo forest is classified as warm temperate climate I (CWB) type (EMA, 1988). The forest is a small enclave in the western section of a chain of hills and ridges that stretch 200 km from north of Addis Ababa westwards up to the Ghedeo highlands, locally river valleys and gorges cut through the chain. A number of rivers, for example, Awash River it is one of the longest rivers in the country, starting from this forest. The forest is also home to over 180 species of birds and 21 species of mammals including endemic subspecies Meneliks bushbuck, vervet monkey, colobus monkey, Anubis baboon and leopard (Woldemariam, 1998). Besides, the forest is found in the nearby the capital city Addis Ababa, easily accessible through all-weather road and having old historical palaces inside it.

Chilimo forest is composed of mixed broad leaved *Podocarpus falcatus*, *Olea europaea* ssp. *cuspidiata*, *Scolopia theifolia*, *Rhus glutinosa*, *Olinia rochetiana* and *Allophylus abyssinicus* and coniferous forest species *Juniperus procera* are the major species in the forest (Bekele, 2003; Kelbessa and Soromessa, 2004; Kassa *et al*., 2008*)*. Accordingly Shumi (2009) investigated 42 species 27 (64 %) of trees and 15 (36 %) of shrubs in the forest. Similarly, the inventory result for this thesis work found a total of 33 different native species (22 tree species and 11 shrub species) in three forest patches (Chilimo, Gallessa and Gaji). The density also varied from 2, 533 stems ha^{-1} found in Chilimo to 848 stems ha^{-1} found in Gallessa patch. Besides, adjacent to the natural forest more than 400 hectares of small patches of plantations of different introduced tree species (*Eucalyptus saligna, Eucalyptus camaldulensis, Pinus patula, Cupressus lusitanica*) and native tree species (*Juniperus procera*, *Hagenia abyssinica, Podocarpus falcatus)* are found (Kassa *et al*., 2008). These plantation forests are serving as sources of income for the local community.

Like in many parts of Ethiopia, Chilimo forest was previously a closed dense forest before the Italian occupation (1936-1941) (Shumi, 2009). Since, Italians introduced a number of expatriate millers (7 sawmills) and established a camp inside the forest for timber extraction and the forest suffered from intensive exploitation. Chilimo forest was among the most commercially exploited forests in the country. Its accessibility and proximity to market centers including Addis Ababa, the capital of Ethiopia contributed to its exploitation (Bekele, 2003). Higher timber extraction rates along with over grazing and agricultural expansion in the forest radically reduced the forest area from 22,000 hectares in 1982 to 11, 000 hectares in 1984 and 6,000 hectares in 1991 and are surrounded by vast areas of agricultural land (Shumi, 2009).

For over a century, Chilimo forest was owned and controlled by the state. Nevertheless, the state control from 1991 to 1996 had weakened. This resulted in increasing conversion of forest land into agriculture land and reckless cutting of trees for timber, construction wood and fuel wood. Thus, to maintain the continuity of the remaining forest, the government classified Chilimo forest into 58 of the National Forest Priority Areas (NFPAs). Then few years ago Chilimo forest was managed by the community through participatory forest management approach facilitated by Farm Africa (Farm Africa, 2000; Negassa and Wiersum, 2006). However, Farm Africa had left the forest in 2005 and it was transferred to Oromiya wildlife and Forest enterprise government office. Currently Chilimo forest is owned by 12 Forest User Groups (FUGs), more than 3,000 households with a total population over 15,000 people live inside or on the periphery of the forest (Kassa *et al*., 2008). Agriculture is the main activity of the community; however, both forestry and crop production contribute almost equal to maintain their livelihoods (Negassa and Weirsum, 2006; Kassa *et al*., 2008). The forest user groups are generating income through selling timber from planted forest. In addition, this research output enables them to harvest some amount of wood from the natural forest. Secondly the outputs obtained from this research result can be taken as a forest management tool for Oromia forest and wildlife enterprise office.

The Oromiya forest and wildlife enterprise office are advocating preservation and protection of the natural forest through participatory forest management approach excluding harvesting from the existed natural forest. Accordingly, cutting of trees in the natural forest is prohibited by law and the community benefited only by collection and using deadwood, fallen twigs and dried trees. Nevertheless, this management approach might not be sustainable in the future because the plantation forest might be depleted soon due to overutilization without regulation. This is supported by several evidences, inventoried stumps found in this study and elsewhere (Negassa and Wiersum, 2006; Kassa *et al*., 2009; Shumi, 2009), showed that, the natural forest is not free from illegal cutting. Besides, there is scanty of information regarding appropriate forest management options to increase productivity and ensure sustainability of the forest. Thus, new informations, at local, national and regional level are needed in relation to carbon stock in the soil and aboveground biomass. Alternative income generating mechanism such as carbon trade should be implemented to support the local community.

(a). Chilimo natural forest

(b). *P. patula* plantation

(c). Remnants of crop residue

(d). Degraded land adjacent to Chilimo natural forest

(e). Litter fall in plantation forest

(f). Herbaceous plant and dead wood in Chilimo natural forest

Fig. 2: *Described the carbon stock found in different land use types adjacent to Chilimo forest; (Fig. 2 (a)): showed natural forest composed of different tree species, Fig. 2 (b): Pinus patula plantation forest planted adjacent to Chilimo natural forest after 25 years of planted, Fig. 2 (c): Showed remnants of wheat crop residue after harvest adjacent to Chilimo natural forest, Fig. 2 (d): A degraded abandoned land adjacent to Chilimo forest, Fig. 2 (e) and 2 (f): Litter fall under Pinus patula plantation and dead wood and litter fall under the Chilimo natural forest.* **Photo by**: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).

1.5. Forest management tools available for African tropical forests

Forest management is a branch of forestry concerned with the overall administrative, economic, legal and social aspects for silvicultural, protection and forest regulation (Glossary of Forest Terms in British Columbia, 2008). Tropical forests are under pressure due to conversion to pastoral and agricultural land or to forest plantations (Kent, 2004; Garder *et al*., 2009). The experience in other countries such as Zambia (Kokwe, 2012), showed that management intervention on natural forests increases wood production, carbon sequestration, besides its benefit in terms of biodiversity conservation and watershed protection. The average accumulation rate of CO_2 in managed forest is around 5.5 tons ha^{-1} yr^{-1} in wood lands and 21 tons ha^{-1} yr^{-1} in tropical rainforests, subtropical forests and woodland forest (Moges *et al*., 2010), while unmanaged tropical rainforests grow at a rate of about 0.5 tons $ha^{-1}yr^{-1}$ (Lewis *et al*., 2009) leading to around 40 fold increase in annual yield. Diverse management tools are available for the sustainable management of African forest including growth and yield modelling and stand density management diagram (Vanclay, 1994).

Forest growth and yield models are key tools for the sustainable forest management. Most of the forest growth and yield modelling studies addressed plantation and temperate forests. While, growth and yield models for mixed tropical forest in general and tropical and subtropical African forest in particular are very limited (Botkin, 1993;Vanclay, 1989, 1994 and 2003; Alder *et al*., 2002, Vanclay, 2003). Moreover, ≥ 90 % of the the forests in developed countries have forest management plan, in the contrary, only 6 % of the total forests found in the developing countries have forest management plan (Nabuurs *et al*., 2007).

In addition, stand density diagrams are a management tools which facilitates decision making process for forest managers. It has been widely used as an important management tool for even-aged stands in many regions across North America and Europe (Drew *et al*., 1979; Smith, 1989; Wilson *et al*., 1999; Valbuena *et al*., 2008). Moreover, to even-aged plantation stands during the early to mid-1990s, SDMDs and stand density index were also developed for mixed species and uneven-aged stands as a management tool (Long, 1995; Shaw, 2000; Ducey and Larson, 2003; Woodall *et al*., 2005; Swift *et al*., 2007).

The application of these forest management tools are very scarce for both Ethiopian and African forest but there are few works done by (Vanclay, 1994; Woldeyohannes, 2005; Zewdie *et* *al*., 2009; Fayolle *et al*., 2013; Ngomanda *et al*., 2014). Thus, adequate research works should be conducted on this topic.

2. OBJECTIVES OF THE THESIS

2.1. Aims and specific objectives

The major aim of this thesis is to generate appropriate forest management options to increase carbon stock and rehabilitation of degraded lands in Chilimo dry afro-montane forest and adjacent land uses, in Central Highlands of Ethiopia. To accomplish this general objective five specific objectives are proposed and implemented.

Specific objective 1: Selection of tree species and soil management for restoring degraded lands in Ethiopian Central Highlands

Land degradation and deforestation are major environmental problems in Central Highlands of Ethiopia in particular and overall the country in general caused by reckless cutting of trees and lack of well-established soil management. Restoration programs need scientific information about the species and soil management best suited for rehabilitating degraded lands. The purpose of this specific objective was to evaluate six tree: *Acacia decurrense, Acacia saligna, Dombeya torrida, Eucalyptus globulus*, *Grevillea robusta, Hagenia abyssinica* and one shrub species: *Chamaecytisus palmensis*, under three soil management options: control, manure and manure plus mulch, in degraded Central Highlands of Ethiopia for four years (2005-2009) and finally to screen the best performing species and soil management for both fuelwood production and rehabilitation of degraded soil.

Specific objective 2: Aboveground biomass equation model development for five native species in a tropical mixed forest of Ethiopia

Among the existing native tree species in the Chilimo dry afro-montane mixed forest: *Allophyllus abyssinicus* (4 %), *Olea europaea* ssp. c*uspidiata* (8 %), *Olinia rochetiana* (5 %), *Rhus glutinosa* (3 %) and *Scolopia theifolia* (5 %) contributed about 25 % of the total population (in number of trees ha^{-1}) and 23 % (5.04 m^2 ha^{-1}) of total basal area in the overall population. Then, the purpose of this specific objective was to develop biomass models to estimate above ground biomass and carbon stocks for the above mentioned tree species in the tropical mixed forest. Finally, the equations will be applied for sustainable management of Chilimo dry afro-montane forest in particular and other dry afro-montane forests in general.

Specific objective 3: Impacts of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands

Information regarding soil organic carbon and nitrogen stock (SOC and SON) and concentration and bulk density are lacking in Chilimo dry afro-montane forest (both in forest floor and mineral soil) and adjacent land uses (plantation forest, crop land and degraded land) along elevation gradient and species. Therefore, the purpose of the specific objective was to quantify soil organic carbon (SOC) and soil organic nitrogen (SON) stock, concentration and bulk density of mineral soil and forest floor following an elevation gradient, land use types and introduced planted species (*Cupressus lusitanica, Eucalyptus saligna* and *Pinus patula*) along four soil depths (0-10 cm, 10-30 cm, 30-50 cm, 50-100 cm).

Specific objective 4: Evaluation and formulation of stand density management diagram model for Chilimo dry afro-montane forest using species proportion.

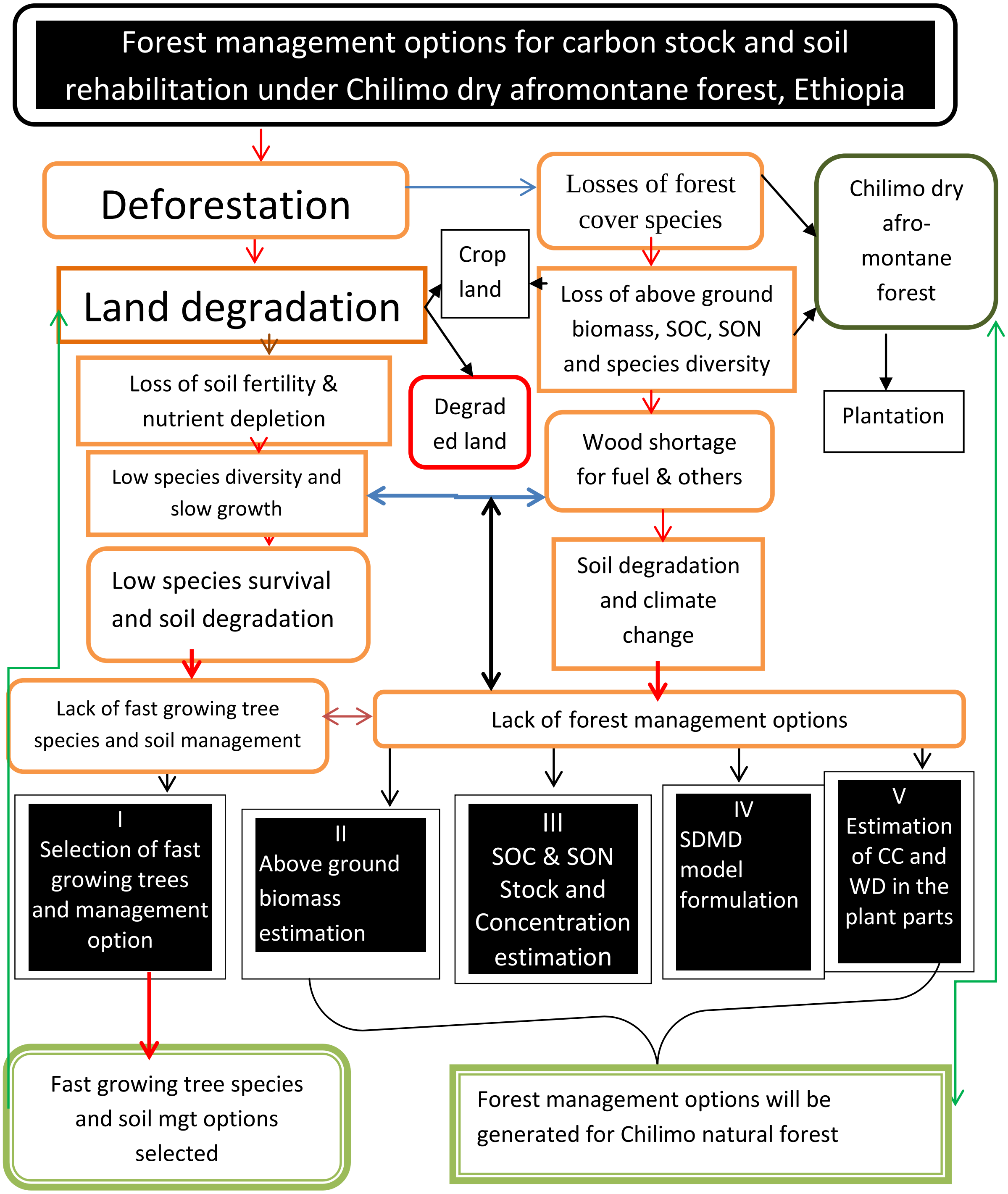
Stand density management diagrams are useful tools for designing, displaying and evaluating alternative density management regime for both even-aged and uneven-aged forests. However, informations in this regards are very scanty in Chilimo dry afro-montane forest in particular and all the Ethiopian forests in general. Thus, the specific objective was to develop stand density management diagram for Chilimo dry afro-montane mixed forest using species proportion.

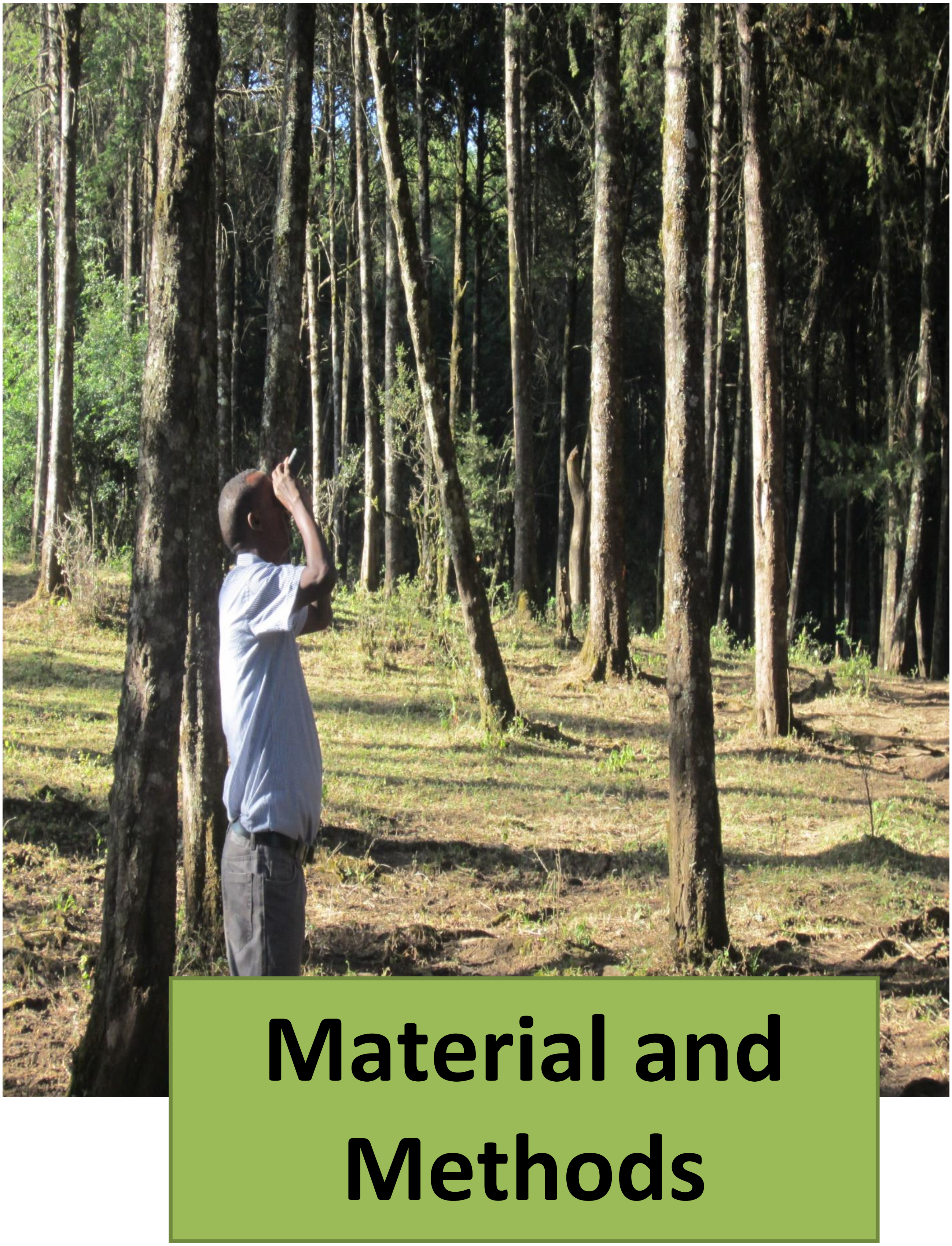
Specific objective 5: Evaluation and estimation of carbon concentration and wood density along plant parts and stem position for five most commonly grown tree species in Ethiopia.

Chilimo forest is one of the few remnants of dry afro-montane forest found in central highlands of Ethiopia. However, informations regarding carbon concentration (% C) and wood density at species level, its parts and stem position (tree height) are lacking, thus the specific objective was to estimate carbon concentration and wood density for five most commonly grown native tree species : *Allophyllus abyssinicus, Olea europaea* ssp. *cuspidiata, Olinia rochetiana,* *Rhus glutinosa* and *Scolopia theifolia* in a tropical mixed forest along plant parts (stem, branch and leave) and stem position (from stump height to commercial height) among and within a species.

2.2. Conceptual model

The conceptual model presented below was showed the cause and effect relationship between deforestion and land degradation in central highlands of Ethiopia. The narrow arrays pointed downwards indicated the other problem caused due to the presence of above problems.The thick red arrows showed the root causes of the problems i.e lack of fast growing tree species and soil management options in degraded land and lack of appropriate forest management options in the Chilimo natural forest. To alleviate these problems five studies (I-V) were done as indicated in the conceptual model. In doing so the results obtained: selection of fast growing tree and shrub species and soil management for fuelwood production and rehabilitation of degaraded lands and generation of appropriate forest management options for sustainable management and utilization of Chilimo dry afro-montane forest were presented and pointed upward using green thick lines to address the prementioined problems.


Forest management options for carbon stock and soil rehabilitation under Chilimo dry afromontane forest, Ethiopia
Deforestation
Losses of forest cover species
Chilimo dry afro-montane forest
Crop land
Land degradation
Loss of above ground biomass, SOC, SON and species diversity
Loss of soil fertility & nutrient depletion
Degraded land
Plantation
Wood shortage for fuel & others
Low species diversity and slow growth
Low species survival and soil degradation
Soil degradation and climate change
Lack of fast growing tree species and soil management
Lack of forest management options
I Selection of fast growing trees and management option
II Above ground biomass estimation
III SOC & SON Stock and Concentration estimation
IV SDMD model formulation
V Estimation of CC and WD in the plant parts
Fast growing tree species and soil mgt options selected
Forest management options will be generated for Chilimo natural forest



Material and Methods

3. MATERIAL AND METHODS

3.1. Study sites

Debrelibanos study site

Debrelibanos degraded site was located geographically at 9º 38’ 19.66’’ N latitude and 38º 49’ 34.46’’ E longitude, 2,600 m above sea level (Figure 3) in Debrelibanos district, Northern shewa zone, Oromia administrative region, Central Highlands of Ethiopia. Meteorological data were obtained from Ethiopian Meteorological Agency in Addis Ababa ((http://www.ethiomet.gov.et/). The averaged mean annual maximum and minimum temperature of the study area were 21 ºC and 8 ºC, respectively, with an annual mean averaged precipitation of 1, 200 mm falling mostly in July and August. Köppen’s classification is temperate highland tropical climate with dry winters.

Chilimo dry afro-montane forest

Chilimo dry afro-montane forest is geographically located at 38° 07′ E to 38° 10′ E and 9° 30′ to 9° 50’ N’ longitude, at an altitude of 2,170-3,054 m above sea level (Figure 3) in Dendi district, Western Shewa zone, Oromia Administrative Region, Central Highlands of Ethiopia. The mean annual temperature of the area ranges between 15-20 °C and receives a mean annual precipitation of 1,264 mm (Shumi, 2009). Köppen’s classification defines the climate of Chilimo forest is classified as warm temperate climate I (CWB) type (EMA, 1988).

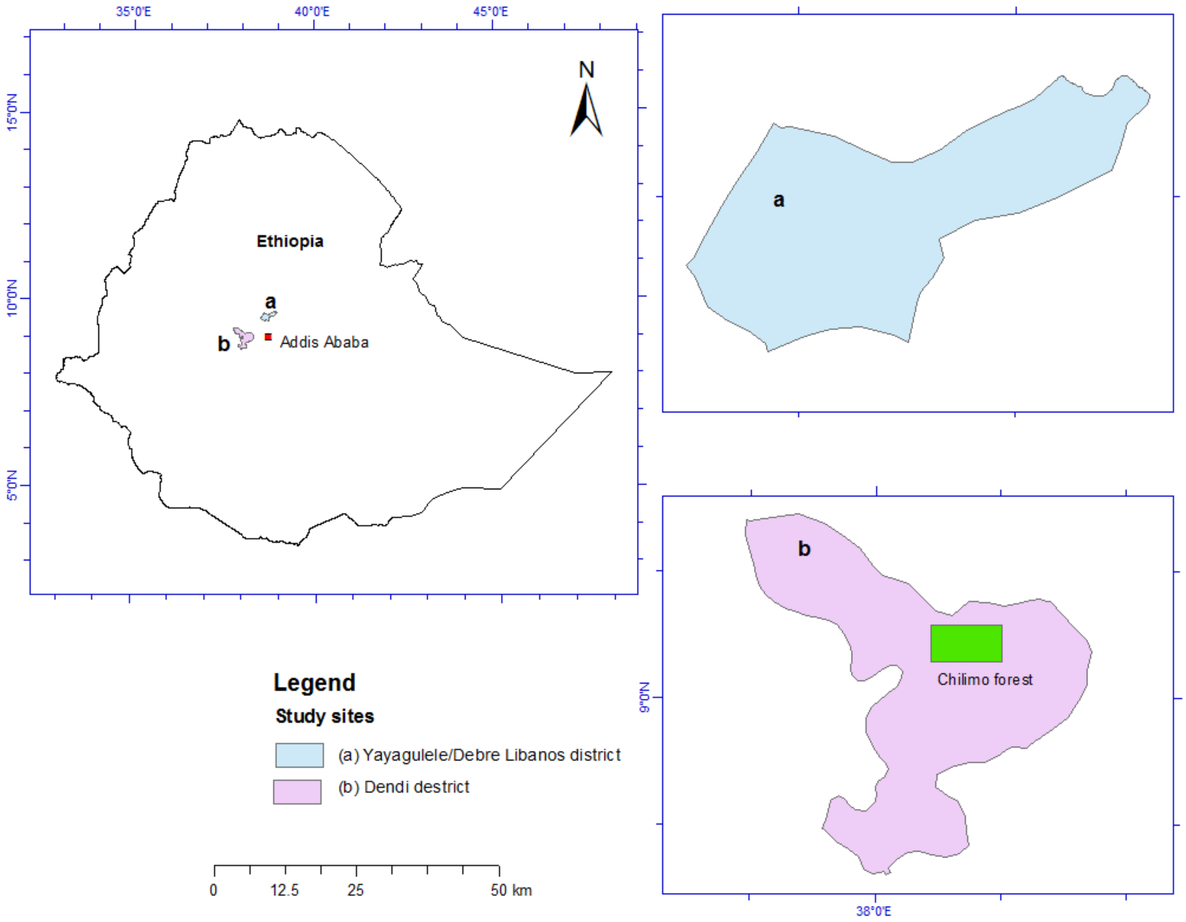


Fig. 3: *Location map of study sites of Debrelibanos district and Chilimo dry afro-montane forest.*

3.2. Experimental design and sampling

Debrelibanos experimental site was selected through a participatory process with local stakeholders. A focus group discussion was conducted with district agricultural experts, development agents and farmers. The experimental site was selected based on accessibility and representativenss of degraded land on sandy soil, rock outcrops and without vegetation cover. A total of seven species: two native tree species (*Dombeya torrida* (J.F.Gmel.) Bamps and *Hagenia abyssinica* (Bruce) J.F.Gmel.), four introduced tree species (*Acacia decurrens* Willd. *Acacia saligna* (Labill.) H. L.Wendl., *Eucalyptus globulus* Labill. and *Grevillea robusta* A.Cunn. ex R. Br.) and one exotic shrub species *Chamaecytisus palmensis* (Christ.) Hutch was identified for this study. Three soil management options i) control ii) addition of manure and iii) addition of manure plus mulch were applied after planting in July 2005 (manure) and in December 2005 (mulching). The experimental layout was organized as a split-plot design, with tree species as the main plot and soil management options as sub-plots; it was organized in three blocks to control variation along a slope gradient and three replicates for each species. The main plot consisted of 90 trees divided into three groups of 30 trees; each arranged into five rows, with six trees in each row. The distance between trees in the same row and between rows in the same sub-plot was 1.5 m, while the distance between treatments in the main plot and sub-plots was 2 m.

A systematic random sampling approach was implemented to conduct inventory in Chilimo dry afro-montane forest. Primarily, Chilimo forest was stratified into 3 major natural forest patches Chilimo, Gallessa and Gaji and an inventory was taken to compile information about species composition, diameter distribution and general forest condition. A total of thirty-five, 20x20 m square sample plots were marked based on Neyman optimal allocation formula (Köhl *et al*., 2006) along elevation gradient. The plots were laid out following top-down parts of the mountain. The distance between plots were 100 m and plot location was determined using measuring tape, GPS, altimeter and compass. Sampling and data collection were done in the measured plots of the mixed natural forest. Individual species were categorized into trees (≥ 5 cm diameter at breast height-dbh-) shrubs and saplings (height ≥ 1.3 m and dbh 2.5-5 cm) and seedlings (height 0.30-1.3 m and dbh ≤ 2.5 cm) following Lamprecht’s classification (1989).

3.3. Data gathering

3.3.1. Tree data

Survival counts, tree height growth and root collar diameter (RCD) growth measurements were taken at 12, 24, 36 and 48 months after planting for *A. decurrense*, *A. saligna*, *C. palmensis*, *D. torrida*, *E. globulus*, *G. robusta* and *H. abyssinica* in Debrelibanos degraded study site fenced experiment (**study I**). For Chilimo dry afro-montane forest, dendrometric tree datas such as: diameter at breast height (1.30 m) (*dbh*), diamater at ground base (*db*), crown diameter (*cd*), crown length (*cl*), total height (*h*), commercial height (*hc*) and height at branching stems (*hb*) were taken from one time inventory from 35 temporary sampled plots (**study IV**). The above dendrometric tree datas were also measured for 90 cut trees (20 tree per species of *O. europaea* ssp. *cuspidiata*, *O. rochetiana*, and *S. theifolia* and 15 trees per species of *A. abyssinicus* and *R. glutinosa*) for biomass equation purpose (**study II)** and more 15 sampled trees (3 trees per species) for carbon concentration and wood density estimation in the plant samples. Tree diameter was measured with a metallic calliper and diameter tape. Crown height and total height were measured using a Vertex III digital tree height measurement instrument.

(a). A degraded land without plantation *(b). A. saligna plantation*

***Fig. 4:** Images of Acacia saligna after 2 years planted in degraded lands.* Fig. 4 (a): Showed a *degraded land before intervention and Fig. 4 (b): Showed a degraed land planted with A. saligna after two years of intervension.* **Photo by**: Mehari A. Tesfaye (2009) (Guder, Ethiopia).

(a). Chilimo natural forest *(b). Biometric data collection for A. abyssinicus*

***Fig. 5:** Biometric data collection in the natural forest. Fig. 5 (a): Showed partial view of the existing natural forest and Fig. 5 (b): showed biometric data collection for A. abyssinicus species in the natural forest.*
Photo by: Mehari A. Tesfaye (2012), (Chilimo, Ethiopia).

3.3.2. Biomass data

A total of 90 trees (20 tree per species of *O. europaea* ssp. *cuspidiata*, *O. rochetiana*, and *S. theifolia* and 15 trees per species of *A. abyssinicus* and *R. glutinosa*) from different diameter classes were selected, cut and divided into different sections (**study II**). The branches were delimbed and separated into different biomass components (stem, large branches (diameter > 7 cm), thick branches (diameter 2-7 cm), thin branches (diameter ≤ 2 cm) plus leaves). Fresh weights of each component were recorded in the field and then samples were taken to the laboratory and oven dried at 67 ºC and 102 ºC to constant weight. Smalian's formula (Nicolas *et al*., 2012) was used to calculate the volume of stems and large branches (Ø > 7 cm). The large branches were obtained only in few trees and its weight was added into stem biomass. However, for *A. decurrense*, *A. saligna*, *C. palmensis*, *D. torrida*, *E. globulus*, *G. robusta* and *H. abyssinica* biomass was calculated from volume and wood specific gravity. Volume was calculated from the average height and diameter of the experiment trees and total biomass calculations were based on tree volume and specific gravity, using values obtained from the specific gravity biomass data were taken at 48 months (**study I**).

(a). Fresh weight biomass data sampling in the field *(b). Stem biomass cutting using cross cut saw*

Fig. 6: *Biomass data collection and sampling in the field Fig. 6 (a): Fresh weight sampling in the field using weigh and Fig. 6 (b): Stem biomass data collection (cutting) using two man cross cut saw in the natural forest.* **Photo by**: Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).

3.3.3 Coarse wood debris and stump data collection

Coarse wood debris (logs and stumps) for *Juniperus procera*, *Podocarpus falcatus* and *Olea europaea* ssp. *cuspidiata* were sampled inside 20 mx20 m plot (**study III**). Weight for coarse wood (logs and fallen branches) were measured in the field and then samples were taken into laboratory and oven dried at 102 ºC to constant weight. Number of stumps found in the plot and the species of the stump were also recorded (**study III**). The diameters of the stumps were measured in their bases and at the top using metallic calliper and diameter tape. Individual height of stumps was also measured using a measuring tape. The volume of the stump was calculated using Smalian's formula (Nicolas *et al.*, 2012). Weighted mean wood density (WD) of 0.66 was used to calculate the biomass i.e. wood density for *Juniperus procera* (0.54), *Podocarpus falcatus* (0.52) and *Olea europaea* ssp. *cuspidiata* (0.91) (WUARC, 1995).

(a). Dead wood collected in the main plot *(b). Illegally cut stump in the plot*

Fig. 7: *Showed dead wood and stump samples in the natural forest Fig. 7 (a): Fallen Juniperus procera dead wood samples collected in one of the main plot and Fig. 7 (b): Illegally cut Juniperus procera stump found in one of the main plot in of the natural forest.* **Photo by**: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).

3.3.4. Soil data (study I and study III)

Soil sampling for planted trees under degraded land in Debrelibanos study site was carried out before and after plantation experiment. Soil augering was carried out in 3 m x 3 m subplot at the initial and final stage of the experiment at 0-10 cm, 10-30 cm and 30-50 cm depth for each treatment and species combination. Seventy two composite soil samples in total were collected from three soil depths. Three random sampling points were mixed to form one composite sample.

Soil sampled also carried out in Chilimo dry afro-montane forest and its adjacent land uses (natural forest, plantation forest, cropland and degraded soils). Both forest floor and mineral soil sampling were done inside main plots (20 m x 20 m). Forty forest floor samples were collected by using 0.25 m x 0.25 m metallic frame quadrant. The depth of the forest floor was measured using a metallic ruler. In eighteen main plots, mineral soil samples were taken below the forest floor up to 1 m depth using pit method (1 m x 60 cm) due to representativeness of the samples. A total of 33 pits in four land use types were dug for soil sample collection. Then, soil samples were taken in four soil depth (0-10 cm, 10-30 cm, 30-50 cm and 50-100) cm. Soil bulk density was calculated using metallic cylinder method (6.5 cm height, diameter and width) for each soil depth. A total of 280 samples (140 soil samples for C % and total N % analysed plus 140 cylinder samples for bulk density analysed) were collected.

Fig. 8: *An example of soil sampling in different land use types of the study area using pit sampling method.* **Photo by**: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).

3.3.5. Wood density and carbon concentration (study V)

Carbon concentration and wood density were collected for five tree species: *A. abyssinicus*, *O. europaea* ssp. *cuspidiata*, *O. rochetiana*, *R. glutinosa* and *S. theifolia* in Chilimo dry afro-montane forest. Total carbon concentration and wood density in the plant sample were estimated using destructive sampling. Trees were felled using local axes and cross cut saw and cut as close to the ground as possible. Wood samples were extracted using crosscut saw and chain saw. A total of 15 trees (3 trees per species) were selected to cover the entire diameter classes. A total of 105 discs, six cross-sectional discs (5 discs from stem and one disc from big branches) having a size of 30-50 mm thick, were collected per single tree. Discs were taken from each section, starting from stump height and every one meter along the stem upto the end of the commercial height (≤ 7 cm) and one sample for large branches per tree. Leaves samples were also taken from each tree for the same purpose. Fresh weights of each wood and leaves samples were taken in the field and then taken into the laboratory.

(a). Allophyllus abyssinicus extracted wood sample *(b). Olinia rochetiana extracted wood sample*

Fig. 9: *Showed wood sampling for the sampled trees, Fig. 9 (a): a wood sampled (white color) extartced from A. abyssinicus tree and Fig. 9 (b): a wood sampled (red color) extracted from O. Rochetiana tree in the study area.* **Photo by**: Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).

3.4. Laboratory methods

3.4.1. Soil analysis

The collected samples were air-dried, sieved (2 mm diameter) and ground before analysis. The samples were analysed for pH (1: 2.5 soil: water ratio) (Schofield and Tailor, 1955), total N

(%) using Kjeldhal’s method (Keeny and Nelson, 1982), organic carbon (%) according to Walkley - Black’s method (Bremmer and Jenkinson, 1960), available Phosphorus (units) using Olsen’s method (Olsen and Sommers, 1982), ammonium and sodium acetate were applied to determine cation exchange capacity, exchangeable K were measured with flame photometer (**study I**) (Thomas, 1982) at Holetta research centre, Ethiopia (www.eiar.gov.et/index.php).

Forest floor layers were air-dried and homogenized before the analyses were performed. All samples were weighted and subsamples were oven dried for 24 hours at 65 ºC to constant weight. The chemical analysis for organic carbon in the forest floor were done by drying samples at 105 ºC and then ashes at 550 ºC (Ben-Dar and Banin, 1989). The loss in weight between 105 ºC and 550 ºC constitutes the organic matter content. Then organic matter content was converted into organic carbon by multiplyin it with 0.58 which has been found to be the most covenient conversion factor from organic matter to carbon content in the forest floor (de Vos *et al*., 2005). Similarly, bulk density for each soil depth was determined using a 5 cm diameter and 5 cm height metallic-cylinder coarse sampling method following the procedure of Blake (1965). Total N was determined using Kjeldahl’s method following the procedure in Keeny and Nelson (1982). Chemical analysis was performed at Holetta research centre, Ethiopia (www.eiar.gov.et/index.php).

3.4.2. Wood density and carbon concentration

Similar to forest floor samples woody parts were oven dried at 102 ºC and 67 ºC to constant weight in the laboratory. The oven dried wood samples were weighed, splatted into pieces, chopped and finally ground into 0.2 mm with a grinding mill. Carbon % was estimated by ash methods described by (Ben-Dar and Banin, 1989; Allen *et al*., 1986; Negi *et al*., 2003; Jone *et al*., 2009). Oven dried and ground plant samples were placed in the graphite furnace at 105 ºC and 400 ºC temperature for four hours. Then, the carbon concentration was determined using the following formula (**study V**):

$$\text{Ash \%} = \frac{w\,105 - w\,400}{w\,105} \text{X } 100 \qquad (1)$$

$$C\% = Ash\%(0.58) \qquad (2)$$

Where, C: the organic carbon concentration, w105: weight of dry ground plant sample at 105 ºC, w400: weight of ground plant sample at 400 ºC and 0.58 is the carbon concentration in the organic matter of wood.

Similarly, volume (cm^{-3}) for wood density calcualtion was estimated using water displacement method. Then wood density was calculated using the ratio of oven dry weight of wood (g) and volume (cm^{-3}). The carbon concentration and wood density analysis were performed at Holetta research centre, Ethiopia (www.eiar.gov.et/index.php).

3.5. Statistical analysis

Before performing actual statistical analysis datas were classified into longitudinal, spatial and autocorrellation datas. Height growth, root collar diameter growth, survival and soil datas (**study I**) were categorized as longitudinal datas. Carbon and nitrogen concentration and stock (**study III**) were spatial datas. The datas were analyzed using general linear mixed model. Tree data, biomass, wood density and carbon concentration are autocorrelation datas and a correllattion analysis was performed. A general linear model was used for these datas. However, some datas lack homogenity and had heteroscedasticity problem, a logarithmic and arcsine transformation were perfomed for these datas. The detailed statistical analysis was presented below.

3.5.1. Mixed models

Survival rate, height growth, root collar diameter growth and biomass (**study I**) and carbon and nitrogen stock and concentration and bulk density datas for (**study I**II) were performed using Proc-Mixed Model on SAS (SAS Inst. Inc., 2012) (**study III**) and mean separation using Tukey-Kramer test. We tested the following general structure to obtain a model of survival, height and root collar diameter (**study I**):

$$y_{ij} = \mu + \beta_{1i} + \beta_{2i}t_{ij} + \varepsilon_{ij} \qquad (3)$$

The model used for biomass data were also presented as (**study I**):

$$\mathrm{y_{skb}} = \mu + \alpha_s + \beta_k + \gamma_{sk} + b_b + v_{kb} + \varepsilon_{skb} \qquad (4)$$

For soil organic carbon and nitrogen stock and concentration we used a linear mixed model analysis of variance with repeated measurements, considering one between-subjects factor (species, land use type or altitude) and one within-subjects factor (depth with four levels) using the mathematical model (**study III**):

$$Y_{ij;k} = \mu + \alpha_i + \beta_k + \alpha\beta_{ik} + \varepsilon_{ij;k} \qquad [5]$$

The assumptions for the errors in the linear mixed model were:

- ✓ $\varepsilon_{ij;k} \sim N(0, \sigma_k^2)$, with σ_k^2= random variance for the errors at depth k.
- ✓ $Cov(\varepsilon_{ij;k}, \varepsilon_{i'j';k'}) = \begin{cases} \sigma_k \sigma_{k'} \rho_{|k-k'|} & \text{if } i = i', j = j' \text{ and } k \neq k' \\ 0 & \text{if } i \neq i' \text{ or } j \neq j' \end{cases}$, with ρ_1=correlation coefficient (6)

3.5.2. General linear models

Soil datas for (**study I)** and carbon and nitrogen concentration and stock (**study III**) were analysed using SAS PROC GLM method (SAS Inst. Inc., 2012). Mean comparison was made using least square means. A significance level of 0.05 is assumed across the analysis (**Study I**). An analysis of equality of means was performed using a Tukey-Kramer test for multiple comparisons among elevation classes at α=0.05 (**Study III**).

For biomass data 12 biomass equations found in the literature (Balboa-Murias, 2006; Ruiz-Peinado *et al*., 2011 and 2012) were evaluated and selected, simultaneously fitted using joint generalized regression. Model fits were performed using the SAS MODEL procedure (SAS Inst. Inc., 2012). The model efficiency were compared with previously developed general models (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 1997; Chave *et al*., 2005) for tropical areas using average deviation (S), relative bias (RB), relative root mean square (RRMSE) and applying a paired t-test for estimation values (**study II**):

$$S(\%) = 100 \cdot \frac{\sum_{i=1}^{n} \left[\frac{|\hat{Y}_i - Y_i|}{Y_i} \right]}{n} \qquad (7)$$

$$RB(\%) = 100 \cdot \frac{\sum_{i=1}^{n} \left[\frac{\hat{Y}_i - Y_i}{Y_i} \right]}{n} \qquad [8]$$

$$RRMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left[\frac{|\hat{Y}_i - Y_i|}{Y_i} \right]^2} \qquad [9]$$

SAS PROC GLM (SAS Inst. Inc., 1999) was used with altitude (3 levels), land use types (4 levels) and species (3 levels) as main factors. The mathematical formulation of the model was (**study III**):

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \qquad [10]$$

SDMD using species proportion and carbon concentration and wood density datas were also analyzed using Proc GLM and Proc logistic model (SAS Inst. Inc., 2012) and the model used for species proportion as (s**tudy IV**):

$$\mathrm{ln\_QMD} = \beta01 + \beta02 * \mathrm{MIXFRAC} + \beta11 * \mathrm{ln\_N} + \beta12 * \mathrm{MIX\_N} + \beta21 * \mathrm{ln\_Ho} + \beta22 * \mathrm{MIX\_Ho} \quad (11)$$

$$\mathrm{ln\_VT} = \beta31 + \beta32 * \mathrm{MIXFRAC} + \beta41 * \mathrm{ln}_{\mathrm{QMD}} + \beta42 * \mathrm{MIX}_{\mathrm{QMD}} + \beta51 * \mathrm{ln\_Ho} + \beta52 * \mathrm{MIX\_H0} + \beta61 * \mathrm{ln\_N} + \beta62 * \mathrm{MIXFRAC} * \mathrm{ln\_N} \quad (12)$$

For carbon concentration and wood density the following models were used (**study V**):

$$\mathrm{Y} = \mu + \alpha i + \beta j + \gamma k + (\alpha\beta)ij + (\beta\gamma)jk + (\alpha\gamma)ik + (\alpha\beta\gamma)jk + (\delta * (\alpha\beta\gamma)ijk) + \varepsilon \quad (13)$$

The logistic model was performed with the following structure:

$$P = \frac{1}{1+e^{-z}} \quad (14)$$

$$(z = \mathrm{a0} + \mathrm{a1x}h + \mathrm{a2xDn} + \mathrm{a3x}d) \quad (15)$$

Table 1*: Summery of the statistical methods used*

Data analysis	Study I	Study II	Study III	Study IV	Study V
Linear Mixed Model	X		X		
GLM		X	X	X	X
Correlation analysis		X			X
Logistic					X

3.5.3. R- software

Interaction plots for height, root collar diameter, survival and soil chemical parametres in the degraded lands (**study I**) and carbon and nitrogen concentration and bulk density along land use type, elevation and species (**study III**) were performed using R (R- Development Core Team, 2012 and 2014).

Results

4. RESULTS

4.1. Performance and soil condition of selected species in degraded highlands of Ethiopia (study I)

The four years evaluation result of survival rate, height growth, root collar diameter growth, biomass production and its effect on soil fertility for six (introduced and native) tree and one shrub species under three soil management option: control, addition of manure, addition of manure plus mulch were species dependent. *G. robusta* and *H. abyssinica* had good survival rate, while *A. decurrense* was poorly survived. *H. abyssinica* and *C. palmensis* showed poor growth rates while these species showed highest soil improvement conditions. *E. globulus* and *Acacia* species outperformed in terms of growth rates and biomass production.

Survival: *G. robusta* (100 %) showed the highest overall survival rate followed by *H. abyssinica* (93.52 %) (Figure 1, **study I**) where as, *A. decurrense* showed the lowest survival rate. Differences in survival rate among species appeared when they were compared at time points. *A. decurrense* showed the lowest survival rate at all measurement times, though; it was similar to *A. saligna* through the experiment. The differences was stronger as early as 24 months after planting (Table III, **study I**).

Height growth: The response of *A. decurrense* and *A. saligna* height growth was similar across the soil management options. Time since planting (age) was also an important variable with considerable variation across species. For example, *A. saligna* height growth was faster upto 24 months after planting and then decreased whereas *E. globulus* experienced fast height growth throughout the whole experiment (Figure 10 (a)). *G. robusta* and *H. abyssinica* showed the same height growth pattern and the application of manure and or manure plus mulch resulted in similar height growth, which was higher than that of the control treatment (Figure 10 (b)). Height growth differences were noticeable 12 months after planting, *H. abyssinica* and *E. globulus* showed the lowest and highest mean differences, respectively (Table V, **study I**).

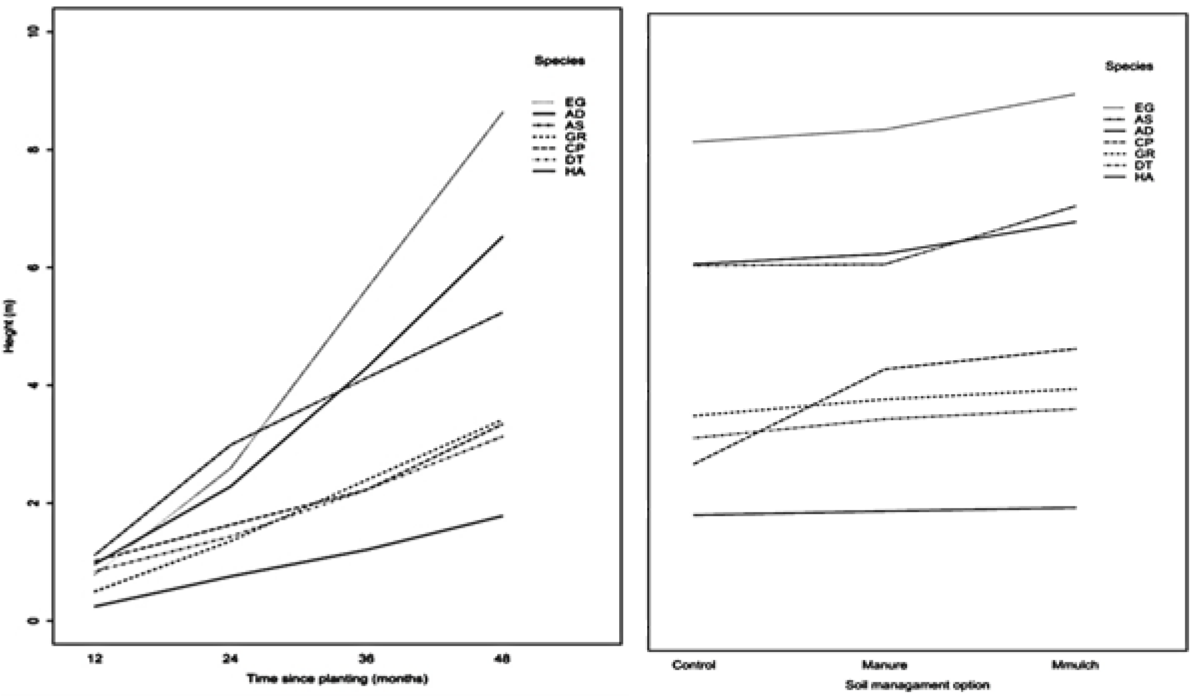


Fig. 10*: Showed the effect of time since planting and soil management on height growth in degraded lands.* ***Fig. 10 (a):*** *Tree height planted species time since planting.* ***Fig. 10 (b):*** *Height (cm) on soil management option.*

Root collar diameter growth: *A. saligna* showed a stronger response to manure plus mulch treatment than other species, whereas *C. palmensis* exhibited increased root collar diameter when either soil management options applied (Figure 2(e), **study I**). The root collar diameter of *A. saligna* increased for 36 months after planting. At 48 months, *E. globulus* showed higher root collar diameter (RCD) average. The other species showed similar values at 12 and 24 months after planting; root collar diameter differences become more pronounced *C. palmensis, D. torrida* and *H. abyssinica* had the lowest RCD average at the end of the experiment (Figure 11 (a)**)**. The final model for RCD showed that neither the fixed effects for species and treatment in the slope nor the interaction between species and treatment were significant (Figure 11(b)). *E. globulus* outperformed all species in height growth but had almost the same root collar diameter as *A. saligna* at the end of the experiment.

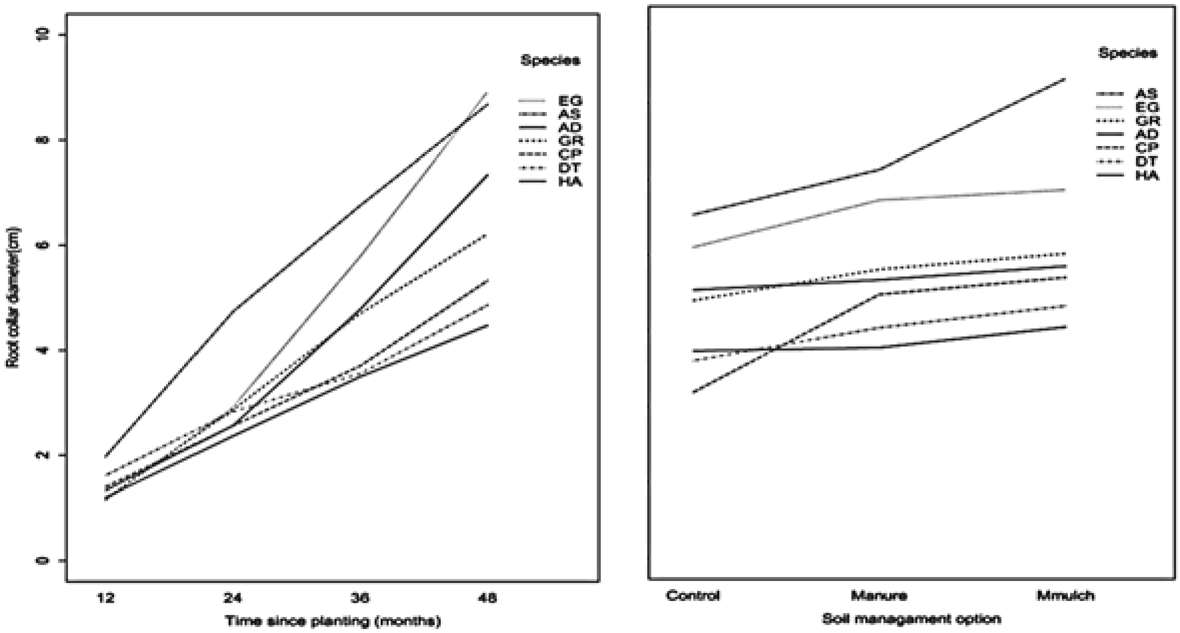


Fig. 11: Showed the effect of time since planting and soil management on root collar dimater growth on degraded lands. ***Fig. 11 (a):*** *RCD (cm) planted species time since planting.* ***Fig. 11 (b):*** *RCD (cm) on soil management option.*

Biomass production: Tree biomass production was similar in all soil management application (Table VII, **study I**), except for *E. globulus* (11.71 kg tree^{-1}), *A. saligna* (8.76 kg tree^{-1}) and *A. decurrense* (6.41 kg tree^{-1}). Mulching induced overlaid results between the control and mulching plus manure treatment. Comparison of control with mulching plus manure treatments revealed the treatment fixed effect to be highly significant ($p < 0.0001$). The interaction between species and treatment was highly insignificant in all cases. *E. globulus* produced more biomass than other species, followed by *A. saligna* (Table 2).

Table 2: *Differences of least squares means for biomass production 48 months after planting and statistical significance of null hypothesis according to Tukey-Kramer's adjustment. Bold values indicate significant at 0.05 significant levels.*

Species comparison	**48 months after planting**	
	Estimate	**P-value**
AD-As	-2.343	0.870
AD-CP	3.609	0.519
AD-DT	5.079	0.189
AD-EG	-5.292	0.160
AD-GR	4.297	0.337
AD-HA	5.693	0.115
AS-CP	5.952	0.093
AS-DT	7.422	**0.026**
AS-EG	-2.949	0.715
AS-GR	6.640	0.052
AS-HA	8.037	**0.015**
CP-DT	1.470	0.984
CP-EG	-8.901	**0.007**
CP-GR	0.688	1.000
CP-HA	2.084	0.919
DT-EG	-10.371	**0.002**
DT-GR	-0.782	1.000
DT-HA	0.614	1.000
EG-GR	9.589	**0.004**
EG-HA	10.986	**0.001**
GR-HA	1.397	0.987

EG: *Eucalyptus globulus*, AS: *Acacia saligna*, AD: *Acacia decurrense*, CP: *Chamaecytisus palmensis*, GR: *Grevillea robusta*, DT: *Dombeya torrida*, HA: *Hagenia abyssinica*.

Soil condition: Nitrogen concentration was affected by species, time, depth and interaction of time and species, indicating a strong species control on this soil parameter. The significant interaction effect of species, time and depth for organic carbon and cationic exchange capacity was mainly controlled by depth. After 4 years since planting, pH did not change. Soil parameter values (% OC, % N, P (ppm), K (meg/100g soil) increased in native *H. abyssinica* and *D. torrida* (Figure 3 and 4, **study I**), whereas nitrogen and carbon concentration decreased in *E. globulus* plantation along the whole profile [Figure 5 (c) and (e), **study I**]. *C. palmensis* showed the highest N and C increase 4 years after plantation [Figure 6 (c), **study I**]. *Acacia* spp showed a decreasing pattern in nitrogen and carbon concentration and available potassium (Figures 12 and 13), whereas *G. robusta* showed increased nitrogen and carbon contents (Figure, 14). All species increased available P in soils. The concentration of nitrogen is significantly low in *Acacia* spp and *E. globulus*. *C. palmensis* showed the highest amount of nitrogen (0.11 %) in the top soil (0-10 cm) 4 years after plantation followed by *H. abyssinica* (0.09 %) and *D. torrida* (0.08 %). Differences in K concentration are found in 10-30 cm. CEC in *E. globulus* and *A. decurrense* plots is significantly lower than that found in *D. torrida* and *G. robusta* plots.

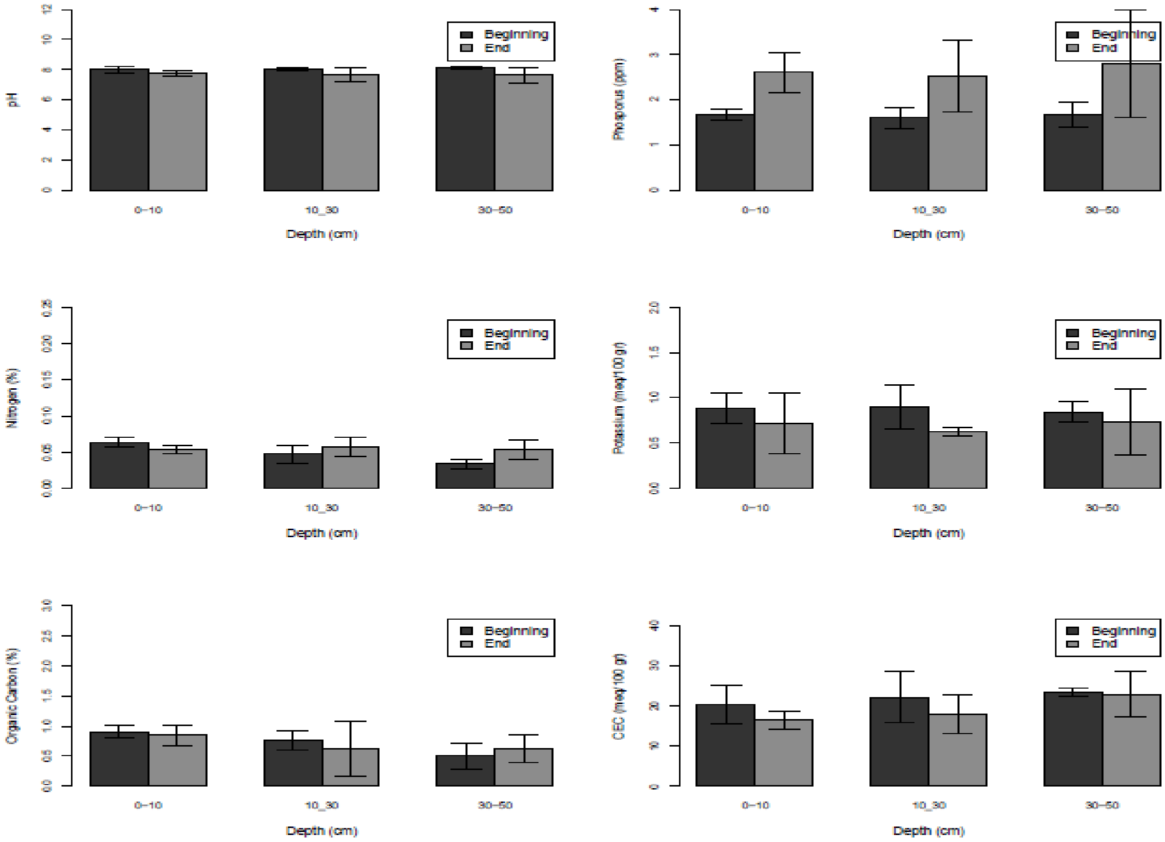


Fig. 12: *Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in native Dombeya torrida plots. Dark bars are mean value before planting. Light bars are mean after 48 months planting.*

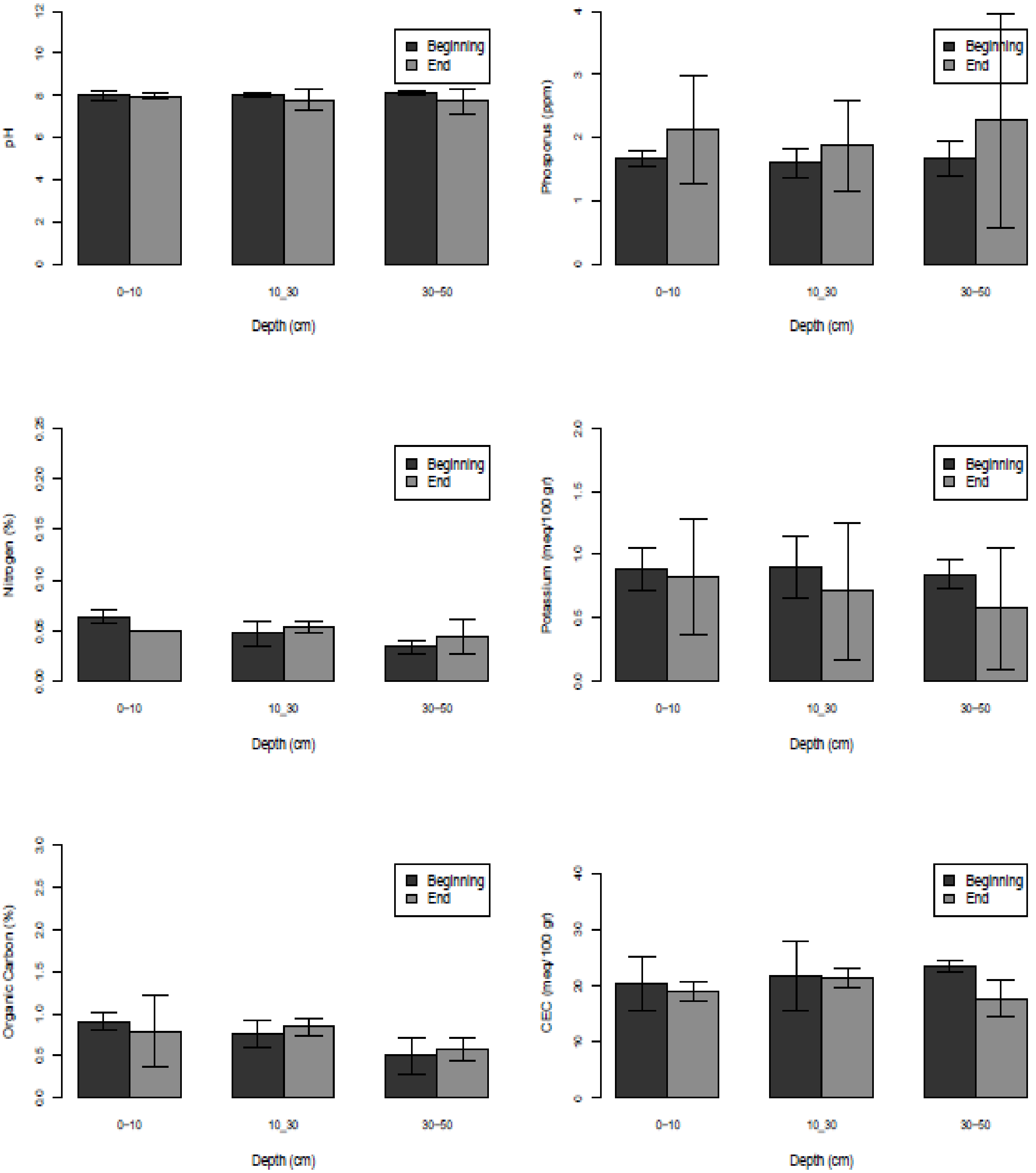


***Fig. 13**: Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in Acacia saligna plots. Dark bars are mean value before planting. Light bars are mean value after 48 months.*

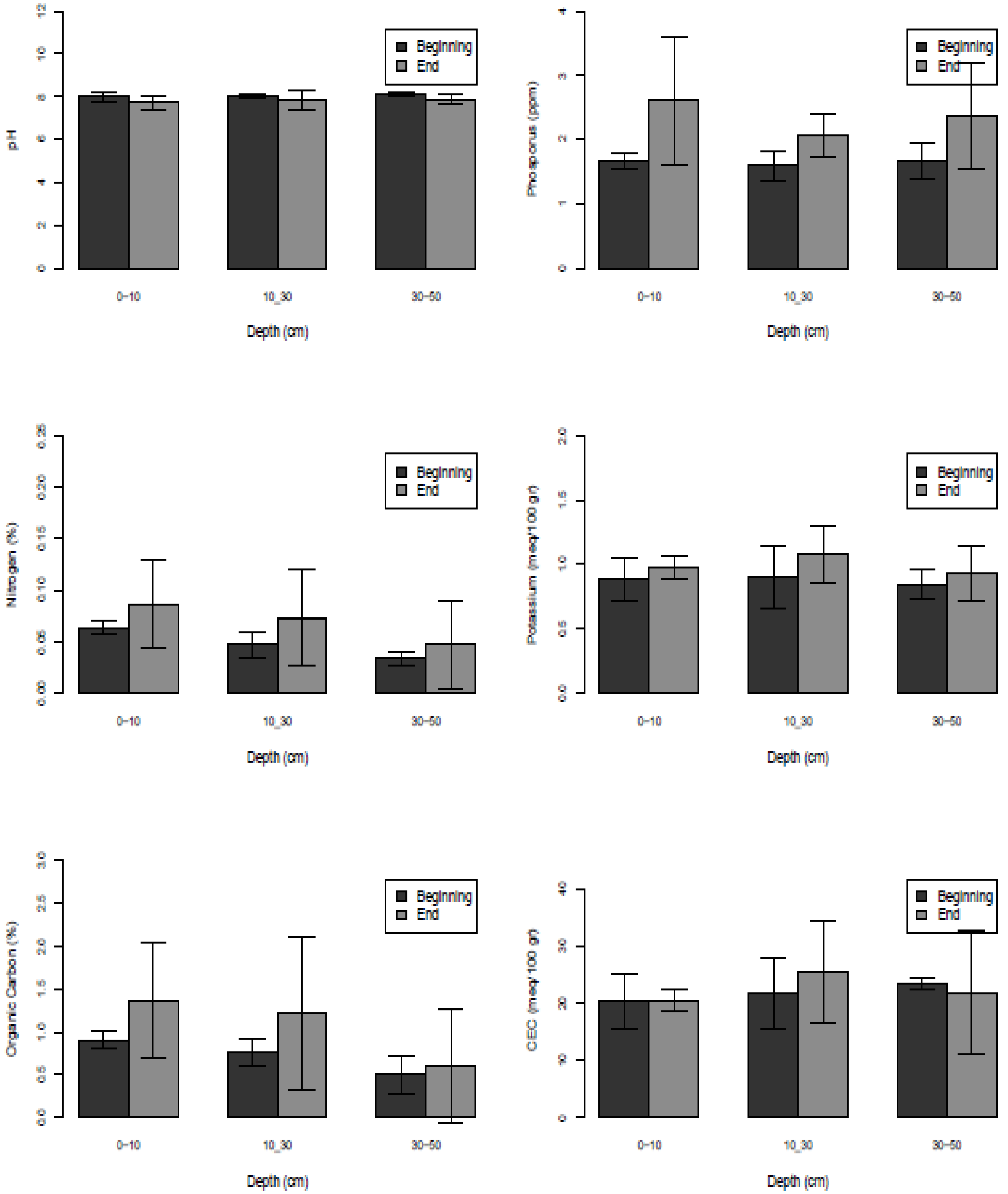


Fig. 14: *Mean value and standard error bars for soil properties at the beginning and at the end of the experiement in Grevillea robusta plots. Dark bars are mean value before planting. Light bars are mean value after 48 months.*

Table 3: *Diagonal table of significance soil parameter differences between species at different soil depths. OC: Organic carbon, N: nitrogen, CEC: Cationic Exchange Capacity, K: Potassium. In parenthesis, p-value at 0.05 level.*

0-10 cm	AD	AS	CP	DT	EG	GR	HA
AD							
AS							
CP	OC (0.0055) N (0.0016)	OC (0.0037) N (0.0458)				N (0.0069)	
DT	CEC (0.0418)		OC (0.0397)				
EG			OC (0.0039) N (0.0004)	CEC (0.0385) N (0.0180)		CEC (0.0473)	N (0.0016)
GR							N (0.0288)
HA	OC (0.0288) N (0.0069)	pH (0.0375) OC (0.0198) N (0.0042)					

10-30 cm	AD	AS	CP	DT	EG	GR	HA
AD							
AS							
CP	OC (0.0270) K (0.0442)						
DT	K (0.0262)						
EG		CEC (0.0383)	OC (0.0305) N (0.0427)	CEC (0.0126)		K (0.0335) CEC (0.0032)	N (0.0232) CEC (0.0365)
GR	K (0.0271) CEC (0.0390)						
HA							

30-50 cm	AD	AS	CP	DT	EG	GR	HA
AD							
AS			K (0.0178) N(0.0314)				
CP					N (0.0118)	N (0.0151)	
DT							
EG							
GR							
HA							

4.2. Biomass model, partitioning and comparison (study II)

The results revealed biomass based equations for *A. abyssinicus, O. europaea* ssp. *cuspidiata, O. rochetiana, R. glutinosa* and *S. theifolia* were different to each other. For example, the aboveground, stem and thin branches plus foliage biomass fractions for all the five studied species were strongly correlated to *dbh* and stump diameter (Table 4, **study II**). Similarly, most biomass fractions were also correlated to total height and commercial height. So, the Spearman's correlation revealed that biomass models could use *dbh* and total height as independent variables. From 12 biomass equations tested only four biomass equations were fitted (Table 3 and 5, **study II**). Crown and stem biomass fractions were fitted for *O. rochetiana*, *R. glutinosa* and *S. theifolia*. However, only above ground biomass was fitted for *A. abyssinicus*. The model parameters were significant at the 99 % confidence level ($p < 0.001$) (Table 5, **study II**). All stem biomass models showed higher biomass efficiency values than crown and branch models. Aboveground biomass models fitted in the Seemingly-unrelated regression (SUR) process showed high R^2-Adj values varying between 0.96 for *O. europaea* and 0.79 for *S. theifolia*. The observed-predicted values for total aboveground biomass did not show any presence of bias in the fitted models (Table 3, **study II**).

O. europaea ssp. *cuspidiata* and *O. rochetiana* exhibited similar biomass allocation trends and in these species the stem fraction accumulated more biomass than the crown fraction. While, in *R. glutinosa* crown fractions accumulated more biomass (53 %) than stem fractions (47 %) at the diameter class of 10 cm. However, stem fractions accumulated more biomass than crown fractions at higher diameter classes (15 and 20 cm). The comparison of general models to our models revealed Brown *et al*. (1989) presented the poorest results in terms of average deviation (ranged from 32 % to 59 %) and over estimation for all species. The higher average deviation (86 %) was found using the model of Brown (1997) for *R. glutinosa* (Table 6, **study II**), other species between 28 % and 39 %. The *t-test* showed Brown *et al*. (1989), model was not appropriate for four of the five studied species (*A. abyssinicus, O. europaea* ssp. *cuspidiata*, *O. rochetiana*, *R. glutinosa*) and Chave *et al*. (2005) model were also not suitable for three species (*A. abyssinicus, O. rochetiana*, *R. glutinosa*).

4.3. SOC and SON concentration and bulk density along elevation, land use and species (study III)

Highest, bulk density value were found under degraded land, cultivated lands and Pinus plantation. The highest Carbon and Nitrogen stock and concentration were found under natural forest, top soil and higher elevation gradients, however; the lowest Carbon and Nitrogen stock and concentration were found under degraded land, sub soil and low elevation gradients. The bulk density was different among the introduced species, however, the carbon and nitrogen concentration were higher in *Eucalyptus saligna* and lowest in *Pinus patula* plantation although statistically non-significant results were found.

Bulk density along attitudinal gradient and land use types

The bulk density of mineral soil was ranged from 0.5 g cm^{-3} dry soil to a maximum value of 1.40 g cm^{-3} dry soil. Bulk density was significantly varied among land use types and soil depth (Table 2, **study III**). Bulk density was significantly lower in the natural forest as compared to the other land use types in all soil depths. The higher value were found in crops and degraded lands (Figure 2, **study III**). Bulk density was significantly different between soil depths in natural forest from low values in the upper layer and higher values in the deepest layer (Figure 3, **study III**).

Carbon and nitrogen concentration along altitude

The forest floor carbon concentration ranged from 319.2 to 666 g C kg^{-1} of soil whereas the nitrogen concentration was ranged from 9.6 to 19.8 g N kg^{-1} of soil with increasing concentrations in the upper part of the gradient for carbon and in the middle part of the gradient for nitrogen although, statistically non-significant (Table 3, **study III**). The mean carbon and nitrogen stock for the forest floor was 9.36 ± 1.17 Mg C ha^{-1} and 0.25 ± 0.03 Mg N ha^{-1}, respectively. The mineral soil C concentration ranged from 7 g C kg^{-1} soil to 129.4 g C kg^{-1} soil, whereas the N concentration was ranged from 0.6 to 10 g N kg^{-1} soil. In the upper part of the gradient there were higher average values of C and N concentration (114.2 and 8.1 N kg^{-1}) (Table 3, **study III**), although, the difference were non-significant (Table 4, **study III**).

Land use type

The results revealed that carbon and nitrogen concentration were highly influenced by land use type and soil depth (Table 2, **study III**). The carbon and nitrogen concentration in the native forest was always higher than other land use types in all the sampled soil depths. Nitrogen concentration was similar in crop and degraded land where as natural forest and plantations showed higher values in the first 30 cm. Carbon stock in the natural forest is the highest of all land uses at all depths (225.03 Mg ha^{-1}) in one meter depth (Table 6, **study III**). In plantations the carbon stock is one third less than in natural forest but 35 % more in crops and 77 % more than in degraded land at the same depth, on the first 10 cm of mineral soil plantations has significant more carbon content than crop and degraded land (Table 6, **study III**).

Introduced species

The species effect was significant on bulk density values (Table 7, **study III**). Soil bulk density in eucalyptus plantation was 22 % significantly higher than in *Cupressus lusitanica* plantations (Figure 4, **study III**). However, species did not influence carbon and nitrogen stock. Total carbon stored upto 1 m in plantations ranged from 112.43 ± 4.32 and 185.83 ± 29.9 Mg C ha^{-1} for *Pinus patula* and *Eucalyptus saligna*, respectively (Table 8, **study III**) whereas total nitrogen stock ranged from 8.50 ± 0.44 and 12.26 ± 1.9 Mg N ha^{-1} for the same species. *Cupressus lusitanica* has an intermediate value.

4.4. Stand density management model evaluation and fitting (study IV)

The stand density management diagram for Chilimo mixed forest revealed that dominant height and quadratic mean diameter were the best endogenous fitting variables (Table 2, **study IV**). All the estimated parameter for *P. falcatus* and five estimated parameters for *J. procera* were significant ($p < 0.05$). Likewise, volume was better fitted than number of stems and basal area. The R^2 adjusted validation data for *P. falcatus* was over 0.80 and 0.95 for the quadratic mean diameter and volume model, respectively. Although, the stand density management diagram for *J. procera* and *P. falcatus* showed similar trends (Figure 2 and 3, **study IV**), the volume, total height and number of stems per hectare varied among the species. *J. procera* was the dominant tree species in the Chilimo dry afro-montane forest with a mean quadratic diameter up to 80 cm. However, *P. falcatus* was structuraley belongs to both dominant and codominant group and dominated by medium sized height and diameter trees. However, higher numbers of naturally regenerated seedlings were observed for the species. Similarly, for species proportion the number of stems was exceeded upto 1025 stems ha^{-1}. Alternative management options were developed by considering species proportion for *J. procera* and *P. falcatus* (Figure 5, **study IV**). The minimum quadratic mean diameter to be thinned will be 25 cm and the maximum diameter will be also 35 cm (Table 5, **study IV**). Thinning will be applied for *J. procera* and *P. falcatus*.

4.5. Carbon concentration and wood density for five most commonly tree species (study V)

The carbon concentration and wood density were different among and within the species, plant parts and stem position (height). The major dendrometric variables were correlated to carbon content and wood density. Wood density was moderately to highly correlate to commercial height, basal area and stem. The carbon concentration ranged from 57.12 % for *O. rochetiana* to 56.43 % % for *A. abyssinicus* (Figure 2, **study V**). The wood density ranged from 0.67 g cm^{-3} for *O. europaea* ssp. *cuspidiata* to 0.42 g cm^{-3} for *A. abyssinicus*. Stem parts had higher (56.98 %) carbon content than branch and leaves parts (Figure 4, **study V**). The carbon concentration and wood density showed a decreasing trend along with increasing in tree height (stem position).

Discussion

5. DISCUSSION

Major finding of five studies conducted in a degraded land and in a tropical dry afro-montane mixed forest located in the Central Highlands of Ethiopia are presented. The species and soil management screened for fuelwood production and rehabilitation of degraded lands can be used in the national afforestation and reforestation programmes. The best performed tree species *E. globulus*, *G. robusta* and *H .abyssinica* can be planted on abandoned degraded lands, along home-steads and farm baundaries in central Highlands of Ethiopia to alleviate fuelwood shortage. In addition, the species can provide construction wood, farm implements and generating income for the society. The information, technologies and practices generated from Chilimo dry afro-montane forest can be applied for the other Ethiopian forests too and for REDD+ (Reducing Emissions from Deforestation and Forest Degradation) projects in the country. In Ethiopia REDD+ is implemented with three major objectives: (i) conservation of indigenous remnant trees and natural forests, (ii) sustainable management of forests and (iii) enhancement of carbon stock. The project is evolving as an integral part of a wider green economic growth strategy and the climate resilience strategy in the country (http://www.theredddesk.org/countries/ethiopia). Ethiopia is also a participant country of the World Bank Forest Carbon Partnership Facility (FCPF) for example under this facility the following projects are ongoing: Bale-mountain ecoregion conservation centre, Keffa biosphere reserve and Humbo clean development mechanism (CDM) projects. Consequently, majority of the remnants of the high forests are managed primarily for protection and conservation pupose while commercial utilization is a secondary objective. These forests have classified into 58 National Forest Priority Areas (NFAs) of the country. The forests also play an important role in the global carbon cycle and contribute to mitigation of climate change through carbon (sequestration, substitution and conservation). However, over two-thirds of these high forests are heavily disturbed forests and needs appropriate management intervension (Bekele, 2001). In addittion, there are scanty informations about how to manage these forests and to show their importances for the above mentioned objectives (Lemenih and Kassa, 2014). The information obtained from this thesis can be taken as an input for sustainable management and utilization of these forests. Between the key information by this thesis is the following, (i) species selection and soil management for simultaneous fuelwood production and soil rehabilitation, (ii) above ground biomass equation, (iii) soil organic carbon and total nitrogen stock and concentration along land use, elevation and species, (iv) stand density management diagram for mixed forest and (v) carbon concentration and wood density in the plant sample for five most commonly grown tree species.

5.1. Performance and soil condition of selected species in degraded highlands of Ethiopia (study I)

The combination of survival, root collar diameter and height growth, total biomass production and changes in soil fertility after 48 months provides a five-dimensional indicator of species suitability for both objectives. The best option would always be that with the highest values in all five indicators; however, none of the species fulfilled these five requirements.

G. robusta, H. abyssinica and *E. globulus* had the highest survival rates while *C. palmensis* and *A. saligna* had intermediate survival rate. Peter *et al*. (2005) reported a survival rate of 100 % in Australia for *G. robusta* and Arredondo *et al*. (1998) reported, in Chile, a survival rate of 25 % and 60 % for *A. saligna* and *C. palmensis*, respectively.

E. globulus, A. saligna and *A. decurrense* had faster root collar diameter and height growth and produced maximum biomass production than other species and the soil management significantly impacted their growth. Similarly, Mekonnen *et al*. (2006) reported greater height and root collar diameter growth for *E. globulus* in central highlands of Ethiopia. *G. robusta* showed intermediate height and root collar diameter growth. *H. abyssinica, D. torrida* and *C. palmensis* had lower root collar diameter and height growth and biomass production but improving nitrogen, carbon and available potassium. *E. globulus* depleted nitrogen, whereas *Acacia* species did not show a clear pattern.

Plantation of selected native or exotic species can play a major role in the rehabilitating degraded land with little enhancement of biodiversity (Chazdon, 2008). *Eucalyptus* is one of the most popular species widely planted in Ethiopia. *E. camaldulensis* and *E. globulus* are the two dominant species (Lemenih and Kassa, 2014). *E. globulus* is the prevailing feature of the rural landscape and important to maintain livelihood for smallholder farmers in the Ethiopian highlands (FAO, 2009; Gil *et al*., 2010). Socio-economic studies on *E. globulus* and *E. camaldulensis* in the country showed, planting of these species generated adequate income to the households more than agricultural crops do especially in degraded soil (Daba, 1998; Gebre-Markos, 1998; Jagger and Pender, 2000; Zerihun, 2002; Holden *et al*., 2003; Tesfaye, 2009).

E. globulus is not improving soil fertility in this experiment, although, it produced highest biomass and better growth, there are two opposite arguements regarding the role eucalyptus for soil fertility improvement and soil rehabilitation, those who are supporting and advocating the species, they considered eucalyptus as a fast growing tree species, it requires minimum care and protection, it is widely grown in a wider ecological zones and poor environments, it coppices after harvest, improving soil fertility and rehabilitation of degraded lands, swampy and drier areas (Ponjonen and Pukkala, 1990; Jagger and Pender, 2000 and 2003; Mekonnen *et al*., 2007; Nduwamugo *et al*., 2007; Kelemu and Tadesse, 2010). In the meantime, Fialho and Zinn (2012) in Brazil found similar carbon concentration under *eucalyptus* plantation as compared to adjacent natural forest. Similarly Oballa *et al*. (2010) in Kenya also found higher nutrient concentration under *eucalyptus* plantation than adjacent tea plantation. Higher regeneration and undergrowth were also reported under *Eucalyptus* plantations than other exotic tree species (*Cupressus lusitanica* and *Pinus patula*) in Ethiopia (Biruk, 2012). Alem and Woldemariam (2010), found *E. grandis* used as a shade in coffee plantation in Southern Ethiopia and the density of coffee stems found under *E. grandis* plantation (1022 stems per ha^{-1}) was more or less similar to the coffee stems found under natural forest (1042 stems per ha^{-1}).

In the contrary, others blamed eucalyptus for its environment deterioration i.e. they stated eucalyptus: depletes under ground water, facilitate soil erosion, depletes soil nutrients and introduces allellophatic effets to mimic the undergrowth of other species (Davidson, 1985; FAO, 1988; Teketay, 2000; Amare, 2002; Munishi, 2009; Ndowamungo *et al*., 2007). In the mean time, Wu *et al*. (2013) reported the negative impact of eucalyptus on dissolved organic carbon concentration and Teketay (2003) found lower carbon concentration under eucalyptus plantation than natural forest. Neverthless, there is no concrete evidence and agreement that proved its detrimental effect on the under growth species (Biruk, 2012).

H. abyssinica increased significantly organic carbon in the top soil to 30 cm deep [Figure 3(e)], **study I**). *G. robusta* also improved soil condition (Figure 16; **study I**) and it has best survival and possess excellent firewood properties in its natural distribution area (Jaing and Singh, 1999). *E. globulus* is the most productive species in terms of biomass production for firewood also shows good survival rate and preferred by farmers for planting (Beweket, 2003). *Eucalyptus* is used as main sources of income for small scale farmers, besides solving shortage of wood demands in central highlands of Ethiopia (Biruk, 2012). *H. abyssinica* might be considered for reforestation programs to rehabilitate degraded lands and exotic *G. robusta* and to a lesser extent *E. globulus*, as a preliminary step to natural vegetation recovery and as good providers of raw material for fuel wood production.

5.2. Biomass model, partitioning and comparison (study II)

Site and species specific biomass based equation models for the five tree species: *Allophyllus abyssinicus*, *Olea europaea* ssp. *cuspidiata*, *Olinia rochetiana*, *Ruth glutinosa* and *Scolopia theifolia* were developed in a tropical dry afro-montane mixed forest, Central Highlands of Ethiopia.

Among the various measured dendrometric variables, diameter at breast height (*dbh)* and total height were considered as independent variables in all the biomass fractions (Table 5, **study II**). Several authors have also been advocated the use of these variables (Brown *et al*., 1989; Basuki *et al*., 2009; Ruiz-Peinado *et al*., 2011 and 2012). Chave *et al*. (2005) reported dbh, wood specific gravity, total height and forest type as important variables for prediction of tree biomass in tropical forests. Later, Henry *et al*. (2011) advocated these variables, due to the variation in wood gravity, volume and biomass, while, Feldpausch *et al*. (2012) reported total height improves the accuracy of biomass estimation in tropical forests. Fitted biomass equations were specific dependent (Table 5, **study I**I) e.g. only total above ground biomass was fitted for *A. abyssinicus* due to low biomass of crown biomass and foliage biomass. For the other four species, biomass equations were developed for the stem and crown biomass fractions. Similar results are also reported by Negash *et al*. (2013). All the estimated parameters of the biomass models showed positive coefficient values. This imples an increasing in height growth resulted in increasing in diameter growth. Although, some authors proposed the use of generalized equations to estimate aboveground biomass in African tropical forests (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 1997; Chave *et al*., 2005), the use of species and site-specific equations are advocated by several authors (Ketterings *et al*., 2001; Litton and Kauffman, 2008; Henry *et al*., 2011). In addition, local or sub-national stage biomass equations are very important for accurate estimate of biomass models for REDD$^+$ measuring, reporting and verification country level natural resources management and inventories (Naesset, 2007; Peterson *et al*., 2007). Biomass mapping in Africa suffers from lack of regional and site specific allometric equations. Besides, the existing general and specific biomass equations in the region (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 2002; Chave *et al*., 2005; Henry *et al*., 2010; Djomo *et al*.,

2010) there is a lack of local biomass equations. Neverthless, Chave *et al*. (2005) did not use trees from Sub Saharan African countries forests used to develop generalized allometric equations for African forests. Some authors have inventoried tree biomass equations for South America (Návar, 2009) and Europe (Zianis *et al*., 2005) but no report from Sub-Saharan Africa and or under studied (Henry *et al*., 2011). Currently, national and continental data bases for allometric equation for Africa are few and it should be continually updated and studied (Chave *et al*., 2005; Zianis *et al*, 2005; Návar, 2009; Henry *et al*., 2011a; Henry *et al*., 2013). Thus, site and species specific biomass equation models are very important for African forests (Ngomanda *et al*., 2014). The comparison of the generalized models (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, *et al*., 1997; Chave *et al*., 2005) to the fitted models for these studies species (Table 6, **study II**) showed that, the accuracy vary with the species. Brown *et al*. (1997) model is valid for only *R. glutinosa* (p-value < 0.05). Chave *et al*. (2005) showed acceptable statistics for only two of the species. Stem biomass proportions in *O. europaea* ssp. *cuspidiata* and *O. rochetiana* were nearly constant along the diameter distribution (Figure 3, **study II**). However, stem proportions over above ground biomass was higher than crown to above ground biomass proportion in *R. glutinosa* and *S. theifolia* were growing when diameter is increasing. Our results are consistent with other findings e.g. Henry *et al*. (2010), found higher biomass accumulation in the stem fraction (72 %) than in crown fractions (28 %) and Mate *et al*. (2014), showed mean biomass partitioning values for three tropical species ranged between 46-77 % for stem and 23-54 % for crown, considering these authors trees with higher diameter than sampled trees of this study.

These biomass equation models are important for the sustainable utilization and management of these five tree species in Chilimo dry afro-montane mixed forest in particular and other dry afro-montane forest in general. In line with this, above ground biomass equation models are important tools for reporting and monitoring carbon stock for reducing land degradation and deforestation in the country and acquiring adequate information to benefit the poor farmers in developing countries from carbon trade in the world market (Siwe *et al*., 2011; UNFCC, 2011).

5.3. SOC and SON concentration and bulk density along elevation gradient, land use and species (study III)

Soil organic carbon stock (SOC) play an important role in productivity and sustainable use of soil for tropical forest ecosystem through the moderation of cation exchange capacity (CEC), water holding capacity, soil structure, resistance against erosion, nutrient retention and availability and buffering against sudden fluctuations and pH. Understanding the soil organic carbon and nitrogen stock and concentration are important for carbon management, climate change mitigation and adaptation. Estimates of soil carbon stocks at regional, national and global scales are important for the understanding of changes in carbon flux (Yimer *et al*., 2006). The information's are useful to implement sustainable management in the Chilimo forest and for carbon trade in REDD$^+$ project.

The carbon and nitrogen concentrations and stocks were higher under the higher and middle altitudinal classes as compared to lower altitudinal classes, although, statistically non-significant results were found (Table 4, **study III**). This was might be due to better nutrient cycling and lower human disturbance. In the contrary, the lower stock and concentration in the lower altitudinal classes was might be due to higher human disturbance and animal interferences. Ngo *et al*. (2013) reported the variation in carbon storage among tropical forests is due to variation in species composition, disturbance history, climate regimes and soil fertility. Higher soil organic carbon was reported in the top soil (0-15 cm) under middle and higher altitudinal elevation (Shrestha *et al*., 2004; Awashi *et al*., 2005; Shrestha and Singh, 2007) a similar result was also reported in Rungwe mountains areas of Tanzania (Zewdu and Hògreb, 2004; Sah and Brumme, 2003; Mwakinsunga and Majule, 2012).

The results revealed land use type and soil depth significantly affected soil organic carbon and nitrogen stock and concentration and bulk density in the mineral soil. The carbon and nitrogen stock (225.03 Mg ha^{-1}) in one meter depth were higher in the natural forest for all the sampled soil depth (Table 6, **study III**). The total nitrogen concentration in natural forest is also higher by 82 %, 52 % and 27 % more than degraded land, crop land and plantation, respectively. In the contrary, the lowest carbon and nitrogen concentration were found under degraded land and deepest soil. The higher stock in the natural forest was might be due to better nutrient input through litter fall, higher species diversity and density, low human disturbance and lower soil erosion. Continous removal, and surface crusting and lack of inputs in degraded and cultivated lands resulted in lower value. Lv and Liang (2012) reported land cover changes affect litters, plant root, soil fauna, soil microorganisms and soil condition. Several authors reported the significant impact of land use change from cropland to forestland and viceversa (Guo and Gifford, 2002; Zhang, 2010), though, the magnitude varies from place to place. Wu *et al*. (2013) estimated a SOC loss of 10 % - 40 % in the cultivated soils than non-cultivated soil in China. Solomon *et al*. (2002), found a reduction in 55 % - 60 % in carbon stock from conversion natural forest to crop land. Ashagrie *et al*. (2005) and Girmay *et al*.

(2008) reported a significant reduction in SOC and SON (50 % and above) when natural forest were converted into plantation.

Soil sampled under *E. saligna* plantation had higher SOC and SON stock as compared to other introduced species, although, statistically non-significant results were found. The higher SOC and SON stock under *Eucalyptus* plantation was might be due to better litter fall and lower soil erosion. Similarly, Lemma *et al*. (2006) found higher SOC under *E. grandis* than *C. lusitanica* and *P. patula*. Berthron *et al*. (2009) found a significant decrease in soil organic C and N with *Pinus* afforestation but not with other studied species (*Eucalyptus*, angiosperm, conifers). On the other hand, our research findings of soil carbon stock was ranged from 112.43 ± 4.32 and 185.83 ± 29.9 Mg C ha^{-1} for *P. patula* and *E. saligna*, respectively (Table 8, **study III**) are in consistent with other findings in Africa e.g. 152 Mg C ha^{-1} for cocoa agroforestry in South Cameroon (Duguma *et al*., 2001) and 66-88 Mg C ha^{-1} in oil palm (Egbe *et al*., 2012) and in other parts of the world, 150 Mg C ha^{-1} (82-242) in Spain (Balboa-Murias *et al*., 2006) an average of 135 Mg C ha^{-1} in *Pinus radiata* and 99 Mg C ha^{-1} in *Pinus pinaster* reported by Balboa-Murias *et al*. (2004).

Bulk density is the most discriminating factor in soil properties in relation to land use and management (Shukla *et al*., 2004), the highest value were found in crops and degraded land. However, bulk density was significantly lower in the natural forest in all sampled soil depths; this was might be due to higher litter fall and decomposition rate in the natural forest and opposite condition in the degraded land and cropland. The bulk density was significantly varied among introduced species; this was might be due to varied in the amount of litter fall and decomposition rate and rooting nature of the species. Similarly, Hajabbasi *et al*. (1997) reported higher soil organic matter content improves soil texture and this resuled in a decreasing of bulk density in natural forests. Celika (2005) showed, cultivated soils have higher bulk density than adjacent soils under forests and pastures in the southern Mediterranean highlands of Turkey.

Although, our measurements results of the soil organic carbon and nitrogen concentration and stock measurements in native natural forest and plantation forest are higher than those reported in some regions (Beets *et al*., 2002; Harms *et al*., 2005; Yimer *et al*., 2006; Twongyirwe *et al*., 2013) the results are consistent with other findings (Michel *et al*., 2004; Omoro *et al*., 2013; Shelukindo *et al*., 2014).

5.4. Stand density management model evaluation and fitting (study IV)

Stand density management diagrams (SDMD) are adequate and simple tools to introduce model forecasting where data are scarce and appropriate decision making processes to enhance future stand dynamics is needed. Between, the key issues that could be addressed with SDMD are for instance volume, wood properties or habitat characteristics of the forest. By using data from 35 temporary plots located in Chilimo dry afro-montane forest density management diagrams were developed. SDMD are important tools for decision making process for forest managers based on stand information of maximum and minimum density of stems, dominant height and total stand volume. By using SDMD we can determine total stand volume, total height, quadratic mean diameter and density directly for any point using the stand volume isolines (Figure 5, **study IV**). Thinning operations were showed based on self-thinning rule starting over 60 % of the maximum Reineke index (Dean and Baldwin, 1996) (Figure 5, **study IV**). Minimum level of Reineke index is 35 % to allow full site occupancy showed in the graph. Whole-stand models as SDMD, allow managers to adopt decisions in an effective-cost manner under low-economic return silvicultural systems. Other modeling approach such as empirical individual-tree or process-based models can be more useful to understand ecosystem dynamics but more detailed data are needed. However, SDMD are practical tools basic in extensive silvicultural applied in low productivity forests (Valbuena *et al*., 2008).

5.5. Carbon concentration and wood density for five most commonly tree species (study V)

The carbon concentration and wood density for the five studied tree species found in Chilimo dry afro-montane forest: *A. abyssinicus*, *O. europea* ssp. *cuspidiata*, *O. rochetiana*, *R. glutinosa* and *S. theifolia* were significantly varied among the tree species, plant parts and stem height within and among the species. These variations were might be due to differences in physical and chemical properties of wood and growth pattern of the tree species under study. Similar results are also reported by Chavan and Rasal (2012) that found a higher carbon concentration in the stem parts than leave, branch and bark parts for *Annona retiacula* and *Annona squamosa* while Herrero *et al*. (2011) and Castaño-Santamaria and Bravo (2012) reported specific variations in carbon concentration and wood density along heart wood, sapwood and bark stem parts of the three Mediterranean *Pinus* spp. These variations in Mediterranean pines were also related with cambial age of the wood. The carbon concentration for our studied species were ranged from with a maximum value 57.12 %

to 56.43 % and the wood density was ranged from with a maximum value 0.67 g cm^{-3} to the minimum value of 0.42 g cm^{-3} (Figure 2, **study V**). Our wood density findings for the five tree species mentioned above are in line with other research results (Brown *et al*., 1989; Brown, 1997; Paroline and Worbes, 2000; Houghton *et al*., 2001). In this study, the carbon concentration and wood density showed a decreasing trend along with increasing in tree height (stem position); this was might be due to variation in wood structure and chemical composition. Similar findings by Barahona (2005) found higher values of wood density and carbon content in the bottom parts of a tree than top parts. Amorim (1991) and Desatro *et al*. (1993) found a decreasing trends in wood density for trees grown in the tropics from breast height of 1.3 m to top commercial height (≤ 7 cm diameter). Higuchi and de Carravalho (1994) found a higher wood density at the breast height than the top parts. Structural differences in wood density are strongly correlated with differences in mechanical and chemical properties of wood, water transportation efficiency, buckling and bending properties of wood and the proportion of juvenile wood (Zobel and van Buijtene, 1989; Gertner and Meinzer, 2005; Pittermannet *et al*., 2006).

Conclusions

6. GENERAL CONCLUSIONS

A total of five studies were conducted in a degraded land fenced experiment and in the Chilimo dry afro-montane forest in Central Highlands of Ethiopia. The studies were focused on: (1) Best performed tree and shrub species and soil management under degraded land, (2) Aboveground biomass equation for mixed tropical forest, (3) Soil carbon and nitrogen stock and concentration and bulk density in the forest floor and mineral soil along elevation, land use and species, (4) Stand density management diagram for mixed species and (5) Carbon concentration and wood density for five tropical native tree species. In addition, the following conclusions can be drawn from these studies:

1 *G. robusta* showed the highest overall survival rate followed by *H. abyssinica*. *A. decurrense* showed the lowest survival rate. *E. globulus* outperformed all species in height growth and biomass production and had a similar root collar diameter growth as *A. saligna*. *H. abyssinica*, *C. palmensis* and *D. torrida* showed the lowest growth and biomass production, but all of them improved soil conditions 48 months after plantation. *A. saligna* showed a stronger response to manure plus mulch than other species.

2 Dry biomass production was highly significant for *E. globulus*, although, it was non-significant across soil management options and there is no clear effect of any of the soil management option in growth. Native tree species might not show better growth performance in harsh environment conditions however, native species improved soil conditions in these environmental conditions.

3 Tree diameter and total height were considered as the best independent variables for biomass estimation for (*A. abyssinicus*, *O. europaea* ssp. *cuspidiata*, *O. rochetiana*, *R. glutinosa* and *S. theifolia*). Crown biomass were fitted for three of the five species studied (*O. rochetiana*, *R. glutinosa* and *S. theifolia*) due to high variability in branch biomass fraction and resulting from inter-specific competition in the mixed tropical forest. However, an aboveground model was developed for *A. abyssinicus* based on its biomass heterogeneity and small weight of crown biomass.

4 The generalized models proved unsuitable for these types of forest and to improve estimation accuracy and reduce uncertainty, we suggest the application of the species-specific models developed in this study to similar Ethiopian mixed forests and other tropical montane forest.

5 Soil depth is a more important factor than elevation gradient in the study area, although, carbon and nitrogen concentration and stock diminished near human settlement which were located in the lower part of the elevation gradient. Bulk density can have an important confounding effect in soil condition assessment and an efficient estimation method of soil carbon and nitrogen must be performed accordingly.

6 Chilimo native dry afro-montane forest stores 225.03 Mg C ha^{-1} in 1 m soil depth and 80 % of 1 m carbon stock is stored on the first 50 cm soil depth. Natural forest stored more carbon and nitrogen than adjacent land uses where as soil degradation resulted 82 % loss of nitrogen stock.

7 Conversion of cropland and degraded land into plantations ameliorate soil condition degradation and species selection did not affect carbon and nitrogen stock despite significantly lower value of bulk density were found in *Pinus patula* plantation.

8 Dominant height and quadratic mean diameter were found to be the best endogenous fitting variables for stand density management diagram for Chilimo mixed forest. Formulating SDMD using species proportion is better than treating each species independently and SDMD have a positive impact in improving growth and yield of the forest. In addition, this SDMD is the first in Africa and can serve to support the sustainable management of Chilimo dry afro-montane forests.

9 The carbon concentration and wood density varied among and within species, plant parts and stem position. Higher carbon concentration and wood density values were found at the stump height as compared to other position. Among the studied species, the wood density of *O. europaea* ssp. *cuspidiata* was higher as compared to other studied species and estimation of carbon concentration and wood density at species level is very important to provide updated information for different institutions regarding carbon conservation and sequestration for Chilimo dry afro-montane natural forest.

10 It is suggested that the use of native tree species and plantations could have a positive impact in C and N storage as other studies demonstrated in the same area. All the above outputs serve as a management tool for the sustainable management of Chilimo forest in general and implementing carbon trade in particular.

6. CONCLUSIONES GENERALES

En total cinco estudios se llevaron a cabo en un experimento cercado en tierras degradadas y en el bosque seco afro-montano de Chilimo en la Sierra Central de Etiopía. Los estudios se centran en: (1) las especies de árboles y arbustos y la manejo del suelo más adecuado para tierras degradadas, (2) ecuación de biomasa aérea para especies de bosques tropicales mixtos, (3) El carbono del suelo y nitrógeno de valores y la concentración y la densidad aparente en el suelo del bosque y suelo mineral a lo largo de la elevación, el uso y las especies de la tierra, (4) Diagrama de manejo de densidad para la gestión especies mixtas y (5) concentración de carbono y densidad de la madera de cinco especies nativas de árboles tropicales. Las siguientes conclusiones se pueden extraer de estos estudios:

1 *G. robusta* mostró que la tasa de supervivencia global más alta, seguido por *H. abyssinica*. *A. decurrense* mostró la menor tasa de supervivencia. *E. globulus* superó todas las especies en crecimiento en altura y la producción de biomasa y tuvo un crecimiento del diámetro de cuello similar a A. saligna. H. abyssinica, C. y D. palmensis torrida mostraron el crecimiento y producción de biomasa más bajo, pero todos ellos mejoraron las condiciones del suelo 48 meses después de la plantación. A. saligna mostró una respuesta más fuerte al estiércol más mulch que otras especies.

2 la producción de biomasa seca fue altamente significativa para E. globulus, aunque fue no significativa comparando las opciones de manejo del suelo y no hay un efecto claro de cualquiera de la opción de gestión del suelo en el crecimiento. Especies de árboles nativos podrían no mostrar un mayor crecimiento en condiciones ambientales duras sin embargo, mejoran las condiciones del suelo en estas condiciones ambientales.

3 El diámetro y altura total fueron consideradas como las mejores variables independientes para la estimación de la biomasa para la (*A. abyssinicus*, *O. europaea* ssp. *Cuspidiata*, *O. rochetiana*, *R. glutinosa* y *S. theifolia*). Modelos para biomasa de la copa fueron ajustados solo para tres de las cinco especies estudiadas (*O. rochetiana*, *R. glutinosa y S. theifolia*) debido a la alta variabilidad en esta fracción de biomasacomo resultado de la competencia inter-específica en el bosque tropical mixto. Sin embargo, un modelo de biomasas para *A. abyssinicus* se ajustó basado en la heterogeneidad y poco peso de la biomasa de la copa.

4 Los modelos generales resultaron ser inadecuados para este tipo de bosque, para mejorar la precisión de la estimación y reducir la incertidumbre se sugiere la aplicación de los modelos específicos de especies desarrolladas en este estudio para los bosques mixtos etíopes similares y otros bosques montanos tropicales.

5 La profundidad del suelo es un factor importante de gradiente altitudinal en el área de estudio, si bien, la concentración de carbono y stock nitrógeno disminuyeron cerca de los asentamientos humanos localizados en la parte inferior del gradiente altitudinal, La densidad aparente puede generar confusión en la evaluación de la condición del suelo y un método de estimación eficiente de carbono y nitrógeno en el suelo debe ser realizado.

6 El bosque seco nativo afro-montano de Chilimo almacena 225.03 Mg C ha^{-1} a 1-m de profundidad del suelo y el 80% del carbono se almacena hasta 50 cm de profundidad. Bosque natural almacena más carbono y nitrógeno que los otros usos de la tierra adyacente, donde la degradación del suelo resulta en un 82% de pérdida del stock de nitrógeno.

7 La conversión de cultivos y tierras degradadas en plantaciones aminoraron las condiciones de degradación del suelo, y la selección de especies no afectaron el stock de carbono y nitrógeno a pesar valor significativamente más bajo de densidad aparente encontrado en la plantación de Pinus patula.

8 Altura dominante y el diámetro medio cuadrático resultaron ser las mejores variables de ajuste endógenos para los diagramas de manejo de densidad para bosques mixtos de Chilimo. Formular SDMD utilizando la proporción de especies fue mejor que tratar cada especie independiente y SDMD tiene un impacto positivo en la mejora del crecimiento y rendimiento del bosque. Además, este SDMD es el primero para bosques de África y puede servir para apoyar la gestión sostenible de los bosques afro-montanos secos de Chilimo.

9 La concentración de carbono y densidad madera varió entre y dentro de una especie, partes de la planta y posición en el fuste, los mayores valores de concentración de carbono y densidad de madera se encontraron a la altura del tocón en comparación con otras posición. Entre las especies estudiadas, la densidad de la madera de *O. europaea* ssp. *cuspidiata* fue mayor en comparación con las otras especies. La estimación de la concentración de carbono y densidad de la madera a nivel de especies es relevante para proporcionar información actualizada a diferentes instituciones realacionadas con la conservación y secuestro de carbono de los bosques naturales afro-montano secos de Chilimo.

10 Se sugiere que el uso de especies y plantaciones de árboles nativos podría tener un impacto positivo en el almacenamiento de C y N como otros estudios lo han demostrados en la misma zona. Todas las alternativas anteriores sirven como herramientas para la gestión sostenible de los bosques de Chilimo en general y especialmente para la implementación de mercados de carbono.

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7. ANNEXES

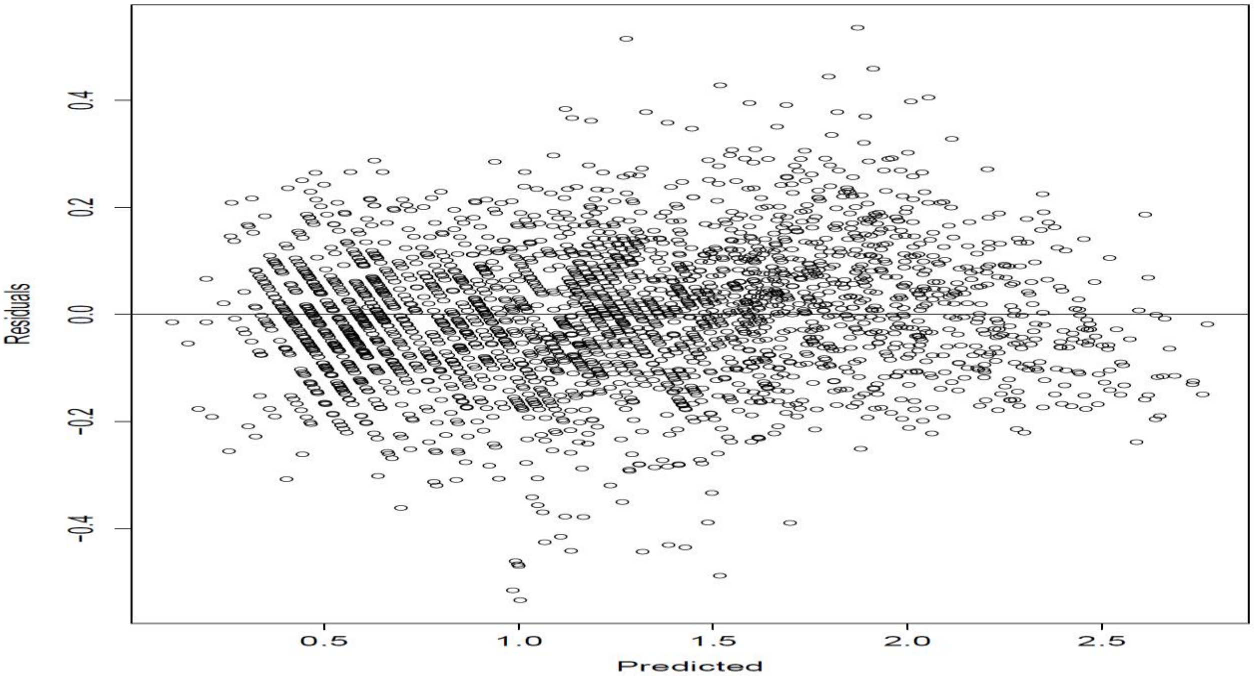


Fig.1*: Predicted and residual values for RCD.*

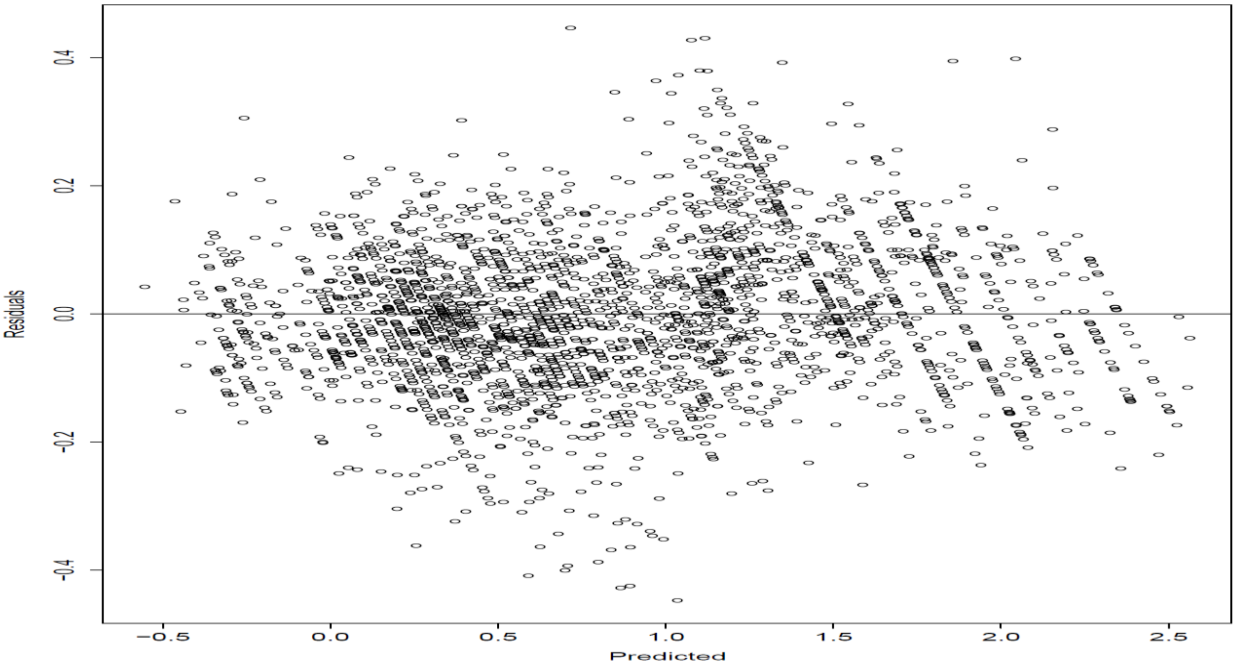


Fig.2*: Predicted and residual values for Height.*

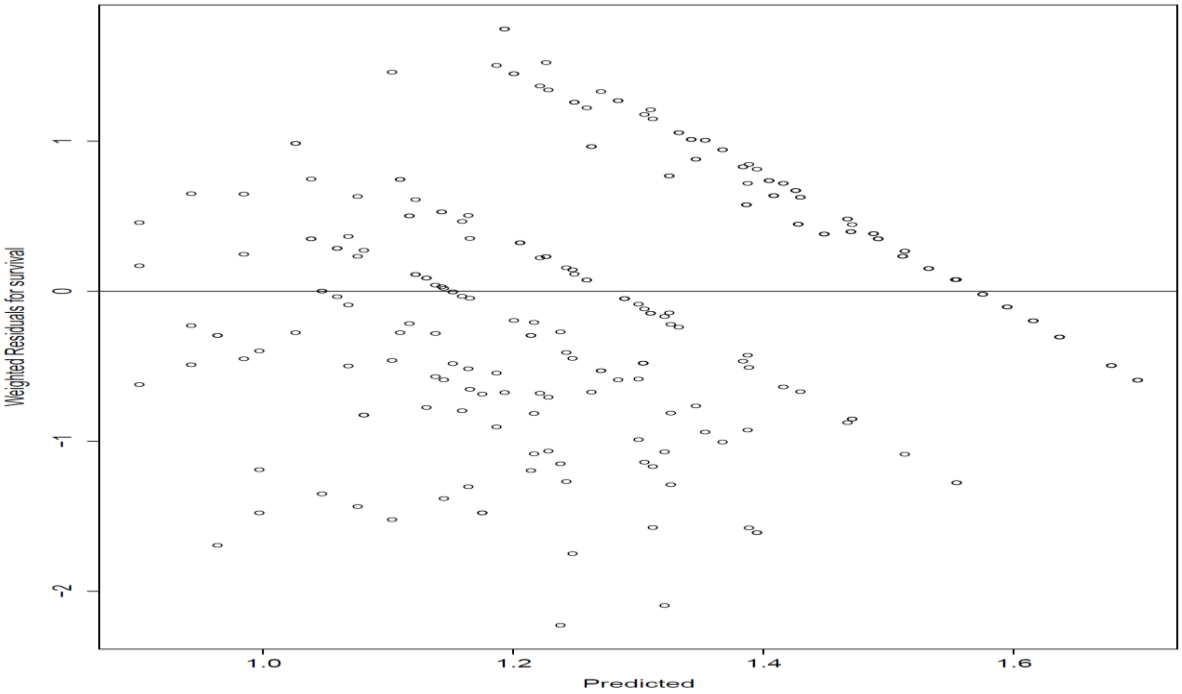


Fig. 3*: Observed and predicted values for survival.*

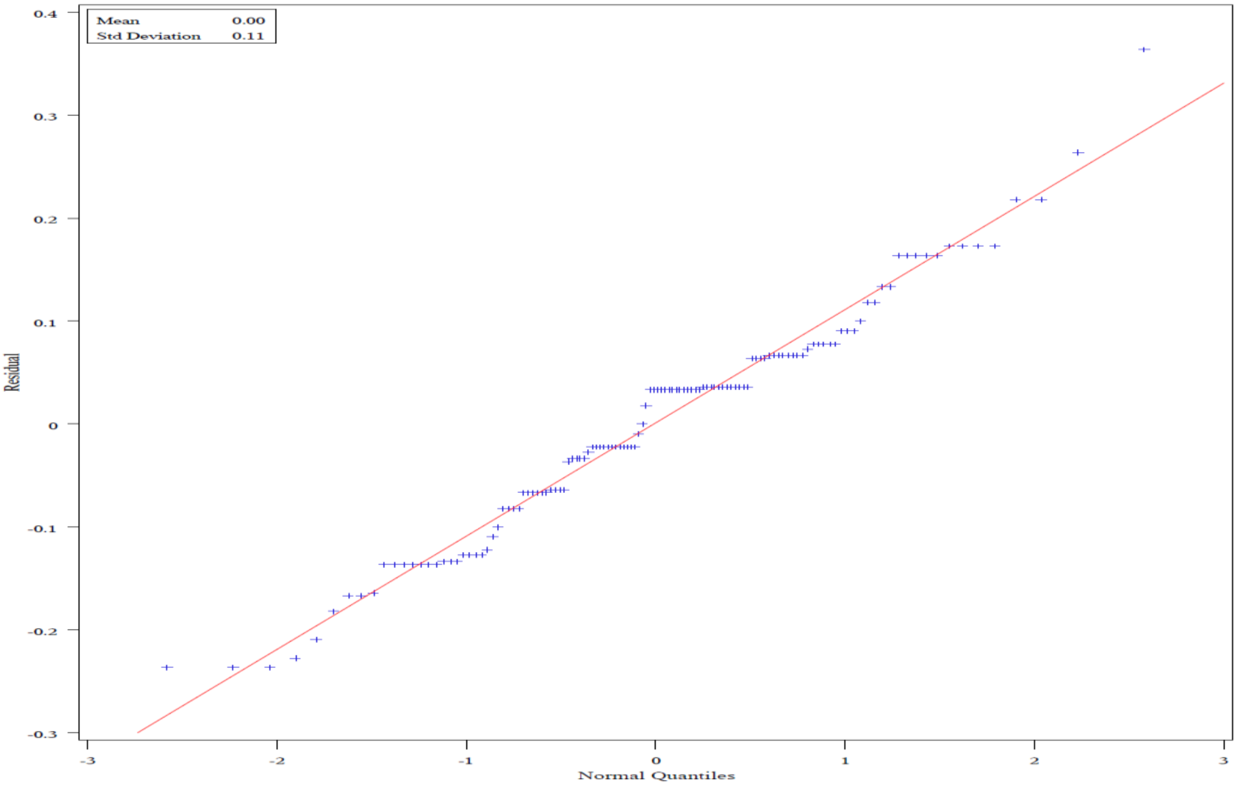


Fig. 4*: Bulk density data distribution along soil depth and land use type.*

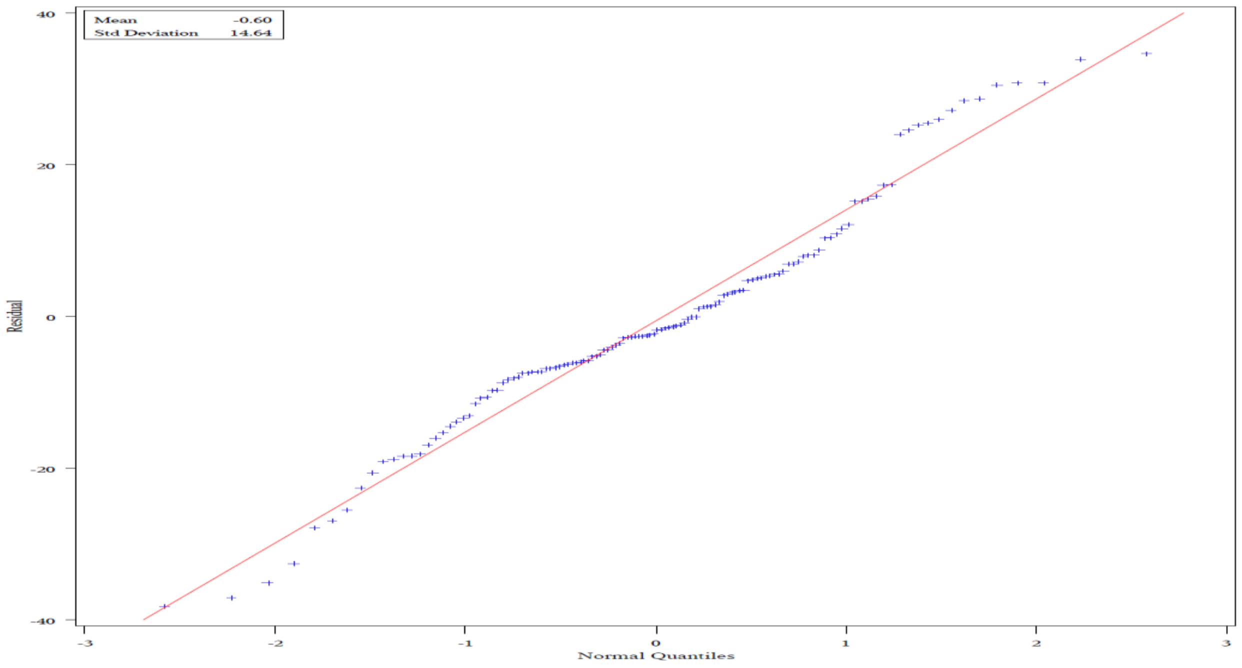


Fig. 5: *Normal distribution data for carbon stock along land use, elevation gradient and species.*

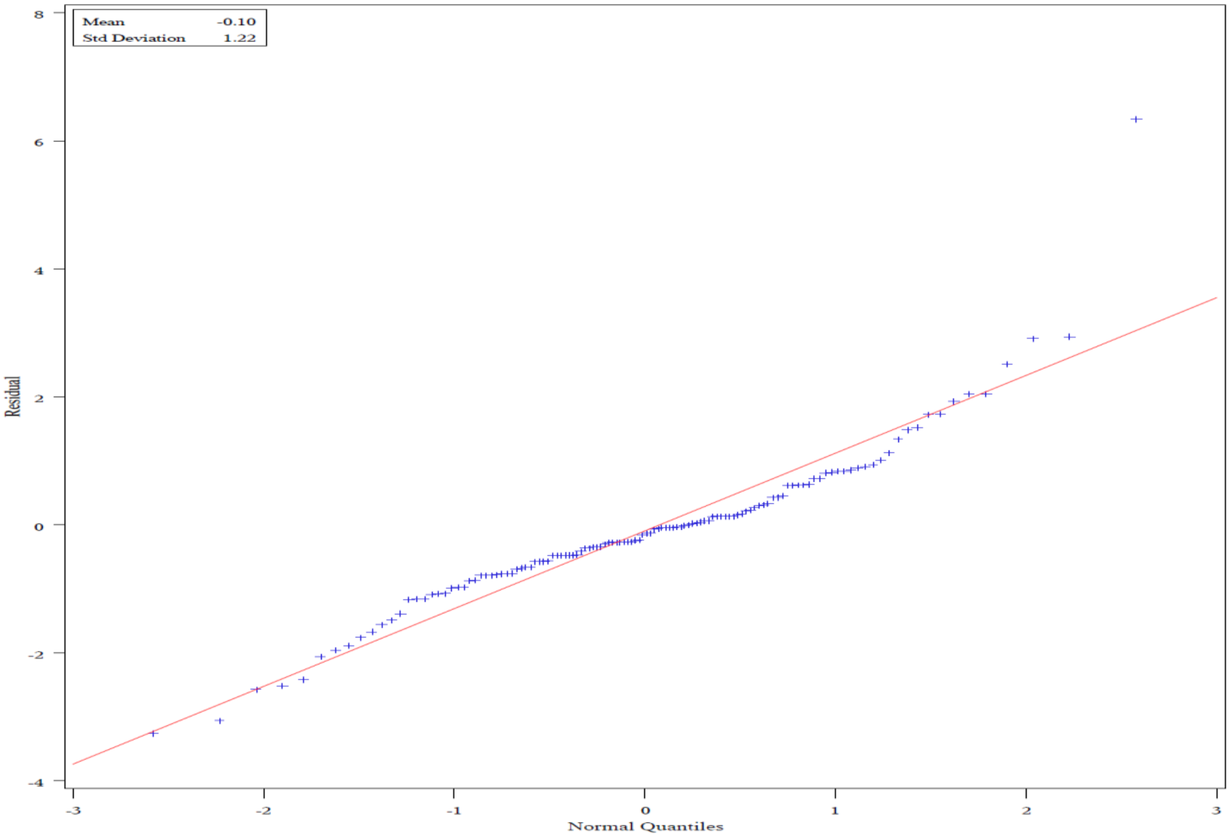


Fig. 6: *Probalaity distribution nitrogen concentration data along land use, elevation gradient and spp.*

Sas codes used for data analysis

Performance and soil condition of selected species in degraded highlands of Ethiopia (study I)

Sas code for survival height, root collar diameter, and biomass data

Sas syntax for height and RCD for degraded data

```
data a;
set mehari.hrcd;
run;
data a;
set a;
logH=log(height_1+0.5);
time=log(1+TSP/10);
LogRCD=log(RCD+0.5);
run;
/*Program for height model*/
proc mixed data=a METHOD=reml;
class treatment species ind ;
 model logH = species treatment time time*species /solution
            outpred=pred_height outpm=pm_height;
 random intercept time/type=UN subject=ind;
 make 'solutionr' out=solut;
 lsmeans species/adjust=Tukey;
 lsmeans treatment/adjust=Tukey;
 lsmeans species/at time=0.78845736 diff adjust=Tukey;
 lsmeans species/at time=1.223775432 diff adjust=Tukey;
 lsmeans species/at time=1.526056303 diff adjust=Tukey;
 lsmeans species/at time=1.757857918 diff adjust=Tukey;
 lsmeans treatment/at time=0.78845736 diff adjust=Tukey;
 lsmeans treatment/at time=1.223775432 diff adjust=Tukey;
 lsmeans treatment/at time=1.526056303 diff adjust=Tukey;
 lsmeans treatment/at time=1.757857918 diff adjust=Tukey;
 title 'Modelo definitivo';
 run;
/*Program for RCD model*/
proc mixed data=a METHOD=reml;
class treatment species ind block;
 model logRCD = species treatment time time*species/solution
            outpred=pred_RCD_full outpm=pm_RCD_full;
 /*random intercept/ type=UN subject=block;*/
 random  intercept time/  type=UN subject=ind;
 lsmeans species/adjust=Tukey;
 lsmeans treatment/adjust=Tukey;
 lsmeans species/at time=0.78845736 diff adjust=Tukey;
 lsmeans species/at time=1.223775432 diff adjust=Tukey;
 lsmeans species/at time=1.526056303 diff adjust=Tukey;
 lsmeans species/at time=1.757857918 diff adjust=Tukey;
 lsmeans treatment/at time=0.78845736 diff adjust=Tukey;
 lsmeans treatment/at time=1.223775432 diff adjust=Tukey;
 lsmeans treatment/at time=1.526056303 diff adjust=Tukey;
 lsmeans treatment/at time=1.757857918 diff adjust=Tukey;
title 'Modelo definitivo';
run;
data b;
set mehari.survival;
time=log(1+TSP/10);
```

```
run;
/*PROGRAM FOR SURVIVAL, ARCSIN (SQUARE ROOT) TRANSFORMATION AND WEIGHTED REGRESSION*/
 proc sort data=b;
		by TSP;
proc means noprint;
		by TSP;
		var arcsen;
		output out=var var=var;
data weight;
 merge b var;
 by TSP;
 WT=1/var;
run;
proc mixed data=weight METHOD=reml;
class treatment species block;
 weight WT;
 model arcsen = species  TSP/ solution
		outpred=pred_weight outpm=pm_survival_weight;
 random  block/;
  lsmeans species/adjust=Tukey;
/* lsmeans treatment/adjust=Tukey;*/
 lsmeans species/at TSP=12 diff adjust=Tukey;
 lsmeans species/at TSP=24 diff adjust=Tukey;
 lsmeans species/at TSP=36 diff adjust=Tukey;
 lsmeans species/at TSP=48 diff adjust=Tukey;
 /*lsmeans treatment/at time=0.78845736 diff adjust=Tukey;
 lsmeans treatment/at time=1.223775432 diff adjust=Tukey;
 lsmeans treatment/at time=1.526056303 diff adjust=Tukey;
 lsmeans treatment/at time=1.757857918 diff adjust=Tukey;*/
 title 'Modelo definitivo';
 run;
data wtres;
		set pred_weight;
		wtres=sqrt(wt)*Resid;
proc plot data=wtres;
 plot wtres*Pred;
proc univariate normal plot data=wtres;
var wtres;
run;
```

Sas code used for analysis of soil data

```
title 'MULTIVARITE ANALYSIS pH';
data ph;
set mehari.ph;
run;
proc sort data=ph;
by species rep;
run;
proc means data=ph n mean std uclm lclm;
by species ;
var y1-y6;
output out=ph_mean mean=media1-media6 stderr=se1-se6;
run;
*To evaluate the impact of time on soil pH*
```

```
proc glm data=ph;
class species;
model y1-y6 = species / nouni;
repeated time 2, depth 3/ summary printe;
lsmeans species / adjust=Tukey pdiff;
run;
title 'MULTIVARIATE ANALYSIS ORGANIC CARBON';
data oc;
set mehari.oc;
run;
proc sort data=oc;
by species rep;
run;
proc means data=oc;
by species;
var y1-y6;
output out=oc_mean mean=media1-media6 stderr=se1-se6;
run;
/*The impact of time on species (initial and final stage)
proc glm data=oc;
class species ;
model y1-y6 = species / nouni;
repeated time 2, depth 3/ summary printe;
lsmeans species / pdiff;
run;
title 'MULTIVARIATE ANALYSIS NITROGEN';
data Nit;
set mehari.Nit;
run;
proc sort data=Nit;
by species rep;
run;
proc means data=Nit;
by species ;
var y1-y6;
output out=nit_mean mean=media1-media6 stderr=se1-se6;
run;
/* The impact of time on species (initial and final stage*
proc glm data=Nit;
class species ;
model y1-y6 = species / nouni;
repeated time 2, depth 3/ summary printe;
lsmeans species / pdiff;
run;
title 'MULTIVARIATE ANALYSIS PHOSPORUS';
data P;
set mehari.P;
run;
proc sort data=P;
by species rep;
run;
proc means data=P;
by species ;
var y1-y6;
output out=p_mean mean=media1-media6 stderr=se1-se6;
run;
```

```
/* The impact of time on species (initial and final stage)
proc glm data=P;
class species ;
model y1-y6 = species / nouni;
repeated time 2, depth 3/ summary printe;
lsmeans species / pdiff;
run;
title 'MULTIVARIATE ANALYSIS POTASIUM';
data K;
set mehari.K;
run;
proc sort data=K;
by species rep;
run;
proc means data=K;
by species ;
var y1-y6;
output out=k_nean mean=media1-media6 stderr=se1-se6;
run;
/* The impact of time on species (initial and final stage)
proc glm data=K;
class species ;
model y1-y6 = species / nouni;
repeated time 2, depth 3/ summary printe;
lsmeans species / pdiff;
run;
title 'MULTIVARIATE ANALYSIS CATION EXCHANGE CAPACITY';
data cec;
set mehari.cec;
run;
proc sort data=cec;
by species rep;
run;
proc means data=cec;
by species ;
var y1-y6;
output out=cec_mean mean=media1-media6 stderr=se1-se6;
run;
/* The impact of time on species (initial and final stage)
proc glm data=cec;
class species ;
model y1-y6 = species / nouni;
repeated time 2, depth 3/ summary printe;
lsmeans species / pdiff;
run;
```

Biomass model, partitioning and comparison (study II)

```
*Spearman correlation syntx*
PROC CORR DATA=olea1 SPEARMAN;
VAR Tree d       db h hc hb cl cd bs br27 br2 bt cr;
TITLE'bs br27 br2          bt cr',
run;
*Biomasa equation model fitting process syntx*
libname bio 'd:\Documents and Settings\mahari\Escritorio';
```

```
run;
options nolabel ;
proc import datafile= "d:\Documents and Settings\mahari\Escritorio\Mehari-Ricardo\olea02.xls" out=olea02;
run;
quit;
PROC IMPORT OUT=bio.olea02
DATAFILE= "d:\Documents and Settings\mahari\Escritorio\Mehari-Ricardo\olea02.xls"
            DBMS=EXCEL REPLACE;
     RANGE="Hoja1$";
     GETNAMES=YES;
     MIXED=NO;
     SCANTEXT=YES;
     USEDATE=YES;
     SCANTIME=YES;
RUN;
data olea02; set bio.olea02;
run;
data one;set olea02;
d=d;
db=db;
h=h;
hc=hc;
hb=hb;
ba=ba;
d2h=d*d*h;
db2h=db*db*h;
d2=d*d;
dh=d*h;
dbhb=db*hb;
dbhc=db*hc;
dbh=db*h;
d2hc=d*d*hc;
db2hc=db*db*hc;
d2hb=d*d*hb;
db2hb=db*db*hb;
dhb=d*hb;
dhc=d*hc;
ba2hc=ba*ba*hc;
ba2hb=ba*ba*hb;
bs=stem;
br27=branches27;
br2=branches2;
br=root;
bt=above;
run;
data one; set one;
ld=log(d);
ldb=log(db);
lh=log(h);
lhb=log(hb);
lhc=log(hc);
d2=d*d;
db2=db*db;
ld2=log(d*d);
ldb2=log(db*db);
d2h=d*d*h;
```

```
d2hc=d*d*hc;
d2hb=d*d*hb;
db2h=db*db*h;
db2h=db*db*hc;
ld2h=log(d2h);
ldb2h=log(db2h);
ldb2hc=log(db2hc);
ldb2hb=log(db2hb);
dh=d*h;
dbh=db*h;
bah=ba*h;
ldh=log(dh);
ldhc=log(dhc);
ldbh=log(dbh);
ldbhb=log(dbhb);
ldbhc=log(dbhc);
ldbhb=log(dbhb);
lba=log(ba);
lba2hc=log(ba2hc);
run;
*/removing outliers/*
data two;set one;
if tree=18 then delete;
if tree=9 or tree=11 then delete;
run;quit;
*Stem biomass;
*model 1;
proc model data=one;
	parms a1;
	bs=a1*(dh);
fit bs start=(a1=0.50275)/out=residualbs;
run; /*for make grap to see outlayers*/
proc gplot data=one;
plot bs*d;
run;
proc gplot data=two;
plot bs*d;
run;
*Stem biomass;
*model 1;
proc model data=one;
	parms a1;
	bs=a1*(dh);
fit bs start=(a1=0.50275)/out=residualbs;
run;
/*for make grap to see outlayers*/
proc gplot data=one;
plot bs*d;
run;
proc gplot data=two;
plot bs*d;
run;
proc model data=two;
	parms a1;
	bs=a1*(dh);
fit bs start=(a1=0.050275)/out=residuolsbs;
```

```
run;
title *modelo2;
proc model data=two;
        parms a1;
         bs=a1*(d2h);
fit bs start=(a1=0.050275)/out=residualbs;
run;
*modelo2.5;
proc model data=two;
        parms a1 a2;
        bs=a1*d+a2*d2;
fit bs start=(a1 0.072525 a2 1.887325 )/out=residualbs;
run;
*modelo3;
proc model data=two;
        parms a1 a2 a3;
         bs=a1*d+a2*d2+a3*(d2h);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residualbs;
run;
*modelo4;
proc model data=two;
        parms a1 a2 a3;
        bs=a1*d+a2*h;
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residualbs;
run;
*modelo5;
proc model data=two;
        parms a1 a2 a3;
        bs=a1*d2+a2*(d2h);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residualsbs;
run;
*modelo6;
proc model data=two;
        parms a1 a2 a3;
        bs=a1*d2+a2*h;
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residualsbs;
run;
*modelo7;
proc model data=two;
        parms a1 a2 a3;
        bs=a1*d2+a2*h+a3*(d2h);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbs;
run;
*modelo8;
proc model data=two;
        parms a1 a2 a3;
        bs=a1*(d2h)+a2*(dh);
fit bs start=(a1 0.072525 a2 1.887325 )/out=residuolsbs;
run;
*modelo9;
proc model data=two;
        parms a1 a2 a3;
        bs=a1*(d2)+a2*(dh)+a3*(d2h);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbs;
run;
*modelo10;
```

```
proc model data=two;
            parms a1 a2 a3;
            bs=a1*(d**a2)*(h**a3);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbs;
run;
*modelo11;
proc model data=two;
            parms a1 a2 a3;
            bs=a1*(d**a2);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbs;
run;
*modelo12;
proc model data=two;
            parms a1 a2 a3;
            bs=a1*((d2h)**a2);
fit bs start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbs;
run; quit;
*biomass and leaves + biomass <2cm;
title modelo1;
proc model data=two;
            parms a1;
            br2=a1*(dh);
fit br2 start=(a1 0.0050275)/out=residuolsbr2;
run; quit;
title *modelo2;
proc model data=two;
            parms a1;
             br2=a1*(d2h);
fit br2 start=(a1 0.020275)/out=residuolsbr2;
run; quit;
*modelo2.5;
proc model data=two;
            parms a1 a2;
            br2=a1*d+a2*d2;
fit br2 start=(a1 0.072525 a2 1.887325)/out=residuolsbr2;
run;
*modelo3;
proc model data=two;
            parms a1 a2 a3;
             br2=a1*d+a2*d2+a3*(d2h);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo4;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*d+a2*h;
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo5;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*d2+a2*(d2h);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo6;
proc model data=two;
```

```
            parms a1 a2 a3;
            br2=a1*d2+a2*h;
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo7;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*d2+a2*h+a3*(d2h);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo8;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*(d2h)+a2*(dh);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo9;
proc model data=two;
 parms a1 a2 a3;
            br2=a1*(d2)+a2*(dh)+a3*(d2h);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo10;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*(d**a2)*(h**a3);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo11;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*(d**a2);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run;
*modelo12;
proc model data=two;
            parms a1 a2 a3;
            br2=a1*((d2h)**a2);
fit br2 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr2;
run; quit;
*/Probamos los modelos branches between2-7cm*/;
title *modelo1;
proc model data=two;
            parms a1;
            br27=a1*(dh);
fit br27 start=(a1=-2.50275)/out=residuolsbr27;
run;quit;
proc gplot data=two;
plot br27*d;
run;
title *modelo2;
proc model data=two;
            parms a1;
             br27=a1*(d2h);
fit br27 start=(a1=-2.50275)/out=residuolsbr27;
run; quit;
```

```
title *modelo2.5;
proc model data=two;
            parms a1 a2;
            br27=a1*d+a2*d2;
fit br27 start=(a1 0.072525 a2 1.887325)/out=residuolsbr27;
run;quit;
title *modelo3;
proc model data=two;
            parms a1 a2 a3;
             br27=a1*d+a2*d2+a3*(d2h);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo4;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*d+a2*h;
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo5;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*d2+a2*(d2h);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo6;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*d2+a2*h;
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo7;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*d2+a2*h+a3*(d2h);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo8;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*(d2h)+a2*(dh);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
 title *modelo9;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*(d2)+a2*(dh)+a3*(d2h);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo10;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*(d**a2)*(h**a3);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo11;
proc model data=two;
```

```
            parms a1 a2 a3;
            br27=a1*(d**a2);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
title *modelo12;
proc model data=two;
            parms a1 a2 a3;
            br27=a1*((d2h)**a2);
fit br27 start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbr27;
run;quit;
*total biomass (bs+b27+b2);
title *modelo1;
proc model data=two;
            parms a1;
            bt=a1*(dh);
fit bt start=(a1 0.50275)/out=residuolsbt;
run;quit;
title *modelo2;
proc model data=two;
            parms a1;
             bt=a1*(d2h);
fit bt start=(a1 0.50275)/out=residuolsbt;
run;quit;
title*modelo2.5;
proc model data=two;
            parms a1 a2;
            bt=a1*d+a2*d2;
fit bt start=(a1 0.072525 a2 1.887325)/out=residuolsbt;
run;quit;
title *modelo3;
proc model data=two;
            parms a1 a2 a3;
             bt=a1*d+a2*d2+a3*(d2h);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo4;
proc model data=two;
            parms a1 a2 a3;
            bt=a1*d+a2*h;
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo5;
proc model data=two;
            parms a1 a2 a3;
            bt=a1*d2+a2*(d2h);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo6;
proc model data=two;
            parms a1 a2 a3;
            bt=a1*d2+a2*h;
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo7;
proc model data=two;
            parms a1 a2 a3;
```

```
		bt=a1*d2+a2*h+a3*(d2h);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo8;
proc model data=two;
		parms a1 a2 a3;
		bt=a1*(d2h)+a2*(dh);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo9;
proc model data=two;
		parms a1 a2 a3;
		bt=a1*(d2)+a2*(dh)+a3*(d2h);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo10;
proc model data=two;
		parms a1 a2 a3;
		bt=a1*(d**a2)*(h**a3);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title*modelo11;
proc model data=two;
		parms a1 a2 a3;
		bt=a1*(d**a2);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;
title *modelo12;
proc model data=two;
		parms a1 a2 a3;
		bt=a1*((d2h)**a2);
fit bt start=(a1 0.072525 a2 1.887325 a3 0.74115 )/out=residuolsbt;
run;quit;

******************************calculamos el peso;
*correction and checking for stems;
proc nlin data=two;  method=marquardt;
model bs=a1*(d2h);
parameters a1= 0.028567;
output sse=est out=dos r=r p=p student=st ;
run;
proc gplot data=dos;
plot st*p =1;
symbol1 v =circle c=blue;
run;quit;
data three; set dos;
r2=r*r;
lr=log(r2);run;
proc reg data=three;
model lr=lh;
run;
quit;
data four;set three;
peso=1/((h**3.77202));
run;
proc nlin data=four;
```

```
model bs=a1*(d2h);_weight_=peso;
parameters a1= 0.0286 ;
output out=resitwo r=r1 p=p1 student=st1 sse=sse;
run;
data four;set resitwo;
rp=st1*(peso**0.5);
run;
proc gplot;
plot rp*p1=1;
symbol1 v=circle c=blue;
run;
quit;
*for see the outlayers;
*Branches 2;
proc nlin data=two  method=marquardt;
model br2=a1*(d2h);
parameters a1 0.006226;
output sse=est out=dos r=r p=p student=st ;
run;
proc gplot data=dos;
plot br2*d =1;
symbol1 v =circle c=blue;
run;quit;
data three; set dos;
r2=r*r;
lr=log(r2);run;
proc reg data=three;
model lr=lh;
run;
quit;
data four; set three;
peso=1/((h**0.09685));
run;
proc nlin data=four;
model br2=a1*(d2h);_weight_=peso;
parameters a1 0.00623;
output out=resitwo r=r1 p=p1 student=st1 sse=sse;
run;
data four; set resitwo; rp=st1*(peso**0.5);
run;
proc gplot;
plot rp*p1=1;
symbol1 v=circle c=blue;
run;
quit;
*Branches 27;
proc nlin data=two  method=marquardt;
model br27=a1*d2+a2*h;
parameters a1 0.059522 a2 0.624346;
output sse=est out=dos r=r p=p student=st;
run;
proc gplot data=dos;
plot br27*d =1;
symbol1 v =circle c=blue;
run;quit;
data three; set dos;
```

```
r2=r*r;
lr=log (r2);run;
*calculo el peso;/* in this part you will get a result*/
proc reg data=three;
model lr=ldh;
run;
quit;
data four; set three;
peso=1/((dh**-0.07514));
run;
proc nlin data=four;
model br27=a1*d2+a2*h;  _weight_=peso;
parameters a1 0.0595 a2 0.6243;
output out=resitwo r=r1 p=p1 student=st1 sse=sse;
run;
data four; set resitwo;
rp=st1*(peso**0.5);
run;
proc gplot;
plot rp*p1=1;
symbol1 v=circle c=blue;
run;
quit;
*total biomass correction;
proc nlin data=two method=marquardt;
model bt=a1*d2h;
parameters a1 0.042519 ;
output sse=est out=dos r=r p=p student=st;
run;
proc gplot data=dos;
plot bt*d =1;
symbol1 v =circle c=blue;
run;quit;
data three; set dos;
r2=r*r;
lr=log(r2);run;
proc reg data=three;
model lr=ld2h;
run;
quit;
data four; set three;
peso=1/((d2h**0.64347));
run;
proc nlin data=four;
model bt=a1*d2h;_weight_=peso;
parameters a1 0.0425;
output out=resittwo r=r1 p=p1 student=st1 sse=sse;
run;
data four; set resitwo;
rp=st1*(peso**0.5);
run;
proc gplot;
plot rp*p1=1;
symbol1 v=circle c=blue;
run;
quit;
```

```
data two;set one;
if tree=18 then delete;
if tree=9 or tree=11 then delete;
run;quit;
data simul;set one;
if tree=18 then delete;
if tree=9 or tree=11 then delete;
run;quit;
ods pdf file= 'd:\Documents and settings\mahari\Escritorio\Olea02.pdf';
title 'Olea02 biomass equation system';
run;
title AJUSTE SUR;
Proc model data=simul;var bs br2 br27 bt d2 d2h h/* this depent on the model that you choose*/;
parms  a1 a2 a3 a4;
   bs=a1*(d2h);
            resid.bs=resid.bs/((h**3.77202)**0.5);
            e1 = actual.bs - pred.bs;
 br2=a2*(d2h);
            resid.br2=resid.br2/((h**0.09685)**0.5);
   e2 = actual.br2 - pred.br2;
 br27=a3*d2+a4*h;
            resid.br27=resid.br27/((dh**-0.07514)**0.5);
   e3 = actual.br27 - pred.br27;
  bt=((a1*(d2h))+
                         (a2*(d2h))+
                         (a3*d2+a4*h)
  );
            resid.bt=resid.bt/ ((d2h**0.64347)**0.5);
   e4 = actual.bt - pred.bt;
            outvars e1 e2 e3 e4;
      fit  br2 br27 bs bt /* here the final estimated parameters*/
      start=(a1 0.0286 a2 0.00623  a3 0.0595 a4 0.6290

           ) /
      sur outs=Smatrix outest=coeff cov out=values outpredict collin;
quit;
run;
ods pdf close;
quit;
run;
```

SOC and SON concentration and bulk density along elevation gradient, land use and species (study III)

Sas code for C and N stock and bulk density for mineral soi

```
data datos;
input lut$ sp$ plotno parcel$ parcel altitude altitude_class sample_depth depth$ length c_pc  c_conc  n_pc n_conc bd
            stoniness SOC_layer SOC_fd mass_layermass_fd mref           mex SOC_fm Thickness SON_layer SON_fd
SON_fm;
cards;
datas;
run;
options pagesize=max;
*ods pdf file="d:\desktop\mahari\desktop\Geoderma_julio2.pdf";
*ods graphics on;
/*Does land use type and depth influence C and N concentration?*/
```

```
/*ANALYSIS OF NORMALITY OF GROUPS AND EQUAL VARIANCES*/
proc sort data=datos;
by lut depth;
run;
proc univariate normal;
var c_conc;
*var n_conc;
by lut depth;
run;
TITLE 'TYPE=TOEPH, TOTAL CARBON (CONCENTRATION)';
data datos;
set datos;
if parcela=10 then delete;
if parcela=12 then delete;
if parcela=13 then delete;
If parcela=14 then delete;
if parcela=15 then delete;
if parcela=16 then delete;
if parcela=17 then delete;
if parcela=21 then delete;
if parcela=25 then delete;
if parcela=27 then delete;
if parcela=28 then delete;
run;
PROC MIXED DATA=datos;
        CLASS PARCEL LUT DEPTH;
        MODEL C_CONC = LUT DEPTH LUT*DEPTH/OUTPM=SOC;
        *RANDOM PARCELA;
        REPEATED DEPTH/SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS LUT DEPTH LUT*DEPTH/diff cl pdiff adjust=Tukey;
RUN;
proc univariate data=soc normal plot;
var resid;
QQPLOT resid /NORMAL(MU=EST SIGMA=EST COLOR=RED L=1);
INSET MEAN STD /CFILL=BLANK FORMAT=5.2;
HISTOGRAM / NORMAL(COLOR=MAROON W=4)CFILL= BLUE CFRAME= LIGR;
INSET MEAN STD /CFILL=BLANK FORMAT=5.2;
run;
TITLE 'TYPE=TOEPH, TOTAL NITROGEN (CONCENTRATION)';
PROC MIXED DATA=datos;
        CLASS PARCEL LUT DEPTH;
        MODEL N_CONC = LUT DEPTH LUT*DEPTH / OUTPM=SON;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS LUT DEPTH LUT*DEPTH/ diff cl adjust=Tukey;
RUN;
proc univariate data=son normal plot;
var resid;
QQPLOT resid /NORMAL(MU=EST SIGMA=EST COLOR=RED L=1);
INSET MEAN STD /CFILL=BLANK FORMAT=5.2;
HISTOGRAM / NORMAL(COLOR=MAROON W=4)CFILL= BLUE CFRAME= LIGR;
INSET MEAN STD /CFILL=BLANK FORMAT=5.2;
run;
*ods pdf close;
*quit;
ods pdf file="d:\Documents and Settings\mahari\Escritorio\Geoderma July2014_julio22.pdf";
```

```
*ods graphics on;
/*Is bulk density different across soil depths and land use types?/
TITLE 'TYPE=TOEPH, BULK DENSITY ACROSS DEPTH AND LUT';
PROC MIXED DATA=datos;
        CLASS PARCEL LUT DEPTH;
        MODEL BD = LUT DEPTH LUT*DEPTH / OUTPM=bulk;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS LUT DEPTH LUT*DEPTH/ diff cl adjust=Tukey;
RUN;
proc univariate data=bulk normal plot;
var resid;
QQPLOT resid /NORMAL (MU=EST SIGMA=EST COLOR=RED L=1);
INSET MEAN STD /CFILL=BLANK FORMAT=5.2;
HISTOGRAM / NORMAL(COLOR=MAROON W=4)CFILL= BLUE CFRAME= LIGR;
INSET MEAN STD /CFILL=BLANK FORMAT=5.2;
run;
/*Is there land use effect on carbon and nitrogen stock?*/
TITLE 'ANALYSIS OF VARIANCE BY LAND USE AND FIXED MASS AT A SPECIFIC DEPTH';
PROC SORT DATA=DATOS;
        BY SAMPLE_DEPTH LUT;
RUN;
TITLE2 'CARBON STOCK AT FIXED MASS';
PROC GLM DATA=datos;
        CLASS LUT;
        MODEL SOC_FM = LUT;
        BY sample_depth;
        LSMEANS LUT / ADJUST=TUKEY TDIFF PDIFF;
        MEANS LUT/ ALPHA=0.05 TUKEY CLM CLDIFF;
RUN;
TITLE2 'NITROGEN STOCK AT FIXED MASS';
PROC GLM DATA=datos;
        CLASS LUT;
        MODEL SON_FM = LUT;
        BY sample_depth;
        LSMEANS LUT / ADJUST=TUKEY PDIFF;
        MEANS LUT/ ALPHA=0.05 TUKEY CLM CLDIFF;
RUN;
/*NATURAL FOREST. Is there an altitudinal effect on carbon/nitrogen concentration in natural forests?*/
DATA NF;
SET DATOS;
IF LUT="NF";
RUN;
TITLE 'TYPE=TOEPH, TOTAL CARBON (CONCENTRATION)';
PROC MIXED DATA=NF;
        CLASS PARCEL ALTITUDE_CLASS DEPTH;
        MODEL C_CONC = ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH/OUTPM=SOC;
        *RANDOM PARCELA;
        REPEATED DEPTH/SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH/ diff cl adjust=Tukey;
RUN;
TITLE 'TYPE=TOEPH, TOTAL NITROGEN (CONCENTRATION)';
PROC MIXED DATA=NF;
        CLASS PARCEL ALTITUDE_CLASS DEPTH;
        MODEL n_CONC = ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH/OUTPM=SOC;
        *RANDOM PARCELA;
```

```
        REPEATED DEPTH /SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH/ diff cl adjust=Tukey;
RUN;
/*NF. Is there an altitudinal effect on bulk density across depths in NF?*/
TITLE 'TYPE=TOEPH, BULK DENSITY IN NATIVE FOREST';
PROC MIXED DATA=NF;
        CLASS PARCEL ALTITUDE_CLASS DEPTH;
        MODEL BD = ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH / OUTPM=SOC;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH/ diff cl adjust=Tukey;
RUN;
/*NATURAL FOREST. Is there an altitudinal effect on carbon/nitrogen stock in NF?
/*Atlitudinal effect on carbon stock in natural forests*/

TITLE 'CARBON STOCK ALTITUDE CLASS NF';
PROC GLM DATA=datos;
        CLASS ALTITUDE_CLASS;
        MODEL SOC_FM = ALTITUDE_CLASS;
        BY sample_depth;
        LSMEANS ALTITUDE_CLASS / ADJUST=TUKEY PDIFF;
        MEANS ALTITUDE_CLASS / ALPHA=0.05 TUKEY CLM CLDIFF;
RUN;
/*Atlitudinal effect on nitrogen stock in natural forests*/
TITLE 'NITROGEN STOCK ALTITUDE CLASS NF';
PROC GLM DATA=datos;
        CLASS ALTITUDE_CLASS;
        MODEL SON_FM = ALTITUDE_CLASS;
        BY sample_depth;
        LSMEANS ALTITUDE_CLASS / ADJUST=TUKEY PDIFF;
        MEANS ALTITUDE_CLASS / ALPHA=0.05 TUKEY CLM CLDIFF;
RUN;
/*PLANTATIONS. Is there a species effect on C/N concentration in PLANTATIONS?*/
DATA Pln;
SET DATOS;
IF LUT="Pln";
if sp="Mixed" then delete;
RUN;
TITLE 'TYPE=TOEPH, TOTAL CARBON (CONCENTRATION) PLANTATION';
PROC MIXED DATA=PLN;
        CLASS PARCEL SP DEPTH;
        MODEL C_CONC = SP DEPTH SP*DEPTH / OUTPM=CCONC;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS SP DEPTH SP*DEPTH/ diff cl adjust=Tukey;
RUN;
PROC MIXED DATA=PLN;
        CLASS PARCEL SP DEPTH;
        MODEL N_CONC = SP DEPTH SP*DEPTH / OUTPM=NCONC;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS SP DEPTH SP*DEPTH/ diff cl adjust=Tukey;
RUN;
TITLE 'TYPE=TOEPH, TOTAL NITROGEN (CONCENTRATION) PLANTATION';
PROC MIXED DATA=NF;
        CLASS PARCEL ALTITUDE_CLASS DEPTH;
```

```
        MODEL n_CONC = ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH / OUTPM=SOC;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS ALTITUDE_CLASS DEPTH ALTITUDE_CLASS*DEPTH/ diff cl adjust=Tukey;
RUN;
/*PLANTATIONS. Is there a spp effect on bulk density across depths in PL?*/
TITLE 'TYPE=TOEPH, BULK DENSITY PLANTATION';
PROC MIXED DATA=pln;
        CLASS PARCEL SP DEPTH;
        MODEL BD = SP DEPTH SP*DEPTH / OUTPM=BULK;
        *RANDOM PARCELA;
        REPEATED DEPTH / SUB=PARCEL TYPE=TOEPH R RCORR;
        LSMEANS SP DEPTH SP*DEPTH/ diff cl adjust=Tukey;
RUN;
/*PLANTATIONS. Is there an altitudinal effect on C/N stock in PLANTATIONS?*/
/*Is there any SPECIES effect on carbon stock in natural forests*/
TITLE 'TYPE=TOEPH, SOC PLANTATION';
PROC GLM DATA=Pln;
        CLASS SP;
        MODEL soc_fm = SP;
        BY sample_depth;
        LSMEANS SP / ADJUST=TUKEY PDIFF;
        MEANS SP / ALPHA=0.05 TUKEY CLM CLDIFF;
RUN;
/*Is there any SPECIES effect on NITROGEN stock in PLANTATIONS*/
TITLE 'TYPE=TOEPH,SON PLANTATION';
PROC GLM DATA=Pln;
        CLASS SP;
        MODEL son_fm = SP;
        BY sample_depth;
        LSMEANS SP / ADJUST=TUKEY PDIFF;
        MEANS SP / ALPHA=0.05 TUKEY CLM CLDIFF;
RUN;
ods pdf close;
quit;
```

Forest floor along soil depth and elevation gradient

```
data forestfloor;
input Plot      Fpatch Transect Altitude Ctotal Ntotal SOC SON;
cards;
data;
run;
proc sort data=forestfloor;
by altitude;
run;
PROC GLM DATA=FORESTFLOOR;
class altitude;
MODEL Ctotal=altitude;
lsmeans altitude / adj=tukey prt;
run;
proc univariate data=forestfloor;
var ctotal;
by altitude;
run;
PROC GLM DATA=FORESTFLOOR;
class altitude;
MODEL ntotal=altitude;
```

```
lsmeans altitude / adj=tukey prt;
run;
proc univariate data=forestfloor;
var ntotal;
by altitude;
run;
PROC GLM DATA=FORESTFLOOR;
class altitude;
MODEL soc=altitude;
lsmeans altitude / adj=tukey prt;
run;
proc univariate data=forestfloor;
var soc;
by altitude;
run;
proc univariate data=forestfloor;
var ntotal;
by altitude;
run;
PROC GLM DATA=FORESTFLOOR;
class altitude;
MODEL son=altitude;
lsmeans altitude / adj=tukey prt;
run;
proc univariate data=forestfloor;
var son;
by altitude;
run;
```

Stand density management model evaluation and fitting (study IV)

sas code for stand density management diagram

```
PROC IMPORT OUT= Mehari
DATAFILE= "d:\Documents and Settings\mahari\Escritorio\SDMD_proportion\spp_proprtion_AUG_2014.xls"
DBMS=EXCEL2000 REPLACE;
GETNAMES=YES;
RUN;
ods pdf file="d:\Documents and Settings\mahari\Escritorio\mixed proportion_chilimo.pdf";
PROC DATA;
SET dataname;
PROP = (VT_VTJP/VT_tot) + (VT_PF/VT_tot);
MIXFRAC_N= 0.5- ABS(PROP - 0.5);
MIX_N= MIXFRAC_N*ln_N;
MIX_Ho = MIXFRAC_N*ln_Ho;
MIX_QMD =MIXFRAC_N*ln_QMD;
**** MODEL statement***
PROC MODEL;
maxiter = 200;
parms a01 a02 a11 a12 a21 a22 a31 a32 a41 a42 a51 a52 a61 a62;exogenous ln_Holn_VT;
ln_QMD = a01 + a02*MIXFRAC_N + a11*ln_N + a12*MIX_N +a21*ln_Ho + a22*MIX_Ho;
ln_VT = a31 + a32*MIXFRAC_N + a41*ln_QMD + a42*MIX_QMD + a51*ln_Ho + a52*MIX_Ho + a61*ln_N+
a62*MIXFRAC_N*ln_N;
fit ln_QMD ln_VT;
run;
ods pdf close;
```

```
quit;
PROC MODEL;
maxiter = 200;
parms a01 a02 a11 a12 a21 a22 a31 a32 a41;
ln_QMD = a01 + a02*ln_QMD+a11*ln_N;
ln_VT = a12 + a21*MIX_N + (a22+ a31*MIX_QMD)*ln_QMD+ (a32 + a41*MIX_Ho)*ln_N;
fit ln_QMD ln_VT;
run;
PROC MODEL;
maxiter = 200;
parms a01 a02 a11 a12 a21 a22 a31 a32 a41 a42 a51 a52;
ln_QMD = a01+a02*ln_QMD+a11*ln_N*+a12*ln_Ho;
ln_VT = a21+a22*MIX_N+(a31+a32*MIX_QMD)*ln_QMD+(a41+a42*MIX_Ho)*ln_Ho+(a51+a52*MIX_N)*ln_N;
fit ln_QMD ln_VT;
run;
```

Carbon concentration and wood density of five most commonly tree species (study IV)

Spearman correlation analysis for carbón content and Wood density

```
PROC IMPORT OUT=Work.carbon1
        DATAFILE= "d:\Documents and Settings\mahari\Escritorio\Mehari Thesis\%OC in 5 spp\carbon1.xls"
        DBMS=EXCEL REPLACE;
   Sheet="Hoja1$";
   GETNAMES=YES;
   MIXED=NO;
   SCANTEXT=YES;
   USEDATE=YES;
   SCANTIME=YES;
RUN;
 Proc Corr data=carbon1;
 by Spp parts height;
 Var OC WD;
 run;
```

Analysis using OC and WD Proc-glm

```
PROC IMPORT OUT=Work.carbon01;
        DATAFILE= "d:\Document and setting\mahari\Escritorio\Mehari Thesis\%OC in 5 spp\carbon01.xls"
        DBMS=EXCEL REPLACE;
   Sheet="Hoja1$";
   GETNAMES=YES;
   MIXED=NO;
   SCANTEXT=YES;
   USEDATE=YES;
   SCANTIME=YES;
RUN;
 Proc glm data=carbon01;
Class spp rep parts height;
model OC=spp parts height spp*parts spp*height parts*height;
run;
Proc glm data=carbon01;
Class spp rep parts height;
model WD=spp parts height spp*parts spp*height parts*height;
run;
Proc glm data=carbon01;
Class spp rep parts height;
model CC=spp parts height spp*parts spp*height parts*height;
run;
```

Studies

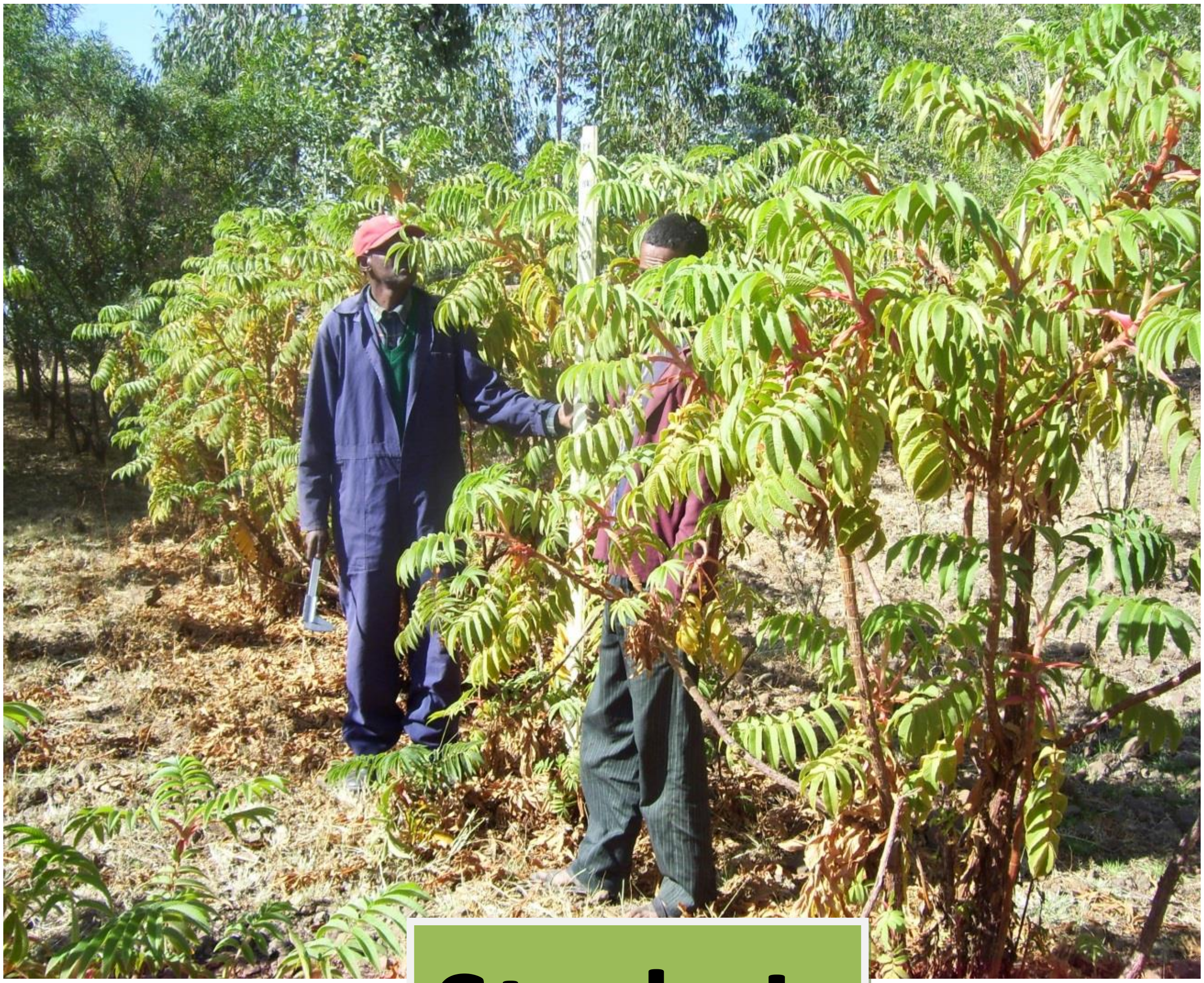
Study I: Selection of tree species and soil management for simultaneous fuelwood production and soil rehabilitation in Ethiopian Central Highlands

Study II: Above ground biomass equations for sustainable production of fuelwood in a native dry tropical afro-montane forest of Ethiopia

Study III: Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands

Study IV: Stand density management diagram for Chilimo dry afro-montane forest using species proportion in Central Highlands of Ethiopia

Study V: Variation in carbon concentration and wood density for five most commonly grown tree species in Ethiopia



Study I

Selection of tree species and soil management for simultaneous fuel wood production and soil rehabilitation in the Ethiopian Central Highlands

Tesfaye, A., Mehari, Bravo-Oviedo, A*., Bravo, F., Kidane, B., Bekele, K., Sertse, D., 2014. Selection of tree species and soil management for simultaneous fuel wood production and soil rehabilitation in the Ethiopian central highlands. ***Land Degradation & Dev*** (2014). Published on Wiley library. Doi: 10.1002/Idr.2268.

Study I

Selection of tree species and soil management for simultaneous fuelwood production and soil rehabilitation in the Ethiopian Central Highlands

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Abstract

In the Ethiopian Central Highlands, a serious soil degradation occurs while fuel wood demand is high. This study consists of an evaluation of seven tree species for fuel wood and soil restoration under three soil management options: control, manure and manure plus mulch, in degraded highlands of Ethiopia. The experimental design was a split-plot, species as the main plot and treatment as subplot, with three replicates. Survival count, height and root collar diameter growth measurements were measured annually until 48 months. Biomass production for fuel wood was inferred at the end of the experiment. Before and after the experiment, soil parameters (pH, organic carbon, N, P, K and cation exchange capacity) were measured to test changes in soil condition because of species plantation. A mixed-model and repeated analysis of variance was performed. *Grevillea robusta* A.Cunn. Ex R. Br. showed maximum survival (100 %), followed by *H. abyssinica* (Bruce) J. F. Gmel. (93.52 %); while the lowest survival rate was recorded for *A. decurrens* Willd. (57.41 %). *Hagenia abyssinica* (Bruce) J.F.Gmel. and *Chamaecytisus palmensis* (Christ.) Hutch showed the lowest growth rates but both species showed the highest soil condition improvement. *E. globulus* Labill. and *Acacia* species presented the highest growth rates and biomass although *Eucalyptus* depleted soil nitrogen. *H. abyssinica* (Bruce) J. F.Gmel. is recommended for soil rehabilitation whereas, *Grevillea robusta* A. Cunn. Ex R. Br. can be used for simultaneous fuel wood production and soil rehabilitation. An ecological based study on *E. globulus'* Labill. an effect in Central Highlands is recommended before recommendation for large scale fuel wood plantations.

Keywords: tree growth; survival; biomass; nitrogen depletion; mixed model

Introduction

Sub-Saharan Africa (SSA) accommodates one of the world's fastest growing populations and it is significantly affected by land degradation because of deforestation, poor land management and conversion of fragile natural habitats into fields for crops. The forest area in East Africa was reduced by 783,000 hectares between 2000 and 2010: equivalent to an annual loss rate of 1.01 % (FAO, 2011). Shortages of forest products, loss of soil fertility and disruption of the water cycle are followed by poverty, hunger and social unrest in the region (Barrowclough and Ghimire, 1996).

This general layout of deforestation and its consequences is similar to other tropical and sub-tropical area (López-García and Ayala-Alcántara, 2012; De la Paix *et al*., 2013) and has made restoration of degraded land an essential challenge. John *et al*. (1997) identified some of the factors that act as a catalyst of such situation: intensive crop expansion, over-grazing and unsustainable fuel wood harvesting. In recent years the fuel wood crisis that links deforestation with fuel wood consumption has been discarded as many of the harvest occurs on species growing "outside" the forest (Mahiri and Howorth, 2001; Bensel, 2008). This pattern of fuelwood consumption is improved by householders' tree plantations, where natural forests are scarce (Bewket, 2003). As a consequence, tree planting has emerged as a plausible option for fulfill the fuelwood demand (Lemenih and Bongers, 2010). However, there may not be a link between tree planting and fuel wood consumption (Gebreegziabher and van Kooten, 2013).

In Ethiopia nearly 1.5 billion tons of topsoil is lost every year (Tadesse, 2001). Despite efforts to combat land degradation in all SSA and Ethiopia in particular (Yitbarek *et al*., 2012), the scope and magnitude of the problem continues and the country is identified among those which has expanded cropland area at the expense of natural habitats (Phalan *et al*., 2013). Currently, the seemingly contradictory objective of restoring vegetation cover and production of fuel wood is a key environmental issue.

With this regard, species selection for afforestation is crucial as the tree species may affect soil properties differently (Li *et al*., 2012). However, interim management solutions such as physical soil retention structures may be needed prior to establishing vegetation (Yitbarek *et al*., 2012). Exclosures have been identified as a valuable rehabilitation option when the main driver of land degradation is grazing (Mekuria and Aynekulu, 2011) or intense recreational use (Özcan *et al*., 2013). However, these measures are expensive for local communities. Effective restoration practices should be based on local perceptions of soil erosion and should include easily available local management options (Kiome and Stocking, 1995). The application of manure has demonstrated to positively affect the infiltration capacity of soils and plant production on grazed lands (Tadesse *et al*., 2003) at low cost. In addition, mulching can both enhance conditions for plant growth in harsh environments (Blanco-García and Lindig-Cisneros, 2005) and protect topsoil against erosion (Roose and Barethès, 2001). The correct selection of plant species and soil management is vital for both fuel wood production and soil rehabilitation.

Motivation for this study stems from the lack of research on species selection for plantations that pursues two objectives: land rehabilitation while assuring fuelwood production in the Ethiopian Central Highlands. The aim was to determine which species and soil management options are better adapted to current Highlands's conditions. On the basis of the observations and previous studies, we hypothesized that native tree species might not show better performance for both objectives in this harsh environment.

Material and Methods

Study Area

The study was conducted from 2005 to 2009 in the central highlands of Ethiopia. The study site was located at 9 º38'19.66'' N latitude and 38º 49' 34.46'' E longitude, at 2, 600 m above sea level (Figure S1). Meteorological data were obtained from Ethiopian Meteorological Agency in Addis Ababa. The 5 year (2005-2009) averaged mean annual maximum and minimum temperature of the study area were 21 ºC and 8 ºC, respectively, with 5 year annual mean averaged precipitation 1,200 mm falling mostly in July and August. Köppen's classification is temperate highland tropical climate with dry winters.

The experimental site was selected through a participatory process with local stakeholders. A focus group discussion was conducted with district agricultural experts, development agents and farmers. The farmers were selected on the basis of age (young: 18-35 years old; adult: 35-55 and old: > 55), average income per household per year (poor: $ 232; medium: $ 407; rich: $ 700) and gender. Ten key informant interviewers (development agents, agricultural experts, community administrators) and 40 random households were selected to ascertain commitment and attitude towards the project, in order to avoid a negative impact on the experimental layout. The experimental site was selected based on accessibility and representativeness of degraded land on sandy soil, rock outcrops and without vegetation cover. The experimental site was a cultivated land until 1995 when it was abandoned due to soil fertility depletion.

Species Selection and Experimental Design

The same participatory process as for selection of experimental site was used for the selection of tree species and soil management options. Species were selected based on local adaptability. A total of seven species were identified in this study: two native tree species (*Dombeya torrida* (J. F. Gmel.) Bamps and *Hagenia abyssinica* (Bruce) J. F. Gmel.), four exotic tree species (*Acacia decurrense* Willd., *Acacia saligna* (Labill.) H.L.Wendl., *Eucalyptus globulus* Labill. and *Grevillea robusta* A.Cunn. Ex R. Br.) and one exotic shrub *Chamaecytisus palmensis* (Christ.) Hutch. All seeds were directly sown in polyethylene bags for eight months and were exposed to similar watering, shading, weeding and hardening off practices until 20-30 cm high.

Three soil management options were applied, based on local perceptions of erosion control: i) a control treatment where nothing was done to correct the initial degraded condition, ii) application of manure, and iii) application of manure plus mulching. Three kilograms of decomposed manure were added to the planting pits (40 cm deep) during seedling planting on 12th, July, 2005, while 0.5 kilogram of mulching with air dried grass was applied in the preceding dry season to conserve moisture and avoid the desiccation of soil and seedlings.

The experimental layout was organized as a split-plot design, with tree species as the main plot and soil management options as sub-plots; it was organized in three blocks to control variation along a slope gradient and three replicates for each species. The main plot consisted of 90 trees divided into three groups of 30 trees, each arranged into five rows, with six trees in each row. The distance between trees in the same row and between rows in the same sub-plot was 1.5 m whereas the distance between treatments in the main plot and sub-plots was 2 m. Weeding and hoeing were applied uniformly to the entire plot on 10th of August and 12th of September 2005 (Figure S3).

Data Collection and Procedure

The 12 inner trees in every sub-plot were assessed for data collection and the rest were considered border trees. Survival counts, along with tree height and root collar diameter measurements were taken at 12, 24, 36 and 48 months after planting.

Volume was calculated from the average height and diameter of the experiment trees; total biomass calculations were based on tree volume and specific gravity, using values obtained from the specific gravity. Table I provides a summary of data 1 and 4 years after planting.

Soil Sampling and Analysis

Soil augering was carried out in 3 mx3 m subplot at the initial and final stage of the experiment, at 0-10, 10-30 and 30-50 cm depth. A total of 72 composite soil samples were collected for analysis. Three random sampling points were mixed to form one composite sample. The collected samples were air-dried, sieved (2 mm diameter) and grounded before analysis. The samples were analysed for pH (1:2.5 soil: water ratio), total N (%) using Kjeldahl’s method, Organic carbon (%) according to Walkely- Black’s method, available phosphorus (units) using Olsen’s method, pH was determined using a suspension of 1:5 soil: water ratio. Ammonium and sodium acetate were applied to determine cation excheangable capacity (CEC), exchangeable K were measured with flame photometer.

The mean values and standard errors for soil variables at the beginning and end of the experiment are shown in Table I.

Table I: *Mean values of response variables 12 and 48 months after planting.*

					pH			**% OC**			**% N**			**P (ppm)**			**K (meg/100g soil)**			**CEC (meg/100g soil)**		
SPP	Period	Height (m)	RCD (cm)	Survival (%)	0-10cm	10-30cm	30-50cm	0-10cm	10-30cm	30-50cm	0-10cm	10-30cm	30-50cm	0-10cm	10-30cm	30-50cm	0-10cm	10-30cm	30-50cm	0-10cm	10-30cm	30-50cm
AD	12	0.97 (0.30)	1.33 (0.39)	83. 2 (11.0)	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.01)	0.033 (0.01)	1.67 (0.12)	1.60 (0.20)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	22.18 (5.69)	23.48 (10.83)
	48	6.52 (2.07)	7.34 (2.09)	56.4 (19.3)	7.96 (0.14)	7.78 (0.47)	7.74 (0.52)	0.85 (0.15)	0.62 (0.40)	0.63 (0.20)	0.053 (0.01)	0.057 (0.011)	0.053 (0.012)	2.60 (0.40)	2.53 (0.70)	2.80 (1.06)	0.84 (0.10)	0.71 (0.30)	0.73 (0.37)	16.50 (1.95)	17.99 (4.24)	22.92 (4.96)
AS	12	1.12 (0.32)	1.98 (0.63)	88.1 (12.1)	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.01)	0.033 (0.01)	1.67 (0.12)	1.60 (0.20)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	21.86 (4.46)	23.50 (0.82)
	48	5.24 (1.33)	8.68 (3.03)	68. 3 (24.2)	7.96 (0.14)	7.78 (0.47)	7.74 (0.52)	0.79 (0.37)	0.84 (0.10)	0.57 (0.12)	0.05 (0.01)	0.053 (0.01)	0.043 (0.02)	2.13 (0.76)	1.87 (0.04)	2.27 (1.50)	0.82 (0.41)	0.71 (0.48)	0.57 (0.42)	19.03 (1.57)	21.32 (1.53)	17.78 (2.81)
CP	12	1.02 (0.34)	1.40 (0.37)	91.7 (11.1)	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.01)	0.033 (0.01)	1.67 (0.12)	1.60 (0.20)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	21.86 (4.46)	23.48 (0.88)
	48	3.34 (1.61)	5.33 (2.87)	70.4 (22.1)	7.64 (0.14)	7.57 (0.25)	7.57 (0.25)	1.89 (0.50)	1.40 (0.17)	0.81 (0.37)	0.107 (0.03)	0.077 (0.05)	0.107 (0.08)	2.93 (0.99)	2.20 (0.60)	2.67 (0.46)	1.07 (0.04)	1.03 (0.11)	1.11 (0.14)	18.75 (2.16)	20.59 (2.48)	24.28 (7.76)
DT	12	0.84 (0.15)	1.62 (0.34)	99.1 (2.7)	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.01)	0.033 (0.01)	1.67 (0.12)	1.60 (0.30)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	21.86 (4.46)	23.50 (0.82)
	48	3.13 (0.97)	4.86 (1.25)	58.3 (19.4)	7.96 (0.10)	7.96 (0.47)	7.93 (0.24)	1.17 (0.45)	0.86 (0.14)	0.71 (0.24)	0.08 (0.03)	0.073 (0.05)	0.05 (0.03)	2.73 (0.70)	2.35 (0.96)	2.33 (0.64)	1.08 (0.17)	1.08 (0.18)	0.89 (0.16)	20.71 (3.86)	23.21 (1.72)	18.54 (0.89)
EG	12	0.79 (0.16)	1.14 (0.23)	88.93 (10.3)	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.01)	0.033 (0.01)	1.67 (0.12)	1.60 (0.20)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	21.86 (5.47)	20.60 (5.53)
	48	8.63 (1.65)	8.92 (2.19)	76.9 (18.7)	7.83 (0.18)	7.62 (0.47)	7.85 (0.23)	0.79 (0.09)	0.64 (0.23)	0.39 (0.13)	0.043 (0.01)	0.03 (0.01)	0.03 (0.01)	1.93 (0.06)	1.83 (0.35)	2.03 (0.74)	0.90 (0.19)	0.65 (0.04)	0.93 (0.04)	16.42 (1.87)	13.85 (1.08)	25.94 (0.55)
GR	12	0.50 (0.12)	1.18 (0.22)	100	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.02)	0.033 (0.01)	1.67 (0.12)	1.60 (0.20)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	21.86 (5.47)	23.50 (0.82)
	48	3.41 (0.89)	6.22 (1.91)	100	7.72 (0.28)	7.85 (0.38)	7.86 (0.20)	1.36 (0.60)	1.22 (0.78)	0.60 (0.58)	0.063 (0.01)	0.047 (0.02)	0.03 (0.01)	2.60 (0.87)	2.07 (0.31)	2.37 (0.74)	0.98 (0.08)	1.08 (0.19)	0.93 (0.19)	20.51 (1.70)	25.45 (7.98)	21.84 (9.56)
HA	12	0.25 (0.08)	1.20 (0.24)	97.3 (4.0)	7.99 (0.20)	8.05 (0.10)	8.15 (0.10)	0.91 (0.10)	0.75 (0.14)	0.51 (0.20)	0.063 (0.01)	0.047 (0.01)	0.033 (0.01)	1.67 (0.12)	1.60 (0.20)	1.67 (0.23)	0.89 (0.14)	0.90 (0.21)	0.84 (0.10)	20.27 (4.27)	21.86 (4.46)	23.48 (0.84)
	48	1.78 (0.85)	4.47 (1.45)	90.7 (9.5)	7.60 (0.28)	7.65 (0.22)	7.68 (0.24)	1.62 (0.25)	1.13 (0.41)	0.51 (0.36)	0.097 (0.01)	0.083 (0.01)	0.053 (0.01)	2.30 (0.50)	2.27 (0.46)	2.40 (0.35)	1.05 (0.04)	0.89 (0.19)	0.75 (0.24)	18.73 (2.18)	21.42 (4.29)	18.36 (0.09)

*Spp: specieas, EG: Eucalyptus globulus, AS: Acacia saligna, AD: Acacia decurrense, CP: Chamaecytisus palmensis, GR: Grevillea robusta, DT: Dombeya torrida, HA: Hagenia abyssinica. Thin lines indicate standard error of the mean.s*tandard deviation of the mean in parenthesis

TSP: Time since planting. Standard deviation of the mean in parenthesis.

Statistical Analysis

Correlation among observations and plausible blocking random effect were accounted for by fitting a multilevel linear mixed model for longitudinal data, using SAS v. 8.01 PROC MIXED software (SAS Inst. Inc., 1999). Species and soil management options were considered as fixed effects, block and tree were considered as random effects and age at time of measurement was considered a covariate. Fixed interaction between treatment and species and random interactions were considered since visual inspection of the interaction plots showed clear patterns. All interactions were considered to affect the slope of the relationship between response and predictors. Interaction plots were performed with R statistical software, version 2.15.0 (R-Development Core Team, 2012).

The linear mixed model requires a linear relationship between response and predictors, as well as normality in residuals. Because survival data is a proportion, normality and homogenous variance were not expected. Consequently, we applied a squared *arcsine* transformation to the response variable (Sabin and Stafford, 1990), i. e. $z = arcsin(sqr(p))$, where z the squared arcsine is transformed response variable for survival data and p is the proportion of individuals.

Height and root collar diameter were plotted over time to discern both heteroscedasticity in data, indicated by greater variability in the response variable and curvature in the temporal pattern (Figure S4). Heteroscedasticity was treated by logarithmic transformation of the response variable to $ln(y + 0.5)$, where *y* is height or root collar diameter. Curvature was taken into account by logarithmic conversion of time according to Verbeke and Molenberghs (2000). Plotting individual height or root collar diameter trajectories over time also served to reveal any random tree effect for individual trees, in both the intercept and the slope (Figure S5).

We tested the following general structure to obtain a model of survival, height and root collar diameter:

$$y_{ij} = \mu + \beta_{1i} + \beta_{2i} t_{ij} + \varepsilon_{ij} \qquad (1)$$

where, y_{ij} is the response variable of the *i*-th tree at time *j*, and μ is the intercept or grand mean, $\beta_{1i} = \beta_1 AD_i + \beta_2 AS_i + \beta_3 CP_i + \beta_4 DT_i + \beta_5 EG_i + \beta_6 GR_i + \beta_7 HA_i + b_{1i}$,
$\beta_{2i} = \beta_0 + \beta_8 AD_i + \beta_9 AS_i + \beta_{10} CP_i + \beta_{11} DT_i + \beta_{12} EG_i + \beta_{13} GR_i + \beta_{14} HA_i + \beta_{15} C_i + \beta_{16} M_i + \beta_{17} MM_i + \gamma_{2i} + b_{2i} + p_{2i} + u_{2i}$
, *AD*: *A. decurrens*, *AS*: *A. saligna*, *CP*: *C. palmensis*, *DT*: *D. torrida*, *EG*: *E. globulus*, *GR*: *G.robusta*, *HA*: *H. abyssinica*, *C*: Control, *M*: Manure, *MM*: Manure plus Mulch. The parameter β_0 reflects the

overall slope for the time effect and makes it possible to test group differences in species or treatment, β_{1-17} are parameters for species

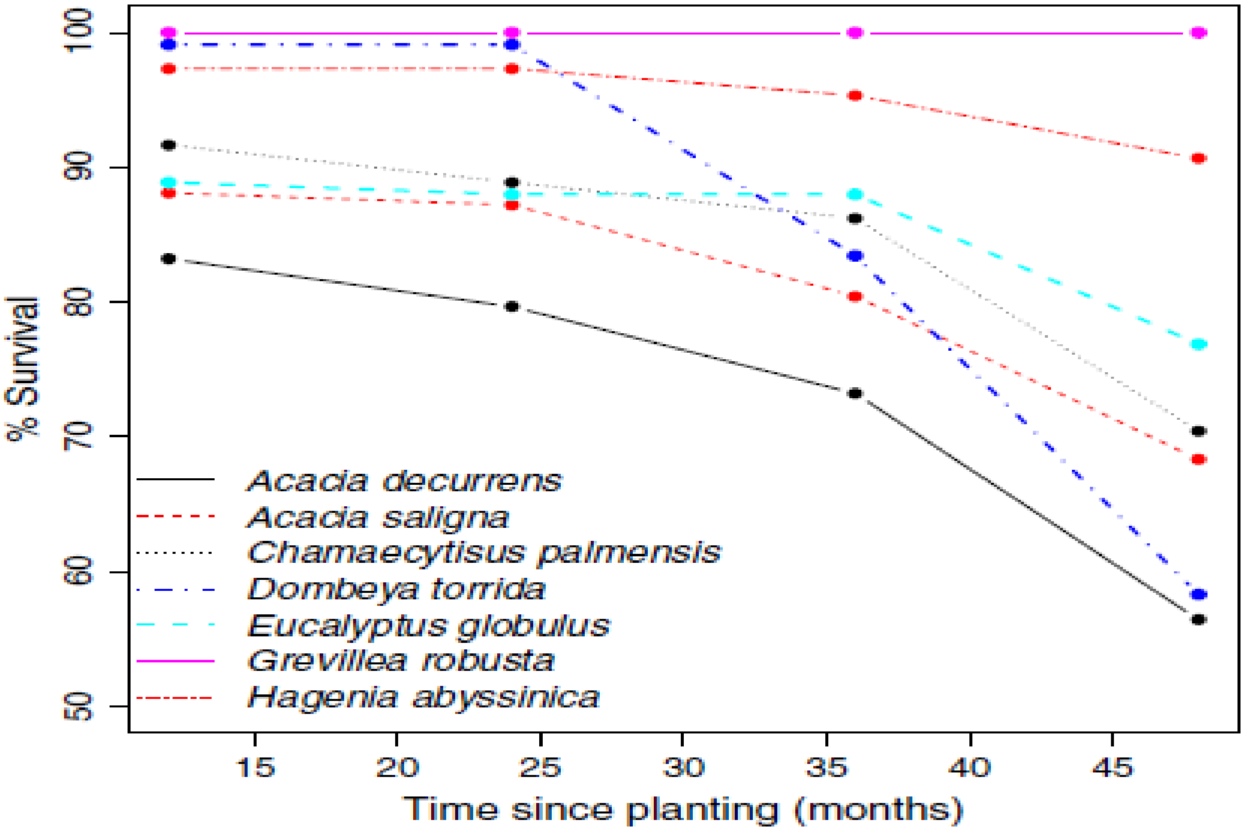

Fig. 1: *Percentage of trees alive by species throughout the life span of the experiment. Points indicate the month of measurement 12, 24, 36 and 48. EG: Eucalyptus globulus, AS: Acacia saligna, AD: Acacia decurrense, CP: Chamaecytisus palmensis, GR: Grevillea robusta, DT: Dombeya torrida, HA: Hagenia abyssinica.*

and treatment fixed effects, γ_{1i} is any fixed interaction, b_{1i} and b_{2i} are random tree parameters with variance σ^2_{b1} and σ^2_{b2}, p_{1i} is the block random effect with variance σ^2_{p1}, u_{1i} is random interaction effect with variance σ^2_{u1i}, and ε_{ij} accounts for within-tree random variation $\sigma^2_{\varepsilon ij}$. Due to both the randomized experimental layout and time transformation, the subject - specific intercepts were considered to be independent of the treatment (Verbeke and Molenberghs, 2000).

Biomass data was analyzed with a mixed linear model approach in order to avoid an error term construction in the generalized linear model (SAS Inst. Inc, 1999). The model tested was:

$$y_{skb} = \mu + \alpha_s + \beta_k + \gamma_{sk} + b_b + v_{kb} + \varepsilon_{skb} \qquad (2)$$

where y_{skb} is the biomass of the average tree of species *s* under *k* treatment in the bth block, μ is the intercept, α_s, is the species fixed effect (*i.e.* $\alpha_s = \alpha_1 AD_i + \alpha_2 AS_i + \alpha_3 CP_i + \alpha_4 DT_i + \alpha_5 EG_i + \alpha_6 GR_i + \alpha_7 HA_i$), β_k is the treatment fixed effect (i.e.$\beta_k = \beta_1 C_i + \beta_2 M_i + \beta_3 MM_i$), γ_{sk} is the interaction fixed effect between species and treatment, b_b is the block random effect with variance $\sigma^2_{b_b}$, v_{kb} is the interaction random effect between treatment and block with variance $\sigma^2_{v_{kh}}$, and ε_{skb} accounts for error due to within-species variation and variance parameter $\sigma^2_{\varepsilon_{skh}}$.

A paired-wise mean comparison by species was made using Tukey's test to reveal the differences in the response variable at every measurement time.

Soil data are repeated measures in both time (before and 4 years after planting) and space (soil depth). We conducted a multivariate approach in which both repetition patterns are taken into account using SAS v. 8.01 PROC GLM software (SAS Inst. Inc., 1999). A least squares mean comparison for the main effect is performed to analyse differences between soil depths before and after plantation. A significance level of 0.05 is assumed across the analysis.

Results

Planted Tree Species Survival Rate

G. robusta showed the highest overall survival rate (100 %), followed by native *H. abyssinica* (93.52 %), (Figure 1). The Figure 2(a) and (b) showed interaction between treatment and species, whereas the effect of block-treatment interaction was slightly lower. The final significant model included the species fixed effect in both the intercept and the slope and a random interaction between block and treatment in the slope (Table II).

Differences among species appear when they were compared at time points. *A. decurrense* showed the lowest survival rate at all measurement times. Although, it was similar to *A. saligna* throughout the experiment, stronger differences appeared as early as 24 months after planting (Table III). The variance of the random interaction between treatment and block was low (0.001386) compared to the residual variance (0.03735); however, the null model likelihood ratio test for appropriateness of the model with the variance component was significant (p-value 0.0273).

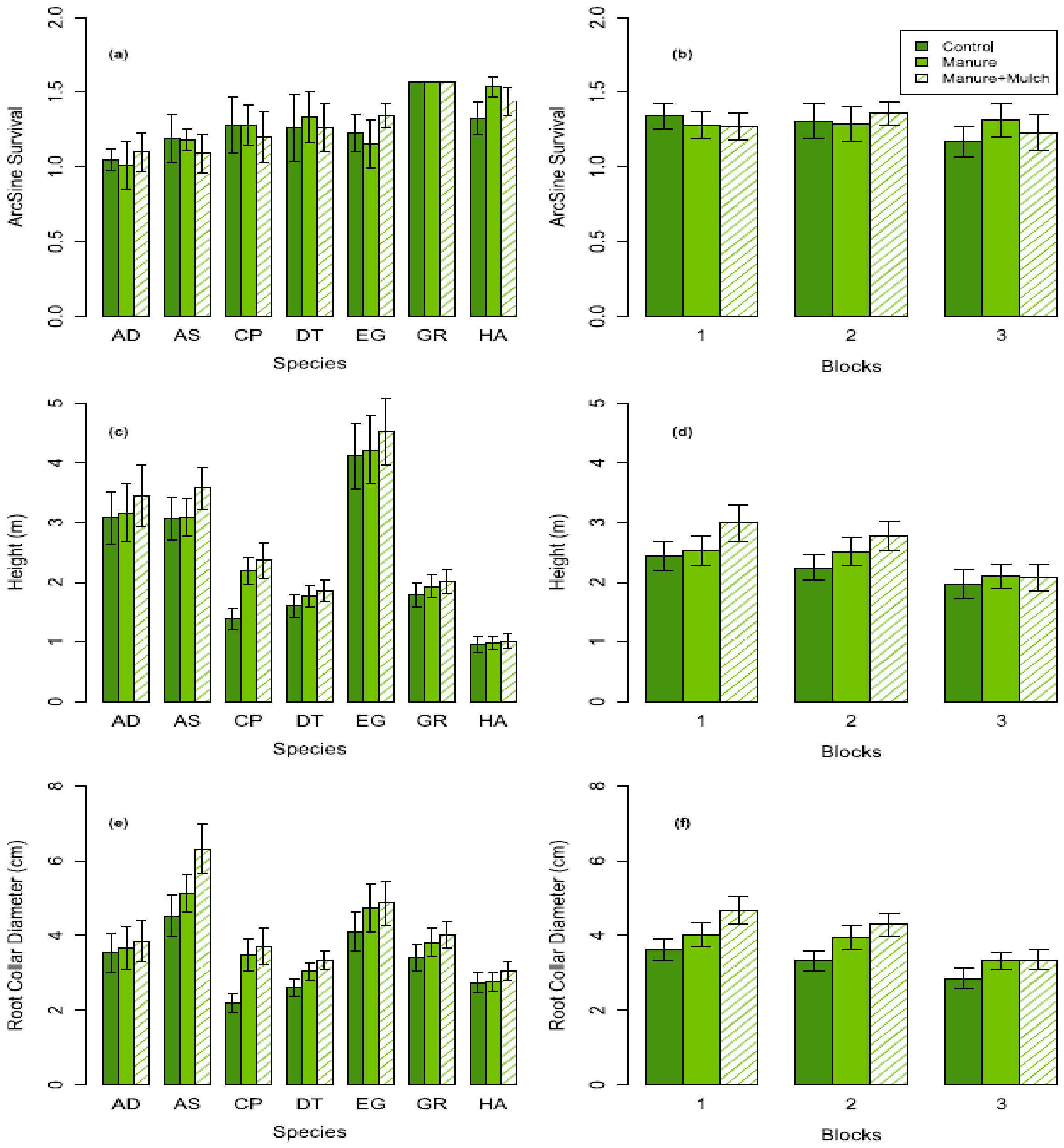

Fig. 2: *Interaction plots for the covariates tested. From top to bottom: survival, height growth and root collar diameter growth. Species X Treatment interaction (left panel). Block X Treatment interaction (right panel). EG: Eucalyptus globulus, AS: Acacia saligna, AD: Acacia decurrense, CP: Chamaecytisus palmensis, GR: Grevillea robusta, DT: Dombeya torrida, HA: Hagenia abyssinica. Thin lines indicate standard error of the mean.*

Table II: *Solution for fixed effects and covariance parameter estimates for survival data.*

Fixed effect	**Parameter in model (1)**	**Estimate**	**S.E**	**P-value**
Intercept	μ	1.5866	0.182	<0.0001
Species	β1	-0.1158	0.1659	0.4857
	β2	-0.1064	0.1659	0.5218
	β3	0.0522	0.1659	0.7533
	β4	0.5643	0.1659	0.0008
	β5	-0.1274	0.1659	0.4431
	β6	-0.01585	0.1659	0.924
	β7	0	-	-
time	β0	-0.1286	0.09423	0.1738
time*spp	β8	-0.222	0.1333	0.0972
	β9	-0.1445	0.1333	0.2792
	β10	-0.1931	0.1333	0.1487
	β11	-0.5945	0.1333	<0.0001
	β12	-0.05538	0.1333	0.6781
	β13	0.1286	0.1333	0.3357
	β14	0	-	-
Random effect				
Block*treatment	$\delta^2\upsilon^2$	0.001386		
Residual variance	δ^2	0.03735		

S.E.: standard error of the mean. β_1- β_7 and β_8- β_{14} stand for *A. decurrense*, *A. saligna*, *C. palmensis*, *D. torrida*, *E. globulus*, *G. robusta and H. abyssinica*, *respectively*.

Table III: *Differences of least squares means for survival and statistical significance of null hypothesis according to Tukey-Kramer's adjustment.*

	Time Since Planting							
Species comparison	**12 months**		**24 months**		**36 months**		**48 months**	
	Estimate	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
AD-AS	-0.063	0.987	-0.094	0.4250	-0.117	0.2796	-0.134	0.499
AD-CP	-0.188	0.241	-0.200	**0.0010**	-0.208	**0.0017**	-0.215	**0.046**
AD-DT	-0.422	**<0.0001**	-0.271	**<0.0001**	-0.164	**0.0313**	-0.081	0.919
AD-EG	-0.104	0.861	-0.171	**0.0070**	-0.219	**0.0007**	-0.257	**0.007**
AD-GR	-0.343	**0.001**	-0.485	**<0.0001**	-0.586	**<0.0001**	-0.664	**<0.0001**
AD-HA	-0.270	**0.018**	-0.360	**<0.0001**	-0.424	**<0.0001**	-0.473	**<0.0001**
AS-CP	-0.125	0.721	-0.105	0.2904	-0.091	0.5827	-0.081	0.919
AS-DT	-0.359	**0.000**	-0.176	**0.0047**	-0.047	0.9724	0.054	0.989
AS-EG	-0.041	0.999	-0.077	0.6696	-0.103	0.4389	-0.123	0.608
AS-GR	-0.280	**0.012**	-0.391	**<0.0001**	-0.469	**<0.0001**	-0.530	**<0.0001**
AS-HA	-0.207	0.148	-0.265	**<0.0001**	-0.307	**<0.0001**	-0.339	**<0.0001**
CP-DT	-0.234	0.065	-0.071	0.7468	0.044	0.9790	0.134	0.499
CP-EG	0.084	0.945	0.028	0.9969	-0.011	1.0000	-0.042	0.997
CP-GR	-0.155	0.477	-0.285	**<0.0001**	-0.378	**<0.0001**	-0.450	**<0.0001**
CP-HA	-0.082	0.952	-0.160	**0.0153**	-0.216	**0.0010**	-0.259	**0.007**
DT-EG	0.318	**0.002**	0.099	0.3600	-0.056	0.9370	-0.176	0.179
DT-GR	0.079	0.959	-0.214	**0.0002**	-0.422	**<0.0001**	-0.584	**<0.0001**
DT-HA	0.152	0.499	-0.089	0.5018	-0.260	**<0.0001**	-0.393	**<0.0001**
EG-GR	-0.239	0.054	-0.314	**<0.0001**	-0.367	**<0.00001**	-0.408	**<0.0001**
EG-HA	-0.166	0.391	-0.188	**0.0019**	-0.204	**0.0023**	-0.217	**0.043**
GR-HA	0.073	0.972	0.125	0.1589	0.162	**0.0336**	0.191	0.110

In bold: significant differences among species at 95% of confidence

EG: *Eucalyptus globulus*, AS: *Acacia saligna*, AD: *Acacia decurrense*, CP: *Chamaecytisus palmensis*, GR: *Grevillea robusta*, DT: *Dombeya torrida*, HA: *Hagenia abyssinica.*

Height Growth

The interaction plot showed weak species and treatment interaction in all soil management options applied [Figure 2(c) and (d)]. The subplot treatment factor had little influence on *H. abyssinica* height growth; whereas *E. globulus* presented greater height value with soil management options. For the remaining species, the response was less pronounced. The response of *A. decurrense* and *A. saligna* height growth was similar across the soil management options. The block effect and the interaction between treatment and block were also weak (Figure 2(d)). Time since planting (age) was also an important variable with considerable variation across species. For example, *A. saligna* height growth was faster up to 24 months after planting and then decreased' whereas *E. globulus* experienced fast height growth throughout the experiment (Figure S4).

Species and treatment effects were significantly different, though; the difference between soil management options was not significantly different. The random effect for the intercept and the slope revealed that the covariances for both effects (0.0393 and 0.0984 respectively) to be higher than the residual variance (0.0195), indicating the strong random effect associated with individuals (Table IV). On average, the fixed effects revealed that *G. robusta* and *H. abyssinica* showed the same height growth pattern and the application of either soil management option resulted in similar height growth, which was higher than that of the control treatment. Height growth differences were noticeable 12 months after planting. *H. abyssinica* and *E. globulus* showed the lowest and highest mean difference, respectively (Table V).

Root Collar Diameter Growth Performance

Visual inspection of the interaction plot showed that the interaction between species and treatment was more pronounced than in height growth [Figure 2(e)], *A. saligna* showed a stronger response to manure + mulch treatment than other species, whereas *C. palmensis* exhibited increased root collar diameter when either soil management options were applied.

Table IV: *Solution for fixed effects and covariance parameters estimates for height and root collar diameter.*

	Parame-ters in model (1)	**Height**			**Root collar diamater**		
Fixed effects		**Estimate**	**S.E**	**p-value**	**Estimate**	**S.E**	**p-value**
Intercept	μ	-1.066	0.031	<0.0001	-0.777	0.039	<0.0001
Species	β1	0.400	0.048	<0.0001	-0.119	0.060	0.049
	β2	0.714	0.046	<0.0001	0.448	0.058	<0.0001
	β3	0.888	0.046	<0.0001	0.227	0.058	<0.0001
	β4	0.717	0.045	<0.0001	0.503	0.057	<0.0001
	β5	-0.182	0.045	<0.0001	-0.673	0.057	<0.0001
	β6	0.046	0.043	0.2807	-0.258	0.055	<0.0001
	β7	0.000	-	-	-	-	-
Time	β0	1.185	0.039	<0.0001	1.485	0.042	<0.0001
Time*spp	β8	0.358	0.057	<0.0001	0.225	0.062	0.0003
	β9	0.154	0.055	0.0051	0.105	0.059	0.0769
	β10	-0.335	0.543	<0.0001	-0.149	0.059	0.0012
	β11	-0.220	0.540	<0.0001	-0.301	0.059	<0.0001
	β12	1.022	0.054	<0.0001	0.851	0.058	<0.0001
	β13	0.339	0.052	<0.0001	0.392	0.056	<0.0001
	β14	0.000	-	0	0.000	-	-
	β15	-0.124	0.020	-0.189	-0.189	0.025	<0.0001
	β16	-0.036	0.020	-0.062	-0.062	0.024	0.011
	β17	0.000	-	0	0.000	-	-
Intercept	$\delta^{2}b1$	0.0393	0.0495				
Slope	$\delta^{2}b2$	0.0984	0.0929				
Residual variance	δ^{2}	0.0198	0.0324				

. *B1*- β_7 and β_8- β_{14} stand for *A. decurrense*, *A. saligna*, C. *palmensis*, *D. torrida*, *E. globulus*, *G. robusta* and *H. abyssinica* respectively. *B15*- β_{17} stands for Control, Manure and Manure + mulch interaction with time respectively.

Table V: *Differences of least squares means for height growth and statistical significance of null hypothesis according to Tukey-Kramer's adjustment.*

	Time Since Planting							
Species	12 months		24 months		36 months		48 months	
comparison	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
AD-AS	-0.172	**<0.0001**	-0.063	0.710	-0.002	1.0000	0.046	0.994
AD-CP	-0.008	1.000	0.360	**<0.0001**	0.569	**<0.0001**	0.729	**<0.0001**
AD-DT	0.084	**0.025**	0.905	**<0.0001**	0.565	**<0.0001**	0.699	**<0.0001**
AD-EG	0.122	**<0.0001**	-0.230	**<0.0001**	-0.431	**<0.0001**	-0.585	**<0.0001**
AD-GR	0.367	**<0.0001**	0.376	**<0.0001**	0.382	**<0.0001**	0.386	**<0.0001**
AD-HA	0.648	**<0.0001**	0.838	**<0.0001**	0.946	**<0.0001**	1.029	**<0.0001**
AS-CP	0.164	**<0.0001**	0.423	**<0.0001**	0.571	**<0.0001**	0.684	**<0.0001**
AS-DT	0.256	**<0.0001**	0.454	**<0.0001**	0.567	**<0.0001**	0.653	**<0.0001**
AS-EG	0.294	**<0.0001**	-0.167	**0.0006**	-0.429	**<0.0001**	-0.631	**<0.0001**
AS-GR	0.538	**<0.0001**	0.440	**<0.0001**	0.383	**<0.0001**	0.340	**<0.0001**
AS-HA	0.820	**<0.0001**	0.901	**<0.0001**	0.948	**<0.0001**	0.983	**<0.0001**
CP-DT	0.092	**0.006**	0.031	0.9847	-0.004	1.0000	-0.030	0.9990
CP-EG	0.130	**<0.0001**	-0.590	**<0.0001**	-1.000	**<0.0001**	-1.314	**<0.0001**
CP-GR	0.374	**<0.0001**	0.017	0.9995	-0.187	**0.0052**	-0.343	**<0.0001**
CP-HA	0.656	**<0.0001**	0.478	**<0.0001**	0.377	**<0.0001**	0.300	**<0.0001**
DT-EG	0.038	0.750	-0.621	**<0.0001**	-0.996	**<0.0001**	-1.284	**<0.0001**
DT-GR	0.283	**<0.0001**	-0.014	0.9997	-0.183	**0.0053**	-0.313	**<0.0001**
DT-HA	0.564	**<0.0001**	0.447	**<0.0001**	0.381	**<0.0001**	0.330	**<0.0001**
EG-GR	0.244	**<0.0001**	0.606	**<0.0001**	0.813	**<0.0001**	0.971	**<0.0001**
EG-HA	0.526	**<0.0001**	1.068	**<0.0001**	1.377	**<0.0001**	1.614	**<0.0001**
GR-HA	0.282	**<0.0001**	0.462	**<0.0001**	0.564	**<0.0001**	0.643	**<0.0001**

In bold: significant differences between species at 95% of confidence

EG: *Eucalyptus globulus*, AS: *Acacia saligna*, AD: *Acacia decurrense*, CP: *Chamaecytisus palmensis*, GR: *Grevillea robusta*, DT: *Dombeya torrida*, HA: *Hagenia abyssinica.*

Table VI: *Differences of least squares means for root collar diameter growth and statistical significance of null hypothesis according to Tukey-Kramer's adjustment.*

Species	Time Since Planting							
	12 months		**24 months**		**36 months**		**48 months**	
comparison	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
AD-AS	-0.483	**<0.0001**	-0.420	**<0.0001**	-0.384	**0.0001**	-0.355	**<0.0001**
AD-CP	-0.087	0.270	0.112	0.229	0.225	**0.0015**	0.311	**0.001**
AD-DT	-0.258	**<0.0001**	0.021	0.999	0.180	**0.047**	0.302	**0.001**
AD-EG	0.120	**0.034**	-0.213	**0.000**	-0.402	**<0.0001**	-0.548	**<0.0001**
AD-GR	0.023	0.996	-0.066	0.791	-0.116	0.4375	-0.155	0.300
AD-HA	0.037	0.956	0.157	**0.014**	0.225	**0.0034**	0.277	**0.002**
AS-CP	0.397	**<0.0001**	0.531	**<0.0001**	0.608	**<0.0001**	0.667	**<0.0001**
AS-DT	0.226	**<0.0001**	0.441	**<0.0001**	0.564	**<0.0001**	0.658	**<0.0001**
AS-EG	0.603	**<0.0001**	0.207	**0.0002**	-0.019	0.9999	-0.192	0.103
AS-GR	0.506	**<0.0001**	0.345	**<0.0001**	0.267	**<0.0001**	0.201	0.054
AS-HA	0.521	**<0.0001**	0.576	**<0.0001**	0.608	**<0.0001**	0.632	<0.0001
CP-DT	-0.171	**<0.0001**	-0.090	0.4239	-0.044	0.9886	-0.001	1.000
CP-EG	0.206	**<0.0001**	-0.325	**<0.0001**	-0.627	**<0.0001**	-0.859	**<0.0001**
CP-GR	0.110	**0.0390**	-0.177	**0.0016**	-0.341	**<0.0001**	-0.466	**<0.0001**
CP-HA	0.124	**0.0120**	0.045	0.9553	0.000	1.000	-0.035	0.9999
DT-EG	0.377	**<0.0001**	-0.234	**<0.0001**	-0.583	**<0.0001**	-0.850	**<0.0001**
DT-GR	0.281	**<0.0001**	-0.087	0.4259	-0.296	**<0.0001**	-0.457	**<0.0001**
DT-HA	0.295	**<0.0001**	0.135	**0.0365**	0.044	0.9867	-0.025	1.0000
EG-GR	-0.096	0.111	0.147	**0.0193**	0.286	**<0.0001**	0.393	**<0.0001**
EG-HA	-0.082	0.270	0.370	**<0.0001**	0.627	**<0.0001**	0.824	**<0.0002**
GR-HA	0.014	1.000	0.222	**<0.0001**	0.341	**<0.0001**	0.432	**<0.0003**

In bold: significant differences between species at 95% of confidence.

EG: *Eucalyptus globulus*, AS: *Acacia saligna*; AD: *Acacia decurrense*; CP: *Chamaecytisus palmensis*; GR: *Grevillea robusta*; DT: *Dombeya torrida*; HA: *Hagenia abyssinica.*

Table VII: *Solution for fixed effects and covariance parameters estimates for biomass 48 months after planting.*

Fixed effects	Parameters in model (2)	Estimate	S.E	p-value
Intercept	μ	1.7251	1.4712	0.3617
Species	α1	5.6933	1.9071	0.0114
	α2	8.0367	1.9071	0.0012
	α3	2.0844	1.9071	0.2959
	α4	0.6144	1.9071	0.7529
	α5	10.9856	1.9071	<0.0001
	α6	1.3967	1.9071	0.478
	α7	0	-	-
Treatment	β1	-2.0543	0.7102	0.0062
	β2	-0.961	0.7102	0.1837
	β3	0	-	-
Random effect				
Block	$\delta^2 bb$	0.5331		
spp*block	$\delta^2 vkb$	3.69		
Residual variace	$\delta^2 \varepsilon$	5.2966		

α_1- α_7 stand for *A. decurrense*, *A. saligna*, *C. palmensis*, *D. torrida*, *E. globulus*, *G. robusta* and *H. abyssinica* respectively. β_1- β_3 stands for Control, Manure and Manure + Mulch treatment, respectively.

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Table VIII: *Repeated multivariate analysis of variance for soil parameters.*

	Between effect			Within effects		
	Effect	**F**	**p_value**	**Effect**	**F**	**p_value**
pH	Species	0.31	0.9193	Time	43.87	**0.0001**
				Time*species	0.74	0.6264
				Depth	5.05	**0.0134**
				Depth*species	1.08	0.4139
				Time*depth	2.62	0.0904
				Time*depth*species	0.49	0.905
Carbon (%)	Species	2.08	0.1217	Time	6.59	**0.0224**
				Time*species	1.76	0.1799
				Depth	59.25	**0.0001**
				Depth*species	1.41	0.221
				Time*depth	5.9	**0.0073**
				Time*depth*species	2.93	**0.0093**
Nitrogen (%)	Species	3.87	0.0174	Time	8.81	**0.0102**
				Time*species	3.13	**0.0368**
				Depth	21.66	**0.0001**
				Depth*species	0.68	0.76
				Time*depth	1.68	0.2042
				Time*depth*species	0.91	0.5497
P (ppm)	Species	0.56	0.7557	Time	21.8	**0.0004**
				Time*species	0.54	0.7729
				Depth	4.18	**0.0258**
				Depth*species	0.41	0.9451
				Time*depth	1.19	0.3192
				Time*depth*species	0.33	0.9773
K (meg/100 gr)	Species	0.93	0.5083	Time	0.04	0.8379
				Time*species	1.48	0.2538
				Depth	5.22	**0.0118**
				Depth*species	1.38	0.2312
				Time*depth	1.59	0.2216
				Time*depth*species	1.18	0.3429
CEC (meg/100 gr)	Species	0.43	0.8179	Time	2.43	0.1413
				Time*species	0.24	0.9577
				Depth	5.78	**0.0079**
				Depth*species	0.86	0.5955
				Time*depth	0.04	0.9641
				Time*depth*species	2.39	**0.0282**

Bold values indicate significance at 0.05 levels.

Time since planting was also an important variable and notably different: the root collar diameter of *A. saligna* increased for 36 months after planting. At 48 months, *E. globulus* showed higher average (RCD) values. The other species showed similar values at 12 and 24 months after planting; from that point on, root collar diameter differences became more pronounced. *C. palmensis*, *D. torrida* and *H. abyssinica* had the lowest RCD values at the end of the experiment (Figure S4).

The final model for root collar diameter included random individual effect on the intercept and the slope. Neither the fixed effects for species and treatment in the slope nor the interaction between species and treatment were significant. The solution for fixed effects gave results similar to those of the height model (Table IV), although, none of the species had RCD values similar to those of *H. abyssinica*. Comparison of the species at each time point showed fewer RCD differences between species than in the height growth comparison (Tables V and VI): *E. globulus* outperformed all species in height growth but had almost the same root collar diameter as *A. saligna* at the end of the experiment.

Biomass Production

Tree biomass production was similar in all soil management applications (Table VII), except for *E. globulus* (11.71 kg tree^{-1}), *A. saligna* (8.76 kg tree^{-1}) and *A. decurrense* (6.41 kg tree^{-1}). Mulching induced overlaid results between the control and mulching plus manure treatment. Comparison of control with mulching plus manure treatments revealed that the treatment fixed effect to be highly significant ($p < 0.0001$), with a biomass production gradient from 3.79 kg tree^{-1}for the control to 4.88 kg tree^{-1} with manure to 5.84 kg tree^{-1} with mulching plus manure treatment. The interaction between species and treatment was highly insignificant in all cases.

Differences of least squares means showed that *E. globulus* produced more biomass than other species, followed closely by *A. saligna*. These were significantly greater than *D. torrida* and *H. abyssinica*, which presented the lowest biomass production (Table SI).

Soil Condition

The significance of treatment effects on growth and biomass production was not very high, indicating that tree species is the main factor controlling the performance of indicator variables (i.e. growth, survival and biomass). For this reason, we tested species effect on soil properties. In so doing we also avoid expensive analysis of soil depths across treatments. Statistical analysis of between and within effects in the multivariate repeated analysis are shown in Table VIII.

Nitrogen concentration was affected by species, time, depth and the interaction of time and species, indicating a

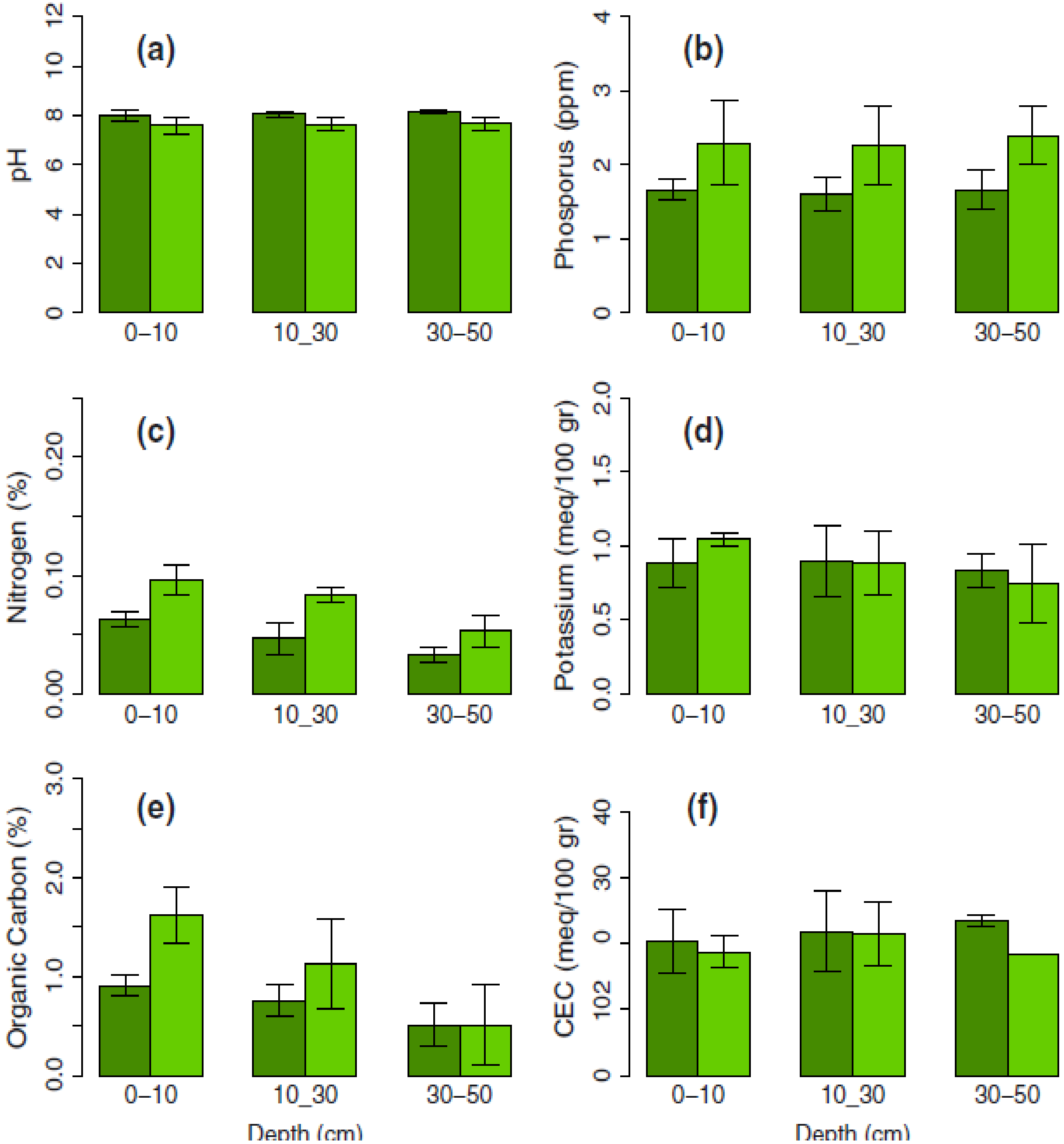

Fig. 3: *Mean value and standard error bars for soil properties at the beginning and end of the experiment in native Hagenia abyssinica plots. Dark bars are mean values before planting. Light bars are mean value after 48 months.*

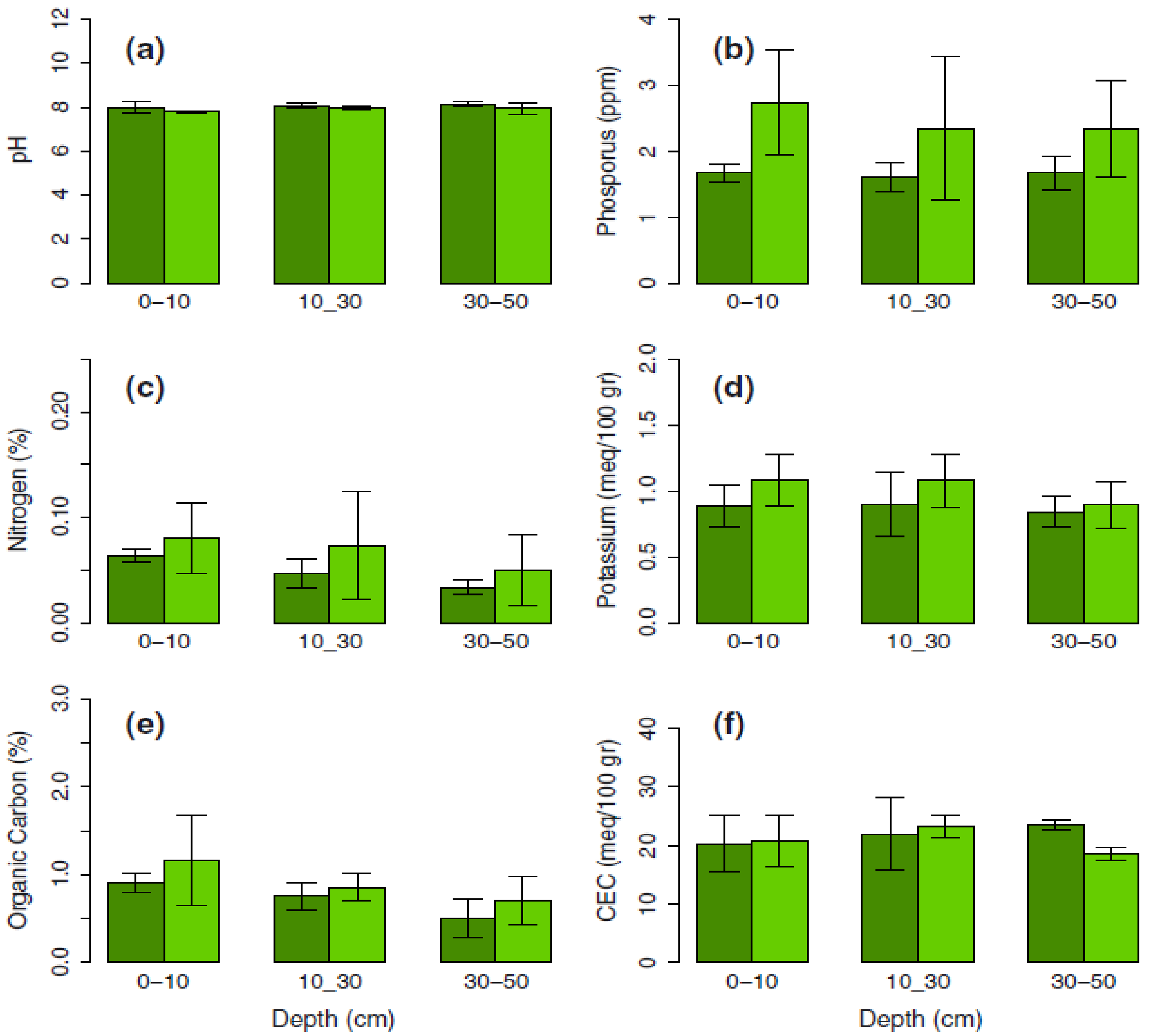

Fig. 4: *Mean value standard error bars for soil properties at the beginning and at the end of the experiment in native Dombeya torrida plots. Dark bars are mean value before planting. Light bars are mean value after 48 months.*

strong species control on this soil parameter. Time was significant for all soil properties except for K and CEC, whereas depth within effect was significant for all soil properties. The significant interaction effect of species, time and depth for organic carbon and cationic exchange capacity was mainly controlled by depth.

Differences in some soil parameters within species between initial conditions and four years after planting were detected. After 4 years since planting, pH did not change. Soil parameter values increased in native *H. abyssinica* and *D. torrida* (Figure 3 and 4) whereas nitrogen and carbon concentration decreased in *E. globulus* plantation along the whole profile [Figure 5 (c) and (e)]. *C.*

palmensis showed the highest N and carbon increase four years after plantation [Figure 6 (c)]. *Acacia* spp showed a decreasing pattern in nitrogen and carbon concentrations and available potassium in top soil [Figure S6 and S7 (c), (d) and (e)], whereas *G. robusta* showed increased nitrogen and carbon contents [Figure S8 (c) and (e)]. All species increased available P in soils.

The higher differences between species are in the top mineral soil and later up to 30 cm and they are mainly due to changes in carbon, nitrogen from 0 to 10 cm; K concentrations from 10 to 30 cm and CEC (Table SII). pH and P concentration did not show differences across species. *Acacia* spp. and *E. globulus* had significantly less organic carbon in the top mineral soil (0-10 cm) than *H. abyssinica*, *G. robusta* and *C. palmensis*. The concentration of nitrogen is significantly low in *Acacia* spp. and *E. globulus* as compared with *C. palmensis* that showed the highest amount of nitrogen (0.11 %) in the topsoil (0-10 cm) four years after plantation followed by *H. abyssinica* (0.09 %) and *D. torrida* (0.08 %). Differences in K concentration are found in 10-30 cm. *Acacia* spp and *E. globulus* showed the minimum K values, which were significantly different from the rest of species. CEC in *E. globulus* and *A. decurrense* (16.4 and 16.5 meq/100g soil) plots is significantly lower than that found in *D. torrida* and *G. robusta* plots (20.7 and 20.5 meq/100g soil). The same pattern occurs from 10 to 30 cm deep.

Discussion

This study presents a screening of six tree species and one shrub species for use in the restoration of degraded land and fuel wood production in the Central Highlands of Ethiopia. The combination of survival, height, root collar diameter growth, total biomass production and soil condition change after 48 months provides a five-dimensional indicator of species suitability for both objectives. The best options would always be that with the highest values in all five indicators; however, none of the species studied perfectly fulfilled these requirements. In fact, contradictory results for restoration and fuel wood production were found.

Native *H. abyssinica* and exotic *G. robusta* and *E. globulus* had the highest survival rates; the lowest survival rates were recorded for native *D. torrida* and exotic *A. decurrense*. An intermediate group was formed by *C. palmensis* and *A. saligna*. Peter *et al*. (2005) reported a survival rate of 100 % for *G. robusta* on a mixed rainforest tree plantation in Australia after six years. In Chile, a screening trial for degraded highlands reported a survival rate of less than 25 % for *A. saligna* and less than 60 % for *C. palmensis* (Arredondo *et al*., 1998).

Exotic *E. globulus*, *A. saligna* and *A. decurrense* had faster root collar diameter and height growth than other species and the soil management significantly impacted their growth. Mekonnen *et al*. (2006) also found, that *E. globulus* had greater height and root collar diameter growth compared to other species growing on nitisols of the Ethiopian.

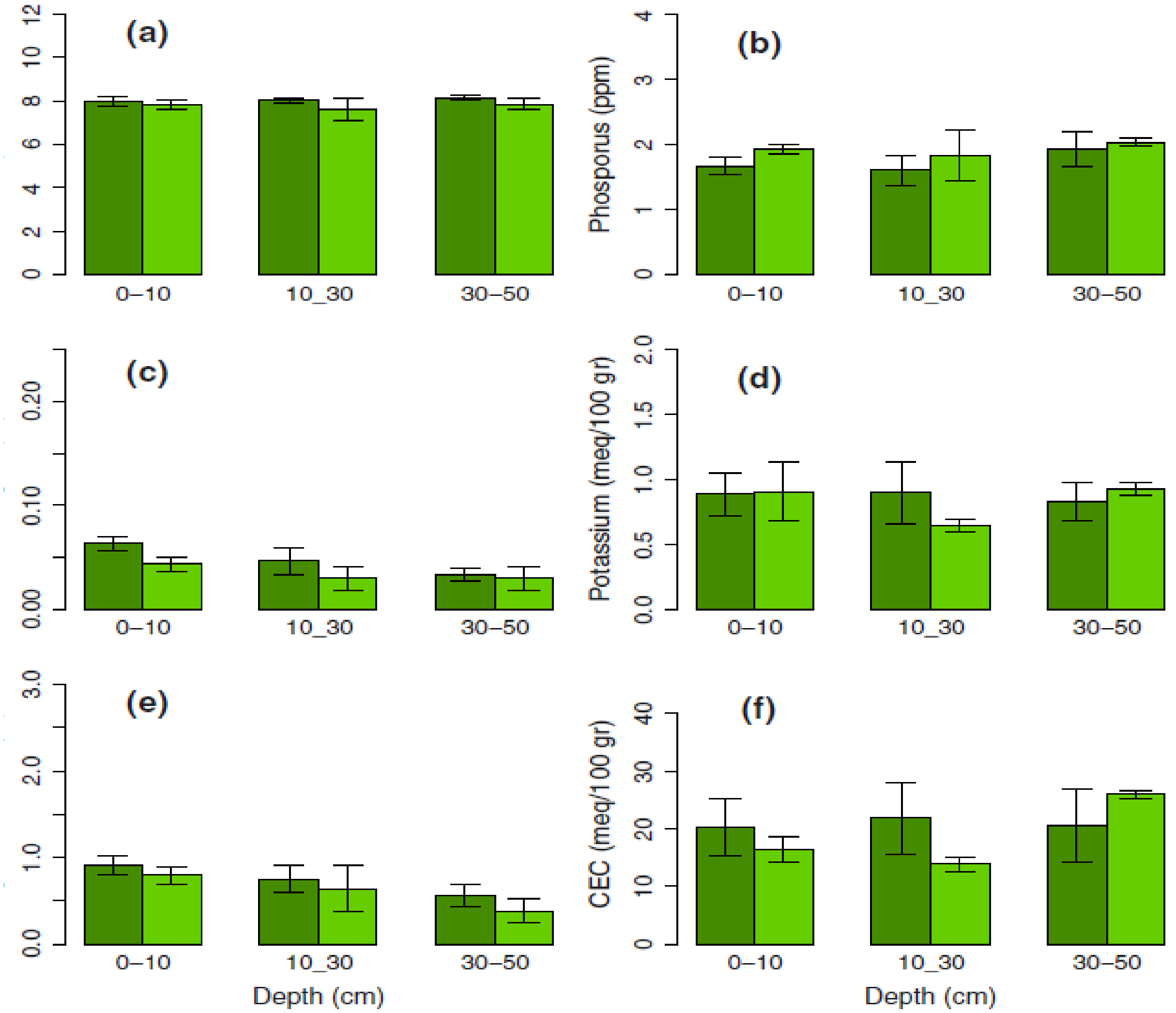

Fig. 5: *Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in exotic Eucalyptus globulus plots. Dark bars are mean value before planting. Light bars are mean value after 48 months.*

Central Highlands. *A. decurrense* and *A. saligna* had rather similar growth patterns, although some reduction in height growth occurred after 24 months in the ground. Although, *G. robusta* showed the highest survival rate, its height and root collar growth was intermediate. Although, soil conditions were enriched by management options, we suspect the improvement was insufficient to meet the fertility requirements for the species, although, the species can slightly improve soil conditions

(Figure S8). This species is highly palatable to sheep so illegal grazing in reforestation areas is common. The species is therefore not recommended for widespread rehabilitation of degraded lands, unless local laws are formulated and implemented to protect from free animal grazing.

Higher dry biomass production occurred with *E. globulus*, *A. decurrense* and *A. saligna*, whereas *C. palmensis*, *G. robusta*, *H. abyssinica* and *D. torrida* presented lower dry biomass production. Contrary to biomass production, the impact of species plantations in soil conditions reversed the ranking. Native *H. abyssinica* and *D. torrida* and exotic *C. palmensis* are the species that best improve nitrogen, carbon and available potassium in soils 48 months after plantation. *E. globulus* plantations depleted nitrogen from soils significantly in the first 10 cm whereas *Acacia* species did not show a clear pattern. In our results it is surprising that *Acacia* species did not increase nitrogen concentrations in the topsoil, which can suggest strong leaching from top soil to deeper layers (Figure S6 and S7). This might affect groundwater as strong NOx contamination has been found in catchments afforested with *A. saligna* (Jovanovic *et al*., 2009) so large restoration programs with these species should take into account long-term negative effects.

Wood energy dependence has traditionally seen as a deforestation and land degradation vector in developing countries (Geist and Lambin, 2002), although it has been also argued that fuel wood collection impacts can be mitigated adapting new managerial practices (Hiemstra-van der Horst and Hovorka, 2009) or collecting species other than the native found in natural forests. Plantation of selected native or exotic species can play a major role in rehabilitating degraded land with little enhancement of biodiversity (Chazdon, 2008). However, *Eucalyptus* plantations in Ethiopia have a high potential for restoring species diversity (Yirdaw and Luukanen, 2003). In this regard, plantations of exotic species are considered as buffers or biological corridors that prevent deforestation in natural forests and foster rapid succession as well as provide fuel wood for local population (Lemenih and Bongers, 2010).

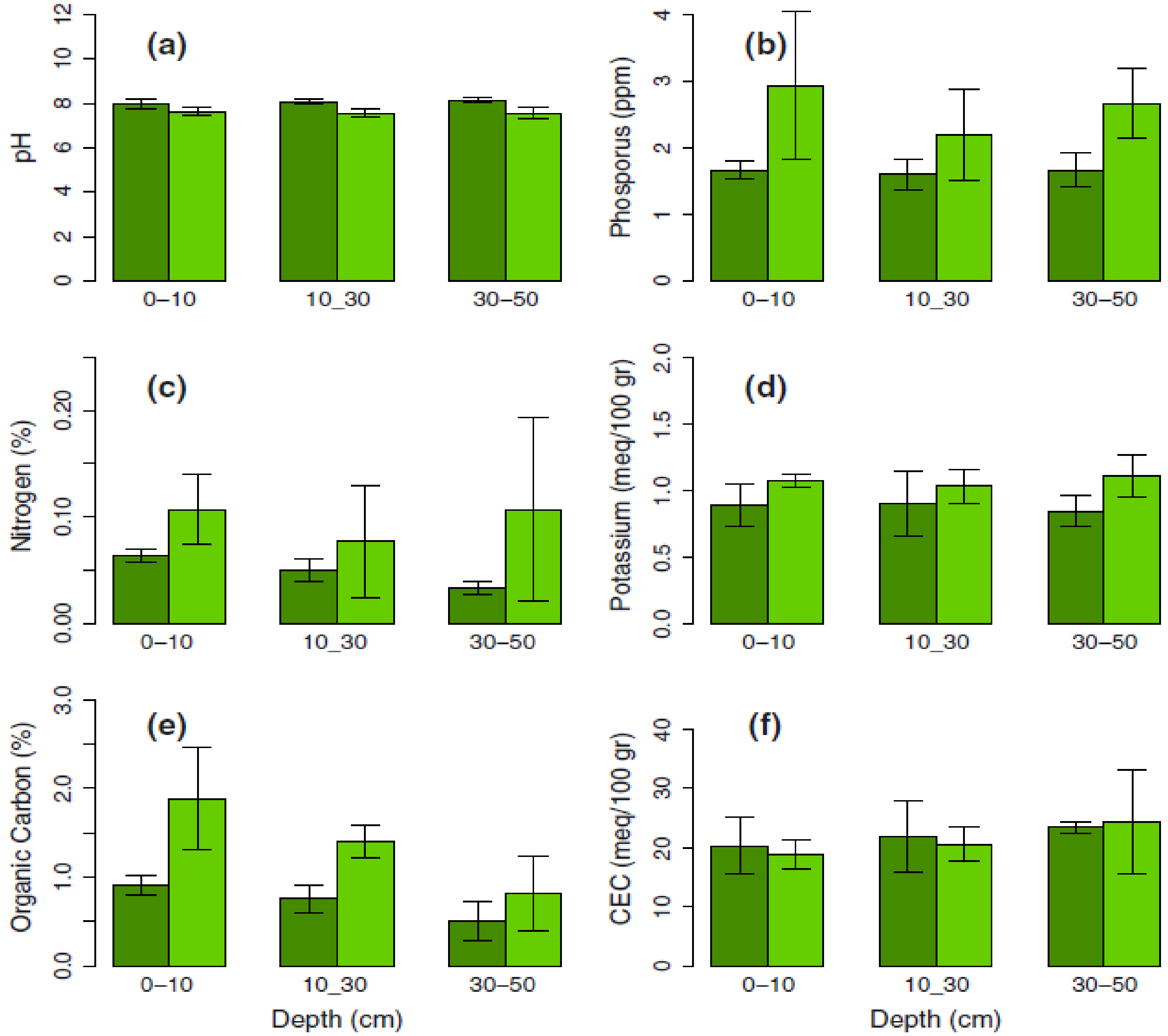

***Fig. 6:** Mean value and standard error bars for soil properties at the beginning and at the end of the experiment in exotic Chamaecytisus palmensis plots. Dark bars are mean value before planting. Light bars are mean value after 48 months.*

Although our results clearly indicated *E. globulus* to be the best performing species for fuel wood production with high survival rates, the best growth rates for height and root collar diameter, and largest biomass production it should be noted that the species do not improve soil conditions and can even deplete nitrogen concentrations 48 months after plantation. Nevertheless, soil carbon concentration is not affected by eucalyptus as earlier noted by Fialho and Zinn (2012) in Brazil. With regards to carbon dynamics, it must be considered to analyse eucalyptus effects on a case by case basis as such species group can have a negative effect on dissolved organic carbon concentration five years after plantation (Wu *et al*., 2013). A balance between wood production for fuel and land reclamation is difficult to meet in areas where scarcity of natural resources is high.

Fast-growing trees help ameliorating harsh and fluctuating microclimate conditions. This creates potential for rapid restoration of degraded lands through the accumulation of organic matter, and for future development of mixed stands that combine fast-growing exotics and naturally regenerated native species (Otsamo, 2000).

With this regard, *H. abyssinica* increased significantly the amount of organic carbon in the top soil and the tendency continues up to 30 cm deep [Figure 3(e)]. *G. robusta* also improved soil condition (Figure S8), and it is the best option in terms of survival and has been considered to possess excellent firewood properties in its natural distribution area (Jaing and Singh, 1999). *E. globulus* is the most productive species in terms of biomass production for firewood and it has shown a good survival rate and growth performance; it is usually preferred as an alternative for farmers and household needs (Bewket, 2003), however, as pointed by our results, a thorough, study on the ecological impact of *E. globulus* is needed for the Central Highlands in Ethiopia. With the information obtained from our experiment, native *H. abyssinica* might be considered for reforestation programs to rehabilitate degraded lands and exotic *G. robusta* and to a lesser extend *E. globulus*, as a preliminary step to natural vegetation recovery and as good providers of raw material for fuel production.

Conclusions

The results of this study confirm that (i) *G. robusta* showed the highest overall survival rate followed by *H. abyssinica*. *A. decurrense* showed the lowest survival rate; (ii) *E. globulus* outperformed all species in height growth and biomass production and had a similar root collar diameter growth as *A. saligna*; however, it depleted nitrogen in the top soil; (iii) *H. abyssinica, C. palmensis* and *D. torrida* showed the lowest growth and biomass production, but all of them improved soil conditions 48 months after plantation; (iv) *G. robusta* and *H. abyssinica* resulted in similar height growth pattern over application of soil management options. *A. saligna* showed a stronger response to manure plus mulch than other species; (v) Dry biomass production was highly significant for *E. globulus*, although it was non-significant across soil management options and (vi) there is not a clear effect of any of the soil management options in growth. Finally, we have to modulate our working hypothesis that native tree species might not show better growth performance in harsh environment because native species improved soil conditions. We recommend the use of native *H. abyssinica* for improving soil conditions of degraded land and exotic *G. robusta* for both soil rehabilitation and firewood production; whereas *E. globulus* plantations should be considered a good alternative for firewood production after a complete study upon the ecological impact of the species has been performed. More research is needed to confirm if planting native *H. abyssinica* in the understory of those species is appropriate to reclaim natural vegetation cover.

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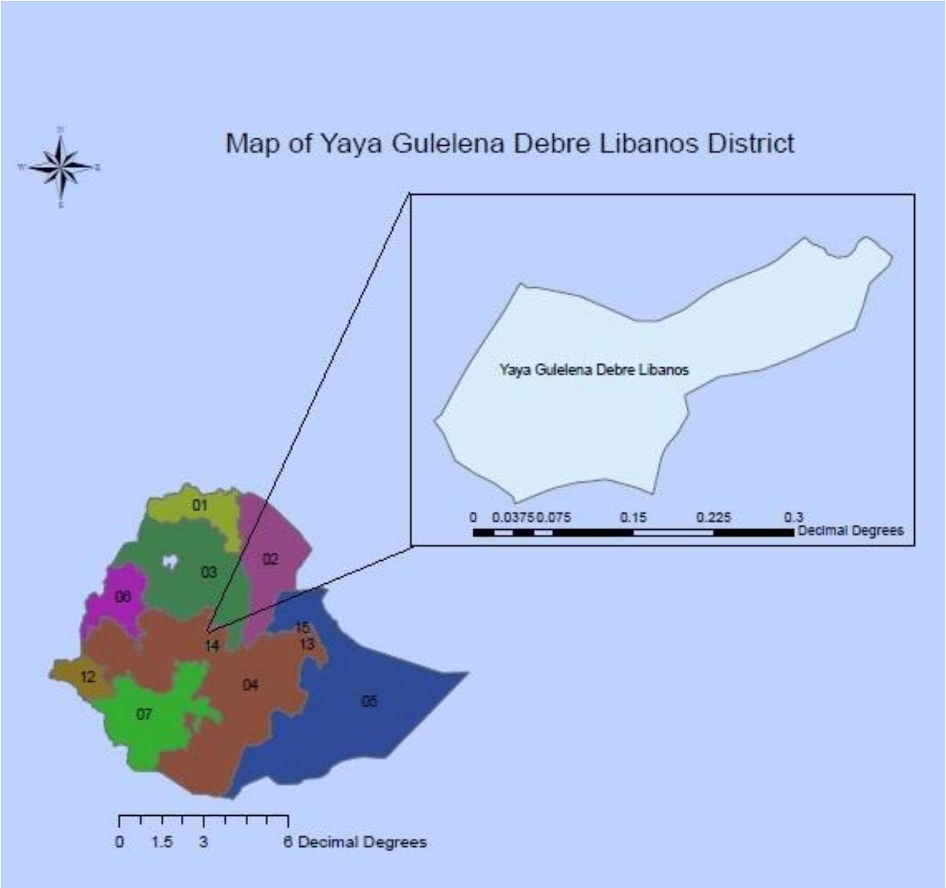
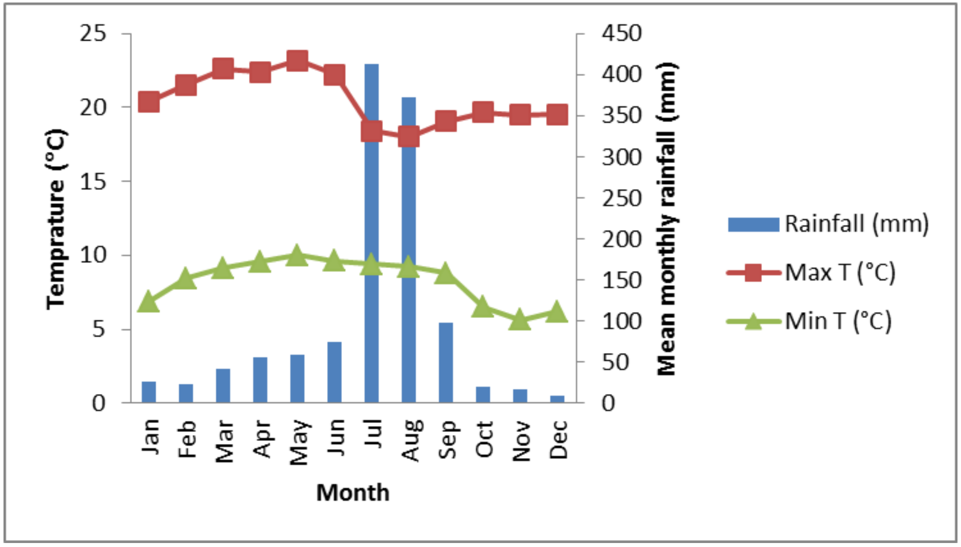
SUPPORTING INFORMATION

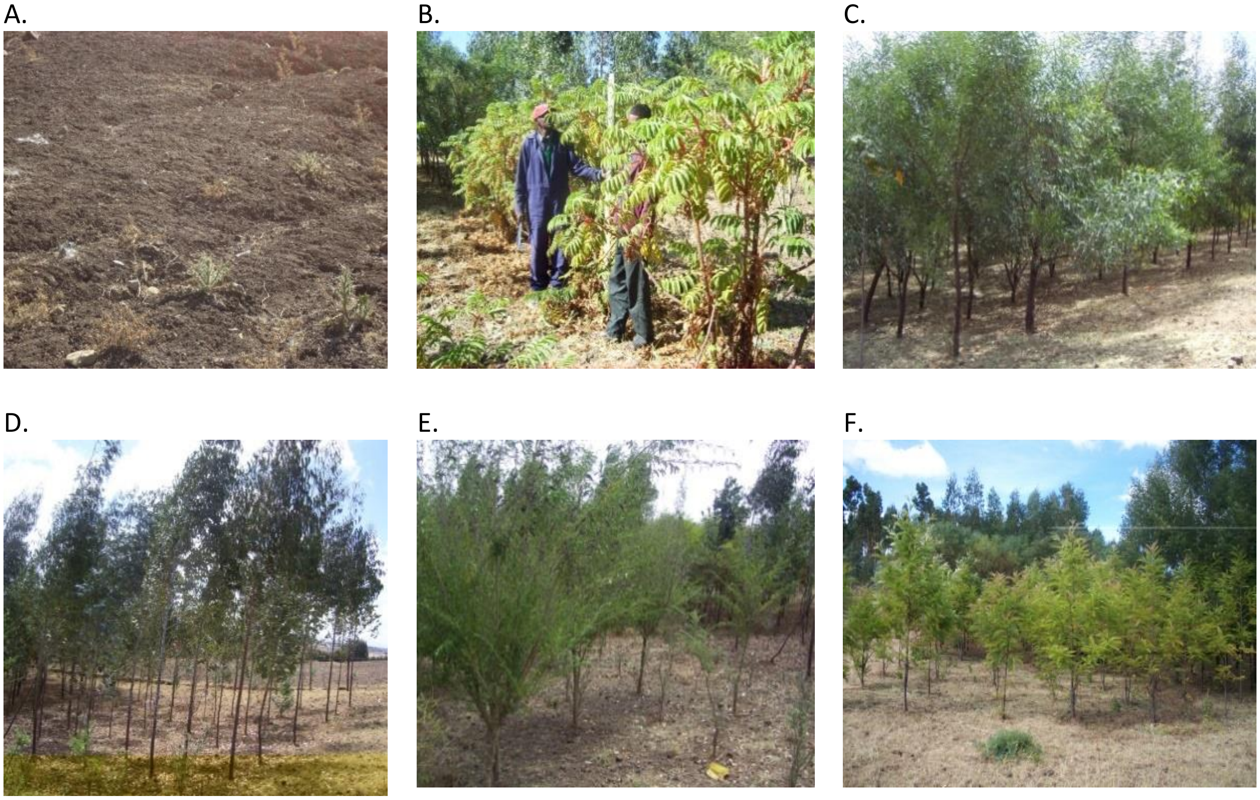
Fig S1. Climate data; Figure S2. Mean growth pattern; Figure S3. Soil properties error bars for *Acacia decurrenes*; Figure S4. Soil properties error bars for *Acacia saligna*; Figure S5. Soil properties error bars for *Grevillea robusta*. Table S1. Differences of least squares means for biomass production. Table S2. Diagonal table of significance soil parameter differences.



Supp Fig. S1*: Location map of study area.*



Supp Fig. S2*: Max temperature, minimum temperature and rainfall of the study area.*



Supp Fig. S3. *Images from the experiment. A. Bare land before plantation. B. Hagenia abyssinica. C. Acacia saligna. D. Eucalyptus globulus. E. Chamaecytisus palmensis, F. Grevillea robusta.*

Table S1. *Differences of least squares means for biomass production 48 months after planting and statistical significance of null hypothesis according to Tukey-Kramer's adjustment. EG: Eucalyptus globulus, AS: Acacia saligna, AD: Acacia decurrense, CP: Chamaecytisus palmensis, GR: Grevillea robusta, DT: Dombeya torrida, HA: Hagenia abyssinica abyssinica.*

Species comparison	**48 months after planting**	
	Estimate	**P-value**
AD-As	-2.343	0.870
AD-CP	3.609	0.519
AD-DT	5.079	0.189
AD-EG	-5.292	0.160
AD-GR	4.297	0.337
AD-HA	5.693	0.115
AS-CP	5.952	0.093
AS-DT	7.422	**0.026**
AS-EG	-2.949	0.715
AS-GR	6.640	0.052
AS-HA	8.037	**0.015**
CP-DT	1.470	0.984
CP-EG	-8.901	**0.007**
CP-GR	0.688	1.000
CP-HA	2.084	0.919
DT-EG	-10.371	**0.002**
DT-GR	-0.782	1.000
DT-HA	0.614	1.000
EG-GR	9.589	**0.004**
EG-HA	10.986	**0.001**
GR-HA	1.397	0.987

Table S2: *Diagonal table of significance soil parameter differences between species at different soil depths. OC: Organic carbon, N: nitrogen, CEC: Cationic Exchange Capacity, K: Potassium. In parenthesis p-value at 0.05 level.*

0-10 cm	AD	AS	CP	DT	EG	GR	HA
AD							
AS							
CP	OC (0.0055) N (0.0016)	OC (0.0037) N (0.0458)				N (0.0069)	
DT	CEC (0.0418)		OC (0.0397)				
EG			OC (0.0039) N (0.0004)	CEC (0.0385) N (0.0180)		CEC (0.0473)	N (0.0016)
GR							N (0.0288)
HA	OC (0.0288) N (0.0069)	pH (0.0375) OC (0.0198) N (0.0042)					

10-30 cm	AD	AS	CP	DT	EG	GR	HA
AD							
AS							
CP	OC (0.0270) K (0.0442)						
DT	K (0.0262)						
EG		CEC (0.0383)	OC (0.0305) N (0.0427)	CEC (0.0126)		K (0.0335) CEC (0.0032)	N (0.0232) CEC (0.0365)
GR	K (0.0271) CEC (0.0390)						
HA							

30-50 cm	AD	AS	CP	DT	EG	GR	HA
AD							
AS			K (0.0178) N(0.0314)				
CP					N (0.0118)	N (0.0151)	
DT							
EG							
GR							
HA							

Study II

Aboveground biomass equations for sustainable production of fuel wood in a native dry tropical afro-montane forest of Ethiopia

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Study II

Aboveground biomass equations for sustainable production of fuel wood in a native dry tropical afro-montane forest of Ethiopia

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Abstract

Biomass equations are needed to correctly quantify harvestable stock and biomass for sustainability in forest management, but information of this kind is scarce in Ethiopia. The objective of this study was to develop biomass equation models five of the most common native tree species in the Chilimo dry afro-montane mixed forest in the central highlands of Ethiopia: *Allophyllus abyssinicus, Olea europaea* ssp. *cuspidiata, Olinia rochetiana, Rhus glutinosa* and *Scolopia theifolia*. A total of 90 trees, (20 trees per species of *O. europaea, O. rochetiana* and *S. theifolia* and 15 trees per species of *A. abyssinicus* and *R. glutinosa*) from different diameter classes were selected, felled and divided into sections: thin branches with leaves (< 2 cm), thick branches (2-7 cm), large branches (>7 cm) and stem with bark. Biomass equation models (the first developed for these five species) were selected and fitted using joint generalized regression to ensure the additivity property between the biomass components of tree fractions and total biomass. Diameter at breast height and total height were used as independent variables. The models were found to be accurate and consistent with other biomass estimations for sustainable fuelwood utilization of these species. A linear correlation between observed and predicted values was found for all five species, along a single, straight line. Thus, the models can be considered reliable for estimating aboveground biomass in the Chilimo forest and applied more generally in similar forest types.

Key words: Chilimo forest, tropical forest, biomass models, carbon stock, additivity, Ethiopia

Introduction

Forests play an important role in mitigating global climate change. The IPCC (2007) estimates that forests cover over 4 billion hectares of the earth's surface and contribute to around 50 % of global greenhouse gas mitigation.

Tropical forests account for about 60 % of global forest cover and store an estimated 193-229 Pg of carbon in aboveground biomass (Brown, 1997; FAO, 2005; Baccini *et al*., 2012), roughly 20 times the annual emissions from combustion and changes in land use (Friedlingstein *et al*., 2010). Tropical dry forests represent around 42 % of all tropical forest ecosystems (Mayaux *et al*., 2005; Miles *et al*., 2006).

The need for accurate estimates of forest biomass is increasing due to its importance in managing commercial and fuelwood, global carbon cycle budgeting and sustainable forest management, along with the assessment of forest structure and condition, forest productivity or carbon fluxes based on sequential changes in biomass (Cole, 2006). In developing countries, about 38 % of primary energy consumption comes from forest biomass (Sims, 2003), in Ethiopia, biomass supplies 93 % of total household energy consumption (Alem *et al*., 2010). To successfully implement mitigating policies and take advantage of the REDD (Reducing Emission from Deforestation and Forest Degradation) programme of the United Nations Framework Convention in Climate Change (UNFCCC) (Chatuvedi *et al*., 2011; Miah *et al*., 2011), these countries need well-authenticated estimates of forest carbon stocks.

Consequently, through direct or indirect methods, it is both important and urgent to quantify tree biomass and how it is distributed among the different tree components (Brown, 2002). Destructive methods directly measure biomass by harvesting the tree and measuring the actual mass of each of its components (Kangas and Maltamo, 2006). Though very accurate (Henry *et al*., 2011), cutting down trees is both costly and time consuming. In contrast, indirect methods using biomass models and biomass expansion factors (BEFs) to estimate tree biomass are inexpensive and time efficient (Peltier *et al*., 2007). However, tools for biomass estimation are scare in the tropics and existing models do not accurately represent the actual forests (Henry *et al*., 2011). Most models for tropical rainforest species were developed in Latin America and South Africa. Though some studies have recently emerged in east Africa and Ethiopia (Zerfu, 2002; Embaye *et al*., 2005; Mamo and Sterba, 2006; Zewdie *et al*., 2009; Henry *et al*., 2010; Fayolle *et al*., 2013; Ngomanda *et al*., 2014), attempts to develop biomass equations for these places and Sub-Saharan Africa in general have been very limited (Henry *et al*., 2011). More research is needed in these areas.

Forest was once naturally abundant in Ethiopia, covering about 40 % of the country in 1900. The numbers have declined drastically since then, to 16 % in 1985 and 2.7 % by 2004 (Nyssen *et al*., 2004). National carbon stocks for the same years have been estimated at 153 Tg C by Houghton (1999), 867 Tg C by Gibbs *et al*. (2007) and 2.5 Gt C by Sisay (2010). Estimates of the naturally high forest carbon stock density range from 101 Mg C ha^{-1} (Brown, 1997; Moges *et al*., 2010) to 200 Mg C ha^{-1} (Temam, 2010), depending on the methodology and tools used soil classification, topography and forest types. Localized carbon stocking capacity studies are urgently needed to aid sustainable management of the existing forest (IBC, 2005; Moges *et al*., 2010).

Located in the central highland plateau of Ethiopia, the Chilimo forest is one of the few remaining dry afro-montane mixed forests and is composed of both broad-leaf and the more dominant coniferous species. The main species (based on density) include *Juniperus procera*, *Podocarpus falcatus, Olea europaea* subsp. *cuspidata, Scolopia theifolia, Rhus glutinosa, Olinia rochetiana* and *Allophylus abyssinicus* (Kelbessa and Soromossa, 2004; Kassa *et al*., 2009). The forest represents a vital ecological space for birds, mammal species and water supply. It is the source of several large rivers, including the Awash River. However, the Chilimo forest has been subjected to human impact for over 2,000 years. The current rate of deforestation is extremely high due to clearing for fuel wood, agricultural land expansion, lumber and farm implements. Chilimo forest cover has shrunk from 22,000 hectares in 1982 to its present-day size of 6,000 hectares (Shumi, 2009; Teshome and Ensermu, 2013). The Ethiopian government has proclaimed this forest as a National Priority Protection Forest area. Since above and below-ground biomass estimates for most Ethiopian species are non-existent, the main objective of this study was to develop biomass and carbon stock estimation models for use in developing sustainable biomass harvesting practices for five of the most common native species in dry tropical afro-montane forest: *Allophyllus abyssinicus* (Hochst.) Radlk. *Olea europaea* L. ssp. *cuspidata* (Wall. ex G. Don) Cif, *Olinia rochetiana* A. Juss, *Rhus glutinosa* Hochst. Ex A. Rich. and *Scolopia theifolia* (Gilg.). Although the coniferous *J. procera* and the broadleaf *P. falcatus* are the most abundant and dominant trees in the forest, cutting them down is prohibited by law and it was therefore not possible to develop biomass-based equations for these endangered species. Consequently, the species included in this study are under increased pressure from the local human population in search of wood for fuel, construction wood, farm implements and charcoal (Kassa *et al*., 2009; Teshome and Ensermu, 2013).

Material and Methods

Study site location

The experimental site was located in the Chilimo dry afro-montane forest of the Western Shewa zone, in the Dendi district of the central highlands of Ethiopia (38° 07′ E to 38° 10′ E longitude and 9° 30′ to 9° 50′ N' latitude), at an altitude of 2,170-3,054 m above sea level (Figure 1). The mean annual temperature ranges between 15 °C and 20 °C and average annual precipitation is 1,264 mm (Shumi, 2009). Köppen's typology classifies the Chilimo forest as a temperate highland climate with dry winters (CWB) (EMA, 1988).

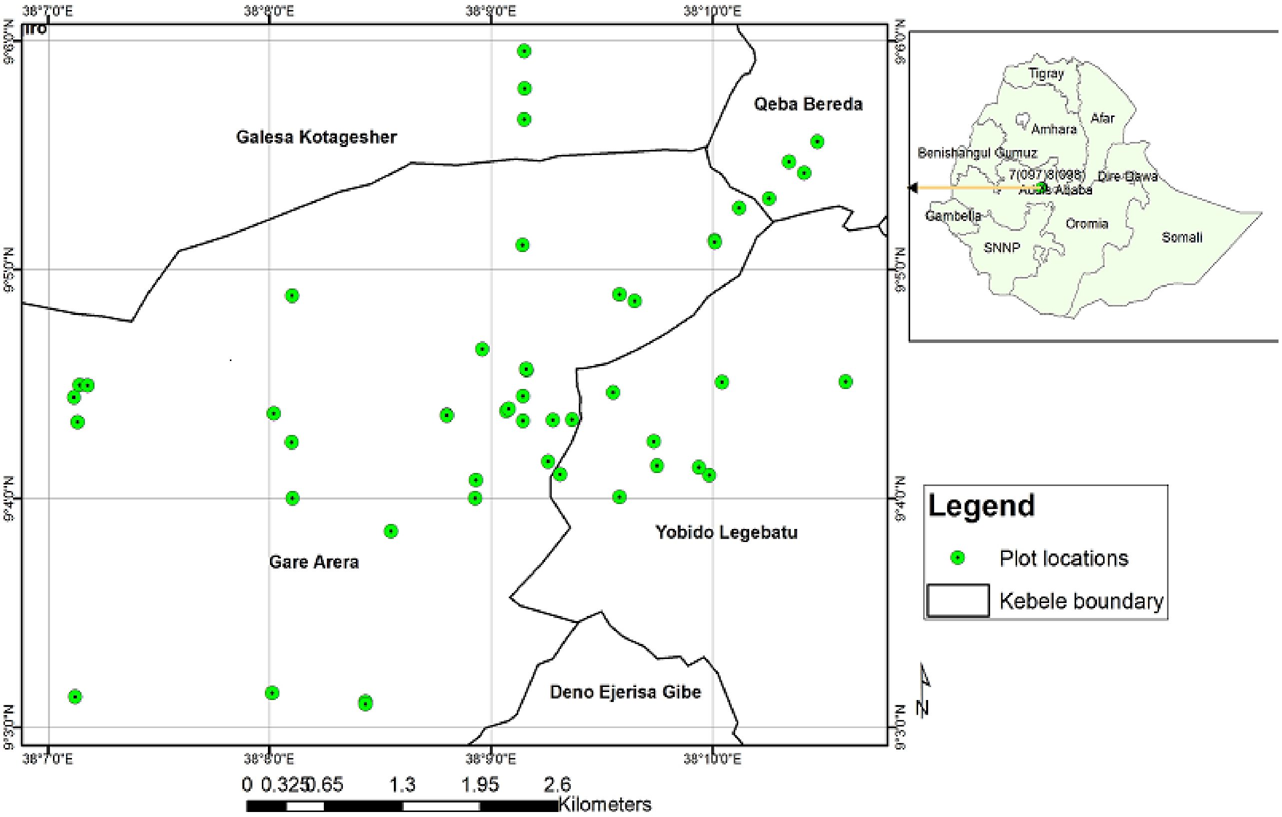

Fig. 1: *Location map and sampling plots of Chilimo dry afro-montane mixed forest (Ethiopia).*

Exploration and pilot survey

A preliminary discussion forum was held with the higher officials of the Oromiya Wildlife and Forest Enterprise in Addis Ababa. Subsequently, a field survey was conducted for physical observation of the Chilimo, Gaji and Gallessa patches.

Prior to biomass data collection, an inventory was taken to compile information about species composition, diameter distribution and general forest conditions. A total of thirty-five 20 x 20 m square sample plots were marked based on the Neyman optimal allocation formula (Köhl et al., 2006) for the altitudinal gradient. The plots were laid out along 100 m of ground distance starting from the highest ridges to the lowest ridges of the mountains, using a measuring tape, GPS, altimeter and compass. The boundaries of the main plots were pegged and marked then altitude, slope, latitude and longitude were recorded from the centre of each main plot. The distance between two consecutive transect lines varied from 300 m to 1 km, depending on the accessibility of the next transect. A total of 33 different native species (22 tree and 11 shrub species) were recorded and density of trees varied from 2, 533 ha^{-1} in the Chilimo patch to 848 ha^{-1} in the Gallessa patch. Similarly, the cumulative density of the five species studied varied from 400 stems ha^{-1} in the Chilimo patch to 94 stems ha^{-1} in the Gallessa patch (Table 1).

Table 1: *General description of Chilimo natural forest (mean ± standard deviation).*

Forest patch	Latitude	Longitude	Altitude (m)	Aspect (%)	Plots	Tree spp	Density (N ha^{-1})	Density studied spp	Dg (cm)	Gm^2 ha^{-1}	Gm^2 ha^{-1} studied species
Chilimo	N09°04´013´´-N09°04’857’’	E038°08´557´´-E038°09´960´’	2470-2770	8-70 %	20	26	2533±28	400±8	26.12±5.3	18.9±1.92	6.21±1.4
Gallessa	N09°05´162´´-N09°05’765’’	E038°09´847´´-E038°10´283´’	2700-2921	25-70 %	11	20	848±10	94±3.5	19.88±2.5	18.18±1.91	3.37±1.1
Gaji	N09°04´269´´-N09°04’340’’	E038°09´861´´-E038°10´025´’	2680-2793	45-50 %	4	18	1638±20	358±5	23.45±4.4	13.81±1.40	5.54±1.2
Total	N09°04´013´´-N09°05’765’’	E038°08´557´´-E038°10´025´’	2470-2921	25-70%	35						

Dg: quadratic mean diameter, G: basal area, spp: species, ha: hectare, m: meter

Data collection and sampling

Sampling and data collection were done in the measured plots of the mixed natural forest. Individual species were categorized into trees (≥ 5 cm diameter at breast height -dbh-), shrubs, saplings (height ≥ 1.3 m and dbh 2.5-5 cm) and seedlings (height 0.30-1.3 m and dbh ≤ 2.5 cm) following Lamprecht's classification (Lamprecht, 1989). All trees and saplings found in the plots were then numbered and marked and tree diameters were measured with a calliper. Crown height, height at branching stems and total height were measured using a Vertex III digital tree height measurement instrument. In cases where trees branched at or below breast height, diameter was measured separately for each branch. Likewise, the diameter of each stem was measured separately for trees with multiple stems connecting near the ground. For irregularities and or buttresses on large trunks, measurement was taken at the nearest lower point. Shrubs, seedlings and saplings were not recorded for the aboveground biomass equation work due to their minimal contribution in this forest. *A. abyssinicus* (4 %), *O. europaea* ssp. *cuspidiata* (8 %), *O. rochetiana* (5 %), *R. glutinosa* (3 %) and *S. theifolia* (5 %) accounted for 25 % of the total native tree population in terms of number of trees ha^{-1} and 23 % (5.04 m^2 ha^{-1}) of total basal area in the overall population. These tree species were selected for developing aboveground biomass-based equations for sustainable fuel wood production because they are the most abundant and dominant tree species in the natural forest after *J. procera* and *P. falcatus* (endangered species). The studied species serve as a source of fuel wood for the local community and the nearby town of Ginchi (Kassa *et al.*, 2009; Shumi, 2009; Teshome and Ensermu, 2013). Further attention and research is needed for the sustainable management of these species.

Data

Trees of each species were selected, cut and sampled based on diameter classes at 5-cm intervals that were obtained from inventory data. Prior to felling, diameter at breast height (dbh = 1.30 m), diameter at ground base (db), crown diameter (cd) and crown length (cl) were measured for each tree. After the trees were cut down, diameter at each meter interval, total height (h), commercial height (hc) (height up to a stem diameter of 7 cm) and height at branching stems (hb) were measured. The branches were de-limbed and separated at first into four biomass components: stem with bark (commercial volume, up to a stem diameter of 7 cm), big branches (diameter larger than 7 cm), thick branches (diameter between 2 and 7 cm) and thin branches (diameter smaller than 2 cm) plus leaves. Fresh weights of each component were recorded in the field and then samples were taken to the laboratory and oven dried at 102 ºC to constant weight. Smalian´s formula (Nicholas *et al*., 2012) was used to calculate the volume of stems and large branches (Ø > 7 cm). Since there were very few large branches (>7 cm) among these species, biomass from this fraction was incorporated into the stem fraction. The main species variables for the sample trees are listed in Table 2. The minimum *dbh* was recorded for *O. rochetiana* (6.15 cm) followed by *O. europaea* (6.20 cm). Inversely, *O. europaea* ssp. *cuspidiata* presented the maximum *dbh* (28.80 cm), followed by *O. rochetiana* (27.50 cm) (Table 2).

Table 2: *Summary of main tree variables for the five most dominant species in Chilimo forest.*

Studied variables	*A. abyssinicus*				*O. europaea*				*O. rochetiana*				*R. glutinosa*				*S. theifolia*			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Dbh (cm)	11.3	3.9	6.4	21.3	14.5	5.9	6.3	28.8	14.9	6.68	6.2	27.5	15.6	4.9	9.0	23.5	11.8	4.1	6.4	22.0
db (cm)	13.9	6.2	0.2	27.3	18.2	6.3	9.9	31.9	17.9	8.36	7.6	34.8	18.8	5.0	12.7	27.5	14.6	4.1	8.0	22.9
h (m)	10.6	3.1	7.0	17.0	10.6	2.1	5.9	14.5	12.6	2.92	7.3	19.4	11.3	3.0	6.0	17.4	8.2	1.9	5.6	13.0
hc(m)	6.7	3.4	0.3	13.5	5.8	2.7	0.5	10.7	8.0	3.58	1.0	14.0	6.3	2.3	1.6	11.4	4.6	2.2	1.9	9.5
hb (m)	4.7	2.6	2.0	12.7	4.0	1.5	1.7	7.0	4.7	1.62	2.0	7.4	4.6	1.9	2.2	9.2	13.7	47.4	1.8	215.0
BS (kg)	32.3	35.6	0.0	130.4	84.2	83.5	4.9	302.9	93.5	97.33	0.0	349.9	65.2	50.4	9.0	168.8	36.3	37.2	5.3	129.3
Br27(kg)	12.1	4.0	4.3	17.4	19.6	11.5	6.0	46.7	26.9	20.42	7.7	89.2	17.2	7.8	5.6	28.3	23.4	14.8	9.8	72.8
Br2 (kg)	7.7	3.5	1.5	13.2	16.7	12.2	1.4	37.9	19.2	14.05	3.0	48.3	8.8	5.7	2.4	22.5	22.6	14.8	6.3	79.1
Crown (kg)	19.8	6.5	5.8	28.3	36.3	22.7	7.4	84.6	46.1	32.19	11.7	129.8	26.0	12.1	8.1	49.6	46.0	28.2	17.8	151.9
Above (kg)	52.1	38.2	11.6	157.6	120.5	104.7	14.3	366.7	139.5	124.1	13.7	451.9	19.2	58.7	17.2	202.4	82.3	52.3	23.0	281.1
N	15	15	15	15	20	20	20	20	20	20	20	20	15	15	15	15	20	20	20	20

Where, SD: standard deviation, *dbh*: diameter at breast height (1.30 m), *db*: diameter at base, *h*: total height, *hc*: commercial height, *hb*: branching height, BS: biomass of stem, Br2: biomass of thin branches plus foliage (< 2 cm), Br27: biomass of thick branches (2-7 cm), above: stem+thick branches (2-7 cm) + (thin branches+ leaves) or stem+crown, N: number of observations.

Data analysis

A correlation analysis between the biomass weight of the different fractions and the biometric tree measurements was carried out using the Spearman method, in order to identify significant predictor variables. To fit the biomass models, different linear and non-linear equations (Table 3) were evaluated for each biomass fraction. The best one was selected based on the MRES (mean residual for evaluating bias), the RMSE (root mean square error for evaluating precision) and biological behavior. The selected models were then simultaneously fitted using joint generalized regression (Seemingly Unrelated Regression, SUR), where cross-equation error correlation was taken into consideration to ensure the additivity property between biomass components and total aboveground biomass (Balboa-Murias *et al*., 2006; Ruiz-Peinado *et al*., 2011 and 2012). Weighted regression was used to avoid heteroscedasticity: each observation was weighted by the inverse of its variance to homogenize the variance of residuals. Models were fitted using the MODEL procedure included in the SAS/ETS software (SAS Institute Inc., 1999). Biomass partitioning between species was studied by applying the best fitted models to the mean value of the diameter classes sampled and the mean height, which was calculated in a dbh-height relationship using field data.

To compare the predictive accuracy of the general equations developed for tropical dry forests (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 1997; Chave *et al*., 2005), the Ethiopian site-specific fitted models were evaluated using average deviation (*S*) [equation 1], relative bias (*RB*) [equation 2], relative root mean square error (*RRMSE*) [equation 3] (Tedeschi, 2006) and a paired *t-test* for estimation values:

$$S(\%) = 100 \cdot \frac{\sum_{i=1}^{n}\left[\frac{|\hat{Y}_i - Y_i|}{Y_i}\right]}{n} \qquad [1]$$

$$RB(\%) = 100 \cdot \frac{\sum_{i=1}^{n}\left[\frac{\hat{Y}_i - Y_i}{Y_i}\right]}{n} \qquad [2]$$

$$RRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{|\hat{Y}_i - Y_i|}{Y_i}\right]^2} \qquad [3]$$

where $\hat{Y}_i$ is the predicted value, Y_i is the observed value and *n* is the number of observations.

Table 3: *Biomass models evaluated for different tree components.*

Model	*Equation*	*Model*	*Equation*
1	$W= \beta*(d*h)$	*7*	$W= (\beta*d^2)+(\lambda*h)$
2	$W= \beta*(d^2*h)$	*8*	$W= (\beta*d^2)+(\lambda*h)+(\theta*d^2*h)$
3	$W= (\beta*d)+(\lambda*d^2)+(\theta*d^2*h)$	*9*	$W= (\beta*d^2)+\lambda*(d*h)$
4	$W= (\beta*d)+(\lambda*h)$	*10*	$W= \beta*(d^2*h)+ \lambda *(d*h)$
5	$W= (\beta*d^2)+\lambda*(d^2*h)$	*11*	$W= \beta*(d^\lambda) *(h^\theta)$
6	$W= \beta*(d^2*h)^{\lambda}$	*12*	$W= \beta*d+ \lambda*d^2$

Where W: biomass weight (kg) for the different fractions, d: dbh (cm), h: tree height (m), β, λ, θ: parameters of the models.

Results

Correlation of dendrometric variables to dry biomass fractions

The aboveground, stem and thin branches plus foliage biomass fractions for all five species were strongly correlated to *dbh* and stump diameter (Table 4). Similarly, most biomass fractions were also correlated to total height and commercial height. However, the thick branches fraction of *A. abyssinicus* and *R. glutinosa* were non-correlated to *dbh* and stump diameter and most biomass fractions were not significantly correlated to tree branching height, crown length or crown diameter. Spearman's correlation results indicated that biomass models could use *dbh* and total height as independent variables. These variables are usually measured in forest inventories and commonly used for biomass estimation models of this type.

Table 4: *Spearman correlation coefficients between biomass components and dendrometric variables for the studied species.*

Spp	Biomass fractions	Dendrometric variables						
		h	***hc***	***hb***	***dbh***	***db***	***cd***	***cl***
A. abyssinicus	Stem	0.72^{**}	0.96^{***}	0.32^{ns}	0.85^{***}	0.82^{***}	0.13^{ns}	0.46^{ns}
	Thick branches (2-7)	0.20^{ns}	0.02^{ns}	0.01^{ns}	0.22^{ns}	0.25^{ns}	0.05^{ns}	-0.08^{ns}
	Thin branches + L	0.64^{*}	0.58^{*}	0.38^{ns}	0.65^{**}	0.64^{*}	0.10^{ns}	0.29^{ns}
	Crown	0.48^{ns}	0.36^{ns}	0.19^{ns}	0.54^{*}	0.48^{ns}	0.11^{ns}	0.15^{ns}
	Above	0.86^{***}	0.93^{***}	0.24^{ns}	0.91^{***}	0.89^{***}	0.07^{ns}	0.50^{ns}
O. europaea	Stem	0.71^{***}	0.81^{***}	0.09^{ns}	0.95^{***}	0.89^{***}	0.67^{**}	0.48^{*}
	Thick branches (2-7)	0.70^{**}	0.86^{***}	0.08^{ns}	0.89^{***}	0.84^{***}	0.81^{***}	0.39^{ns}
	Thin branches + L	0.54^{*}	0.76^{***}	-0.11^{ns}	0.92^{***}	0.88^{***}	0.51^{*}	0.36^{ns}
	Crown	0.62^{**}	0.84^{***}	-0.02^{ns}	0.95^{***}	0.91^{***}	0.67^{**}	0.39^{ns}
	Above	0.68^{**}	0.85^{***}	0.05^{ns}	0.96^{***}	0.93^{***}	0.68^{*}	0.48^{*}
O .rochetiana	Stem	0.84^{***}	0.87^{***}	0.36^{ns}	0.92^{***}	0.93^{***}	0.75^{***}	0.69^{**}
	Thick branches (2-7)	0.69^{**}	0.57^{**}	0.41^{ns}	0.76^{**}	0.83^{***}	0.64^{**}	0.64^{**}
	Thin branches + L	0.67^{***}	0.56^{**}	0.29^{ns}	0.82^{***}	0.82^{***}	0.55^{*}	0.62^{**}
	Crown	0.69^{**}	0.57^{**}	0.37^{ns}	0.83^{***}	0.87^{***}	0.62^{**}	0.82^{***}
	Above	0.83^{***}	0.83^{***}	0.40^{ns}	0.94^{***}	0.95^{***}	0.74^{***}	0.68^{**}
R. glutinosa	Stem	0.49^{ns}	0.88^{***}	0.19^{ns}	0.98^{***}	0.94^{***}	0.44^{ns}	0.69^{**}
	Thick branches (2-7)	0.63^{*}	0.36^{ns}	-0.38^{ns}	0.41^{ns}	0.44^{ns}	0.58^{*}	0.59^{*}
	Thin branches + L	0.61^{*}	0.59^{*}	0.04^{ns}	0.68^{*}	0.68^{*}	0.14^{ns}	0.73^{**}
	Crown	0.61^{*}	0.52^{ns}	-0.26^{ns}	0.68^{*}	0.71^{**}	0.47^{ns}	0.73^{**}
	Above	0.63^{*}	0.83^{***}	0.10^{ns}	0.92^{***}	0.89^{**}	0.46^{ns}	0.74^{**}
S. theifolia	Stem	0.90^{***}	0.89^{***}	0.14^{ns}	0.92^{***}	0.88^{***}	0.34^{ns}	0.48^{*}
	Thick branches (2-7)	0.79^{***}	0.81^{**}	0.02^{ns}	0.73^{***}	0.71^{**}	0.35^{ns}	0.47^{*}
	Thin branches+ L	0.49^{*}	0.53^{*}	0.17^{ns}	0.70^{***}	0.70^{**}	0.33^{ns}	0.39^{ns}
	Crown	0.76^{***}	0.81^{***}	0.05^{ns}	0.85^{***}	0.88^{***}	0.40^{ns}	0.48^{*}
	Above	0.87^{***}	0.90^{***}	0.16^{ns}	0.89^{***}	0.83^{***}	0.41^{ns}	0.53^{*}

Note: Above: stem+thick branches (2-7 cm) + (thin branches plus leaves) or stem+crown,* = $p \leq 0.05$, **= $p \leq 0.01$, *** = $p \leq 0.001$, *hc*: commercial height, *hb*: branching height, *h*: total height, *dbh*: diameter at breast height, *db*: tree basal diameter, *cd*: crown diameter, *cl:* crown length. L: leave.

Fitted models

Based on goodness-of-fit statistics and biological behaviour, models 1, 2, 5 and 7 (Table 3 and 5) were selected for different components and species. Due to fitting problems, biomass for all branches and leaves were combined into a crown fraction for *O. rochetiana*, *R. glutinosa* and *S. theifolia*; and one model was fitted for this fraction. Similarly, the model that treated all components together as aboveground biomass provided the best fit for *A. abyssinicus*. These calculated model parameters were statistically significant at the 99 % confidence level ($p < 0.001$) (Table 5). All fitted models for stem biomass showed R^2 -Adj values higher than 0.75. Due to high variability, branch or crown models presented lower values, ranging from 0.79 for the thick branches fraction in *O. europaea* to 0.55 for crown biomass in *S. theifolia*. Aboveground biomass models fitted with SUR (except for *A. abyssinicus*) showed high R^2-Adj values ranging from 0.96 for *O. europaea* to 0.79 for *S. theifolia*.

The selected models were also tested for accuracy based on observed and predicted data. The observed vs predicted values for total aboveground biomass revealed no bias in the fitted models, though, efficiency varied among the species (Table 5). The results indicated that the selected models are efficient. Figure 2 shows how observed and predicted aboveground biomass values are close to 1:1 line.

Table 5: *Simultaneous fit of biomass models for the most important native species of Chilimo natural forest.*

Species	**Fraction**	**MRES**	**RMSE**	**R^2_Adj.**	**Selected model**	**Estimated parameters**	**$\mathrm{Pr} > \lvert t \rvert$**
A.abyssinicus	Above	0.01	10.27	0.84	$W_a= \beta*(d*h)$	0.3937	<.0001
Olea europaea	Stem	0.72	12.01	0.93	$W_s= \beta*(d^2*h)$	0.02746	<0.0001
	Br27	-0.53	4.47	0.79	$W_{br27}= (\beta*d^2)+(\lambda*h)$	0.05744 0.6856	<.0001 0.0008
	Br2	0.09	5.29	0.69	$W_{b2}= \beta*(d^2*h)$	0.006584	<.0001
	Above	0.27	12.03	0.96	$W_a=\sum W_i$		
Olinia rochetiana	Stem	0.25	35.06	0.76	$W_s=\beta*(d*h)$	0.3990	<.0001
	Crown	1.31	14.41	0.58	$W_c= (\beta*d^2)+\lambda*(d^2*h)$	0.4550 -0.02163	<.0001 <.0001
	Above	1.56	33.38	0.85	$W_a=\sum W_i$		
Rhus glutinosa	Stem	3.34	10.57	0.79	$W_s=\beta*(d^2*h)$	0.01604	<.0001
	Crown	-1.24	6.28	0.68	$W_c= (\beta*d^2)+(\lambda*h)$	0.04867 1.3033	0.0017 <.0001
	Above	2.11	11.11	0.88	$W_a=\sum W_i$		
Scolopia theifolia	Stem	1.52	6.94	0.75	$W_s=\beta*(d^2*h)$	0.02107	<.0001
	Crown	0.65	7.67	0.55	$W_c= \beta*(d*h)$	0.4253	<.0001
	Above	2.17	11.04	0.79	$W_a= \sum W_i$		

Where, Above: stem+Br2+Br27 or stem+crown, Wi: biomass weight (kg) of the different fractions, d: dbh (cm), h: tree height (m), β, λ: parameters of the models, Br2: branches with a diameter less than 2cm plus leaves, Br27: thick branches between 2-7cm, MRES: mean residual, RMSE: root of the mean quadratic error (kg), R2-Adj.: r2 adjusted correlation coefficient.

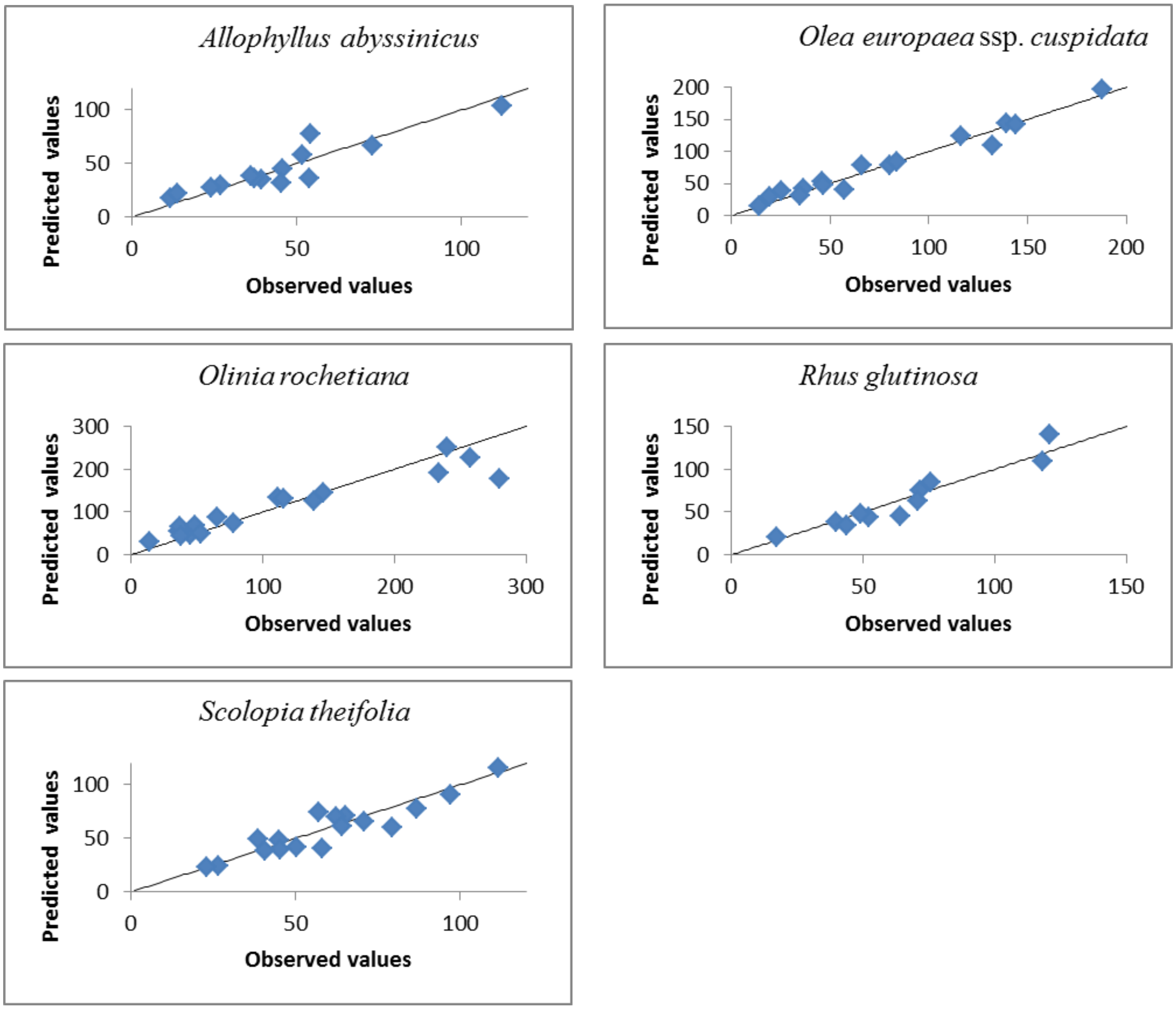

Fig. 2: *Observed vs predicted values for aboveground biomass of the studied species*

Biomass partitioning

Aboveground biomass partitioning of *O. europaea* ssp. *cuspidiata*, *O. rochetiana*, *R. glutinosa* and *S. theifolia* into stem and crown biomass fractions is summarized in figure 3. The biomass proportions were estimated by applying the fitted models to the sample diameter classes and the corresponding estimated total height. *O. europaea* and *O. rochetiana* exhibited similar biomass allocation: the stem fraction accumulated more biomass than the crown fraction (60-70 %) in all diameter classes. *R. glutinosa* crown fractions accumulated more biomass (53 %) than stem fractions (47 %) in the 10 cm diameter class; but stem fractions accumulated more biomass than crown fractions in the 15 and 20 cm diameter classes (61 % and 69 %, respectively). The *S. theifolia* crown fraction was greater than the stem fraction in all diameter classes.

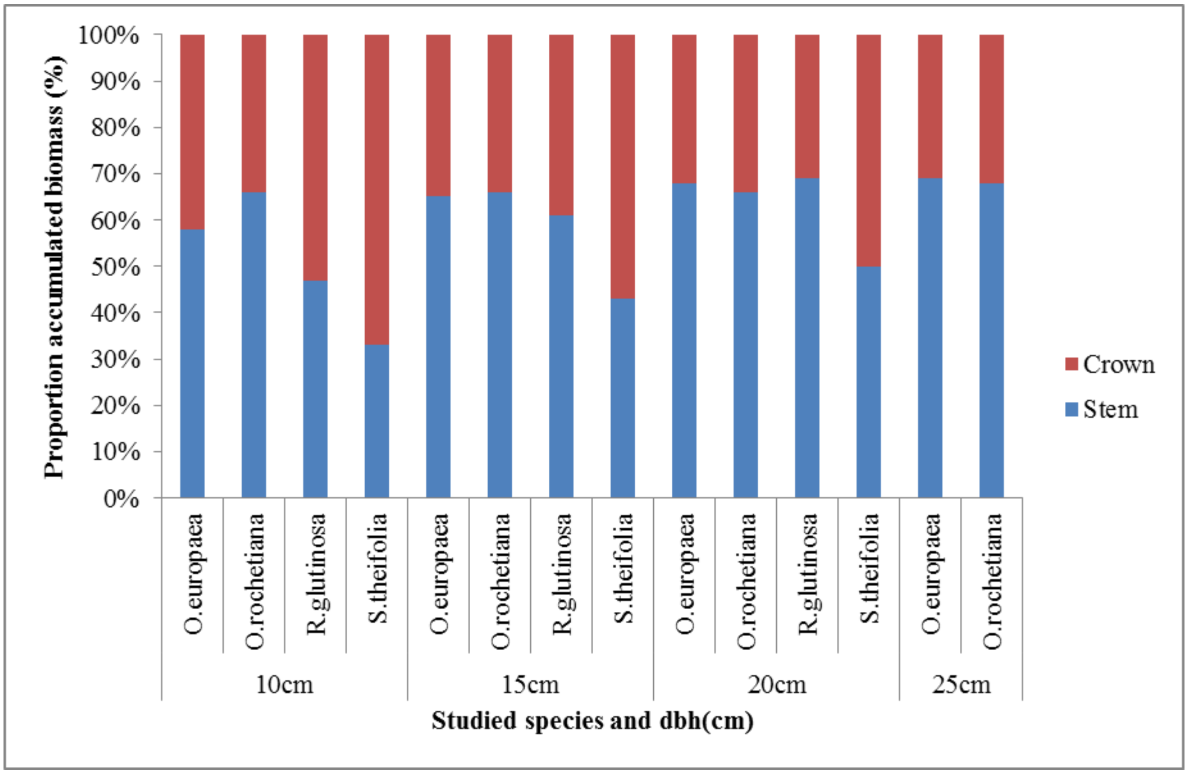

Fig. 3: *Aboveground biomass partitioning for the main sampled tree species.*

Model comparison

The comparison of fitted models using generalized equations developed for tropical forest (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 1997; Chave *et al*., 2005) showed that the equation developed by Brown *et al*. (1989) presented the poorest results (32-59 % average deviation) for aboveground biomass predictions. The deviation values were species-dependent and the highest average deviation (86 %) occurred when the Brown model (Brown, 1997) was applied to *R. glutinosa* (Table 6). Deviation for the other species ranged from 28 % to 39 %. Relative bias showed over-or- underestimation of the generalized models, showing the Brown *et al*. (1989) model overestimation in all species. The *t-test* also revealed the inadequacy of the Brown *et al*. (1989) model for four of the five species studied (*A. abyssinicus, O. europaea, O. rochetiana, R. glutinosa*). Similarly, the Chave *et al*. (2005) model was also unsuitable for three species (*A. abyssinicus, O. rochetiana, R. glutinosa).*

Table 6: *Comparison of models for aboveground biomass estimation in tropical forest (site-specific and generalized equations).*

					t-test	
Species	**Model reference**	**Average deviation (%)**	**Relative bias (%)**	**Relative RMSE**	**t-Statistic**	**p-value**
A. abyssinicus	This study	21.09	-7.41	0.280	0.004	0.9969
Generalized	Brown *et al*. (1989)	38.95	36.14	0.416	4.4287	0.0006
Generalized	Brown & Lugo (1992)	23.36	-2.58	0.342	-0.8096	0.4327
Generalized	Brown (1997)	33.75	-19.19	0.495	-1.7582	0.1022
Generalized	Chave *et al*. (2005)	19.61	6.99	0.271	0.4332	0.6720
Olea europaea	This study	14.32	-5.29	0.204	0.0955	0.9251
Generalized	Brown *et al*. (1989)	43.21	40.81	0.445	6.2926	<.0001
Generalized	Brown & Lugo (1992)	18.41	15.12	0.216	4.0902	0.0008
Generalized	Brown (1997)	28.30	-9.95	0.341	-1.9002	0.0756
Generalized	Chave *et al.* (2005)	21.76	-16.51	0.276	-3.5292	0.0028
O. rochetiana	This study	29.18	-19.43	0.408	0.2015	0.8427
Generalized	Brown *et al*. (1989)	46.50	44.16	0.497	4.2731	0.0005
Generalized	Brown & Lugo (1992)	22.23	9.46	0.303	-0.2241	0.8253
Generalized	Brown (1997)	39.38	-8.31	0.507	-1.7996	0.0897
Generalized	Chave *et al.* (2005)	19.33	11.02	0.249	0.5996	0.5167
Rhus glutinosa	This study	13.32	4.17	0.156	0.6595	0.5244
Generalized	Brown *et al*. (1989)	32.05	13.07	0.374	0.4016	0.6965
Generalized	Brown & Lugo (1992)	29.77	-22.89	0.390	-2.126	0.0593
Generalized	Brown (1997)	85.98	-78.59	1.082	-2.7029	0.0222
Generalized	Chave *et al.* (2005)	37.45	-36.47	0.461	-2.8738	0.0166
S.theifolia	This study	13.59	2.43	0.168	0.4193	0.8290
Generalized	Brown *et al*. (1989)	58.71	55.45	0.582	10.1593	<.0001
Generalized	Brown & Lugo (1992)	43.31	40.91	0.444	9.2180	<.0001
Generalized	Brown (1997)	31.25	19.47	0.344	1.9076	0.0750
Generalized	Chave *et al*. (2005)	38.94	36.78	0.401	8.4323	<.0001

Discussion

Biomass and carbon stock estimates for tropical forest species help us to better understand the importance of tropical forests in the global carbon cycle and how to manage these forests for sustainable production and fuel wood harvesting. They also serve as valuable tools for policy-makers and stakeholders. Developing specific biomass models for species in Ethiopian dry afro-montane mixed forests will contribute to the sustainable management of these forests. The models developed in this study included *dbh* and total height as independent variables in all the biomass fractions (Table 5). Although, commercial height showed a high correlation with biomass weight (Table 4), accurate measurement of these variables in the field is difficult (Segura and Kanninen, 2005). Combining these values provided better fit results and estimation values than the use of *dbh* alone. Several authors have advocated the combined use of *dbh* and height as independent model variables (Basuki *et al*., 2009; Ruiz-Peinado *et al*., 2011 and 2012), because height could incorporate indirect information about site conditions (competition, fertility...). Henry *et al.* (2011) advocated the combined use of these variables due to variations in wood gravity, volume and biomass among and within ecological zones and trees. Feldpausch *et al*. (2012) found that including total height in models improved the accuracy of biomass estimates in tropical forest because it avoided biomass overestimation in large trees. Chave *et al*. (2005) also found *dbh*, wood specific gravity, total height and forest type (in decreasing order) to be important variables for predicting tree biomass in tropical forests. These authors observed a standard error reduction from 19.5 % when total height was not available to 12.5 % when total height was available, across all types of tropical forests. Brown *et al*. (1989) developed general biomass models for wet, moist and dry tropical mixed forests by including *dbh* and height as predictive variables. Such models facilitate practical, effortless and timely applications, because the independent variables are easily measured in the field and commonly recorded in forest inventories (Ketterings *et al*., 2001).

Equations were developed for each biomass fraction according to species (Table 5). Models were developed for all biomass fractions of *O. europaea*; but only an aboveground biomass equation could be developed *for A. abyssinicus*, possibly due to the low crown and foliage biomass of this species. Models were developed for stem and crown biomass fractions of the other three species studied (*O. rochetiana, S. theifolia* and *R. glutinosa*). Combining thick branches and thin branches with leaves into a crown biomass fraction resulted in better fitting efficiency, due to the high variability in these fractions. Similar results reported by other authors corroborate the lower prediction potential of the branch and foliage biomass models over the stem model (Negash *et al*., 2013). Cole and Ewel (2006) argue that weather, herbivores and inter-plant competition affect the variability of the crown biomass fraction. In mixed forest, inter-specific competition strongly influenced crown geometry, resulting in high biomass heterogeneity.

All the estimator parameters of the biomass models showed positive coefficient values for all species and biomass fractions, except one parameter for crown biomass in *R. glutinosa*. It affected total height as an independent variable and could indicate that taller trees allocate less biomass to crown due to light competition processes for this species (Vanninen and Mäkelä, 2000).

Although some authors have proposed the use of generalized equations to estimate aboveground biomass in African tropical forests (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 1997; Chave *et al*., 2005) others advocate the use of species-specific and site-specific equations. Such equations reflect the great variability in tree architecture and wood gravity among and within the species (Ketterings *et al*., 2001; Litton and Kauffman, 2008; Henry *et al*., 2011), making it possible to more accurately quantify harvestable biomass for fuel wood and other purposes. Several authors have also reported that generalized equations were unsuitable for African tropical forests (Henry *et al*., 2010; Ngomanda *et al*., 2014). Comparison of the generalized models (Brown *et al*., 1989; Brown and Lugo, 1992; Brown, 1997; Chave *et al*., 2005) to the fitted models for the studied species (Table 6) showed that accuracy varied according to species. The Brown *et al*. (1997) model was not valid for these species (*p-value* < 0.05 in four species and high statistics for *R. glutinosa*). The Chave *et al*. (2005*)* model was unsatisfactory for three of the studied species, but showed acceptable statistics for the other two. Although, the Brown and Lugo (1992) and the Brown (2002) models were valid for three and four species, respectively, they also showed poor statistics (average deviation, relative bias and relative *RMSE*). In light of these results and the high heterogeneity of species in tropical mixed forests, we advise the use of site-specific models if they are available. This conclusion is based on results for five relatively small tree species (maximum sampled diameter: 28.8 cm; maximum sampled height: 19.4 m); the accuracy of generalized models might improve when applied to large trees. In the literature on biomass estimation in tropical forests, there are findings regarding both the precision of generalized equations (Fayolle *et al*., 2013) and the advantages of site-specific equations (Segura and Kanninen, 2005; Ngomanda *et al*., 2014). Deo (2008) argued that the relatively small sample number of trees used for developing generalized biomass equations in the tropics led to biased predictions and emphasized the need for site-specific equations. In recent years, several site-specific models have been developed for tropical species in general and sub-Saharan species in particular; which are described in the review of Henry *et al*. (2011).

Biomass partitioning is an important factor in quantifying exploitable dendromass (for timber yield or firewood). Stem biomass proportions in *O. europaea* and *O. rochetiana* were nearly constant across the diameter classes (Figure 3), but increased with increasing diameter in *R. glutinosa* and *S. theifolia*. However, the crown fraction in *S. theifolia* was always greater than the stem fraction. This might be due to its umbrella-shaped crown, which contributes significantly to branch volume. Tropical species vary greatly in leaf morphology and crown structure, leading to differences in biomass allocation among species (Poorter *et al*., 2006). Henry *et al*. (2010) found mean figures with higher biomass accumulation in the stem fraction (72 %) than in crown fractions (28 %) for 16 tropical species in Africa. The results of Mate *et al*. (2014) for three tropical species (of greater diameter than those sampled in this study) showed mean biomass partitioning values that ranged between 46 % and 77 % for stems and from 23 % to 54 % for crowns. Likewise, Henry *et al*. (2010) found that stem biomass tended to decrease as crown biomass increased, and vice versa. This finding was not corroborated for the species we examined, where the stem fraction always increased with tree size and diameter range. Biomass distribution among tree components might be related to site conditions, mainly light and space competition in dense forest (as sampled at this study), resulting in trees with lower crowns than in open forests.

Conclusions

Tree diameter and total height were considered the best independent variables for biomass estimation of the species studied in the Chilimo dry afro-montane mixed forest, due to their high correlation with biomass dry weight. Crown biomass models were fitted for three of the five species studied (*O. rochetiana*, *R. glutinosa* and *S. theifolia*) due to high variability in branch biomass fractions resulting from inter-specific competition in the mixed tropical forest. An aboveground model was developed for *A. abyssinicus* based in its biomass heterogeneity and small weight of crown biomass. The generalized models proved unsuitable for this type of forest. To improve estimation accuracy and reduce uncertainty, we suggest the application of the species-specific models developed in this study to similar Ethiopian mixed forests and other tropical montane forests. Such equations can be used for estimating the carbon stock of the forest, identifying its role as a carbon sink, establishing its carbon trade value and informing management policies regarding sustainability and biomass harvesting for these species for fuel wood.

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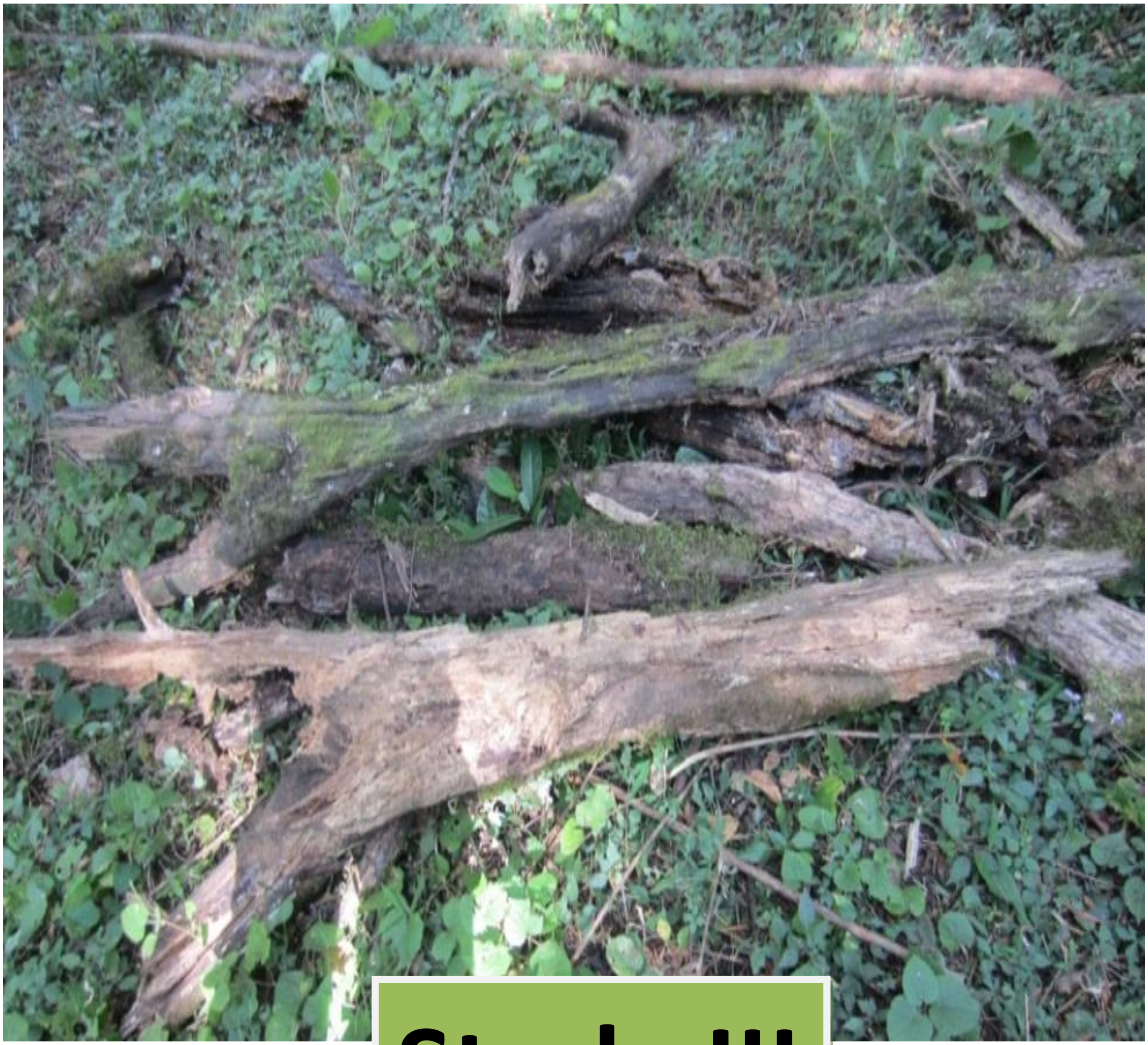

Study III

Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands

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Study III

Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands

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Abstract

African tropical forests are claimed to play a prevalent role in carbon sequestration at the global scale. However, the rate of deforestation is increasing and the impact of land use change deserves an updated and critical look. This work emphasizes the role of bulk density as a main driver in carbon and nitrogen stock across four land use types: natural forest, tree plantations, crops and degraded soil. The study is conducted in the Central Highlands of Ethiopia where deforestation and human pressure on native forests is exacerbated and erosion has caused large soil losses. The methodological approach consists of evaluating first the bulk density confounding effect and estimate C and N stock based on a fixed mass method rather than the usual fixed depth method to compare differences across land use types. In the native forest an elevation gradient is hypothesized as a main factor in controlling C and N concentration and stock whereas in plantations, tree species identity is considered the main factor. The C and N concentration and bulk density in mineral soil were analyzed as repeated measures in an irregular vertical space ranging from 0-10 cm, 10-30 cm, 30-50 cm and 50-100 cm using a linear mixed model approach, whereas single observations from the forest floor are analyzed by a generalized linear model. Results indicate that soil depth is a more important factor than elevation in native forests although C and N concentration and stock diminished near human settlements. The native forest stored on average 84.4 %, 26.4 %, 33.7 % more carbon than bare soil, crops and plantations respectively and 82.4 %, 51.8 %, 27.1 % more nitrogen. However, conversion of crop and degraded land to plantations ameliorates soil condition degradation, although, species selection did not affect carbon and nitrogen stock. It is suggested that the use of native tree species in plantations could have a positive impact in C and N storage as other studies have demonstrated in the same area.

Key words: forest floor, mineral soil, soil depth, mixed model, species identity, impact assessment

Introduction

Forests in general and forest soils in particular play a vital role in the global carbon balance. The global soil carbon pool has been estimated to contain more than 3.3-fold the atmospheric carbon pool and 4.5-fold the biotic pool (Lal, 2004) and forest soils account for 54 % of stored carbon in old-growth forests (Luyssaert *et al*., 2008). Pan *et al*. (2011) quantified the forest carbon sinks at global level and estimated the total stock to be 861 Pg of which 383 Pg (45 %) are in soil (to a depth of 1 m), 363 Pg (42 %) in above and belowground biomass, 73 Pg (8 %) in deadwood and 43 Pg (5 %) in litter. One third of the global soil carbon is found in the tropics (Lemma *et al*., 2006).

In forest ecosystems, biomass and soil carbon are stored in dynamic equilibrium with the environment. Soil Organic carbon (SOC) is affected by environmental factors such as topography, parent material or soil depth (Fu *et al*., 2004; Johnson *et al*., 2000). The key relationships between environmental factors and soil depth are indirect and potentially complex. Topography influences precipitation, temperature, solar radiation and relative humidity (Tsui *et al*., 2004); aspect determines length of exposure to sunlight and can influence soil weathering and vegetation (Rech *et al*., 2001; Sidari *et al*., 2008; Yimer *et al*., 2006).

Land use and plant species also significantly influence SOC estimations. In the tropics, deforestation and changes in land use are significantly impacting the global carbon cycle by increasing the rate of carbon emissions (Silver *et al*., 2000). Conversion of forest into agricultural ecosystems negatively affects SOC concentration and stock by 20-50 % (Solomon *et al*., 2002; Lemenih and Itanna, 2004; Lal, 2005). In tropical forests, which serve as powerful carbon sinks, deforestation accounts for 20 % of total anthropogenic CO_2 emissions into the atmosphere (Baccini *et al*., 2008).

Mitigation strategies to reduce the impact of climate change (FAO, 2006) by augmenting carbon sequestration and reducing CO_2 emissions from soils include proper forest management and afforestation or reforestation programs. Quantification and continuous assessment of changes in C and N pool sizes and fluxes is fundamental to understanding the effects of changes in land use/land cover on ecosystem functioning and limiting greenhouse gas emissions (Jaramillo *et al*., 2003; Lemma *et al*., 2006).

Forest cover in Ethiopia decreased by more than 90 % between 1900 and 2004 (4,073, 213 ha) (Nyssen *et al*., 2004). Tree plantations cover approximately 500,000 ha (WBISPP, 2005), of which 133,041 ha were established as public plantations between 1978 and 1989. The most common species are *Eucalyptus spp.* (58 %), *Cupressus lusitanica* (29 %), *Juniperus procera* (4 %) and *Pinus spp* (2 %) (Moges *et al*., 2010). The Highlands account for 45 % of the country's total area, supporting about 85 % of the human population and 75 % of the livestock population. Forest cover can be broadly separated into dry or moist montane forest. Dry montane forests are dominated by scherophyll evergreen, while moist montane forests are characterized by large broadleaf and soft-leaf species (Gatzweiller, 2007). However, much of the Highland forest is disappearing or being converted into agricultural land (Teketay, 2001). Annual deforestation in the Highlands is estimated at 150,000 to 200,000 hectares fertile topsoil loss is estimated at 1.9 billion Mg of soil yr^{-1} and an average of 42 Mg ha^{-1} is eroded annually (UNEP, 2002; World Bank, 2001). Ethiopia also has one of the highest rates of soil nutrient depletion (Lemma *et al*., 2006). However, there is very little research about how land use category, species composition and elevation affect carbon and nitrogen concentration and stock.

The Chilimo forest is one of the few remnants of native dry afro-montane forest, located in the central highland plateau of Ethiopia. Native coniferous species predominate in this mixed broad-leaf and coniferous forest, where the main species include *Juniperus procera, Podocarpus falcatus, Prunus africana, Olea europaea ssp. cuspidiata, Scolopia theifolia, Rhus glutinosa, Olinia rochetiana, Allophylus abyssinicus* (Kelbessa and Soromessa, 2004). A centre of biodiversity and endemism, the Chilimo forest is also home to over 180 bird species, 21 mammal species and several precintive subspecies such as the Meneliks bushbuck, vervet monkey, Colobus monkey, Anubis baboon and leopard (Woldemariam, 1998). Soromessa and Kelbessa (2014) reported a total 213 different plant species categorized into 83 families, including 17 plant species that are unique to the Chilimo forest. Due to continuous deforestation, the Chilimo forest cover has declined from 22,000 ha in 1982 to 6,000 ha in 1991 (Shumi, 2009). Consequently, some plant species are becoming endangered (Soromessa and Kelbessa, 2014) as the need for fuel wood, arable land and timber drive forest degradation (Soromesa and Kelbessa, 2013). In order to minimize deforestation, the forest has been categorized as one of Ethiopia's 58 national priority forest protection areas and receives more attention due to its potential as a carbon sink. Alternative strategies to reduce the pressure on the native forest by alleviating the fuel wood shortage include fast-growing tree and shrub plantations around homesteads, establishment of clear farm boundaries and wood lots in nearby rural communities (Alebachew, 2012). At the same time, carbon assessment of the forest floor and mineral soil is generating vital information regarding the importance of the forest for carbon exchange and climate change mitigation at local, regional and international levels. The history, topography, stewardship and intense transformation in land use of the Chilimo forest make it an optimal case study.

On these premises, we hypothesized that soil organic carbon (SOC) and soil organic nitrogen (SON) stock in the forest floor and in mineral soil would vary along an elevation gradient in native forest. Likewise, land use and tree species would also determine SOC and SON stock at different depths. The specific research questions to be addressed in this study are (1-4):

1. Does soil bulk density significantly vary across land use categories and or soil depths? Do carbon and nitrogen concentration and stock in the forest floor vary along an elevation gradient?
2. Do carbon and nitrogen concentrations and stocks in mineral soil change at different soil depths along an elevation gradient in native dry afro-montane forests?
3. How does intensive land use change soil carbon and nitrogen concentrations and stocks at different soil depths?
4. Does species selection have any effect on carbon and nitrogen concentrations and stocks at different soil depths in plantations?

Material and Methods

Study site location and description

The experimental site is located in the Chilimo-Gaji dry afro-montane forest of the Western Shewa zone of the Dendi district in the central Highlands of Ethiopia. The forest is surrounded by crop land (mainly teff, *Eragrostis tef*), degraded areas and three 28 years old plantations of *Eucalyptus saligna*, *Cupressus lusitanica* and *Pinus patula*. Geographically it is located from 38° 07′ E to 38° 10′ E longitude and 9° 30′ to 9° 50′ N' latitude, at an elevation of 2,170 to 3,054 m above sea level (Figure 1, Table 1). The mean annual temperature of the area ranges between 15 and 20 °C and the mean annual precipitation is 1,264 mm. A total of 33 different native species (22 tree and 11 shrub species) were recorded in the forest. The quadratic mean diameter i.e. the square root of the ratio of square of diameter at breast height to number of stems of the sampled plantation and natural forest ranged from 12.79 to 26.12 cm and the basal area for the sample plots studied ranged from 13.81 to 25.5 m^2 ha^{-1} (Table 1).

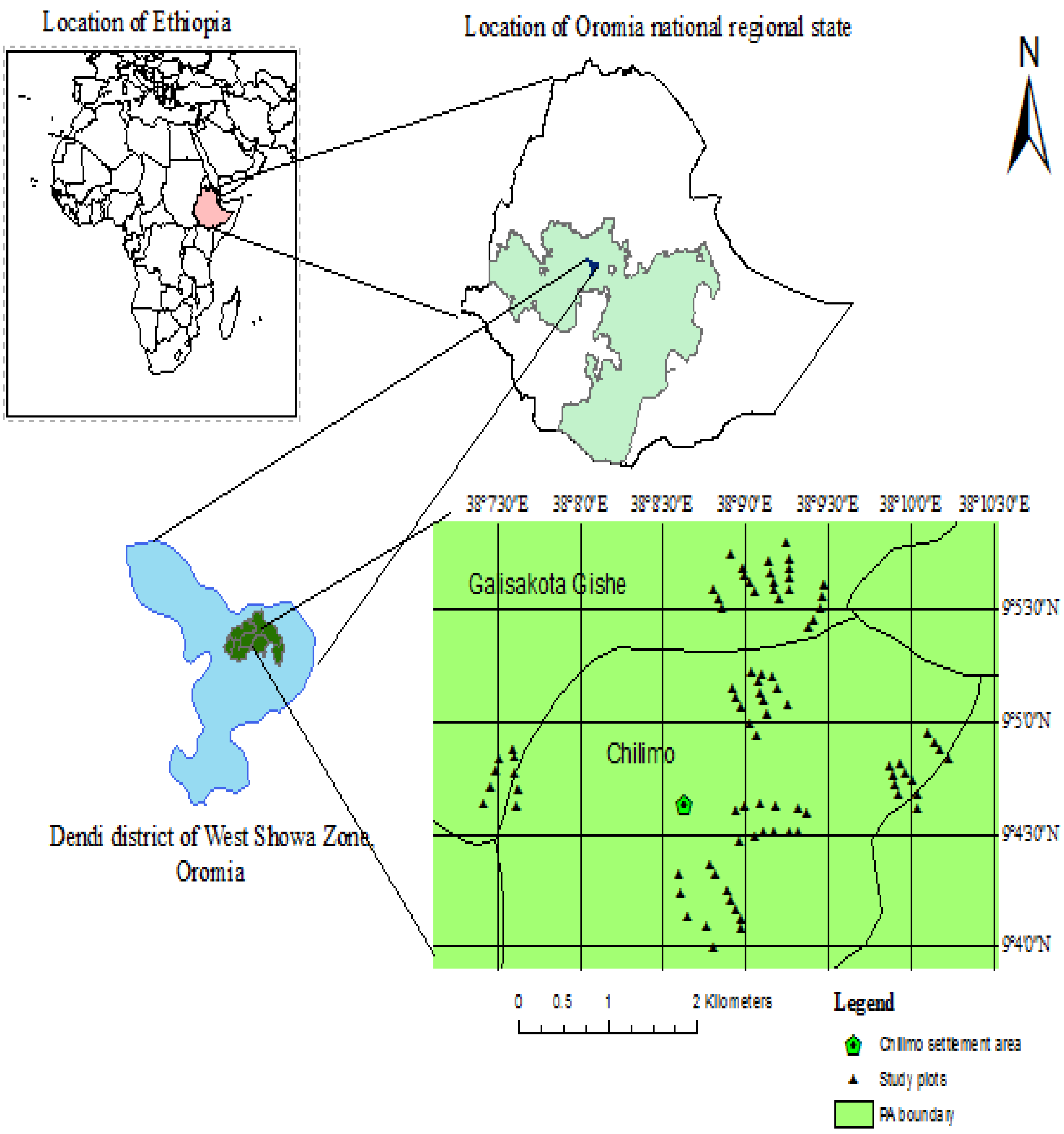

***Fig. 1:** Location map of Chilimo dry afro-montane forest.*

***Table 1:** General description of Chilimo natural forest and adjacent land use types.*

Land use type	Forest patch	Latitude	Longitude	Altitude range (m)	Aspect (%)	No. sample plots	No soil samples	Density (N ha^{-1})	Dg (cm)	G (m^{2}ha^{-1})
Native forest	Chilimo	N09°04´013´´- N09°04’857’’	E038°08´557´´- E038°09´960´’	2470- 2770	8-70 %	20	40	2533±28	26.12±5.3	18.9±1.92
Native forest	Gallessa	N09°05´162´´- N09°05’765’’	E038°09´847´´- E038°10´283´’	2700- 2921	25-70 %	11	20	848±10	19.88±2.5	18.18±1.91
Native forest	Gaji	N09°04´269´´- N09°04’340’’	E038°09´861´´- E038°10´025´’	2680- 2793	45-50 %	4	12	1638±20	23.45±4.4	13.81±1.40
Plantation	*Cupressus*	N09°04´115´´- N09°04’297’’	E038°07´808´´- E038°07´849´’	2370- 2420	3-12 %	3	12	575±8	23.42±4.4	25.5±2.60
Plantation	*Eucalyptus*	N09°04´155´´- N09°04’298’’	E038°03´0011´´- E038°08´0011´’	2360- 2400	3-10%	3	12	1000±13	12.79±2.2	14.67±1.50
Plantation	*Pinus*	N09°03´514´´- N09°03’676’’	E038°08´260´´- E038°08´329´’	2396- 2405	6-20 %	3	12	1167±15	14.52±3.2	21.25±2.16
Crop	Chilimo	N09°04´48´´- N09°03’532’’	E038°08´559´’- E038°08´612’’	2406- 2423	5-15 %	3	12			
Degraded land	Chilimo	N09°03´805´´- N09°04’266’’	E038°07´703´’- E038°07´793’’	2350- 2425	8-30 %	3	12			

Dg: quadratic mean diameter, Gm^2: basal area.

Forest floor sampling

The Chilimo forest site was stratified into 3 major natural forest patches: Chilimo, Gallessa, and Gaji. Thirty-five 20 x 20 m plots were laid out following a top-down gradient, from the top edge of the mountain to the bottom (10 plots in Chilimo, 5 plots in Gallessa, 3 plots in Gaji), and approximately 150 m away from the outer ridge in order to avoid edge effects. The distance between one plot edges to the next plot edge was 100 m and plot location was determined using measuring tape, GPS, altimeter and compass. Forty forest floor samples were collected within a 0.25 x 0.25 m (0.0625 m^2) metallic frame in the centre of the main plot. A metallic ruler was used to measure the depth of the forest floor.

Mineral soil sampling

Mineral soil samples were taken below the forest floor up to a nominative depth of 1 m. Firstly, sample pits (1 m long x 60 cm wide) were dug at the centre of the main plot in every other plot. A total of 33 pits (18 in natural forest, 9 in plantations, 3 in cultivated land and 3 in degraded lands) were dug for soil collection. Samples were taken from four soil depth categories (0-10 cm, 10-30 cm, 30-50 cm and 50-100 cm). Soil bulk density was calculated with a 5-cm high cylinder that was introduced vertically in one sampling point for each depth interval. A total of 280 samples (140 soil samples for C % and total N % analysed plus 140 cylinder samples for bulk density analysed) were collected.

Laboratory analysis

Forest floor sample layers were air-dried and homogenized prior to analysis. All samples were weighed and sub-samples were oven-dried for 24 hours at 65 °C to constant weight. The chemical analysis for organic carbon in the forest floor was done by drying samples at 105 °C and subsequently burning it at 550 °C (Ben-Dar and Banin, 1989). The loss in weight between 105 ºC and 550 ºC constitutes the organic matter content. Then organic matter content was converted into organic carbon by multiplyin it with 0.58 which has been found to be the most covenient conversion factor from organic matter to carbon content in the forest floor (de Vos *et al*., 2005).

Mineral soil sampled was air dried and passed into less than 2 mm sieve size to obtain the fine fraction for chemical analysis. The coarse rock fragments (> 2 mm) sieved sizes were removed from the sample and their percentage (% of stoniness and or rockiness) were calculated by oven dried samples at 67 ºC for 24 hours for each soil depth. Total organic carbon analysis was made for ground fine soil samples using dry potassium dichromate oxidation following the procedure described in Anderson and Ingram (1996). Bulk density for each soil depth was the ratio of mass of core sampled oven dry weight of dry soil to volume of 5 cm diameter and 5 cm height steel-cylinder following the procedure of Blake (1965). Total N was determined using Kjeldahl's method, following the procedure in Keeny and Nelson (1982).

Data analysis approach

Elevation was converted to three discrete classes in order to analyze the effect of the altitudinal gradient: Class 1 (low elevation): ≤ 2599 m, Class 2 (middle elevation): 2600-2700 m and Class 3 (high elevation): ≥ 2701 m. A preliminary analysis of normality and equal variances among groups was performed before selecting the most suitable statistical analysis.

Carbon and nitrogen concentration in forest floor

Data for carbon and nitrogen concentrations and stocks in the forest floor were analysed using the SAS PROC GLM method (SAS Inst. Inc., 1999). To analyse equality of means, we used a Tukey-Kramer test for multiple comparisons among elevation classes at α=0.05.

Bulk density, Carbon and nitrogen concentration in mineral soil

The C and N concentration and bulk density in mineral soil were analyzed as repeated measurements in an irregular vertical space ranging from 0-10 cm, 10-30 cm, 30-50 cm and 50-100 cm. Results from a previous analysis of bulk density differences among treatments (elevation classes, land use and species planted) indicated the most appropriate method for estimation of carbon and nitrogen stock (fixed-mass *vs* fixed-depth). For these analyses, the SAS PROC MIXED method was used with a Toeplitz heterogeneous variance structure (SAS Inst. Inc., 1999). We used a linear mixed model analysis of variance with repeated measurements, considering one between-subjects factor (species, land use type or elevation) and one within-subjects factor (depth at four levels) according to the mathematical model:

$$Y_{ij;k} = \mu + \alpha_i + \beta_k + \alpha\beta_{ik} + \varepsilon_{ij;k} \qquad \text{(eq.1)}$$

where *i*=1,…,n for the between-subjects factor (n=3 for species and elevation, n=4 for land use type), *j*=1,…,n for the replicates and *k*=1, 2, 3, 4 for the within-subject factor (depths), $Y_{ij;k}$ = observed value of the dependent variable for the plot *j* of level *i* in the between-subject factor at depth *k*; μ is the general mean effect, α_i is the main effect of the i^{th} level for the between-subject factor; β_k is the main effect of the k^{th} depth; $\alpha\beta_{ik}$ is the interaction effect of the i^{th} level for the between-subject factor and the k^{th} depth; $\varepsilon_{ij;k}$ is the random error in the dependent variable for the plot *j* of level *i* in the between-subject factor at depth *k*.

The assumptions for the errors in the linear mixed model were:

$\varepsilon_{ij;k} \sim N(0, \sigma_k^2)$, with σ_k^2= random variance for the errors at depth *k*.

$$Cov(\varepsilon_{ij;k}, \varepsilon_{i'j';k'}) = \begin{cases} \sigma_k \sigma_{k'} \rho_{|k-k'|} & \text{if } i = i', j = j' \text{ and } k \neq k' \\ 0 & \text{if } i \neq i' \text{ or } j \neq j' \end{cases},$$

where $\rho_{|k-k'|}$ is the correlation coefficient for the errors at consecutive depths.

We used the TOEPH variance-covariance matrix for the errors (Heterogeneous Toeplitz), with four variance parameters and three correlation coefficients, which were estimated using the restricted maximum likelihood method (REML).

Carbon and nitrogen stock in the mineral soil were calculated by depths using carbon concentrations, thickness of each layer and soil bulk density at each depth, on a fixed-depth basis (Ellert *et al*., 2008):

$$y_{FD} = \sum D_{CS} C_{CS} L_{CS} 0.1 \qquad \text{(eq. 2)}$$

Where y_{FD} is the soil organic carbon (SOC_{FD}) stock or nitrogen stock (SON_{FD}) to a fixed depth (Mg C ha^{-1} to the specified depth), D_{CS} is the bulk density of core segment (g cm^{-3}), C_{CS} is the organic C concentration of core segment (mg C g^{-1} dry soil), and L_{CS} is the length of core segment (cm). The statistical analysis approach for comparing C and N stock at different depths (0-10 cm; 10-30 cm; 30-50 cm and 50-100 cm) was similar to the mixed model approach already described.

However, calculating element stock with eq.2 can lead to biased comparisons if bulk density is significantly different between land uses or treatments (Ellert *et al*., 2008). As an alternative, SOC stock to fixed mass was calculated if differences in bulk density were detected (research question 2), using the following equation:

$$y_{FM} = y_{FD} - M_{ex} C_{sn}/1000 \qquad \text{(eq. 3)}$$

where y_{FM} is the soil organic carbon (SOC_{FM}) or nitrogen (SON_{FM}) stock for a fixed mass of M_{ref} (the lowest soil mass at a specified depth), M_{ex} is the soil mass subtracted to equalize soil mass among treatments and C_{sn} is the stock concentration in the deepest soil core segments (mg C g^{-1} dry soil) (core segment = n) (Ellert *et al.*, 2008). For analysing stock calculated at fixed mass, we selected an SAS PROC GLM general linear model (SAS Inst. Inc., 1999) that compared species (3 levels), elevation (3 levels) and land use (4 levels) as main factors at different soil sampling depths (0-10 cm, 0-30 cm, 0-50 cm and 0-100 cm). The mathematical formulation of the model was:

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \qquad \text{(eq. 4)}$$

with *i*=1,…,n for the levels of the factor (n=3 for species and elevation, n=4 for land use type) and *j*=1,…,n for the replicates; Y_{ij} is the observed value of the dependent variable for the plot *j* in the level *i* of the factor; μ is the general mean effect; α_i is the main effect of the level *i* of the factor; ε_{ij} is the random error in the dependent variable for the plot *j* in the level *i* of the factor. Errors were assumed to be independent and equally distributed with normal distribution; $\varepsilon_{ij} \sim N(0, \sigma^2)$, and σ^2 is the random variance for the errors.

Finally, the Tukey-Kramer test was used for comparisons of least squares means. Values are reported as mean ± standard error of the mean.

Results

Does soil bulk density significantly vary across land uses and soil depths?

The bulk density of mineral soil ranged from a minimum value of 0.5 g cm^{-3} dry soil to a maximum value of 1.40 g cm^{-3} dry soil. Bulk density significantly varied among land use types and soil depth and the interaction of both (Table 2). Studentized residuals followed a normal distribution ($p < 0.3693$). Bulk density was significantly lower in natural forest compared to other land use categories in the upper 10 cm. Values were higher in crop land and degraded land (Figure 2). Bulk density was only significantly different between the upper and the lower layer in natural forest soils with lower values in the upper layer than in the deepest (Figure 2, capital letters); whereas bulk density in the first 10 cm of plantation soils was significantly lower than in the other profiles. For crop land and degraded soils, bulk density was rather constant across soil depths; there were no significant differences among these two land use categories or across depths in the same category (Figure 2).

Table 2: *Mixed effects model for bulk density (g cm^{-3}) carbon and nitrogen concentration (mg g^{-1}).*

Response variable	**Effect**	**F-test**	**p-value**	**Covariance parameters**	
Bulk density	Land use	13.47	<0.0001	σ_1^2	0.0138
	Depth	6.86	0.0004	σ_2^2	0.01348
	Land use x depth	2.53	0.0062	σ_3^2	0.01989
				σ_4^2	0.01177
				Toeph 1	0.7029
				Toeph 2	0.508
				Toeph 3	0.4119
Carbon concentration	Land use	11.33	<0.0001	σ_1^2	810.52
	Depth	14.75	<0.0001	σ_2^2	507.75
	Land use x depth	3.57	0.0009	σ_3^2	167.566
				σ_4^2	43.23
				Toeph 1	0.643
				Toeph 2	0.54
				Toeph 3	0.3481
Nitrogen concentration	Land use	6.23	0.0025	σ_1^2	4.5237
	Depth	10.91	<0.0001	σ_2^2	4.5619
	Land use x depth	2.31	0.0231	σ_3^2	1.2349
				σ_4^2	0.3353
				Toeph 1	0.7866
				Toeph 2	0.6454
				Toeph 3	0.4226

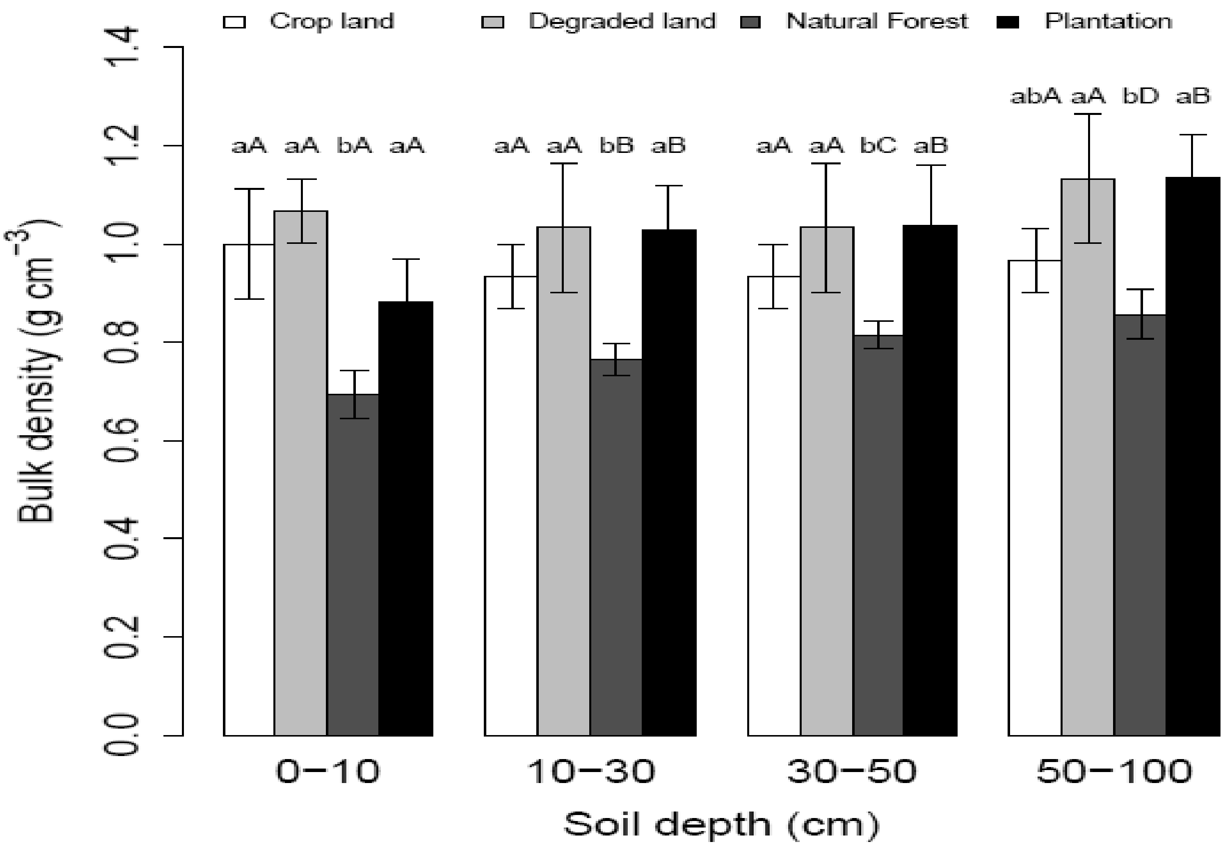

Fig. 2: *Bulk density (g cm^{-3}) at different depths by land use type. Different letters indicate significance.*

Do carbon and nitrogen concentrations and stocks in the forest floor and at different depths in mineral soil in native dry afro-montane forest vary along an elevation gradient?

The minimum and maximum forest floor carbon concentrations ranged from 319.2 mg C g^{-1} to 666 g C kg^{-1} of soil, whereas the nitrogen concentration ranged from 9.6 to 19.8 mg N g^{-1} of soil, with concentrations in the upper part of the elevation gradient and increasing mean nitrogen concentrations in the middle part (Table 3). The general linear model revealed no association of carbon and nitrogen concentration with elevation in natural forest (F-test p-value > 0.05 in both cases). The same occurred for carbon and nitrogen stock, there was no significant variation with elevation (F-test p-value > 0.05 in both cases). The mean carbon and nitrogen stocks for the forest floor were 9.36 ± 1.17 Mg C ha^{-1} and 0.25 ± 0.03 Mg N ha^{-1}, respectively.

In mineral soil, carbon concentration ranged from 7 mg C g^{-1} to 129.4 mg C g^{-1} of soil, whereas nitrogen concentration ranged from 0.6 to 10 mg N g^{-1} of soil. In the upper part of the gradient there were higher average C and N concentration values (114.2 mg C g^{-1} and 8.1 mg N g^{-1}, Table 3), though the mixed model suggested that these differences were not significant (Table 4).

Results from the bulk density analysis (research question 1) confirmed the appropriateness of using the fixed-mass approach to analyse carbon and nitrogen stock changes along an altitudinal gradient in natural forests. There was no strong departure from normality and the general linear model for carbon stock showed no significant variation along the gradient at the same soil depth (Table 5). This indicated that the soil storing capacity was quite homogenous across the elevation gradient studied. For nitrogen stock, however, significant variation appeared in the first 10 cm (Table 5) between the upper part of the gradient (4.07 ± 0.46 Mg C ha^{-1}) and the lower part (2.06 ± 0.48 Mg C ha^{-1}).

Table 3: *Carbon (C) and nitrogen (N) concentration (mg g^{-1}) in forest floor and mineral soil at different depths (cm) by altitude classes.*

Altitude class	Depth (cm)	C (mg g^{-1})	N (mg g^{-1})
1	Forest floor	424.5 ± 34.8	11.16 ± 0.5
	0-10	80.5 ± 13.5	4.06 ± 0.94
	10-30	50.13 ± 15.12	2.96 ± 1.22
	30-50	24.17 ± 13.95	2.17 ± 1.25
	50-100	18.16 ± 5.33	1.56 ± 0.37
	0-100	46.5 ± 8.7	2.8 ± 0.5
2	**Forest floor**	517.02 ± 31.5	14.63 ± 1.05
	0-10	98.98 ± 9.95	6.5 ± 0.68
	10-30	70.23 ± 11.29	2.23 ± 0.91
	30-50	35.35 ± 13.68	2.58 ±0.46
	50-100	17.33 ± 3.33	1.63 ± 0.29
	0-100	55.6 ± 7.6	3.9 ± 0.5
3	**Forest floor**	524.15 ± 36.44	13.85 ± 0.94
	0-10	114.2 ± 13.64	8.1 ± 0.94
	10-30	62.35 ± 19.34	4.42 ± 1.41
	30-50	30.7 ± 11.28	2.55 ± 0.99
	50-100	17.75 ± 7.02	1.42 ± 0.61
	0-100	56.2 ± 11.4	4.1 ± 0.79

Table 4: *Mixed effects model of carbon and nitrogen concentration (mg g^{-1}) in natural forest along the altidudinal gradient and by sampling depths.*

Response variable	Effect	F-test	p-value	Covariance parameters	
Carbon concentration	Altitude	0.29	0.7559	σ_1^2	825.91
	Depth	35.94	0.0001	σ_2^2	1007.22
	Altitude x depth	1.12	0.3755	σ_3^2	336.94
				σ_4^2	86.94
				Toeph 1	0.658
				Toeph 2	0.5983
				Toeph 3	0.3704
Nitrogen concentration	Altitude	0.74	0.502	σ_1^2	3.281
	Depth	45.13	0.0001	σ_2^2	5.799
	Altitude x depth	3.97	0.0048	σ_3^2	2.707
				σ_4^2	0.6917
				Toeph 1	0.8052
				Toeph 2	0.7715
				Toeph 3	0.5455

Table 5: *Soil organic carbon (SOC) and nitrogen stock (SON) (Mg ha^{-1}) in natural forests by altidude classes and soil depths.*

Altitude class	Depth (cm)	SOC (Mg ha^{-1})	SON (Mg ha^{-1})
1	0-10	40.3 ± 6.77	2.06^{a} ± 0.48
	0-30	105 ± 18.73	5.73 ± 1.80
	0-50	154 ± 33.21	5.62 ± 3.24
	0-100	198.33 ± 44.16	12.4 ± 4.19
2	0-10	49.52 ± 4.98	3.26^{ab} ± 0.34
	0-30	136.12 ± 15.63	9.3 ± 1.27
	0-50	190.97 ± 23.33	13.27 ± 1.93
	0-100	233.58 ± 29.42	16.8 ± 2.47
3	0-10	57.12 ± 6.81	4.07^{b} ± 0.46
	0-30	137.07 ± 23.71	9.78 ± 1.88
	0-50	189.25 ± 41.6	13.72 ± 3.33
	0-100	232.22 ± 57.71	17.2 ± 4.78

Different letters in the upper 10 cm of mineral soil indicate significant differences ($p < 0.05$)

How does land use change soil carbon and nitrogen concentrations and stocks at different soil depths?

The results showed that the carbon and nitrogen concentrations were highly influenced by land use and soil depth (Table 2). Analysis of studentized residuals showed that the normality assumption was not met for carbon concentration ($p < 0.0047$) or nitrogen concentration ($p < 0.0001$). Among the four land use types, carbon and nitrogen concentration in native forest was always higher than other land use types at all soil depths. Non-parametric comparison of least squares means indicated significant differences (Figure 3a) in carbon concentration, whereas native forest and plantations showed differences according to depth. Nitrogen concentration analysis showed differences in natural forest and plantations according to soil depth, whereas crop land and degraded land were quite homogenous (Figure 3b). Nitrogen concentration was similar in crop land and degraded land, whereas natural forest and plantations showed higher values in the upper 30 cm.

Mean carbon stock was higher in natural forest than in all other land use categories and at all depths (225.03 ± 22.7 Mg C ha^{-1} at one meter depth) (Table 6). In plantations, carbon stock at the same depth was one-third less than in natural forest but 35 % more than in crop land and 77 % more than in degraded land. The first 10 cm of mineral soil plantations had significantly more carbon content than crop land and degraded land (Table 6), though; the differences vanished at depths below 50 cm.

Native forest stored more nitrogen per hectare but the differences were only significant compared to crop land and degraded land in the upper 10 cm. The total nitrogen confidence interval in native forest to 1 meter was 15.90 ± 1.98 Mg N ha^{-1}, which was 82 %, 52 % and 27 % more than in degraded land, crop land and plantations, respectively.

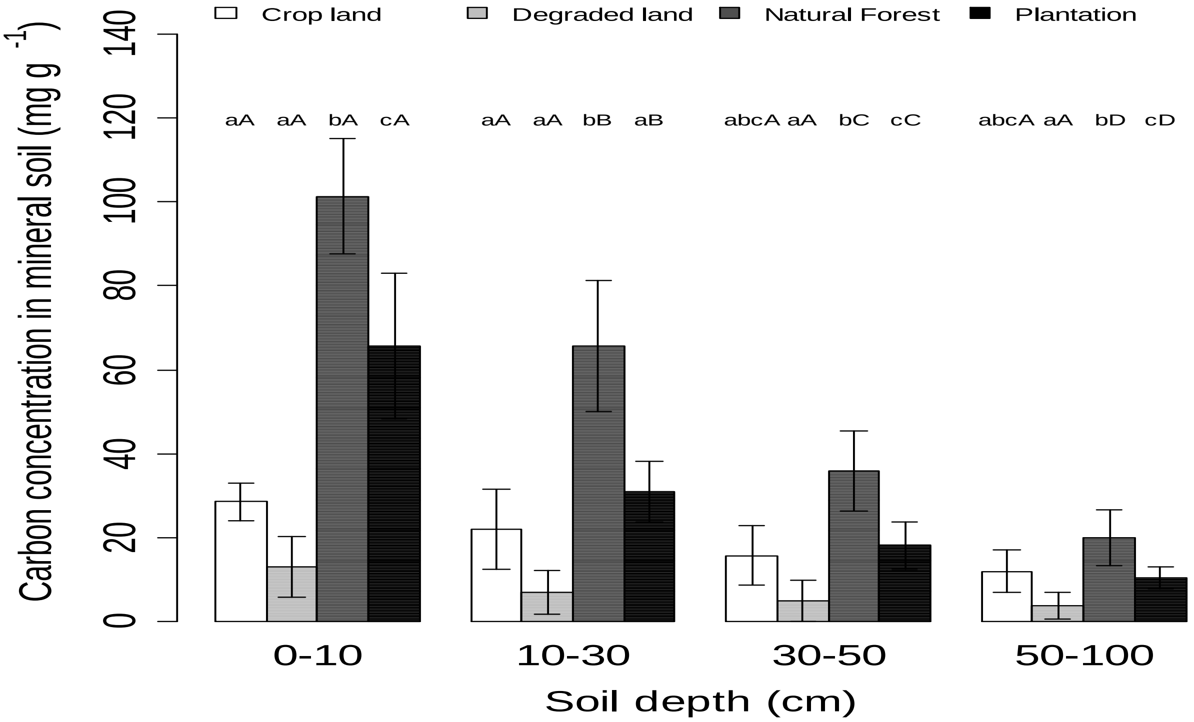

Fig. 3a: *Carbon concentration (mg g^{-1}) at different depths by land use type. Different letters indicate.*

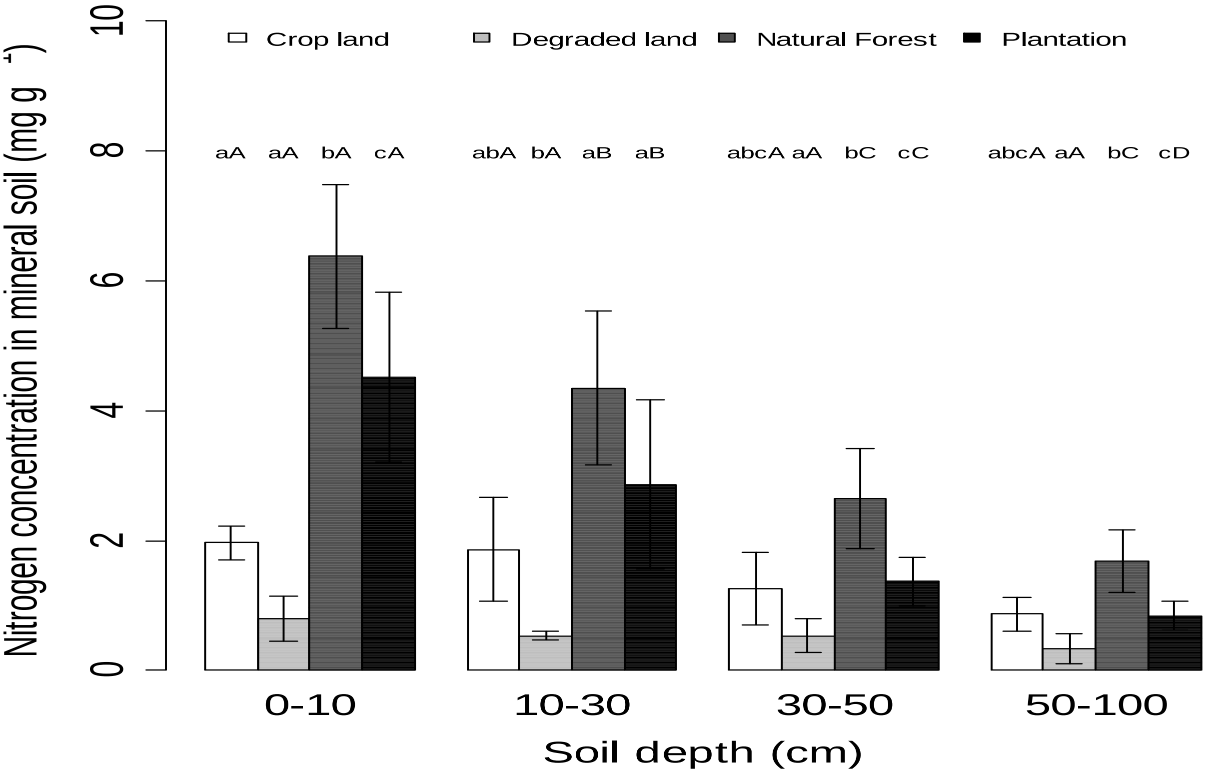

Fig. 3b: *Nitrogen concentration (mg g^{-1}) at different depths by land use type. Different letters indicate.*

Table 6: *Carbon and nitrogen stock (Mg ha^{-1}) in mineral soil at different sampling depths by land use type.*

Response variables	Depth (cm)	Crop	Degraded land	Natural forest	Plantation
C stock (Mg ha^{-1})	0-10	$14.3^{ac} \pm 1.15$	$6.56^{a} \pm 1.84$	$49.73^{b} \pm 3.63$	$32.83^{c} \pm 4.42$
	0-30	$43.60^{ac} \pm .97$	$17.73^{a} \pm 4.19$	$129.27^{b} \pm 10.87$	$79.15^{c} \pm 8.29$
	0-50	$69.26^{a} \pm 10.09$	$26.26^{a} \pm 6.26$	$182.02^{b} \pm 17.28$	$116.08^{a} \pm 12.92$
	0-100	$98.10^{a} \pm 16.09$	$35.10^{a} \pm 9.89$	$225.03^{b} \pm 22.7$	$149.21^{a} \pm 16.10$
N stock (Mg ha^{-1})	0-10	$1.03^{ac} \pm 0.07$	$0.43^{a} \pm 0.09$	$3.23^{b} \pm 0.30$	$2.28^{bc} \pm 0.33$
	0-30	$3.23^{ab} \pm 0.38$	$1.13^{b} \pm 0.20$	$8.62^{a} \pm 0.96$	$6.13^{a} \pm 1.05$
	0-50	$5.40^{ab} \pm 0.79$	$1.80^{b} \pm 0.26$	$12.42^{a} \pm 1.51$	$9.10^{a} \pm 1.19$
	0-100	$7.66^{ab} \pm 1.25$	$2.80^{b} \pm 0.40$	$15.90^{a} \pm 1.98$	$11.59^{a} \pm 1.70$

Does species selection have any effect on carbon and nitrogen concentration and stock at different soil depths in plantations?

Sampling depth had a strong effect on carbon and nitrogen concentrations. The species effect was significant on bulk density values (Table 7). Soil bulk density in *Eucalyptus* plantations was 21 %, significantly higher than in *Pinus patula* plantations (Figure 4). However, species did not influence carbon and nitrogen stock calculated with the fixed-mass method. To a depth of 1 m, total carbon stored in plantations ranged from 112.43 ± 4.32 to 185.83 ± 29.9 Mg C ha^{-1} for *Pinus patula* and *Eucalyptus saligna*, respectively (Table 8), whereas total nitrogen stock ranged from 8.50 ± 0.44 to 12.26 ± 1.9 Mg N ha^{-1} for the same species. *Cupressus lusitanica* plantations presented intermediate values for carbon storage (126.1 ± 32.2 Mg C ha^{-1} ± standard error) and nitrogen stock (9.1 ± 1.8 Mg N ha^{-1}).

Table 7: Mixed effects model of carbon, nitrogen concentration (mg g^{-1}) and bulk density (g cm^{-3}) in plantations.

Response variable	Effect	F-test	p-value	Covariance parameters	
C (mg g^{-1})	Species	1.64	0.274	σ_1^2	508.620
	Depth	22.35	<0.0001	σ_2^2	139.290
	Species x Depth	0.8	0.5835	σ_3^2	18.130
				σ_4^2	7.700
				Toeph 1	0.420
				Toeph 2	-0.050
				Toeph 3	0.025
N (mg g^{-1})	Species	1.15	0.3784	σ_1^2	1.748
	Depth	27.22	<0.0001	σ_2^2	0.433
	Species x Depth	0.42	0.8555	σ_3^2	0.095
				σ_4^2	0.041
				Toeph 1	0.382
				Toeph 2	-0.205
				Toeph 3	-0.040
Bulk density (g cm^{-3})	Species	12.2	0.0077	σ_1^2	0.015
	Depth	11.3	0.0002	σ_2^2	0.006
	Species x Depth	4.03	0.0099	σ_3^2	0.024
				σ_4^2	0.001
				Toeph 1	0.525
				Toeph 2	-0.060
				Toeph 3	-0.301

Table 8: *Carbon and Nitrogen stock (Mg ha^{-1}) in plantations at different sampling depths.*

Species	Depth (cm)	SOC (Mg ha^{-1})	SON (Mg ha^{-1})
Eucaliptus saligna	0-10	33.53 ± 5.56	2.1 ± 0.21
	0-30	90.80 ± 10.34	5.83 ± 0.47
	0-50	142.96 ± 21.78	2.12 ± 1.23
	0-100	185.83 ± 29.94	12.26 ± 1.89
Cupressus lusitanica	0-10	26.8 ± 10.75	1.86 ± 0.68
	0-30	66.70 ± 22.50	4.63 ± 1.34
	0-50	98.46 ± 32.82	6.93 ± 1.87
	0-100	126.1± 32.20	9.10 ± 1.76
Pinus patula	0-10	24.96 ± 1.03	1.80 ± 0.1
	0-30	62.9 ± 1.80	4.67 ± 0.12
	0-50	89.00 ± 1.80	6.76 ± 0.26
	0-100	112.43 ± 4.32	8.50 ± 0.44

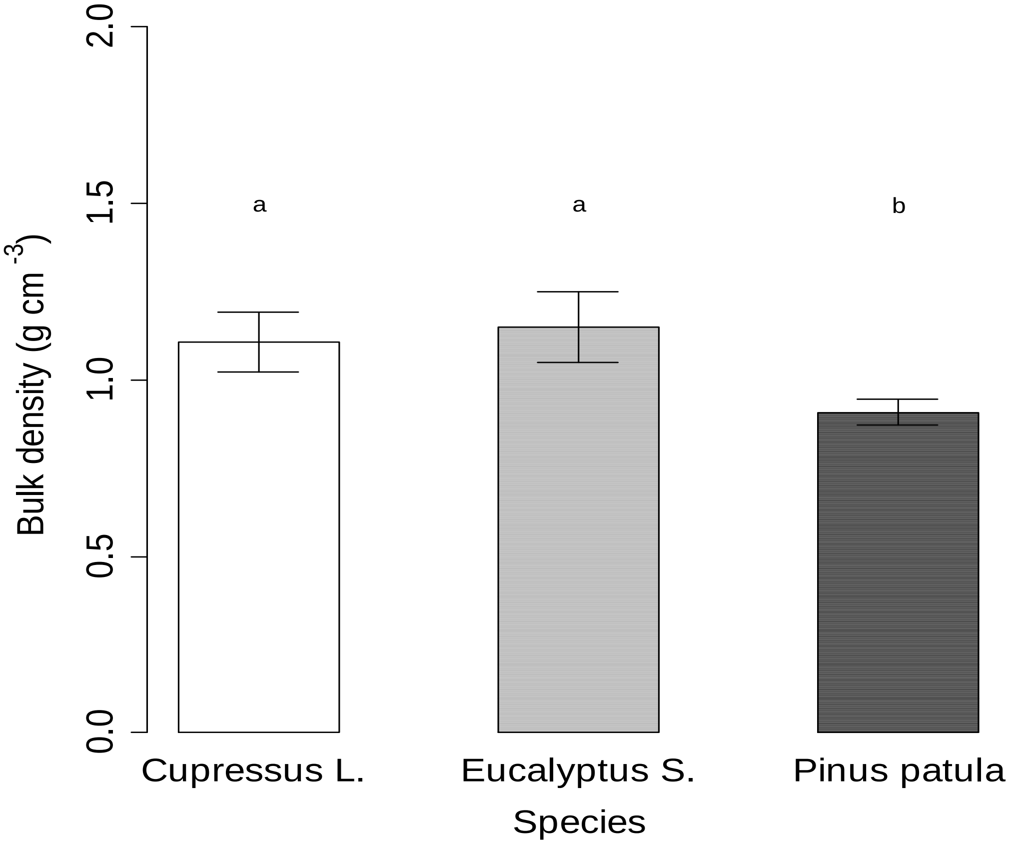

Fig. 4: *Bulk density (g cm^{-3}) in plantations by species. Different letters indicate significant differences ($p < 0.05$).*

Discussion

The effect of changes in land use on carbon and nitrogen stock can be exacerbated if differences in bulk density are not taken into account (Wendt and Hauser, 2013). In this study, we analysed bulk density to see if it was significantly different among treatments (land use type, elevation classes in native forests and tree species in plantations) and applied the fixed-mass method when necessary (Ellert *et al*., 2008). By modifying the type of statistical analysis used, we obtained more accurate results. Assad *et al*. (2013) applied the fixed-mass method and found differences in carbon stocks among different land uses, to a maximum depth of 60 cm. We extended the sampling depth to 1 m and include nitrogen stock in the analysis.

Bulk density was significantly influenced by type of land use and soil depth. Higher bulk densities were observed in degraded land and sub-soil, due to higher soil compaction, higher erosion rate, lack of inputs and low soil fertility. This finding is consistent with other studies on the impact of changes in land use (Gebremariam and Kebede, 2010; Michel *et al*., 2010; Awotoye *et al*., 2013; Sierra *et al*., 2013). The strong confounding effect of soil bulk density may lead to overestimation of soil carbon accumulation capacity (Murty *et al*., 2002) and misleading conclusions in assessments of the impact of changes in land use. For example, SOC variation after forest conversion was non-significant using the fixed-depth method (Twongyirne *et al*., 2013), due to large site-to-site variation. We argue that accurate C and N stock estimation can only be performed when the bulk density effect is discounted and that the fixed-mass method is more appropriate. However, much debate continues regarding which is the best estimation method of bulk density (Lee *et al*., 2009; Wendt and Hauser, 2013).

The fixed-mass method of calculating soil carbon and nitrogen stocks provides the added advantage of facilitating comparison of the percentage of carbon/nitrogen stored at different depths. Figures 5a and 5b show the distribution of carbon and nitrogen stock by sampling layers. Remarkably, around 80 % of both elements (to 1 m depth) is stored in the upper 50 cm of soil. The implication of this finding is clear for large-scale evaluation of carbon stocks in dry afro-montane forests. Sampling effort would be drastically reduced if the nominal 1 m sampling pit depth found in local studies can be reduced by half. Soil tillage in crop land can reduce the amount of total carbon stored in the upper 10 cm. Figure 5a indicates that sampling depth should be greater for crop land than for natural forests, where most of the carbon is stored in the upper-most part of the soil (Murty *et al*., 2002).

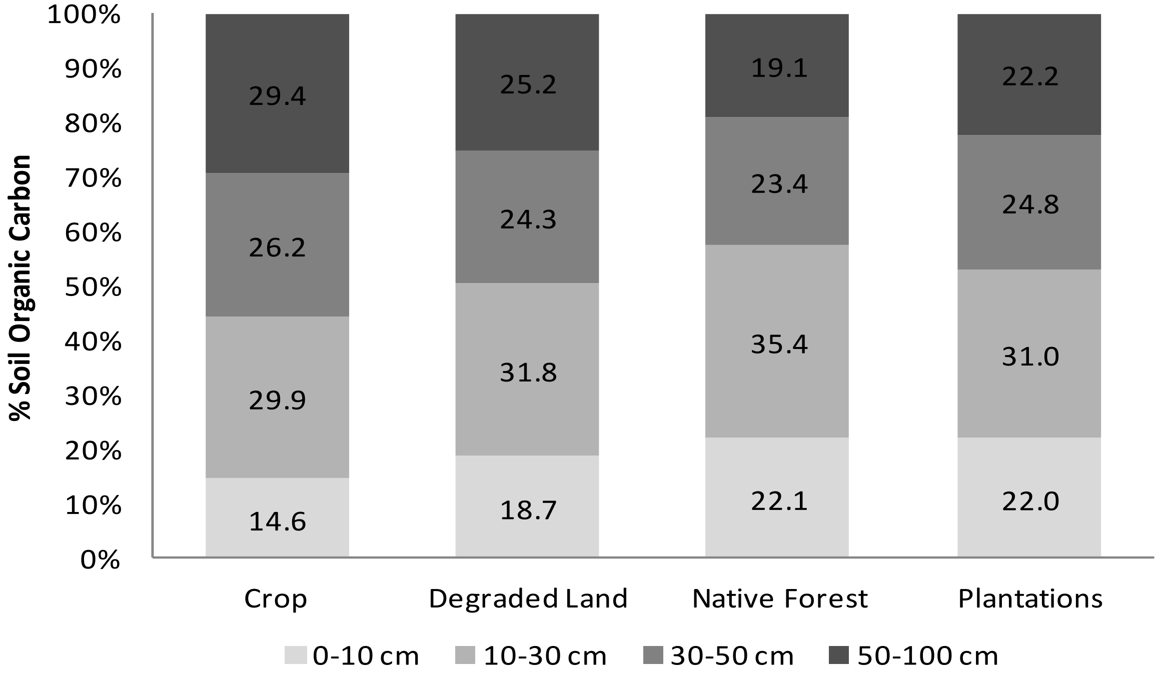

Fig. 5a: *Percentage of soil organic carbon distribution at sampling depths.*

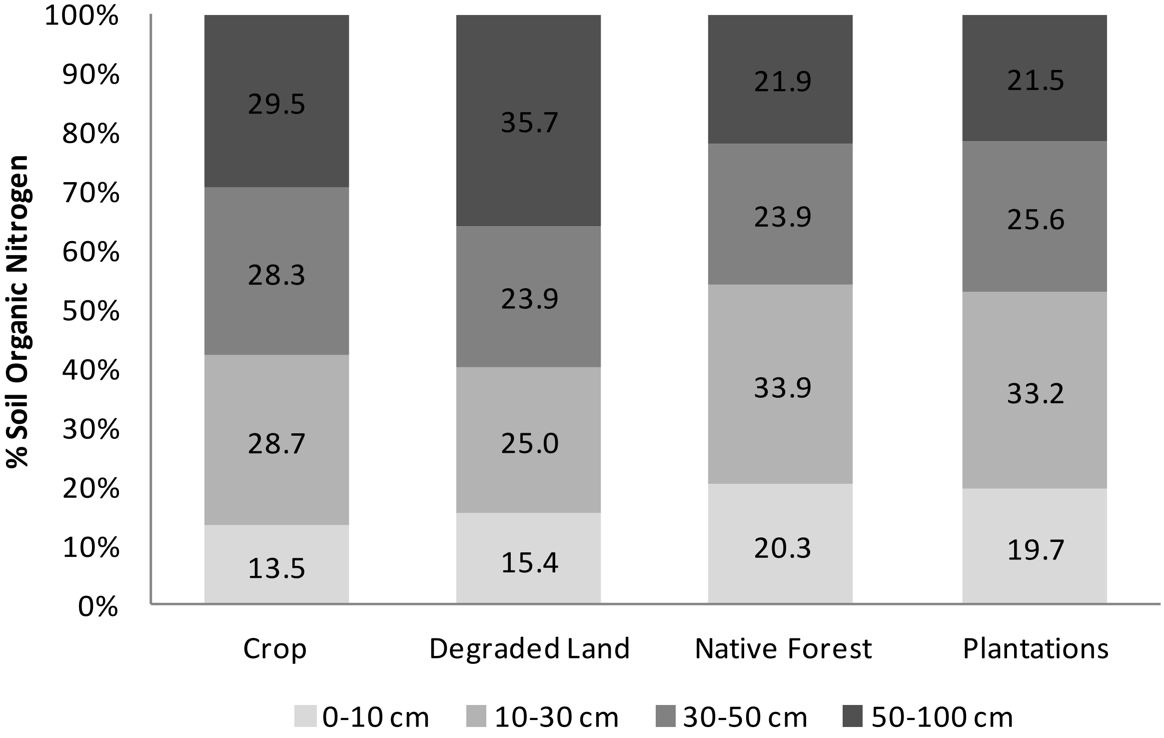

Fig. 5b: *Percentage of soil organic nitrogen distribution at sampling depths.*

As suggested by other studies (Zewdu *et al*., 2004; Twongyirne *et al*., 2013), carbon stock did not vary significantly with elevation. Nevertheless, the pattern indicated lower carbon and nitrogen stock at lower elevation, which might be due to the higher impact of anthropogenic factors. Greater numbers of farming communities live in or around the forest at this end of the elevation gradient and their livelihoods depend on the forest. This implies continuous removal of fallen litter, dead wood and twigs, collection of firewood, charcoal making, logging for construction wood, forest clearing for agricultural land and livestock overgrazing.

Land use is a major factor in carbon and nitrogen stocks. Girmay *et al*. (2008) reviewed the carbon stock in topsoil (0-10 cm) in Ethiopia and found it decreased after conversion of native forest into crop lands (-63 %) and plantations (-83 %). Solomon *et al*. (2002) indicated that conversion of humid tropical forests for maize (*Zea mays*) cultivation in Southern Ethiopia resulted in a 55-60 % reduction in SOC stock, from 58.3 to 63.9 Mg C ha^{-1} in forest soil to 33.9 to 39.7 Mg C ha^{-1} in cultivated land. In Brazil, Zinn *et al*. (2002) reported a 23-48 % loss in SOC after a native wooded savannah was converted to *Eucalyptus* plantation. Ashagrie *et al*. (2005) also reported losses of 13 Mg C ha^{-1} over a period of 21 years in southern Ethiopia when natural forest was converted to *Eucalyptus* plantation. Rhoades *et al*. (2000) reported a 70 % reduction in SOC in Ecuador in the upper 30 cm of top soil when original forest was converted to sugarcane plantation (*Saccharum* spp.). Berhangaray *et al*. (2013) investigated the impact of changes in land use on soil carbon and found higher SOC under trees than under pasture and agricultural lands. In our study, tree plantations stored 34 % less carbon than native forest, but the land use change sequence was different. Plantations were originally planted outside the forest on bare or degraded land. In this situation, tree plantations stored 80 % more carbon than degraded land and 56.4 % more than crop land.

The finding that nitrogen concentration and stock was higher in these plantations than in crop land or degraded land may be explained by a recovery of soil conditions 28 years after plantation establishment. However, the exotic species selected by local communities might have diminished the potential recovery effect of plantations, as native species improve soil conditions to a greater extent than exotic species do (Tesfaye *et al*., 2014).

Tree species can alter soil carbon sequestration capacity, total nitrogen and other soil characteristics. Our results showed that species selection for plantation purposes impacted soil carbon and nitrogen concentration and stock across soil depth. Soil sampled under an introduced *E.*

saligna plantation had higher SOC and SON stock compared to other non-native species. SOC and SON were also significantly higher under *E. saligna* at all soil depths and under *P. patula* in the upper 50 cm. Afforestation of farmland (formerly degraded land) resulted higher in carbon and nitrogen accretion after 28 years. However, the magnitude of accretion was species dependent: for example, net increases of 41.9 ± 4.24 Mg C ha^{-1} for *E. saligna*, 19.95 ± 1.36 Mg C ha^{-1} for *C. lusitanica,* and 15.1 ± 1.08 Mg C ha^{-1} for *P. patula* were found. The higher SOC and SON stock under *Eucalyptus* plantation might be due to higher litter fall, better decomposition rate and lower soil erosion rate compared to other introduced tree species. This was also evident in the higher number of gullies and rills recorded in the *C. lusitanica* plantation, compared to the *E. saligna* and *P. patula* plantations.

Our results are also consistent with findings by other authors. In a similar carbon isotope analysis, Lemma *et al*. (2006) in South-western Ethiopia, found higher amounts of total SOC in the soil under *E. grandis* than under *C. lusitanica* and *P. patula*. Solomon *et al*. (2002) in southern Ethiopia found land converted from mixed native species to *C. lusitanica* plantation showed a 27 % loss in SOC stock over a period of 25 years. In contrast, Zerfu (2002) indicated increased SOC stock under a *Eucalyptu*s plantation established on degraded land. Similarly, in south-western Ethiopia Lemma *et al*. (2006) reported a net SOC increase of 69.9 Mg ha^{-1} under *C. lusitanica* and 29.3 Mg ha^{-1} under *P. patula* 20 years after plantation establishment.

Finally, our results showed that C and N concentrations and stock under native natural forest and plantation forest in Chilimo were generally higher than those reported in other regions (Beets *et al*., 2002; Harms *et al*., 2005; Yimer *et al*., 2008; Twongyirwe *et al*., 2013) and suggest two management strategies for improving soil conditions in the central Highlands. The first is to maintain and preserve the Chilimo natural forest in order to maintain carbon storage in the future as other African tropical forests do (Lewis *et al*., 2009). The second is to recover abandoned crop land and degraded lands by establishing tree plantations to avoid overharvesting in natural forests and considering the inclusion of native species that can improve soil condition in a more efficient way (Tesfaye *et al*., 2014).

Conclusions

This study has successfully answered the research questions presented in the introduction and yields the following conclusions: (i) Bulk density can have an important confounding effect on soil condition assessment and an efficient estimation method for soil carbon and nitrogen must be applied accordingly. (ii) Soil depth is a more important factor than elevation in the study area, though C and N concentration and stock diminished near human settlements located in the lowest part of the elevation gradient. (iii) Chilimo natural forest stored more carbon and nitrogen than adjacent land use categories, but crop land and degraded land converted to plantations ameliorated soil degradation. (iv) Species selection did not affect carbon and nitrogen stock, despite the significantly lower bulk density values found in *Pinus patula* plantations. We suggest that using native tree species in plantations could have a positive impact on C and N storage, as other studies have demonstrated.

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Study IV

Stand density management diagram for Chilimo dry afro-montane forest using species proportion in central highlands, Ethiopia

Tesfaye, A. Mehari, Bravo, F., Bravo-Oviedo, A., 2015. Stand density management diagrams for five most commonly grown native trees species in dry afro montane forests, Ethiopia (**manuscript**).

Study IV

Stand density management diagram for Chilimo dry afro-montane forest using species proportion in Central Highlands of Ethiopia

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Abstract

Chilimo forest is one of the few remnants of dry afro-montane forest located in Central Highlands of Ethiopia. Also it has been during the last century one of the most exploited and disturbed forest in the country. Stand density management diagram (SDMD) is a stand-level model that graphically illustrates the relationships between wood yield, density and mortality throughout all stages of stand development. SDMD is a useful tool for designing, displaying and evaluating alternative density management regime for both even-aged and uneven-aged forest stands. However, information in this regards and other silvicultural management operations are lacking for most Ethiopian forests in general and for Chilimo dry afro-montane forest in particular. The purpose of the study is to develop a stand density management diagram model for the existing mixed natural forest using appropriate species proportion for *Juniperus procera* and *Podocarpus falcatus*. Two linear equations were simultaneously fitted to relate quadratic mean diameter with stand density and dominant height and to relate total stand volume with quadratic mean diameter, stand density and dominant height for each species. Dominant height and quadratic mean diameter were found to be the best endogenous variables for SDMD for Chilimo forest. The relationship between stand density, dominant height, quadratic mean diameter and stand volume are represented in the SDMD. Formulating SDMD using species proportion is better than treating each species independently. This stand density management diagram is the first diagram developed for mixed-forest in Africa and can be serve to support the sustainable management of Chilimo dry afro-montane forest in particular and other dry afro-montane forests in general.

Key words: Species proportion, mixed species, thinning operation, dominant height, Chilimo

Introduction

Stand density management control (through initial spacing in forestation and/or pre-commercial and commercial thinning) modifies the level of growing stock to achieve the management objectives established for a given stand (Newton, 1997; Barrio-Anta *et al*., 2006; Castedo-Dorado *et al*., 2009). Stand Density Management Diagrams (SDMDs) graphically illustrate the relationships between, yield, density and density-dependent mortality during the stand development phases (Newton and Weetman, 1994). Also, SDMDs are management tools which facilitate decision making process for forest managers under limited information. Appropriate decision must enhance future stand values, trees and wood properties and habitat characteristics. SDMDs are designed to assist managers in applying different density management regimes regarding the timing and intensity of thinning treatments based on the theory of self-thinning and the relationships between average diameter, top height and volume of stands within the stand density (trees ha^{-1}) (Woods, 1999; Farnden, 2002 ; Álvarez-González *et al*., 2005). Due to the increasing interest on biomass, maximization of wood yield in addition to financial return became a key objective for foresters (Cole and Ewel, 2006; Bravo *et al*., 2008; Castedo and Dorado, 2009). This objective requires estimation of the tree size distribution as it is related with product price so during the last decade, structural yield prediction has been included in SDMDs (i.e, Newton *et al*., 2005; Castedo-Dorado *et al*., 2009).

Since Ando (1962) seminal paper on SDMDs several improvements and modifications have been developed such as the replacement of the original yield, density equations and the application of different density indexes (i.e., McCarter and Long, 1986; Newton and Weetman, 1994; Newton, 1997; Diaz-Maroto *et al*., 2010). Due to its easy use and applicability it is not surprising that SDMDs became an important management tool for even-aged stands in many regions across North America and Europe (Drew and Flewelling, 1979; Smith, 1989; Wilson *et al*., 1999; Valbuena *et al*., 2008; Bravo *et al*., 2012). Moreover, during the last decade and late XXth century, SDMDs were also developed for mixed species stands (Newton, 1997; Woodall *et al*., 2005; Swift *et al*., 2007). Determining appropriate levels of growing stock at the stand level is a complex process involving both biological and technological aspect. It requires selection of upper and lower limits for growing stock (Dean and Baldwin, 1996). SDMDs are one of the most effective methods available for the design, display and evaluation of alternative density management regimes for both even-aged and uneven-aged stands (Woodall *et al*., 2005) due to the relative low effect of site variance on the diagram's shape (Kershaw *et al*., 1991). SDMDs are used in combination with data reflecting stand structure to project stand future development including yield prediction.

Management of stocking using SDMD for both natural and plantation forest are also lacking in the country. Thus, adequate research works should be made in this regard.

Chilimo forest is one of the few remnants of dry afro-montane forest, located in the central highland plateau of Ethiopia managed by local community through participatory forest management (Shumi, 2009). Currently the Oromiya forest and wildlife enterprise is a governmental organization aimed at facilitation the management approach. In the process they are advocating preservation and protection of the natural forest with little benefit to the local community. However, different assessment works showed the forest is suffered from illegal harvesting (Shumi, 2009). Implementation of alternative management options could be very useful to benefit the society by maintaining sustainability of the forest. Stand density management is an option in both circumstances. Thus, the specific objective of this work is to develop a SDMD for the management of Chilimo mixed dry afro-montane forest using appropriate species proportion of two dominant species: *Juniperus procera* (Hoechst. Ex. Endl) and *Podocarpus falcatus* (Thunb. Mirb). The selected tree species were accounted about (52 %) of the total population i.e. *J. procera* (28 %), *P. falcatus* (24 %).

Material and Methods

Study site location

The experimental site is located in the Chilimo dry afro-montane forest of the Western Shewa zone, in the Dendi district of the central highlands of Ethiopia (38° 07′ E to 38° 10′ E longitude and 9° 30′ to 9° 50′ N' latitude), at an altitude of 2,170-3,054 m above sea level (Figure 1, study II). The mean annual temperature ranges between 15 ºC and 20 ºC and the area receives an average of 1,264 mm precipitation yearly (Shumi, 2009). Köppen's typology classifies the Chilimo forest as a temperate highland climate with dry winters (CWB) (EMA, 1988).

Reconnaissance survey

A preliminary discussion forum was held with the higher officials of the Oromiya Wildlife and Forest Enterprise in Addis Ababa. Subsequently, a reconnaissance survey was conducted through a field visit and physical observation across the Chilimo forest. Three patches (Chilimo, Gaji and Gallessa) were selected based on accessibility and representativeness for further study. Then an inventory work had been done starting from Chilimo proceed to Gallessa and finally to Gaji forest patches.

Plot sampling

A total of thirty five -20 x 20 m square sampled plots were marked out, based on the Neyman optimal allocation formula (Kangas, 2006; Köhl *et al*., 2006) for the altitudinal gradient. The plots were laid out along 100 m of ground distance, starting from the highest ridges to the lowest ridges of the mountains' using a measuring tape, GPS, altimeter and compass. The boundaries of the main plots were pegged and marked, then altitude, slope, latitude and longitude data were recorded from the centre of each main plot. The distance between two consecutive transect lines was 300 m to 1 km, depending on the accessibility of the next transect. A total of 33 different native species (22 tree species and 11 shrub species) were recorded; density varied from 2,533 stems ha^{-1} in the Chilimo forest patch to 848 stems ha^{-1} in the Gallessa forest patch.

Data collection and sampling

Individual species were categorized into trees (≥ 5 cm diameter at breast height), shrubs, saplings (height ≥ 1.3 m and dbh 2.5-5 cm) and seedlings (height 0.30-1.3 m and dbh ≤ 2.5 cm) following the Lamprecht classification (Lamprecht, 1989). All trees and saplings found in the plots were then numbered and marked. Tree diameter (cm) was measured to the nearest two digits using a metallic calliper. Crown height and total height (meter) was measured using Vertex III digital electronics tree height measurement instrument. In cases where trees branched at or below the breast height, diameter was measured separately for each branch. Likewise, the diameter at each stem was measured separately for trees with multiple stems connecting near the ground. For irregularities and or buttresses on large trunks, measurement was taken at the nearest lower point. Diamater measurements and height measurements were made for 822 stems. Basal area (BA) (m^2 ha^{-1}), Volume (Vt) (m^3 ha^{-1}) and quadratic mean diamater (D_q) (cm) were calculated using inventoried data. Both commercial volume and total volume was calculated using the conventional volume equation because local volume equations not available for these species:

$$V = \pi\left(\frac{DBH}{4}\right)2 * h * f \quad \text{(Atta-Boateng and Moser, 1998)} \qquad [1]$$

Where V= tree volume, DBH= diameter at breast height, h = total height and or commercial height f = form factor (0.42) (Atta-Boateng and Moser, 1998)

SDI (Reineke index) was calculated using the formula

$$\text{SDI} = N\left(\frac{Dq}{25}\right)^{1.605} \qquad [2]$$

where SDI= stand density index, Dq= quadratic mean diameter, N =number of stems ha^{-1}

Studied species proportion

The species proportion for *Juniperus procera* and *Podocarpus falcatus* were calculated using number of stems, basal area and total volume with the general formula:

$$\text{MSP (N)} = \frac{N_A}{N_A + N_B} \quad \text{(Pretzsch, 2007)} \qquad [3]$$

Where MSP species proportion in stems, NA: number of stems of species A, NB: number of stems spp B

Data analysis

The data was analyzed by using density, quadratic mean diameter and total height primarily equation 4 was fit by species group using least square regression:

$$\ln\,(volume) = \alpha - \beta.\ln\,(density) \qquad [4]$$

Volume is the mean tree gross total volume (m^3 $tree^{-1}$) and density is the total number of stems per hectare. The magnitude of the coefficients in eq. 5 appeared to decrease for mixed species stands relative to pure *Juniperus procera* and *Podocarpus falcatus* stands. So according with Swift *et al.* (2007) an alternative form of eq. 5 was fitted by expanding the coefficients to include a term for the mixture proportion as deviation from the pure stands (mixfrac) degree of departure from pure species condition using the formula (Swift *et al*., 2007):

$$\ln(volume) = \alpha 0 + \alpha 1.mixfac - (\beta 0 + \beta 1.\boldsymbol{mixfrac}).\ln(\boldsymbol{density})$$

[5] Where

$$\text{mixfrac} = \text{0.5-ABS(JP(PF))frac-0.5)}$$

$$JP(PF)\boldsymbol{fracBA} = \frac{\boldsymbol{JP(pf)basal\ area}}{\boldsymbol{total\ basal\ area}}$$

$$JP(pf)\ fracN = \frac{JP(PF)\ N}{Ntot}$$

$$JP(PF) fracV = \frac{JP(PF)Vi}{Vtot}$$

$$MIX\_N = MIXFRANK * \ln\_N \qquad [6]$$

$$MIX\_Ho = MIXFRANK * \ln\_Ho \qquad [7]$$

$$MIX\_QMD = MIXFRANK * \ln\_QMD \qquad [8]$$

Where: $MIXFRANK$ = mixed proportion, N= number of stems, Ho: dominant height and QMD: quadratic mean diameter, JP: *Juniperus procera*, PF: *podocarpus falcatus, ABS: absolute*

Dbhq isoline

The relationship between ln (volume) and ln (density) was found close to linear for a given quadratic mean diameter and parallel when quadratic mean diameter was changed. Thus, the relationship between ln (volume) and ln (density) were given by equation:

$$\ln(volume) = \beta 0 + \beta 1. \ln(dbhq) + \beta 2. \ln(density) \qquad [9]$$

The $\beta 0 + \beta 1 \ln(dbhq)$ expand the intercept parameter of the linear relationship between ln (volume) and ln (density). In a similar way as Swift *et al*. (2007) did, we expanded each of the coefficients in eq. 9 to include the *Juniperus-Podocarpus* fraction, resulting in the following equation:

$$\ln(volume) = \beta 01 + \beta 02. Jpfrac + \beta 11 + \beta 12. Jpfrac). \ln(dbhq) + (\beta 21 + \beta 22. Jpfrac). \ln(density) \qquad (10)$$

Total height isolines

We found a species-dependent relationship between volume and top height and density curve downwards as density increases and the slope of the relationship between ln (volume) and ln (density) increases as top height increases so (eq. 11) was developed by using weighted linear regression (the mean tree volume was used to weight the residuals) and including species proportions to expand paremeters (eq. 12):

$$\frac{1}{volume} = \beta^{\circ}. topht\ \beta 1 + \beta 2. density. topht\beta 3 \qquad [11]$$

$$\frac{1}{volume} = (\beta 00 + \beta 01. MIXFRAC). Ho\char`^(\beta 10 + \beta 11. MIXFRAC) + (\beta 20 + \beta 21. MIXFRAC) * N. HO\char`^(\beta 30 + \beta 31. MIXFRAC \qquad [12]$$

Over all model structure and data analysis

Two general linear models (eq. 13) and (eq. 14) relating quadratic mean diameter and stand volume with density and dominant height were considered for SDMD model evaluation and fitting process were used primarily for *J. procera* and *P. falcatus* and these models were further expanded to model (eq. 15) and (eq. 16) by incorporation of species proportion:

$$\mathrm{Ln\ QMD} = \beta o + \beta 1.\,\mathrm{LnN} + \beta 2.\,\mathrm{LnHo} \qquad [13]$$

$$\mathrm{Ln\ VT} = \beta 3 + \beta 4.\,\mathrm{LnQMD} + \beta 5.\,\mathrm{LnHo} + \beta 6.\,\mathrm{LnN} \qquad [14]$$

Where

N: stand density (stem ha^{-1})

QMD: Quadratic stem diameter (cm)

Ho: Dominant height (m)

VT: Stand volume ($m^3\ ha^{-1}$)

$_{\beta}$i (I = 0-6): regression coefficients

$$\mathrm{ln\_QMD} = \beta 01 + \beta 02 * \mathrm{MIXFRAC} + \beta 11 * \mathrm{ln\_N} + \beta 12 * \mathrm{MIX\_N} + \beta 21 * \mathrm{ln\_Ho} + \beta 22 * \mathrm{MIX\_Ho} \qquad (15)$$

$$\mathrm{ln\_VT} = \beta 31 + \beta 32 * \mathrm{MIXFRAC} + \beta 41 * \mathrm{ln}_{QMD} + \beta 42 * \mathrm{MIX}_{QMD} + \beta 51 * \mathrm{ln\_Ho} + \beta 52 * \mathrm{MIX\_H0} + \beta 61 * \mathrm{ln\_N} + \beta 62 * \mathrm{MIXFRAC} * \mathrm{ln\_N} \qquad (16)$$

N: stand density (stem ha^{-1})

QMD: Quadratic stem diameter (cm)

MIXFRAC : mixture fraction

MIX: mixture

Ho: Dominant height (m)

VT: Stand volume (m^3ha^{-1})

$_{\beta}$i (i= 01-62): regression coefficients

Thus, Ln N and Ln Ho are exogenous variables (defined) independently of the system while VT and QMD are instrumental endogenous variables (Borders, 1989). The best independent fitting variables were selected using volume, basal area and density. Model fitting and data analysis were performed using the MODEL procedure in the SAS/ETS software (SAS Institute Inc., 2012). Best fitting models were selected based on higher regression correlation coefficient and the quality of the graph performed.

The quadratic mean and total height isoline graphs were formulated using the fitted models. Besides, the density management diagram were developed using quadratic mean diameter on the x-axis (logarithmic scale) while the number of stems per hectare (logarithmic scale) on the y-axis. However, thinning operation was recommended using species proportion for overall the Chilimo dry afro-montane forest.

Results

General description

The results revealed, quadratic mean diameter (QMD), volume, dominant height (Ho) and number of stems (N) were varied among the tree species (Table 1). *J. procera* and *P. falcatus* accounted morethan 50 % of the total basal area and density in the Chilimo dry afro-montane mixed forest. These species are very important both economically and ecologically. Moreover, use for high quality timber which is durable and resistant to termite attack. Other species i.e. *Allophyllus abyssinicus*, *Olea europaea* ssp. *Cuspidiata*, *Olinia rochetiana*, *Ruth glutinosa* and *S. theifolia* accounted about 25 % of the total population interms of basal area and density and belong to both in the dominat and co-dominant group in the forest. These species are widely utilized for fuelwood, construction wood and lumber by the local community as compared to the above mentioned species.

Table 1: ***Summary of the data sets used to develop the Juniperus-Podocarpus SDMD: n=number of plot measurements.***

Attributes	***Juniperus procera***		***Podocarpus falcatus***		**All species in the forest**	
	n	**Mean (range)**	**n**	**Mean (range)**	**n**	**Mean (range)**
Density (stems/ha)	35	145.71 (0-525)	35	115 (0-475)	35	596.43 (125-1025)
Top height (m)	35	15.98 (0-32.10)	35	7.78 (0-22.73)	35	24.16 (13.29-34.24)
Basal area (m^2/ha)	35	12.39 (0-64)	35	2.23 (0-17)	35	25.92 (6.25-76.00)
Volume (m^3/ha)	35	114.55 (0-692.75)	35	20.99 (0-230.22)	35	228.11 (5.5-692.75)
Quadratic mean diamater (QMD) (cm)	35	23.90 (0-79.84)	35	8.65 (0-43.48)	35	24.29 (12.19-79.84)

Model evaluation and fitting results

The model evaluation and simultaneous fitting results of the two dominant species and their proportion under study were summarized in table 2 and 3. The results revealed dominant height and quadratic mean diameter were found to be the best endogenous fitting variables for stand density management diagrams (Table 2). Goodness of fit was adequate (the R^2 adjusted validation data set was over 0.60 for the quadratic mean diameter equation and over 0.95 for the volume equation) in all models.

***Table 2:** Results of the variance analysis, adjust and nonlinear regression obtained from making the simultaneous adjust of the system of equation to calculate the quadratic stem diameter [1] and the stand volume [2] using two equations and two species composition.*

Equation	***J. procera***		***P. falcatus***		**species proportion**	
	QMD	**V**	**QMD**	**V**	**QMD**	**V**
DF Model	3	4	3	4	6	8
DF error	19	18	13	12	29	27
SSE	1.67	1.59	1.24	0.89	1.45	6.43
MSE	0.09	0.09	0.10	0.07	0.05	0.24
RMSE	0.30	0.30	0.31	0.27	0.22	0.49
R^2	0.64	0.93	0.80	0.98	0.70	0.76
R^2 adj.	0.60	0.92	0.77	0.95	0.65	0.70

Where: DF: degree of freedom, SSE: sum of squared error, MSE: mean Residuals, RMSE: root of the mean quadratic error, R2: correlation coefficient, R2_adj: adjusted correlation coefficient, QMD: quadratic mean diameter, V: volume.

The correlated coefficient value for the estimated parameters is presented in table 3 and 4, the model efficiency varied among the species. All the estimated parameters for *P. falcatus* and five parameters for *J. procera* were significant ($p < 0.05$). However, for the species proportion, seven parameters in volume, six parameters in number of stems and five parameters in basal area were also significant. The estimated parameters for the volume data set were better than basal area and number of stems. The R^2 adjusted values for the validation data set for *P. falcatus* was higher, which was over 0.80 for the quadratic mean diameter and over 0.95 for the volume model. However, the adjusted R^2 value for the validation data of diameter at breast height for *J. procera* was lower than *P. falcatus* (0.60). Thus, two linear-equation models which consider the same sets of independent variables were selected to develop the SDMD.

Table 3: *Values of the coefficients of the nonlinear regression obtained from the simultaneous adjust of the system of equations to calculate quadratic stem diameter [1] and stand volume [2] for J. procera and P. falcatus separately using (eq. 13 and eq. 14).*

Coefficients	***J. procera***		***P. falcatus***	
	Estimate ± SE	**Pr > /t/**	**Estimate ± SE**	**Pr > /t/**
β_0	-0.804794±0.87	0.3653	1.61596±0.75	**0.0491**
β_1	-0.24993±0.17	0.1608	-0.50234±0.17	**0.0119**
β_2	1.388187±0.28	<.0001	3.119281±0.50	**<.0001**
β_3	-10.1877±1.49	<0.0001	-11.9455±1.50	**<0.0001**
β_4	1.55153±0.23	<0.0001	2.418808±0.23	**<.0001**
β_5	1.942324±0.58	0.0036	0.951593±0.38	**0.0285**
β_6	1.039522±0.25	0.0006	1.11629±0.17	**<0.0001**

Where*: β0: the y-intercept for QMD, β3: y-intercept for VT, β1: model parameter for N, β2: model parameter for Ho; β4: model parameter for QMD, β5: model paramete for Ho and β6: model parameter for N.*

Table 4: *Values of the coefficients of the nonlinear regression obtained from the simultaneous adjust of the system of equations to calculate quadratic stem diameter [1] and stand volume [2] for mixed forest studied species using (eq.15 and eq.16).*

Paramater	**Volume**			**Basal area**			**Number of stems (N)**		
	Estimate	**SE**	**Pr > /t/**	**Estimate**	**SE**	**Pr > /t/**	**Estimate**	**SE**	**Pr > /t/**
$\boldsymbol{\beta_{01}}$	2.897416	0.654	**0.0001**	3.382004	0.879	**0.0006**	3.116092	0.632	**<.0001**
$\boldsymbol{\beta_{02}}$	-0.00117	0.002	0.5539	-3.57605	3.654	0.3358	-2.26465	1.421	0.1218
$\boldsymbol{\beta_{11}}$	-0.58115	0.107	**<0.0001**	-0.56839	0.099	**<.0001**	-0.67893	0.122	**<.0001**
$\boldsymbol{\beta_{12}}$	-0.06936	0.120	0.5688	-0.0674	0.115	0.5632	0.654378	0.482	0.1851
$\boldsymbol{\beta_{21}}$	0.646314	0.180	**0.0012**	0.487582	0.257	0.0676	0.673544	0.168	**0.0004**
$\boldsymbol{\beta_{22}}$	0.011675	0.083	0.8892	1.111381	1.125	0.3316	-0.00697	0.081	0.9321
$\boldsymbol{\beta_{31}}$	-12.60544	2.237	**<.0001**	-12.7042	2.746	**<.0001**	-11.3893	1.935	**<.0001**
$\boldsymbol{\beta_{32}}$	2.444265	7.661	0.7521	5.230836	12.471	0.6783	-2.0532	3.972	0.6094
$\boldsymbol{\beta_{41}}$	2.198373	0.494	**0.0001**	2.108279	0.508	**0.0003**	2.016638	0.460	**0.0002**
$\boldsymbol{\beta_{42}}$	1.29198	2.967	0.6667	1.197907	3.576	0.7402	2.280185	2.900	0.4386
$\boldsymbol{\beta_{51}}$	1.472016	0.523	**0.0090**	1.761332	0.581	**0.0053**	1.527939	0.563	**0.0114**
$\boldsymbol{\beta_{52}}$	-1.14605	2.725	0.6790	-3.34268	3.057	0.2839	-2.07677	2.746	0.4560
$\boldsymbol{\beta_{61}}$	0.972655	0.389	**0.0186**	0.782145	0.406	0.0643	0.671582	0.413	0.1154
$\boldsymbol{\beta_{62}}$	-0.6712	2.106	0.7524	0.741133	1.888	0.6977	0.813058	1.305	0.5384

Where*: β01:the y-intercept for QMD, β02:model paramater for MIXFRAC, β11: Model parameter for N, β12: Model parameter fro MIX_N, β21:model parameter for Ho, β22: model parameter fro MIX_Ho, β31: the y-intercept for VT, β32: model parameter for MIXFRAC, β41: model parameter for QMD, β41: model parameter for MIX_QMD, β51: model parameter for Ho; β52: model parameter for MIX_Ho, β61: model parameter for N, β62: model parameter for MIXFRAC_N. Number in bold are statistically significant p < 0.05.*

Table 5: *The result of fitting eq. 9 and 10, 11 and 12.*

	Equation 9 and 10			**Equation 11 and 12**		
Paramater	**estimate**	**S.E**	**Pr > /t/**	**estimate**	**S.E**	**Pr > /t/**
β0	-44E-14	0.0982	**0.0001**	-388E-15	0.1094	**0.0001**
β1	1.0000	0.0388	**0.0001**	1.0000	0.0388	**0.0001**
β2	6.8E-14	0.0180	**0.0001**	1.2E-10	0.0002	**0.0001**
β3	-	-	**-**	0.0001	0.00001	**0.0001**
$\beta0^{o}$	-	-	**-**	-11.361	1.9982	<**.0001**
β01	-10.5325	1.9283	<**.0001**	-0.38768	1.4603	0.7927
β02	0.276774	0.2732	0.3193	-	-	-
β10	-	-	**-**	2.033989	0.4764	**0.0002**
β11	2.814531	0.3605	**<0.0001**	0.346418	0.5071	0.5003
β12	-0.01337	0.2984	0.9646	-	-	-
β20	-	-	**-**	1.469933	0.5584	**0.0138**
β21	1.13389	0.3409	**0.0024**	-0.28699	0.4543	0.5329
β22	0.025535	0.2704	0.9254	-	-	-
β30	-	-	-	0.726249	0.4206	0.1047
β31	-	-	-	0.171168	0.4502	0.7068

Number in bold are statisticall significant at $p < 0.05$.

Where*: β0 : the y-intercept for volume eq.9 and the estimator parameter for top height eq.11, β1: the estimator parameter for dbhq eq.9 and the power estimator for density eq.11, β2: the estimator parameter for density eq.9 and the power estimator for density eq.11, β01: the y-intercept for volume eq.10 and the estimator parameter for MIXFRAC eq.12, β02: the estimator parameter for J.procera eq.10, β11: the y-intercept for J. procera density eq.10 and the estimator parameter for MIXFRAC_Ho eq.12, β12: the estimator parameter for dbhq eq.10: β21: the y-intercept for density, eq.10 and the estimator paramete for MIXFRAC_N eq.9 and 10, β22: the estimator parameter for mixfrack J.procera eq.10, β31: the power estimator for density eq.11, β0° : the y-intercept for eq.12, β10: the y-intercept for MIXFRAC eq.12, β20: y –intercept for MIXFRAC eq.12, β30: the y-intercept eq.12, β31: the estimator parameter for MIXFRAC eq.12.*

Stand density management diagram model for the species proportion

Maximum density lines plus diameter and height isolines were graphed using actual data for *J. procera*, *P. falcatus* and *J. procera/P. falcatus* species proportion as shown in figure 2 and 3. The relationship between volume and density was apperead to be linear for a given dbh and parallel as dbh changed (Figure 2). The graph produced using top height and density was also showed a linear relationship between top height and density for both pure species and species proportion, though, the relationship was weak (Figure 3).

The SDMD was formulated using quadratic mean diameter and total height for *J. procera*, *P. falcatus* and *Juniperus*/*Podocarpus* proportion and the results are presented in figure 4. In the graph the total volume, total height and number of stems were presented using different colours and features. The total volume was represented using blue dotted lines running diagonally from x-axis to y-axis and the total height (m) was represented using red solid lines running from x-axis to y-axis with similar fashion. Similarly, the number of stems and stand density index was represented using black solid lines running in the same position as volume and total height do. In the graph we can read any combinations of quadratic mean diameter, density, total volume and total height.

Volume, total height and number of stems per hectare were varied among the species. *J. procera* dominated by big diameter stemmed trees with a mean quadratic mean diameter upto 80 cm while *P. falcatus* was dominated by medium sized stems with a higher regeneration status in the forest. The number of stems in the SDMD of Chilimo mixed forest was exceeded up to 1025 stem ha^{-1}.

Alternative management options were developed for the Chilimo dry afro-montane forest by considering species proportion of *J. procera* and *P. falcatus*, because species specific management option is not advisable for such a type of forest to maximize productivity of the forest and benefiting the local community (Figure 4). The quadratic mean diameter, stand volume and number of stems to be retained and removed before and after thinning was also estimated (Table 5). The volume after thinning was also showed increment (Table 5). The minimum and maximum quadratic mean diameter to be thinned will be 25 and 35 cm, respectively (Table 5). Natural mortality was not considered between thinning operations. Thus, thinning will be applied for *J. procera* and *P. falcatus*. A similar assumption was also reported in the previous SDMDs developmet for other species (McCarter and Long, 1986; Dean and Baldwin, 1996; Barrio-Anta *et al*., 2005).

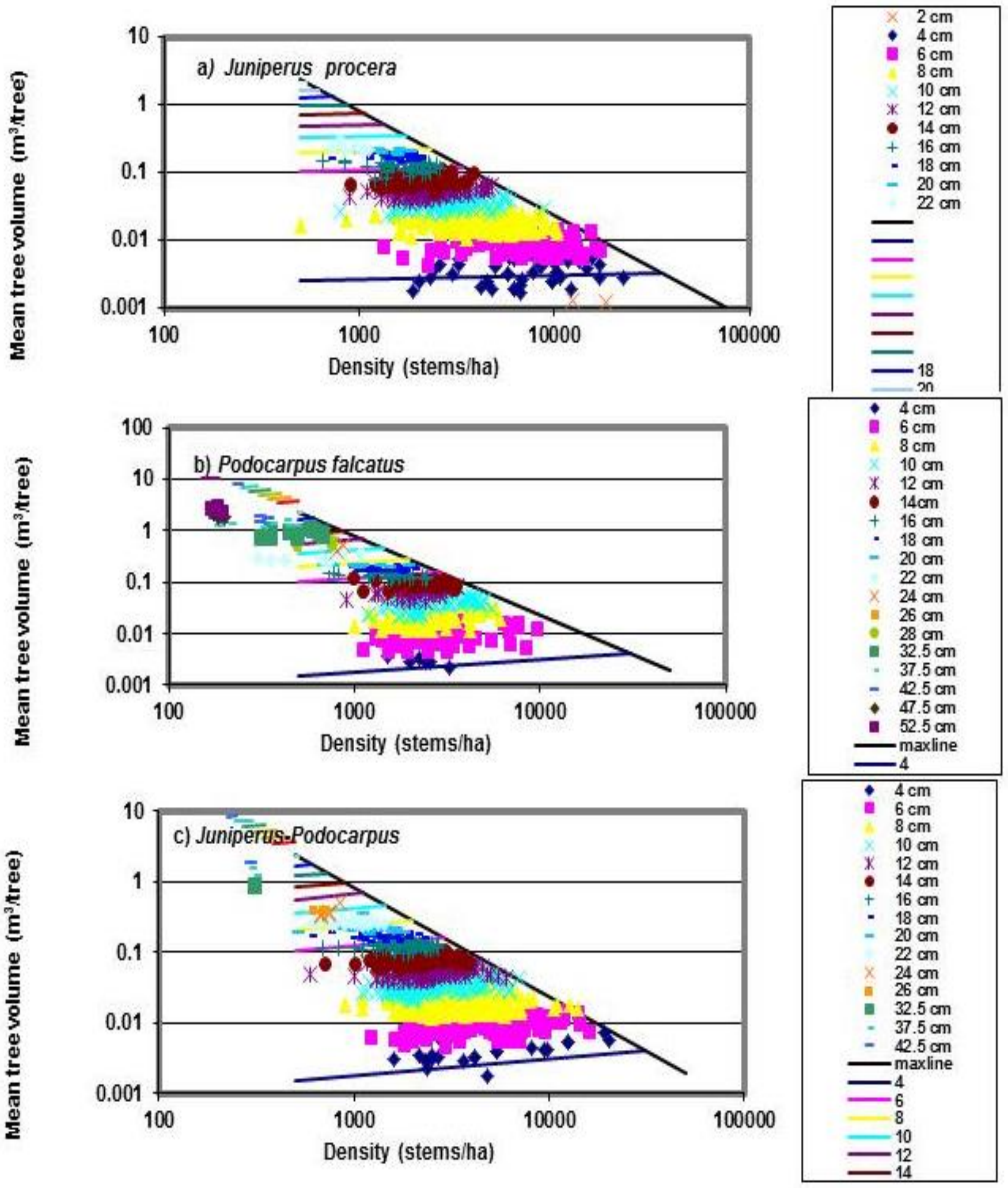

Fig. 2: *The maximum size density line and the quadratic mean diameter isolines form eq. 7 are plotted through the actual data.*

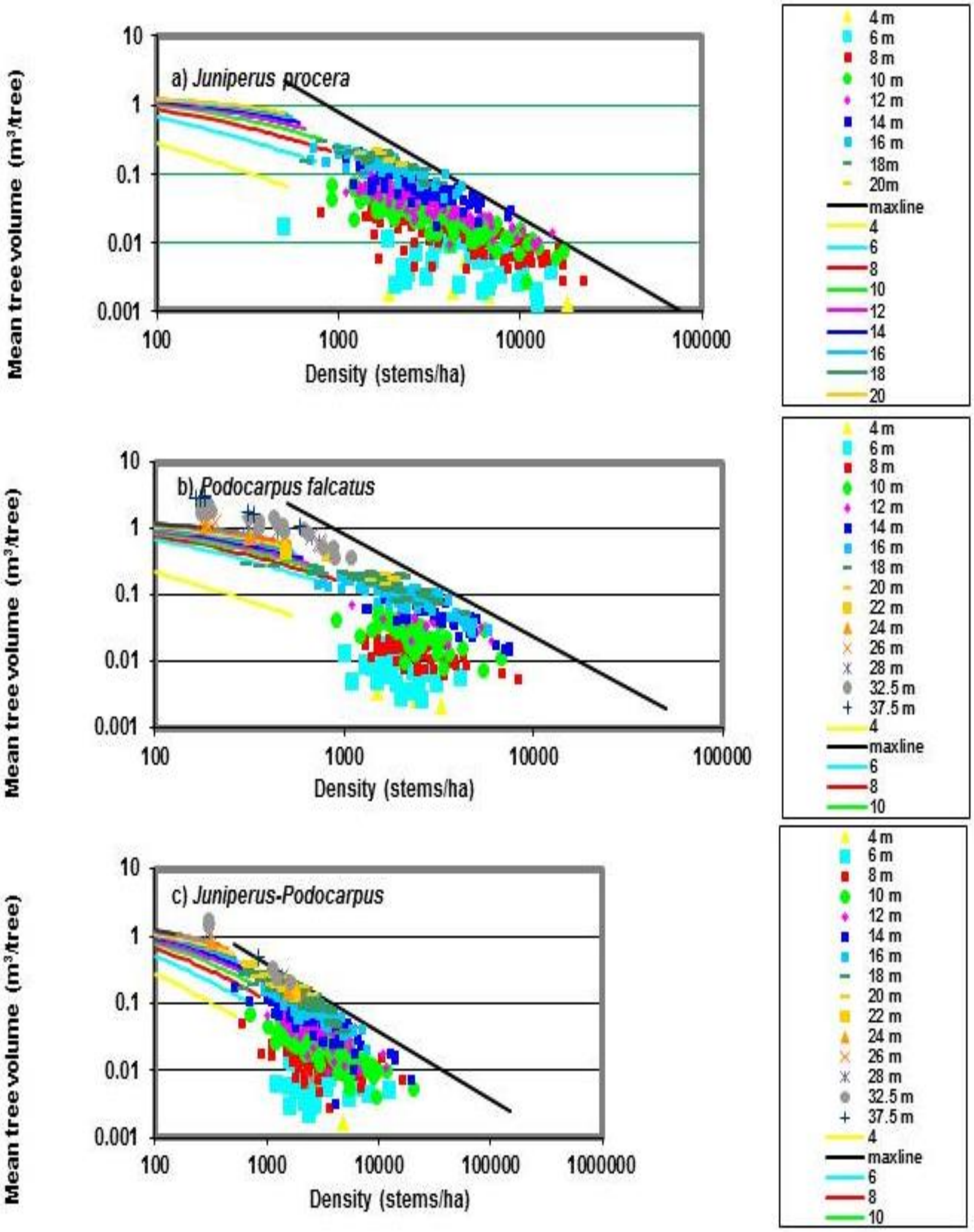

Fig. 3: *The dominant height isolines from eq. 8 are plotted through the actual data.*

Discussion

Forest management is included as a key tool in REDD+ projects (Moges and Tenkir, 2014) and proper biomass and carbon stock estimations in tropical forests will help foresters to better understand the importance of tropical forest management in the global carbon cycle budgeting and how to implement in sustainable management at operational level. Also this information could serve as a valuable tool for policy-makers and stakeholders during the decision making proccess to maintain and improve forest condition while the provision of valuable environmental services (incling timber and firewood) is ensure so local communities could be engage in forestry related activities. In this study, data from a single measurement 35 plots were analyzed to develop stand density management diagram for *J. procera, P. falcatus* and *Juniperus/Podocarpus* mixed forests useful for operational forestry in Chilimo forest but also can be used in other dry afro-montane forests. The density management diagrams reflect the impact of stand compositon and structure on stand development including wood yield. Appropriate decision making processes must enhance future stand volume, wood properties and habitat characteristics and SDMDs can help foresters to establish appropriate management guidelines including carefully designed thinning operations to benefit the local communities. Although, SDMD are widely used for even aged pure stands in the past, currently it is also used for the management of mixed stands (Swift *et al*., 2007).

The growth and yield of trees and stands are fundamental tools for understanding the relationships between density management and wood production. By using SDMDs managers can recommend appropriate thinning operations where the maximum yield will be obtained. Due to the lacking of permanent plot in the study area (Chilimo natural forest), Dean and Baldwin's (1996) bounds of self thining and full site occupancy were adopted (Figure 4). These values (60 and 35% of maximum RDI) must be locally estimated in the near future by establishing a permanent plot network. Other modeling approach as empirical or process-base models can be also useful to understand ecosystem dynamics and propose management guidelines. However, as Valbuena *et al*. (2008) stated SDMDs are practical tools that can be easily implemented where silvicultural knowledge is scarce and in low productivity forests where it is not realistic invest funds to improve management tools.

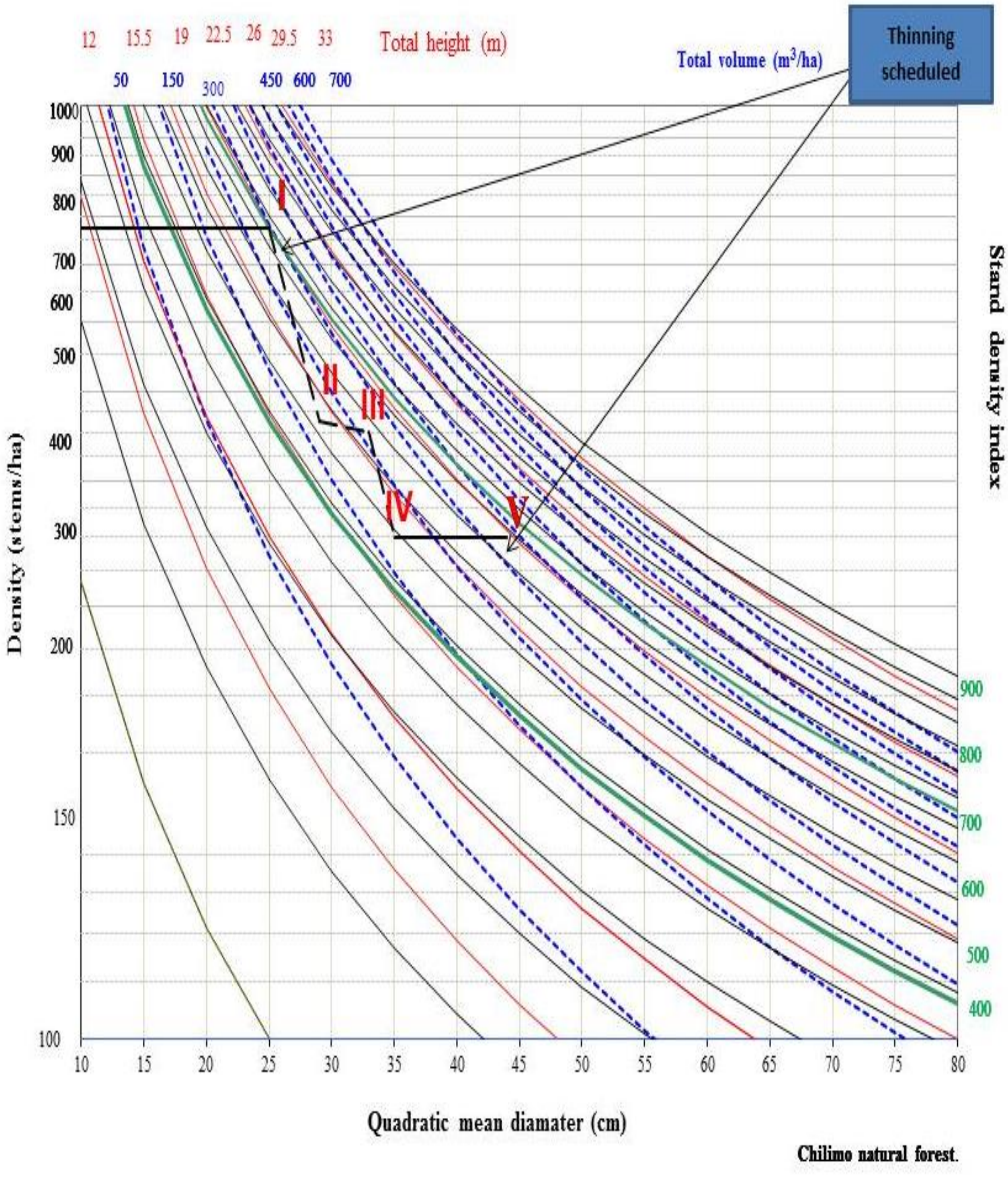

Fig. 4: *Stand density management diagram and alternatives for chilimo natural forest with Juniperus and Podocarpus proportion.*

Table 5: *Alternative silvicultural density management options for Chilimo dry afro-montane forest.*

Alternative	Quadratic mean diameter (cm)		Stand volume (m^3 ha^{-1})		Density (stem ha^{-1})	
	Before	after	before	after	before	after
I-II	25	29.00	265.00	150.00	673	362
III-IV	29.00	33.00	150.00	210.00	362	350
V-IV	33.00	35.00	210.00	330.00	350	250

Conclusions

Stand density management diagrams can be used as a foundation tool to develop thinning operation schedules to benefit the local community living inside or around Chilimo dry-afro-montane forest in particular and to enhance productivity of the forest in general. Dominant height and quadratic mean diameter were found to be the best endogenous variables for SDMD for Chilimo forest. The SDMD fitted for the volume data set were better than basal area and number of stems. Formulating SDMD using species proportion is better than treating each species independetly. This stand density management diagram is the first diagram developed for mixed-forest in Afrixa and can be serve to support the sustainable management of Chilimo dry afro-montane forest in particular and other dry afro-montane forests in general. Similar studies should be continued for Chilimo dry afro-montane forest in particular and other natural and man-made plantation forest in general.

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Study V

Variation in carbon concentration and wood density for five most commonly grown tree species in Ethiopia

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Study V

Variation in carbon concentration and wood density for five most commonly grown tree species in Ethiopia

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Abstract

Chilimo forest is one of the few remaining dry afro-montane mixed forests and is composed of both broad-leaf and the more dominant coniferous species. However, information's regarding carbon concentration and wood density for the existed tree species, its parts and stem position are lacking, thus the study was conducted with the objective to estimate carbon concentration and wood density for: *Allophyllus abyssinicus, Olea europaea* ssp. *cuspidiata*, *Olinia rochetiana*, *Rhus glutinosa* and *Scolopia theifolia* in a tropical mixed forest, Ethiopia. A total of 105 wood samples 30-50 mm thickness were collected based on diameter distribution. Fresh weight of wood and leaves samples were taken in the field and oven dried at 102 ºC and 67 ºC to constant weight, respectively. The oven dried wood and leave samples were weighed, splatted into pieces, chopped and finally grinded into 0.2 mm with a grinding mill. Carbon concentration was analysed using ash method while, volume for wood density was estimated using water displacement method. The data was analysed using SAS PROC GLM and PROC logistic model. The results revealed that both carbon concentration and wood density were highly significant among and within a species, plant parts and stem position. The highest carbon concentration (57.12 %) was found for *O. rochetiana*, however, the lowest carbon concentration (56.43 % %) was found for *A. abyssinicus*. Stem parts had higher carbon concentration (56.98 %) than branch (56.74 %) and leaves parts (54.53 %). The maximum carbon concentration was also found at stump height (57.10 %) than commercial height (54.53 %). The wood density was also varied among and within a species and stem position. *O. europaea* ssp. *cuspidiata* exhibited the highest wood density (0.67 g cm^{-3}) than others.

Keywords: native trees species, Chilimo forest, stem position, plant parts and logistic model.

Introduction

Carbon dioxide (CO_2) is contributing the dominant figure to the greenhouse effect. The increasing carbon emission due to anthropogenic effects is a major concern for all over the world. It has been well addressed in Kyoto protocol (Ravindranath *et al.*, 1997; Charan and Rasal, 2010). Carbon sequestration is a natural method for the removal of carbon from the atmosphere and storing it (Dhruba, 2008; Charan and Rasal, 2010). The atmospheric CO_2 is captured and stored in plants, soil, ocean or atmosphere in the form of biomass through photosynthesis. Wood production has a positive environmental effect by fixing large amounts of carbon dioxide (CO_2) (Herrero *et al.*, 2011). Carbon constituents approximately 50 % of the dry weight of wood (Robinson and Kile, 2007) however, different plant tissues contain different amounts of carbon, for e.g. a carbon concentration of 42 % for leaves and 47 % to 52 % for roots was reported by Lamlom and Savidge (2006). The amount of carbon sequestered by a particular tree species is increasing substantially over the time and age of a tree until it matures (Jone *et al.*, 2009). Accurate estimation of forest biomass is important for commercial uses (e.g. fuel wood and fiber, national development planning, scientific studies of ecosystem productivity of carbon cycle), nutrient flows and assessing the contribution of changes in forest lands to the global carbon cycle (Basuki *et al.*, 2009). The estimation of the above-ground biomass with a sufficient accuracy to assess the variations in C stored in the forest is becoming increasingly important (Ketterings *et al.*, 2001; Chave *et al.*, 2004). Variability of biomass is due to differences in climate, topography, soil fertility, water supply, wood density, tree functional types and forest disturbance (Fearnside, 1997; Luizáo *et al.*, 2004; Sicard *et al.*, 2006). For a particular tree, tree mass is influenced by the size of a tree, its architecture, form, health condition and soil fertility (Fearnside, 1997; Patino *et al.*, 2009).

The biomass of tropical forests has been measured for a few sites scattered around the tropical world but the area represented by these studies is extremely low (approximately 30 ha) compared with the total area of tropical forest (about 18 million km^2) (Brown and Lugo, 1982). Furthermore, there is strong evidence that the selection of these few sites was biased towards high biomass forest (Brown and Lugo, 1984).

Past experiences revealed that, 50 % of the dry biomass of wood was considered as carbon; however, recent findings indicated, this assumption is not always true. Because, the amount of carbon concentration was varied among and within a species, individual tree, stem position and plant tissue (Herrero *et al*., 2011; Thomas and Martin, 2012). Thus, species and site specific research investigations should be made.

According to Perera *et al*. (2012) wood density is a function of the proportion of cell wall materials versus cellular voids. Accordingly wood density is a key wood property it affects yield and quality of both fibrous and solid wood products (Haslett and Young, 1990). Wood density is a measure of wood quality (Zobele and van Buitjenen, 1989; Woodcock and Shier, 2002). It is also one of the most important biological traits in plants. It has both ecological and economical importance for a particular tree and or species. Wood density is directly related to tree growth because of the volume of wood produced for a given unit biomass is inversely proportional to its density (King *et al*., 2005). Light demanding tree species growing in the tropics have low wood density than shade-tolerant tree species (Muller-Landov, 2004; King *et al*., 2006; van Gelder *et al*., 2006; Poorter, 2008). Wood density varies within and among a species, provenances and individual tree, stem position, tissue type and plant parts (Chave, 2006; Grabner and Wimmer, 2006; Chave *et al*., 2009; Beck, 2010).

Wood density is used to estimate forest biomass, carbon flux and greenhouse gas emissions from a particular forests (Brown *et al*., 1989; Fearnside, 1997; Nogueira, 2007; Preece *et al*., 2012). Species and site specific wood density and carbon concentration assessments are required to reduce uncertainities regarding biomass and carbon estimation (Zhang *et al*., 2009). However, the wood densities of majority of tree species grown in the tropics are unknown (Slik, 2008). Consequently, little information exists on wood density for native tree species grown in Ethiopia and other sub-Saharan African countries.

Located in the central highland plateau of Ethiopia, the Chilimo forest is one of the few remaining dry afro-montane mixed forests and is composed of both broad-leaf and the more dominant coniferous species. The main species (based on density) include: *Juniperus procera, Podocarpus falcatus, Olea europaea* ssp. *cuspidiata, Scolopia theifolia, Rhus glutinosa, Olinia rochetiana* and *Allophylus abyssinicus* (Kelbessa and Soromessa, 2004; Kassa *et al*., 2008). The forest represents a vital ecological space for birds, mammals and water supply. It is also the source of several large rivers, including the Awash River. However, the Chilimo forest has been subjected to human impact for over 2,000 years. The current rate of deforestation is extremely high due to clearing for fuel wood, agricultural land, lumber and farm implements. Chilimo forest cover has shrunk from 22,000 ha in 1982 to 6,000 ha at present (Shumi, 2009). The Ethiopian government has proclaimed this forest as a National Priority Protection Forest area. As information's regarding % C and wood density at species level, plant parts and stem position are lacking for the majority of Ethiopian species in general and Chilimo dry afro-montane forest native tree species in particular, the main aim of this study was to estimate carbon concentration and wood density for five most commonly native species: *Allophyllus abyssinicus* (Hochst.) Radlk. *Olea europaea* L. ssp. c*uspidiata* (Wall. ex G. Don) Cif, *Olinia rochetiana* A. Juss, *Rhus glutinosa* Hochst. Ex A. Rich. and *Scolopia theifolia* (Gilg.) along plant parts and stem position in a tropical dry afro-montane forest.

Although the coniferous *J. procera* and the broadleaf *P. falcatus* are the most abundant and dominant trees in the forest, cutting them down is prohibited by law and it was therefore not possible to take samples for carbon concentration and wood density determination for these endangered species. Consequently, the species included in this study are under increased pressure from the local human population in search of wood for fuel, construction wood, farm implements and charcoal (Kassa *et al*., 2008; Teshome and Ensermu, 2013).

Material and Methods

Study site location

The experimental site was located in the Chilimo dry afro-montane forest of the Western Shewa zone, in the Dendi district of the central highlands of Ethiopia (38° 07′ E to 38° 10′ E longitude and 9° 30′ N to 9° 50′ N' latitude), at an altitude of 2,170-3,054 m above sea level (Figure 1, **study II**). The mean annual temperature ranges between 15 ºC and 20 ºC and average annual precipitation is 1,264 mm (Shumi, 2009). Köppen's typology classifies the Chilimo forest as a temperate highland climate with dry winters (CWB) (EMA, 1988).

Forest inventory

A total of thirty-five 20 x 20m square sample plots were marked. Sampling and data collection were done in the measured plots of the mixed natural forest. Individual species were categorized into trees (≥ 5 cm diameter at breast height), shrubs, saplings (height ≥1.3 m and dbh 2.5-5 cm) and seedlings (height 0.30-1.3 m and dbh ≤ 2.5 cm) following Lamprecht's classification (1989). All trees and saplings found in the plots were then numbered and marked. Tree diameter (cm) was measured to the nearest two digits using a metallic calliper. Crown height and total height (meter) were measured using Vertex III digital electronics tree height measurement instrument. Then the inventory data was summarized using descriptive statistics. Five dominant and abundant tree species were selected for further study. These species namely, *A. abyssinicus* (4 %), *O. europaea* ssp. *cuspidiata* (8 %), *O. rochetiana* (5 %), *R. glutinosa* (3 %) and *S. theifolia* (5 %) accounted for 25 % of the total native tree population (in number of trees ha^{-1}) and 23 % (5.04 m^2 ha^{-1}) of total basal area in the overall population. These tree species were selected for % OC in the plant sample and wood density study using destructive sampling.

Wood sampling and analytical procedures

A total of 15 trees (3 trees spp^{-1}) were selected and cut based on diameter classes at 5-cm intervals obtained from inventory data. Prior to felling: diameter at breast height (*dbh* =1.30 m), diameter at ground base (*db*), crown diameter (*cd*) and crown length (*cl*) were measured for each tree using metallic calliper and Vertex digital height measurement instrument. Then, trees were felled using local axes and cross cut saw and cut as close to the ground as possible. A total of 105 discs, six cross-sectional discs (5 discs from stem and one disc from large branches) having a size of 30-50 mm thickness, were collected per single tree. Discs were taken from each section, starting from stump height to every one meter along the stem up to the end of commercial height (≤ 7cm) and large branches (≥ 7cm diameter). Leaves samples were also taken from each tree for the same purpose. Fresh weights of each wood and leaves samples were taken in the field and leaves were oven dried at 67 ºC for 24 hours and wood samples were oven dried at 102 ºC for 48 hours to constant weight, then samples were weighed, splatted into pieces, chopped and finally grinded into 0.2 mm using a grinding mill.

Carbon % was estimated coversion of ground plant samples into ash using ignition method described by (Ben-Dar and Banin, 1989; Allen *et al*., 1986; Negi *et al*., 2003; Jone *et al*., 2009). Five to 10 gram of ground plant sample was placed in the ashing vessel at 105 ºC temperature for four hours. Oven dried samples were removed, cooled, air dried and weighed and again placed in a muffle furnace at 400 ºC and oven dried for four hours. Then, the carbon concentration was calculated using the following formula:

$$\text{Ash }\% = \frac{w\,105 - w\,400}{w\,105} \text{X } 100 \qquad (1)$$

$$C\% = Ash\%(0.58) \qquad (2)$$

Where, C: the organic carbon concentration, w105: weight of dry ground plant sample at 105 ºC, w400: weight of ground plant sample at 400 ºC and 0.58 is the carbon concentration in the organic matter of wood.

Similarly, volume (cm^{-3}) for wood density estimation was estimated using water displacement method. Wood density was the ratio of oven dry weight of wood (g) and volume (cm^{-3}) (McDonalds *et al*., 1995). The carbon concentration and wood density analysis were performed at Holetta research centre, Ethiopia (www.eiar.gov.et/index.php).

The carbon mass in the above ground biomass of each stem section was estimated using volume of a particular section calculated using Smalians method (Henry *et al*., 2010) multiplied with wood density of each section.

Statistical methods

The wood density and carbon concentration among and within a species were analysed using three way of analysis of variance (α=0.05). Tree species, plant parts and h_{rel} considered as fixed factors and each tree was considered as random factor. The analysis was performed using SAS/STAT® GLM procedure (SAS Institute Inc., 2012). The general model can be expressed as:

$$Y = \mu + \alpha i + \beta j + \gamma k + (\alpha\beta)ij + (\beta\gamma)jk + (\alpha\gamma)ik + (\alpha\beta\gamma)jk + (\delta * (\alpha\beta\gamma)ijk) + \varepsilon \qquad (3)$$

Where ,Y is the % C and wood density of the sample, μ is the mean value, αi is the species effect, β_j is the plant parts effect, γ_k is the stem position effect, $(\alpha\beta)_{ij}$ is the interaction effect of between species and plant parts, $(\alpha\gamma)_{ik}$ is the interaction effect of between species and stem postion , $\alpha\beta\gamma)_{jk}$ is the interaction effect of between species, plant parts and stem position and $(\delta*(\alpha\beta\gamma)_{ijk})$ is the random effect of each tree on the fixed factors, and ε is the error.

A Pearson correlation analysis was performed using SAS/STAT® CORR procedure (SAS Institute Inc., 2012) for carbon concentration and wood density along tree species and dendrometric variables. Similarly, a logistic model analysis was performed using SAS/STAT® LOGISTIC procedure (SAS Institute Inc., 2012) to see wether the carbon concentration and wood density difference among the tree species, plant parts and tree height.

The logistic model was performed with the following structure:

$$P = \frac{1}{1+e^{-z}} \qquad (4)$$

In which P is the probability that there will be organic carbon difference at a specified height and z is a linear function, expressed as follows:

$$(z = a0 + a1xh + a2xDn + a3xd) \quad (5)$$

Where h is the h_{rel} of the sample, *DBH* is the tree diameter of the sample disc.

Results

General description

The mean, maximum, minimum and standard deviation for the major tree datas and above ground biomass for the cut sampled trees were summarized in table 1. The values were varied among the species. The mean *d* was ranged from 12.62 cm to 14.7 cm for *R. glutinosa* and *S .theifolia*, respectively. The *db* was ranged from with a maximum value of 28.10 cm to a minimum value of 6.35 cm for *O. europaea* ssp. *cuspidiata*. Similarly, the mean *ba* was ranged from 0.018 m^2 to 0.037 m^2 $tree^{-1}$ for *R. glutinosa* and *O. europaea*, respectively. The total height was ranged from with a maximum value of 14.37 m for *O. europaea* to a minimum value of 7.80 m for *S. theifolia*. The above ground biomass was varied from with a maximum value of 189.16 kg $tree^{-1}$ for *S. theifolia* to a minimum value of 26.78 Kg $tree^{-1}$ for *A. abyssinicus*.

Table 1: *Mean growth characteristics of sampled trees for % OC and wood density for five studied tree species.*

Tree spp	Spp	*d* (cm)	*db* (cm)	*h* (m)	*hc* (m)	*hb* (m)	*ba* (m^2)	Dry biomass (kg)			
								Stem	Br27	Br2	Above
A. abyssinicus	Mean	13.08	18.17	12.63	7.53	4.53	0.029	52.10	14.66	9.87	76.63
	Std dev	3.79	7.99	4.76	4.76	2.64	0.025	67.92	2.46	3.80	70.71
	Minimum	7.40	12.25	10.20	4.30	2.20	0.012	8.45	12.60	5.73	26.78
	Maximum	21.25	27.25	17.00	13	7.40	0.058	130.36	17.38	13.20	157.36
	N	3	3	3	3	3	3	3	3	3	3
O. europaea	Mean	16.18	21.08	10.63	6.80	2.70	0.037	108.16	20.44	22.53	151.14
	Std dev	5.48	6.35	1.10	1.82	1.48	0.022	95.51	5.46	15.28	115.68
	Minimum	10.80	15.75	10.00	5.70	1.70	0.020	22.96	16.56	6.57	46.09
	Maximum	21.75	28.10	11.90	8.90	4.40	0.062	211.40	26.68	37.03	275.11
	N	3	3	3	3	3	3	3	3	3	3
O. rochetiana	Mean	13.32	16.43	14.37	8.50	4.97	0.023	95.99	41.86	20.48	158.33
	Std dev	6.40	6.45	4.41	5.17	2.12	0.017	118.31	41.24	17.55	176.91
	Minimum	8.60	10.35	11.20	3.90	3.50	0.008	11.77	13.42	10.08	35.81
	Maximum	20.60	23.20	19.40	14.10	7.40	0.042	231.25	89.15	40.75	361.15
	N	3	3	3	3	3	3	3	3	3	3
R. glutinosa	Mean	12.62	15.33	12.57	5.13	3.30	0.018	34.14	21.62	8.22	63.99
	Std dev	0.98	0.83	4.19	1.01	1.82	0.002	1.97	9.14	3.61	11.68
	Minimum	12.00	14.45	9.90	4.00	2.20	0.016	32.01	11.21	4.29	52.22
	Maximum	13.75	16.10	17.40	5.90	5.40	0.020	35.90	28.29	11.38	75.57
	N	3	3	3	3	3	3	3	3	3	3
S. theifolia	Mean	14.07	16.92	9.37	5.80	3.53	0.024	62.07	27.71	25.43	115.21
	Std dev	1.50	4.23	2.36	2.36	1.54	0.011	52.37	15.77	4.68	72.17
	Minimum	9.70	12.25	7.80	3.10	2.50	0.012	13.92	10.84	20.21	44.97
	Maximum	16.50	20.50	10.80	7.50	5.30	0.033	117.82	42.09	29.25	189.16
	N	3	3	3	3	3	3	3	3	3	3

Where; N: number of trees, d: dbh, db: diameter at the stump height, h: total height, hc: commercial height, hb: branching height, ba: basal area, br27: biomass of thick branches (2-7 cm), br2: biomas of thin branches (≤ 2 cm) plus leaves, above: total above ground dry biomass.

Correlation of dendrometric variables to dry biomass fractions

The Pearson correlation coefficient value was summarized in table 2. The results revealed carbon concentration, wood density and carbon mass along tree volume were non-correlated to most tree variables. However, wood density was moderately to highly correlate to commercial height, basal area and stem biomass for *A. abyssinicus* and total height, branch biomass and above ground biomass for *S. theifolia*. The carbon concentration was correlated to total height, commercial height and stem biomass in *A. abyssinicus*, to thick branches in *O. europaea* ssp. *cuspidiata* and to diamater at breast height, total height, basal area, stem biomass, small branches plus leaves and total above ground biomass in *R. glutinosa*.

Table 2: *Pearson coorelation values for different dendrometric variables.*

Spp	**Properties**	**Tree variables**								
		dbh	**h**	**hc**	**ba**	**stem**	**Br27**	**Br2**	**above**	**Volume**
A. abyssinicus	WD	-0.21^{ns}	-0.05^{ns}	0.99^{*}	0.99^{*}	0.99^{**}	-0.9^{ns}	-0.64^{ns}	-0.12^{ns}	-0.04^{ns}
	C (%)	-0.99^{ns}	-0.95^{ns}	-0.96^{ns}	-0.97^{ns}	-0.95^{ns}	-0.2^{ns}	-0.95^{ns}	-0.97^{ns}	-0.95^{ns}
	Cmass	0.99^{ns}	0.99^{*}	0.99^{*}	0.99^{ns}	0.99^{*}	-0.2^{ns}	0.79^{ns}	0.99^{ns}	0.04^{ns}
O. europaea	WD	0.56^{ns}	0.89^{ns}	0.90^{ns}	0.64^{ns}	0.67^{ns}	0.82^{ns}	0.52^{ns}	0.32^{ns}	0.76^{ns}
	C (%)	0.42^{ns}	-0.06^{ns}	-0.09^{ns}	0.33^{ns}	0.30^{ns}	0.08^{ns}	0.52^{ns}	0.32^{ns}	0.17^{ns}
	Cmass	0.96^{ns}	0.98^{ns}	0.97^{ns}	0.98^{ns}	0.99^{ns}	0.99^{*}	0.92^{ns}	0.99^{ns}	0.99^{*}
O. rochetiana	WD	-0.77^{ns}	-0.78^{ns}	-0.64^{ns}	-0.81^{ns}	-0.79^{ns}	-0.8^{ns}	-0.87^{ns}	-0.80^{ns}	-0.82^{ns}
	C (%)	0.48^{ns}	0.46^{ns}	0.64^{ns}	0.43^{ns}	0.46^{ns}	0.44^{ns}	0.31^{ns}	0.44^{ns}	0.41^{ns}
	Cmass	0.99^{*}	0.99^{*}	0.97^{ns}	0.99^{**}	0.99^{**}	0.99^{ns}	0.99^{*}	0.99^{**}	-0.81^{ns}
R. glutinosa	WD	0.44^{ns}	0.34^{ns}	-0.74^{ns}	0.44^{ns}	-0.28^{ns}	-0.5^{ns}	0.89^{ns}	0.12^{ns}	0.41^{ns}
	C (%)	0.41^{ns}	0.31^{ns}	-0.77^{ns}	0.41^{ns}	-0.31^{ns}	-0.5^{ns}	0.88^{ns}	-0.16^{ns}	0.01^{ns}
	Cmass	0.95^{ns}	0.98^{ns}	0.56^{ns}	0.95^{ns}	0.92^{ns}	0.82^{ns}	0.55^{ns}	0.99^{ns}	0.13^{ns}
S. theifolia	WD	-0.95^{ns}	-0.99^{*}	-0.86^{ns}	-0.95^{ns}	-0.97^{ns}	-1.0^{**}	-0.99^{ns}	-0.98^{ns}	-0.91^{ns}
	C (%)	0.02^{ns}	-0.36^{ns}	0.23^{ns}	-0.00^{ns}	-0.54^{ns}	-0.3^{ns}	-0.18^{ns}	-0.47^{ns}	0.12^{ns}
	Cmass	0.99^{ns}	0.86^{ns}	0.99^{*}	0.99^{ns}	0.74^{ns}	0.89^{ns}	0.93^{ns}	0.79^{ns}	0.99^{*}

Note: Above: stem+thick branches (2-7) + (thin branches+ leaves), $* = p \le 0.05$, $** = p \le 0.01$, $*** = p \le 0.001$, *Hc: commercial height, h: total height, dbh: diameter at breast height, db: tree basal diameter, WD: wood density, C % carbon content, Cmass; carbon mass*

Variation in carbon concentration and wood density

The carbon concentration and wood density data was analyzed using sas proc glm and the result was presented in table 3. The carbon concentration was significantly varied among and within a species, plant parts and interaction of tree species with plant parts. Similarly, the wood density was significantly varied among the species, plant parts and stem position and interaction tree species with plant parts. Carbon mass along volume of a tree was significantly varied among plant parts and tree height. However, interaction of tree species with stem position was non-significant.

Table 3: *Main results of the GLM procedure for % C (n=105, R^2 =0.68) and WD (n=105, R^2=0.61).*

Sources	DF	Type III SS	Mean square	F value	Pr >F
Carbon content					
Species	4	8.76496642	2.19124161	11.07	<.0001
Parts	2	75.27960206	37.63980103	190.14	<.0001
Height	4	1.17057333	0.29264333	1.48	0.2181
Spp* parts	8	6.15808061	0.76976008	3.89	0.0008
Spp*height	16	1.05554667	0.06597167	0.33	0.9915
Wood density					
Species	4	0.31047130	0.07761783	75.74	<0.0001
Parts	2	4.41151200	2.2057560	2152.46	<0.0001
Height	4	0.111800800	0.02950200	27.29	<0.0001
Spp* parts	8	0.17576990	0.02197124	21.44	<0.0001
Spp*height	16	0.01060533	0.00066282	0.65	0.8342
C mass					
Species	4	0.30199450	0.07549863	0.66	0.6191
Parts	2	5.03748760	2.51874380	22.15	<0.0001
Height	4	1.28663912	0.32165978	2.83	0.0310
Spp* parts	8	0.39690706	0.04961338	0.44	0.8952
Spp*height	16	0.54423355	0.03401460	0.30	0.9953

Where, Spp: species, C: carbon, DF: degree of freedom, ss: sum of squares.

The carbon concentration, wood density and carbon mass under tree species, plant parts, tree height and its interaction was evaluated using a single logistic model analysis and the results were presented in table 4 and 5. The evaluated paramater revealed that the carbon concentration and wood density were highly significant ($p < 0.001$). However, the Wald analyzed results of carbon mass was revealed that non-significant ($p = 0.8111$). The maximum livelihood estimated for these parameters were highly significant along plant parts (stem, branch and leave), tree height and interaction of plant parts with tree height ($p \leq 0.0001$). However, the carbon concentration among tree species, interaction of tree species with plant parts and trees with tree height were non-significant. The evaluated results for the presence and absence of wood density and carbon mass concentration among, tree species, plant parts and tree height and its interaction were non-significant (Table 5).

Table 4: *Logistic model analysis results.*

Carbon content (%)				**Wood density**			**Carbon mass content**		
Parameter	χ^2	DF	Pr > χ^2	χ^2	DF	Pr > χ^2	χ^2	DF	Pr > χ^2
Likelihood ratio	217.60	34	<.0001	310.45	34	<.0001	152.69	34	<.0001
Score	83.9907	34	<.0001	97.09	34	<.0001	77.30	34	<.0001
Wald	84.1350	34	<.0001	81.92	34	<.0001	26.65	34	0.8111

Table 5: *Anlaysis of maximum likelihood estimates with logistic model.*

Carbon content (%)						**Wood density**				**C mass content**			
Parameter	DF	Estimate	SE	Wald value	Pr > χ^2	Estimate	SE	Wald value	Pr> χ^2	Estimate	SE	Wald value	Pr> χ^2
Spp	1	-0.2	0.3	0.5	0.5	0.10	0.43	0.05	0.82	-0.02	5.69	0.00	1.00
Parts	1	-19.1	5.7	11.3	0.0	-48.55	83.64	0.34	0.56	62.89	140.6	0.20	0.66
Height	1	-3.3	0.9	12.9	0.0	-6.98	13.94	0.25	0.62	8.39	20.38	0.17	0.68
Spp*parts	1	-0.2	0.3	0.6	0.5	0.27	0.46	0.34	0.56	0.01	5.69	0.00	1.00
Spp*height	1	0.1	0.1	1.1	0.3	-0.11	0.10	1.27	0.26	-0.00	0.10	0.00	1.00
Parts*height	1	3.3	0.9	14.1	0.0	8.05	13.93	0.33	0.56	-7.92	20.38	0.15	0.70

Carbon concentration and wood density along tree species

The carbon concentration was statistically significant with *O. rochetiana* with all other tested species. But, it was statistically non significant among the other four studied species (*A. abyssinicus*, *O. europaea* ssp. *cuspidiata*, *R. glutinosa* and *S. theifolia*), although, numerical difference was observed. Neverthless, wood density was statistically significant among all the five studied species. The carbon concentration was ranged from with a maximum value (57.12 %) for *O. rochetiana* to the minimum value for (56.43 %) for *A. abyssinicus* (Figure 2). Similarly, the wood density was ranged from with a maximum value 0.67 g cm^{-3} for *O. europaea* ssp. *cuspidiata* to the minimum value 0.42 g cm^{-3} for the same species of carbon concentration (Figure 3). *O. europaea* ssp. *cuspidiata* and *R. glutinosa* had intermediate carbon concentration while *O. rochetiana*, *R. glutinosa* and *S. theifolia* had intermediate wood density (Figure 3).

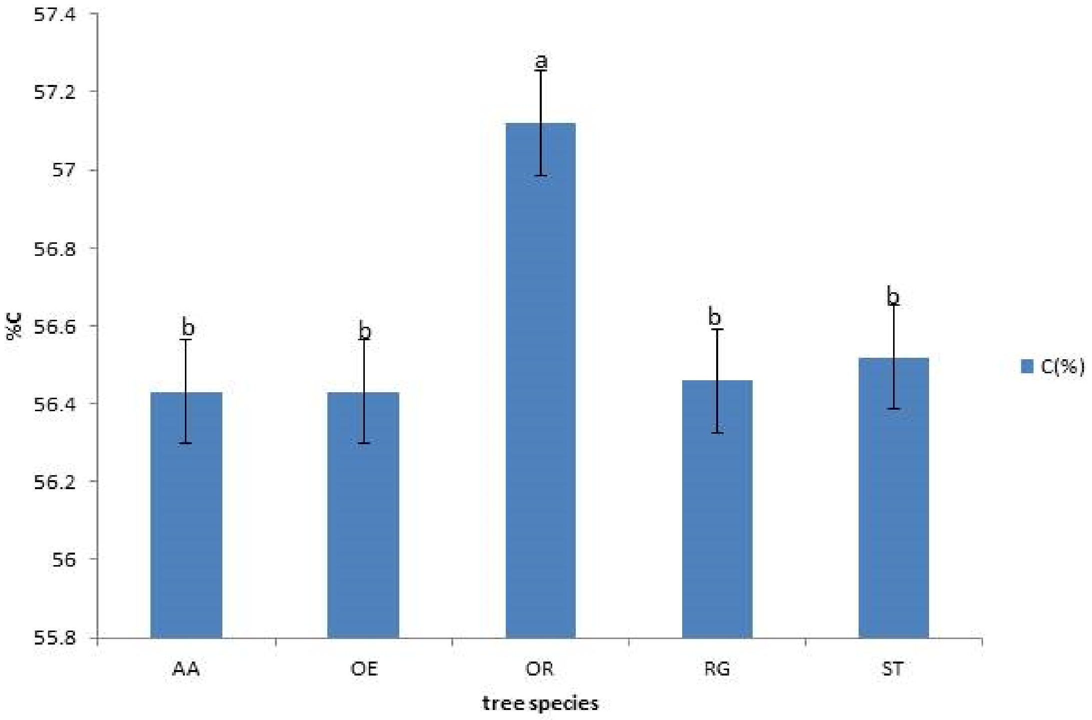

Fig. 2: *Carbon concentration (%) by species.*

Where, AA: *Allophyllus abyssinicus,* OE*: Olea europea* ssp. *cuspidiata,* OR*: Olinia rochetiana,* RG*: Ruth glutinosa,* ST*: Scolopia theifolia*.

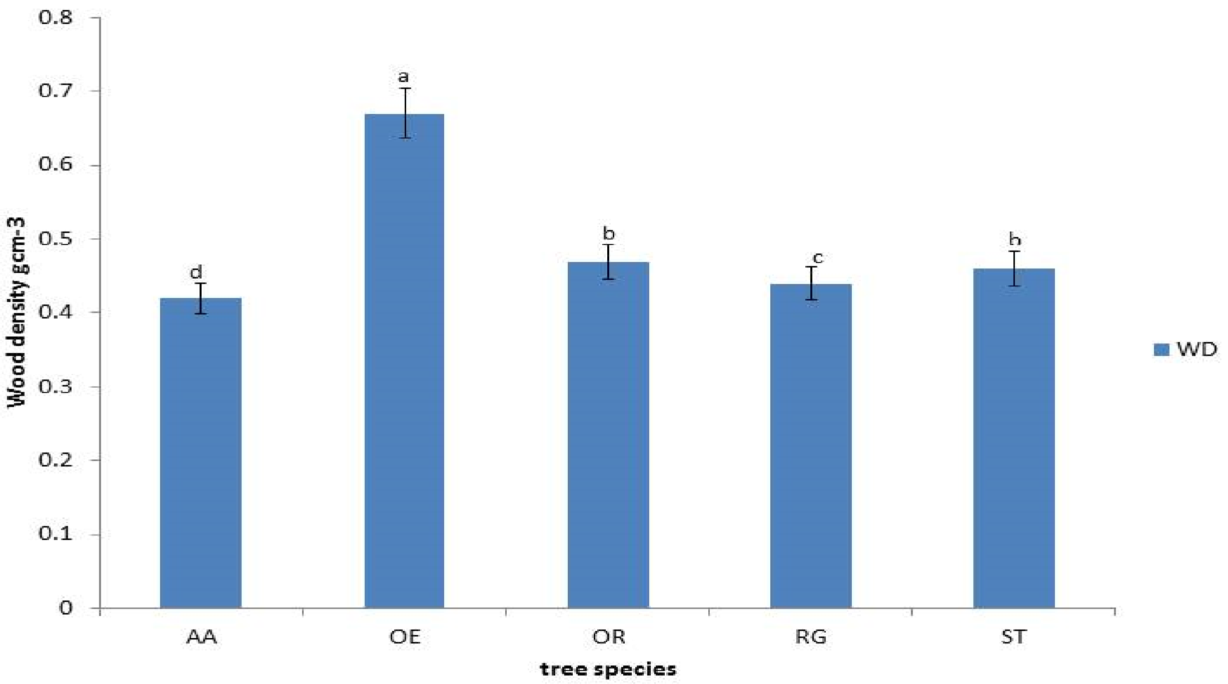

Fig. 3: *Wood density (g cm^{-3}) along the five studied species.*

Where, AA: *A. abyssinicus*, OE: *O. europaea*, OR: *O. rochetiana*, RG: *R. glutinosa*, ST: *S. theifolia*.

Carbon concentration along plant parts

A carbon concentration and wood density was statistically significant along plant parts within and among a species. The carbon concentration and wood density for stem parts was always higher than branch and leaves parts. The carbon concentration in the plant parts was ranged from with a maximum value (56.98 %) for stem parts to the minimum value (54.53 %) for leaves parts (Figure 4). The wood density in the plant parts was also ranged from with a maximum value (0.59 g cm^{-3}) for the stem parts to the minimum value (0.47g cm^{-3}) for branch parts (Figure 5). *O. rochetiana* and *O. europaea* stem, branch and leaves parts had the highest carbon concentration and wood density values than *A. abyssinicus*, *R. glutinosa* and *S. theifolia* stem, branch amd leaves parts, respectively. On the contrary *A. abyssinicus* stem, branch and leaves parts had the lowest carbon concentration and wood density values than *O. rochetiana*.

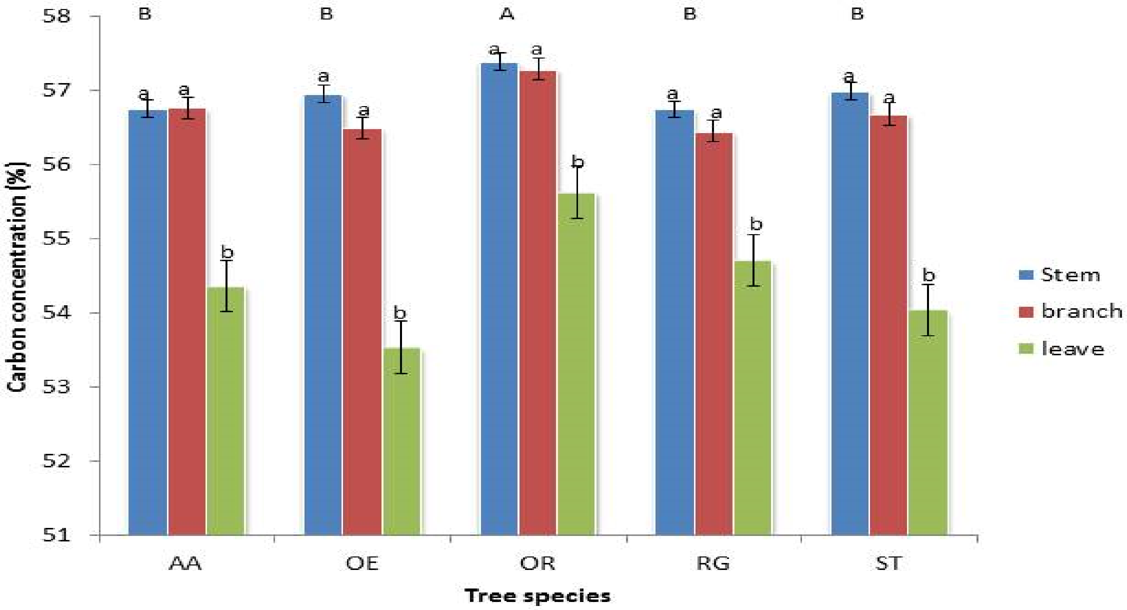

Fig. 4: *Carbon concentration (%) species with plant parts.*

Where, AA*: A. abyssinicus*, OE*: O. europaea*, OR*: O. rochetiana*, RG*: R. glutinosa*, ST*: S. theifolia. Capital letters represent carbon concentration (%) differences among species where as small letters represent differences in carbon concentration (%) among plant parts within a species.*

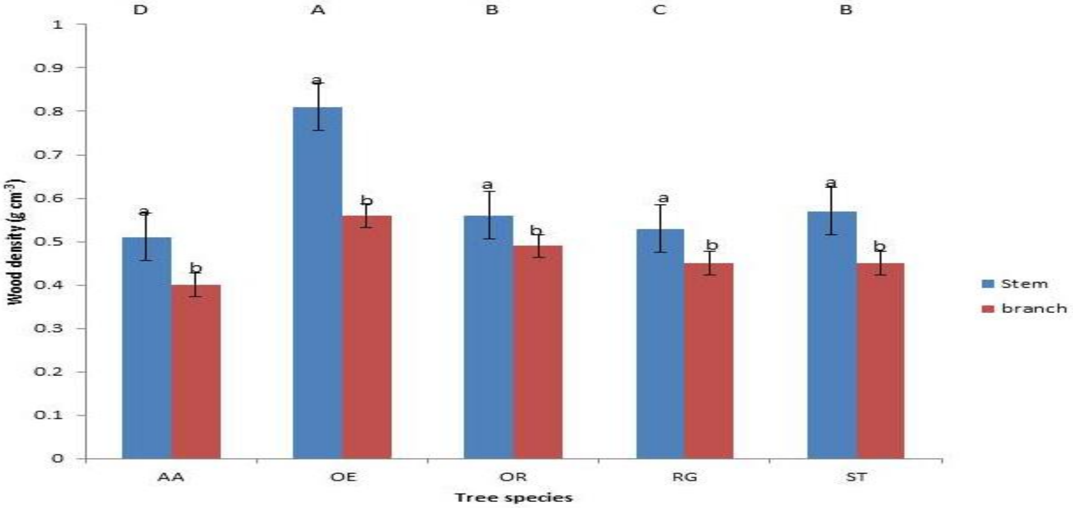

Fig. 5: *Wood density (g cm^{-3}) species interaction*parts.*

Where, AA*: A. abyssinicus*, OE*: O. europaea*, OR*: O. rochetiana*, RG*: R. glutinosa*, ST*: S. theifolia. Capital letters represent wood density differences among species where as small letters represent wood density difference among plant parts within a species.*

Carbon concentration and wood density along stem position

The carbon concentration and wood density along stem position within and among a species were statistically significant. In addition, the carbon concentration and wood density was showed a decreasing trend along with increasing in stem position for all the species (Figure 6 and 7). The carbon concentration in the stem position was ranged from with a maximum value (57.10 %) for stump position to the minimum value (54.53 %) for top height position. Similarly, the wood density in the stem position was ranged from with a maximum value (0.62 g cm^{-3}) for stump height (position) to the minimum value (0.4 g cm^{-3}) for commercial height (≤ 7 cm). *O. rochetiana* and *O. europea* ssp. *cuspidiata* stem positions had higher value of both carbon concentration and wood density as compared to other tested species (Figure 6 and 7).

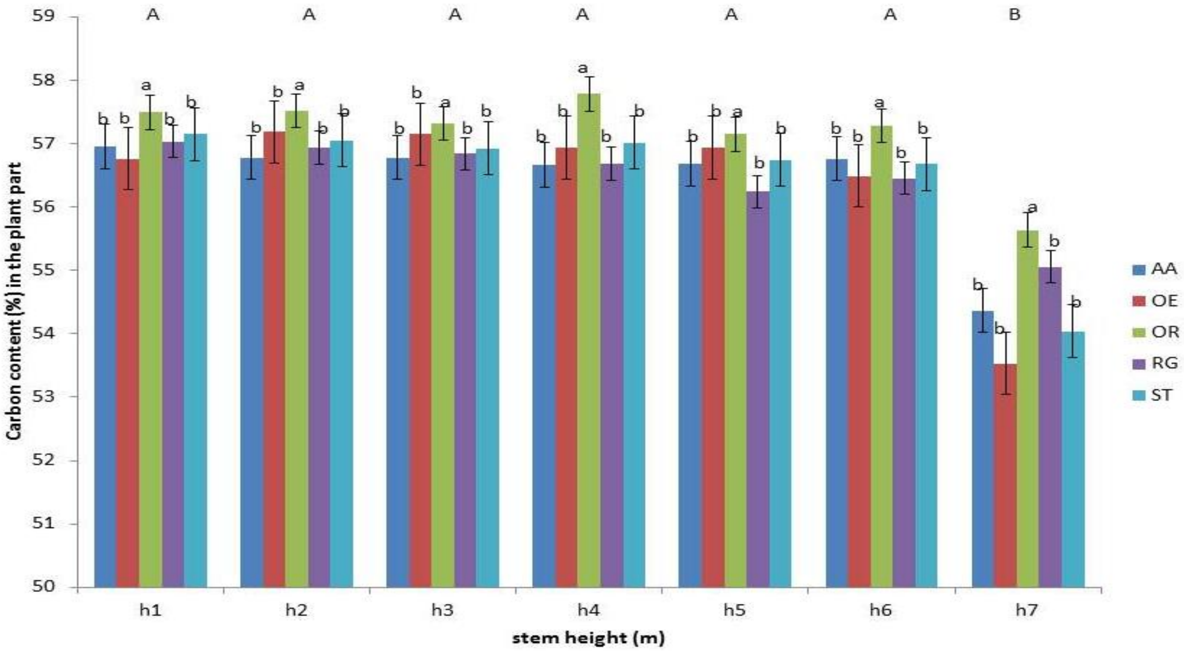

Fig. 6: *Carbon concentration (%) along plant height (spp*height).*

Where, AA: *A. abyssinicus*, OE: *O. europaea*, OR: *O. rochetiana*, RG: *R. glutinosa*, ST: *S. theifolia, h1: stump height, h2: stem height at 1m, h3: stem height at 2 m, h4: stem height at 3 m, h5: stem height at 4 m, h6: stem height at 5m, h7: stem at commercial height. Capital letters represent carbon concentration (%) differences among species where as small letters represent carbon concentration differences among stem height within a species.*

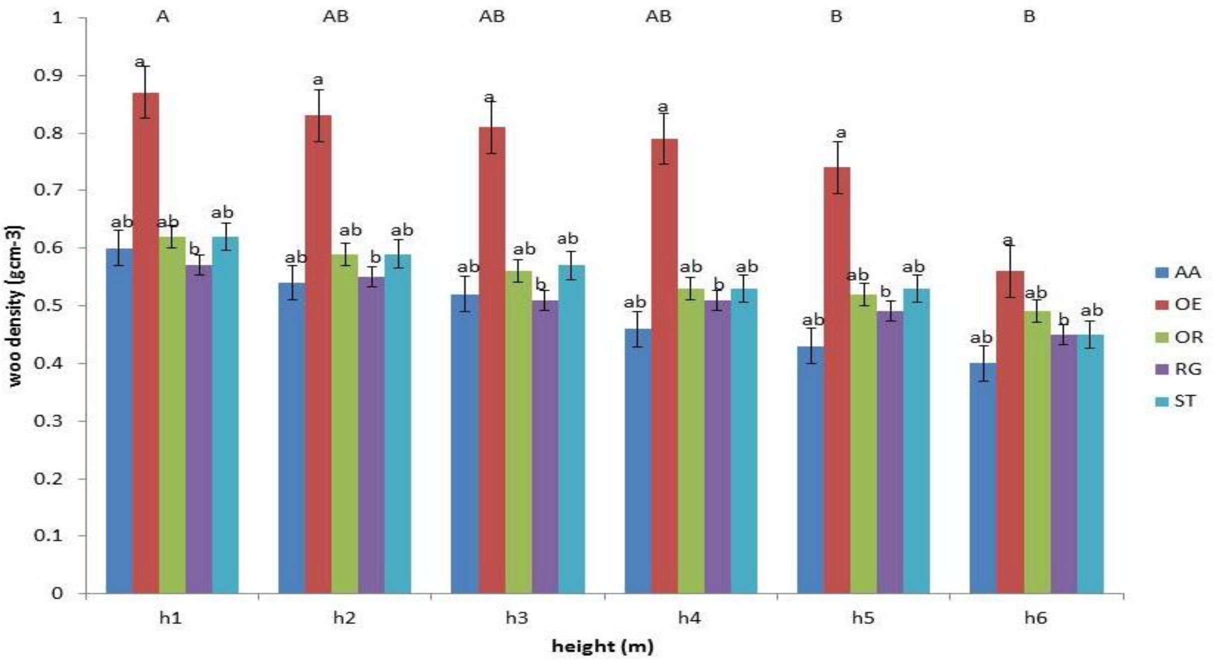

Fig. 7: *wood density (g cm^{-3}) along species with plant height (species *different tree height).*Where, AA: *A. abyssinicus*, OE: *O. europaea*, OR: *O. rochetiana*, RG: *R. glutinosa*, ST: *S. theifolia, h1: wood density at stump height, h2: wood density at 1 m, h3: wood density at 2 m, h4: wood density at 3 m, h5: wood density at 4 m, h6: wood density at 5m. Capital letters represent wood density (g cm^{-3}) difference among species where as small letters represent wood density differences among stem height within a species.*

Discussion

Estimation of carbon concentration and wood density for tropical forests is important to have a better understanding and better information about these species in their forests and to show their importance in global carbon cycle budgeting and commercial use of wood (Brown, 2002; Woodcock and Shier, 2002; Nogueira *et al*., 2005). Destructive sampling methods are better in carbon concentration estimation than non distructive sampling methods. Wood density is the second most important parameter after tree diameter for above ground biomass estimation (Chave *et al*., 2005).

The carbon concentration and wood density for five native species: *A. abyssinicus, O. europaea* ssp. *cuspidiata, O. rochetiana, R. glutinosa* and *S. theifolia* were estimated at laboratory condition for plant parts: stem, branch, leaves and seven stem position: from stump height to commercial height. The results revealed that the carbon concentration and wood density were varied among and within the species, plant parts and stem position. This was might be due to differences in physical and chemical properties of wood, elevation gradient and growth habit of the species. The amount of carbon concentration found in this study was also in line with other findings (Herrero *et al*., 2011; Chavan and Rasal, 2012). Thomas and Martin (2012) reported a wood carbon concentration from 41.9 % to 51.6 % for tropical species, 45.7 % to 60 % for subtropical/Mediterranean species and 43.5 % to 55.6 % for temperate/boreal species. In this study, stem part had higher carbon concentration than branch and leaves parts. Thomas and Martin (2012) reported a stem C concentration was varied from 37 %, 76 %, 81 % and 63 % for bark, branch, twig, coarse root and fine root, respectively.

The wood density our studied species was ranged from with a maximum value 0.67 g cm^{-3} to the minimum value 0.44 g cm^{-3}, this result was also in line with a wood density reported by several authors for tropical tree species: (0.69 g cm^{-3}) (Brown *et al*., 1989; Brown, 1997; Houghton *et al*., 2001), (0.58 g cm^{-3}) (Nogueira *et al*., 2007), (0.65 g cm) (Chave, 2006), (0.35 to 0.87 g cm^{-3}) (Parolin and Worbes, 2000) and (0.27 to 0.76 g cm^{-3}) (Yeboah *et al*., 2013).

The wood density for our studied species was also varied among and within a species plant parts and stem postion. This was might be due to differences in physical and chemical properties of wood and the presence of late wood and early wood and difference in heart wood and sapwood as well and stem morphology and growth habit. *O. europaea* ssp. *Cuspidiata* had the highest wood density as compared other studied species, this was might be due to its slow growing nature, higher wood strength and chemical composition of wood. However, *A. abyssinicus* had the lowest wood density as compared to others studied species, this was might be due to its fast growing nature and lower wood strength. Several findings reported variation in wood density among and within a species for tree species grown in the tropics (Thomas, 1996; Henry *et al*., 2010; Redondo-Brenes and Montagnini, 2006; Weber and Sotelo Montes, 2005 and 2008).

Wood density was significantly different among the stem position and generally increased from top to bottom. The difference in wood density was might be due to differences in structural variations at the molecular, cellular and organ levels. Higher values were found at stump height and showed a decreasing trend along with increasing in stem position (height). Daniel *et al*. (2013) found an increasing trend of wood density from top to bottom parts of a tree for different tree species grown in the tropics and similar studies elsewhere (Espinoza, 2004; Nogueira *et al*., 2005; Weber and Sotelo-Montes, 2005 and 2008). Nogueira *et al*. (2005) found decreasing trends in wood density from breast height to the top parts of the bole for trees grown in Amazone forest. This decreasing in wood density was might be due to increasing proportions of juvenile wood (Zobel and van Buijtene, 1989),

The other reason for the difference in wood density and carbon concentration was might be due to differences in heart wood and sap wood within and among a species. Several researchers are also reported higher values of wood density and carbon concentration in the bottom parts of a tree than top parts of a tree (Desatro *et al*., 1993; Higuchi and de Carravalho, 1994; Barahona, 2005). Fearnside (1997) found difference in wood densities along heartwood, sapwood and bark. Herrero *et al*. (2011) reported higher wood density and carbon concentration in heart wood than sap wood and bark for three Mediterranean *Pinus* species grown in Spain. Castaño-Sanramaría and Bravo (2012) reported significant difference in carbon concentration between tree species along stems of sessile oak (*Quercus petrae*a) (Matt.) Leibl.) and Pyrenean oak (*Quercus pyrenica* Willd.) in the Cantabrian Range (NW Spain).

Generally the carbon concentration and wood density in the five studied species mentioned above showed similar trends along plant parts and stem position, although, variation was observed among and within a species. In addition, this carbon concentration and wood density for these studied species can be serving as a source of information for similar dry afromontane forests found in the country.

Conclusions

The carbon concentration and wood density varied among and within a species, plant parts and stem position where wood was sampled. The carbon concentration and wood density for *O. rochetiana* and *O. europaea* ssp. *cuspidiata* were higher as compared to other studied species. Higher carbon concentration and wood density were found at the stump height (stem position) than other tree parts. Similarly, stem parts of the wood had higher carbon concentration and wood density than other parts. Estimation of carbon concentration in the plant sample and wood density at species level is very important to show the important of these species for climate change mitigation and adaptation, we suggest the application of the species and site specific carbon content estimation and wood density models in similar mixed forests of Ethiopia in particular and other tropical montane forest in general.

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Photographs

Photo 1: *Partial view of Gallessa forest patch.* **Photo by***: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 2: *Partial view of Chilimo forest patch.* **Photo by***: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 3: *Partial view of Gaji forest patch.* ***Photo by:*** Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).

Photo 4: *Big trees of Juniperus procera in the natural forest.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 5: *Diamater measurement using diameter tape for big trees of Podocarpus falcatus.*
Photo by: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).

Photo 6: *Different stratification of the natural forest.* ***Photo by***: *Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 7: *Eucalyptus saligna plantation adjacent to Chilimo natural forest where soil sampled.* **Photo by***: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 8: *Cupressus lusitanica plantation adjacent to Chilimo natural forest where soil sampled.* **Photo by***: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 9: *Pinus patula plantation adjacent to Chilimo natural forest where soil sampled.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 10: *Degraded land adjacent to Chilimo natural forest where soil sampled.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 11: *Crop land with teff cultivation adjacent to Chilimo natural forest where soil sampled.*
Photo by*: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 12: *Different fractions of biomass components of a particular tree in the natural forest.*
Photo by*: Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).*

Photo 13: *Leave plus small branches (≤ 2 cm) of the biomass fractions.* ***Photo by:*** *Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).*

Photo 14: *Thick branches biomass (2-7 cm) fraction.* ***Photo by****: Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).*

Photo 15: *Soil sampling in the natural forest.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 16: *Bulk density sampling using metallic cylinder in the natural forest.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 17: *Forest floor sampling in the natural forest.* ***Photo by:*** *Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 18: *Big dead wood samples had fallen in the natural forest.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 19: *Illegally cut stumps found in the natural forest.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 20: *Litter fall of Eucalyptus saligna plantation.* ***Photo by****: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*

Photo 21: *Wood sampled in different stem of Allophyllus abyssinicus.* ***Photo by****: Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).*

Photo 22: *Wood sampled for Olinia rochetiana.* ***Photo by****: Mehari A. Tesfaye (2013) (Chilimo, Ethiopia).*

***Photo 23:** Shrubs grown inside the Chilimo natural forest.* ***Photo by**: Mehari A. Tesfaye (2012) (Chilimo, Ethiopia).*