Tesfaye *et al. Journal of Ecology and Environment* (2020) 44:3
https://doi.org/10.1186/s41610-019-0146-z

Journal of Ecology
and Environment

RESEARCH Open Access

Aboveground biomass, growth and yield for some selected introduced tree species, namely *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula* in Central Highlands of Ethiopia

Mehari Alebachew Tesfaye[1]*, Oliver Gardi[2], Tesfaye Bekele Anbessa[3] and Jurgen Blaser[2]

Abstract

Background: Species of the genera *Eucalyptus*, *Cupressus*, and *Pinus* are the most widely planted tree species in the country in general and in Chilimo dry Afromontane forest in particular. Eucalyptus covers 90% of the total planted forest area in the country. However, only limited information exists in the country regarding aboveground biomass (AGB), belowground biomass (BGB), growth, and yield. This study was conducted to assess the variables on 25 and 30 years of age for three planted species: *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula* in Chilimo plantation forest, in the Central Highlands of Ethiopia. A two-times inventory was conducted in 2012 and 2017. A total of nine square sampled plots of 400 m^2 each, three plots under *Cupressus lusitanica*, 3 *Eucalyptus saligna*, and 3 *Pinus patula* were used for data collection. Data on height, diameter, soil, and tree stumps were collected. Percent C, % N, and bulk density was performed following chemical procedure.

Results: The aboveground biomass ranged from 125.76 to 228.67 t C ha^{-1} and the basal area and number of stems from 3.76 to 25.50 m^2 ha^{-1} and 483 to 1175 N ha^{-1}, respectively. The mean annual basal area and volume increment were between 0.97 and 1.20 m^2 ha^{-1} year^{-1} and 10.79 and 16.22 m^3 ha^{-1} year^{-}1. Both carbon and nitrogen stock of the planted forest was non-significant among the tree species.

Conclusion: The aboveground biomass, growth, and yield significantly varied among the species. *Cupressus lusitanica* had the highest aboveground biomass, volume, and basal area, while *Eucalyptus saligna* had the lowest value .To a depth of 1 m, total carbon stored ranged from 130.13 to 234.26 t C ha^{-1}. The total annual carbon sequestration potential was 12,575.18 t CO$_2$ eq. *Eucalyptus* has the highest carbon stock density and growth rate than other species.

Keywords: Biomass, Carbon, Cupressus, Chilimo, Nitrogen, *Eucalyptus*, Planted forest, Pinus and Soil assessment

---

* Correspondence: meharialebachew25@gmail.com
[1]Central Ethiopia Ethiopian Environment and Forest Research Centre, Box 30708, Addis Ababa, Ethiopia
Full list of author information is available at the end of the article

Background

The world natural forest area coverage is decreasing from time to time due to deforestation (Moges et al. 2010). These result in shortage of forest products and increased environmental degradation. Forest plantations address many of these concerns. Globally, 4 million ha of plantations are established annually (Brown 1998; Cossalter and Pye-Smith 2003). Intensively managed plantations are profitable and generate competitive financial returns for their owners (Yin et al. 1998; Siry et al. 1999). The development of forest plantations reduce pressure on the remaining natural forests, rehabilitate degraded lands and improve soil fertility (Sedjo et al. 1997; Yin 1998; Tesfaye et al. 2015 and 2016). Plantation forests contribute to the livelihood improvement of many people in developing countries and provide raw materials for wood-based processing industries and wood product consumers both in the developed and developing nations (Chamshama et al. 2009). The main fast-growing and short-rotation species for plantation in the tropics and subtropics are *Eucalyptus* and *Acacia* species (FAO 2009).

Tree plantations started in the tropical world in the early twentieth century to meet the increasing demand for wood products and relieve the pressures on natural forests (Lemenih and Teketay 2004). Some planted species such as *Acacia spp*, *Cajanus cajan*, *Sesbania sesban*, and *Chamaecytisus palmensis* improve soil fertility of degraded sites by increasing soil organic matter, nutrient recycling and biological activity while reducing soil compaction (Islam and Weil 2000; Carnus et al. 2003; Tesfaye et al. 2015). Lugo (1992) reported that tree plantations accumulated more carbon and nutrients in the litter than secondary forests do with similar age. Several studies have also shown that plantation forests of *Cupressus lusinatica*, *Eucalyptus spp*, and *Pinus patula* established on degraded sites are nursing rich number of native forest flora under their canopies (Carnus et al. 2003; Lemenih et al. 2004; Lemenih and Teketay 2004b). Studies on *Cupressus lusinatica* and *Pinus patula* plantation in the South-Central highlands of Ethiopia showed that within 15–17 years after establishment on abandoned farmland, plantations assisted the restoration of 78% of native woody flora recorded in adjacent natural forests (Lemenih et al. 2004; Lemenih and Teketay 2004b). Plantation forests also facilitate recolonization of native forest flora as they provide an environment that closely resembles that of a natural forest (Yosef et al. 2017).

Historical records reveal that tree planting has begun in the country as early as the 1400s by the order of King Zera Yakob (1434 to 1468) (Bekele 2001). The practice of modern plantations, however, started by Emperor Menillik II (1889–1913) in 1895 by introducing exotic tree species from Italy, Portugal, Australia, and Greece to alleviate firewood and construction wood shortage in the newly established capital, Addis Ababa (Bekele 2003). Similar endeavors during the Derge regime (1974–1991) led to a rapid expansion of large-scale afforestation and community plantations (Moges et al. 2010). In 1981, peri-urban fuelwood plantation projects were launched in major cities such as Addis Ababa, Adama, Debre Berhan, Gondar, and Dessie (EPA 1998). The current government uses afforestation/forest restoration/plantations for the rehabilitation of degraded lands and has pledged to reforest/afforest 15 million ha for the coming 20–30 years, including 5 million ha in the Climate-Resilient Green Economy (CRGE) strategy (CRGE 2011). Deforestation rate in Ethiopia amounts to 92,000 ha^{-1} year^{-1}, while, new plantation area change is about 18,000 ha^{-1} year^{-1} (Moges 2015). This results in dwindling of natural forests and critical shortage of forest products (Mussa et al. 2016).

Although forest plantation has a long history in the country, plantations are mainly monocultures of non-native species from four genera: *Eucalyptus*, *Cupressus*, *Pinus*, and *Acacia*. *Eucalyptus* species alone cover more than 90% of the total planted forest area (Bekele 2011). This species tree species are also the first non-native tree species formally introduced to Ethiopia by Emperor Minilik II from Australia in the 1890s (Pukkala and Ponjonen 1989 and 1993; Bekele 2003). About 60 different species of the genus *Eucalyptus* are reported to have been introduced in Ethiopia, but *E. globulus* and *E. camaldulensis* are the most widespread of all (Lemenih and Kassa 2014). The area coverage of *Eucalyptus* is estimated to have been 5000 ha in the 1890s (Getahun 2010) and increased to 896,240 ha in 2011 (Bekele 2011). The government also conducted a serious restoration of degraded lands to provide woody and non-woody forest products and improve the soil quality by increasing soil organic matter (SOM), biological N_2 fixation, recycling of nutrients, soil water infiltration, storage capacity, and soil biological properties using the fast-growing *Cupressus lusitanica*, *Eucalyptus spp*, and *Pinus patula* (Young 1997). As a result, the forest plantation area has increased from 190,000 in 1990 to 1,000,000 ha in 2010 (Bekele 2011). Typical biological attributes that attract farmers to plant *Eucalyptus* include its fast-growing nature, outcompeting most native tree species, its coppicing ability, ease of management (such as non-palatability by cattle), market demand, and its ability to grow well on degraded lands (Jagger and Pander 2014). Moreover, farmers' having limited farm size and planting up to 40,000 stems per ha^{-1} (Jenbere et al. 2011; Mekonnen et al. 2007) still experience a relatively good growth performance. Farmers themselves have preference for *Eucalyptus* poles, for farm implements, constructing houses, and fences. In addition, the sale of *Eucalyptus* poles and products has contributed to raise farm income, reduce poverty, increase food security, and diversify smallholder farming systems in many areas of the country (Zerfu 2002). One other advantage of *Eucalyptus* plantations is that they play a great role as a main source of fuelwood for urban and rural people. Similar benefits that are achieved with *Cupressus lusitanica* and *Pinus patula* are fast-growing compared to native tree species, have high market demand, and plantations are easy to establish.

Plantations of non-native species are the main source of round wood and energy wood in Ethiopia (EFSR 2015); this is because forest policies related to management of natural forests are mainly conservation-oriented. Plantations enhance natural regeneration of native tree species in degraded lands much faster than physical soil-water conservation measures do (Tesfaye et al. 2004). They also contribute to local and national economy through income diversification and wood industry expansions. Local communities protect and conserve most of the natural forests and in return, they are allowed to harvest non-timber forest products (NTFPs) but do not have the right to cut trees. In addition, cutting high-value indigenous tree species such as *Juniperus procera*, *Podocarpus falcatus*, *Hagenia abyssinica*, *Olea europea*, and *Cordia africana* is prohibited by law, because these species are endangered due to deforestation. This had encouraged the expansion of plantations of fast-growing tree species.

The various community forestry development approaches in the past was criticized for being forceful and ignoring the local communities' interests, rights, and lack of clearly set objectives, benefit sharing-mechanisms and genuine community participation and fail to attain its goals. A report indicates that millions of hectares of degraded lands have been annually planted with billions of seedlings. However, success in plantations of degraded sites is greatly constrained by poor survival of seedlings and technology support because of lack of appropriate post-planting care including protection from free grazing, poor seedling quality, and poor species-site matching. In addition, no proper silvicultural activities were implemented in this regard. Therefore, all the forest development and conservation efforts were not unable to prevent deforestation and forest degradation in the country.

Well-designed silvicultural management option—with a strong research support is required. But there are no detailed and well-organized research outputs in these regards in the country in general and in the study areas in particular. In addition, the forest management tools are very scarce except few works done by the following authors: Vanclay (1994), Woldeyohannes (2005), Zewdie et al. (2009), Fayolle et al. (2013), Ngomanda et al. (2014), and Tesfaye et al. (2015, 2016). These researchers reported forest growth and yield models are key tools for the sustainable forest management of both plantation.

In order to reduce pressure on Chilimo dry Afromontane forest, around 450 ha of degraded lands around the natural forest were planted using *Eucalyptus saligna*, *Pinus patula*, and *Cupressus lusitanica* in 1988. These forests served as income generation schemes for more than 20,000 inhabitants and sources of fuel wood, construction wood, and farm implements (Shumi 2009; Tesfaye 2015). The plantations seem to be adapted to the site conditions, seem to be socially acceptable, and showed good performance (Mekonnen et al. 2006; Alebachew 2012; Amha et al. 2017).

Unfortunately, since their establishment, no adequate information was collected and analyzed with regards to their growth rate, timber production potential and carbon storage potential, what would be important for rational decision-making by forest managers and local farmers, for the sustainable management of the plantations and their promotion. Their role for climate change mitigation and adaptation, both at local and national levels is not yet known. Therefore, the aim of this study was to assess variation in carbon stock among the species, their growth and yield of the three aforementioned fast-growing plantation forests in Chilimo in order to establish about management options for optimizing the productivity, and carbon potential of such plantations. Moreover, this research output can serve as a working document for the promotion of these tree species in the study in particular and other areas in general.

Material and methods

Species description

Eucalyptus saligna (Key Bahirzaf)

E. saligna belongs to the family Mytraceae. *E. saligna* is named as Keybahirzaf (Amh.), Barzaf (Ader.), Akakiliti Barzaf dima (Or.), Red River gum, or Murray red gum (Eng.) (Bekele et al., 1993). In Ethiopia, large-scale dieback of seedlings in the first dry season following plantings has frequently occurred with *E. globulus* species and has not been recorded with *Eucalyptus saligna* set of new species elimination trials in rainfall zones of less than 1000 mm and altitude of less than 2000 m needed in Ethiopia (Little et al. 1985). Research results stated that *E. saligna* tolerates high levels of soil salinity and periodic flooding (Hills and Brown 1978). It also grows in areas receiving less than 200 mm rainfall per annum (Hills and Brown 1978). A study conducted by Gartner et al. (2002), in a site polluted by Cr, finally found that Cr could be remediated using *E. saligna*.

Cupressus lusitanica (Yeferenji Tid)

Cupressus lusitanica belongs to the family Cupressaceae. *Cupressus lusitanica* is named as Yeferenji tid (Amh.), Ferenji Gatira (Or.) Mexican cypress (Eng.) (Bekele et al., 1993). It originates from the moist mountain forests of Mexico and Central America. *C. lusitanica* is a large evergreen conifer to 35 m with a straight trunk, generally conical but not regular in shape, and branches that are wide spreading. In Ethiopia, it grows in dry and moist weyna dega and dega agro-ecological zones. The branchlets grow in many planes and the branches hang down. Its bark is red-brown with vertical grooves and is gray with age. Leaves are a dull blue-green, in 4 ranks, with spreading pointed tips. It has wale cones like fat tips on branchlets, produce clouds of yellow pollen; female cones are round, 1.5 cm across, with a waxy-gray color when young. Cones ripen in 2 years, becoming brown; scales open to release many winged seeds. It is used fire wood, timber (furniture, construction), poles, posts, shade, ornamental, wind break, and live fence. Seed germination rate about 30–45% in 10–20 days and 160,000–290,000 seed per kg is found. The seed does not require treatments and can be stored for some months. The best management practices required for this species is pruning and thinning of trees in woodlots managed for timber production and trimming if grown as a live fence (Bekele Tessema 1993).

Pinus patula

Pinus patula belongs to the family Pinaceae. *Pinus patula* is named as *Pachula* (Amh.), Patula (Or.), *and Mexican weeping pine* (Eng.) (Bekele et al., 1993). An evergreen tree to 35 m with light green, weeping foliage and a long straight trunk; branches are more or less horizontal, turning up at the tips. The bark is gray to dark brown, fairly smooth, papery reddish brown on young branches. Leaves are long slender "needles", soft but hard tipped, 15–23 cm long, in bundles of 3. *Pinus patula* is the most widely planted pine tree species in tropical Africa. It is tolerant of most soils and will grow in grassland. It grows best with good water supplies but can also survive adverse conditions. In Ethiopia, it does well in moist and wet Weyna Dega agroclimatic zones in Showa, Arsi, Sidamo, and Keffa regions, 1900–3000 m (Bekele – Tessema 1993). It is used for firewood, timber, posts, and long-fiber pulp. It propagates by seedlings and the numbers of seeds per kg are 110,000–170,000 with germination 75–85% in 35–60 days. Seed treatment is live in symbiosis with mycorrhiza fungi. Inoculation may be required. A simple method is to mix the nursery soil with a part of soil where the pine species has grown before, and seeds can be stored. The required management is pruning and thinning for trees grown in timber plantations (Bekele et al., 1993).

Study site location

Chilimo dry afromontane forest is geographically located at 38° 07′ E to 38° 10′ E latitude and 9° 30′ N to 9° 50′ N longitude, with an altitude of 2170 to 3054 m above sea level in Dendi district, Western Shewa zone, Oromia Administrative Region, Central Highlands of Ethiopia. The sampled plots are located 09° 03′ 514″ N–09° 04′ 808″ N and 038° 03′ 808″ E–038° 08′ 995″ E with altitude range of 2360 to 2420 masl and slope percent of 3–20% (Table 1). The mean annual temperature of the area ranged between 15 and 20 °C and receives a mean annual precipitation of 1264 mm (Shumi, 2009). The planted site is dominated by black cotton soil with a soil depth of up to 1 m (Tesfaye 2015) and received high rainfall (> 1400 mm) mainly concentrated in June, July, and August (Adimassu et al. 2012). The farming system in the nearby area is a mixed—crop livestock system that is carried out on a subsistence scale. The dominant crops grown in the area are barley (*Hordeum vulgare*) and potato (*Solanum tubercsom*). Livestock including cattle, sheep, and equines are also an important part of the farming system. Köppen's classification defines the climate of Chilimo forest as warm temperate climate I (CWB) type (EMA 1988).

Reconnaissance survey

A preliminary discussion was held with officials of the Oromiya Wildlife and Forest Enterprise in Addis Ababa in order to get general information about Chilimo dry Afromontane natural forest and planted forests. Subsequently, a reconnaissance survey was conducted across the planted forests to have an overall impression about the forests and the study area. Then, three planted forests adjacent to the natural forest, namely *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula*, plantations were selected for further study.

Scheme of sample plot

A systematic sampling approach was implemented to conduct inventory. A total of nine squared sampled plots, 20 m × 20 m were established in plantation forest, i.e., three in *Cupressus lusitanica*, 3 in *Eucalyptus saligna*, and 3 in *Pinus patula* along elevation gradient. The first plot was laid out systematically using Silva compass, 150 m away from the outer edge to avoid an edging effect. The transect line was made along the center of the plantation, from bottom to top parts of the gradient. To attain a 90° corner of the main plots, the Phythagoras theorem was applied. Then, four sharpened wooden pegs were stalked in the four corners of the main plot. Environmental data such as altitude, latitude, and slope measurements were collected in the center of the main plot using a measuring tape, GPS, compass, and clinometer. All trees in the main plot were marked

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

Plot number	Species	Forest patch	Latitude	Longitude	Altitude (m)	Slope (%)	No. plots	No soil samples
01	*Cupressus lusitanica*	Chilimo	N09º04´115´´	E038º07´847´´	2370	3	1	4
02			N09º04´808´´	E038º07´808´´	2420	12	1	4
03			N09º04´297´´	E038º07´849´´	2413	3	1	4
04	*Eucalyptus saligna*	Chilimo	N09º04´298´´	E038º07´849´´	2400	3	1	4
05			N09º04´155´´	E038º07´891´´	2380	10	1	4
06			N09º04´223´´	E038º08´995´´	2360	10	1	4
07	*Pinus patula*	Chilimo	N09º03´676´´	E038º08´260´´	2396	6	1	4
08			N09º03´612´´	E038º08´259´´	2398	15	1	4
09			N09º03´514´´	E038º08´329´´	2405	20	1	4

and numbered before doing any measurements. The horizontal distance between two consecutive plots was 100 m. A total of three transect lines (one in each of the three plantations, *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula*) were used. Two inventories were conducted respectively in 2012 and 2017 within the same established sampling plots.

Data collection and sampling

Tree diameter (cm) was measured to the nearest one digit using a metallic caliper. Total height, commercial bole height, and crown height (meter) were determined to the nearest two digits using Vertex III digital electronics tree height measurement instrument.

Stump sampling

Stumps were sampled inside the 20 m × 20 m plot. Diameter measurements for all the stumps were made in the main plot in their bases and at the top using metallic caliper and diameter tape, while height measurements were done using a measuring tape.

Mineral soil sampling

Mineral soil samples were taken to a nominative depth of 1 m using pit sampling method with 1 m long × 60 cm wide dug at the center of each plot. Separate samples were taken at four soil depths: 0–10, 10–30, 30–50, and 50–100 cm. Soil bulk density was calculated for each plot and each soil depth with a 5-cm high cylinder that was introduced vertically in the corresponding depth in each pit. Resampling of mineral soil and bulk density were made by digging new sample pits 10 cm away from the older pit following appropriate direction.

Laboratory analysis

Mineral soil sample was air dried and passed into less than 2-mm sieve size to obtain the fine fraction for chemical analysis. The coarse fragments (> 2 mm) were removed from the sample and their percentage (% weight of stoniness and or rockiness) was calculated by oven-dried samples at 67 °C for 24 h for each soil depth

$$\mathrm{CFW\%} = \frac{\text{Weight not passing 2 mm sieve}}{\text{Weight of total soil}} \times 100 \tag{1}$$

where CFw is the percentage of coarse fragments by weight (Page-Dumroese et al. 1995).Then total organic carbon (C %) was analyzed following Walkley-Black's method described by Anderson and Gram (1996) procedure. Bulk density was determined following the procedure of Blake (1965). The oven-dried soil was weighed and divided by the volume of the metallic cylinder. Total nitrogen (N %) was determined using the Kjeldahl method, following the procedure in Keeny and Nelson (1982).

Data analysis

Aboveground biomass

Aboveground biomass was calculated using Chave et al. (2014) (Eq. 4) because this equation is the most recent and important predictive variable for estimation using diameter at breast height (DBH), total height (H), basic wood density (ρ), and forest type.

$$\mathrm{AGBest} = 0.0673\left(\rho H D^2\right)^{0.976} \tag{2}$$

where AGBest = aboveground biomass (kg), D = DBH (cm), H = height (m), and ρ = basic wood density (g cm^{-3}). Accumulated aboveground and belowground carbon density was calculated following Eqs. 5 and 6 (IPCC 2006).

(IPCC 2006)

$$\mathrm{ACD} = \mathrm{AGB} \times 0.47 \tag{3}$$

(Gibbs et al. 2007; Ponce-Hernandez 2004)

$$\mathrm{BCD} = \mathrm{ACD} \times 0.24 \tag{4}$$

where ACD = aboveground carbon density, BCD = belowground carbon density.

The aboveground and below biomass for each tree was calculated separately in each plot; then, the biomass of each tree was summed up to give plot biomass and converted into ha.

Stump carbon density analysis

For stump carbon density volume was calculated using Smalian's formula (Nicholas et al. 2012) (Eq. 2).

$$V = \frac{\pi}{8} L\left(D_1^2 + D_2^2\right) \tag{6}$$

where
V = volume (cm^3)
L = length of the trunk (cm)
$D_1{}^2$ = diameter of the narrow end of the trunk (cm)
$D_2{}^2$ = diameter of the large end of the trunk (cm)

Once the volume is determined, the mass was calculated using the following (Eq. 3):

$$m = p \times v \tag{7}$$

The wood density ρ was obtained from the Wood Technology Research Center, Addis Ababa (Desalegne 2012). The stump carbon density was converted into carbon density by considering 47% as carbon (IPCC 2006).

Soil carbon and bulk density estimation

The SOC and SON stock in mineral soil was calculated based on fixed depth method using carbon and nitrogen concentration, thickness of each layer, soil bulk density, and coarse fragmented matter at each depth, according to (Ruiz-Peinado et al. 2013):

$$\mathrm{SOC_{stock}} = \mathrm{SOC\,conc.BD.L(1{-}CFM)} \tag{8}$$

where $\mathrm{SOC_{stock}}$ is the soil organic carbon stock (t C ha^{-1}), SOC conc. is the carbon concentration in the soil layer (kg C t^{-1} soil), BD is bulk density (t soil m^{-3}), L is the depth of the sample layer (m), CFM is percent mass coarse fragmented matter > 2 mm, and 10 is required to express the result in correct units.

Total forest ecosystem carbon estimation

The total carbon stocks (carbon density) were calculated by summing up all the carbon stocks of each carbon pool of the plantation forest ecosystem developed by (Pearson et al. 2005), i.e., aboveground carbon density, belowground carbon density, stump carbon density and soil organic carbon density. The total ecosystem carbon stock was then converted into tonnes of CO_2 eq. by multiplying 3.67 (Pearson et al. 2007) (Eq. 9). Carbon stock density of the study area was calculated as

$$\mathrm{TECD} = \mathrm{ACD} + \mathrm{BCD} + \mathrm{StCD} + \mathrm{SOCD} \tag{9}$$

where TECD is the total ecosystem carbon density (t C ha^{-1}); ACD, the aboveground carbon density; BCD, the belowground carbon density; StCD, the stump carbon density; and SOCD, the soil organic carbon density. The aboveground carbon density, belowground carbon density, stump carbon density, and soil organic carbon density were calculated for each biomass pool in the plot; then, the different carbon pools were summed up to give total ecosystem carbon density per plot basis and converted into hectares.

Growth and yield data

Dendrometric measurements were made for 58 trees for *Cupressus lusitanica*, 60 trees for *Eucalyptus saligna*, and 136 trees for *Pinus patula*. Basal area (BA) (m^2 ha^{-1}) and volume (Vt) (m^3 ha^{-1}) for the planted forest were calculated using inventory data. Total volume was calculated using the conventional volume equation because local volume equations were not available for these species:

(Atta-Boateng and Moser 1998)

$$V = \pi\left(DBH^2/4\right) \times \mathrm{h.f.} \tag{10}$$

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

BA (basal area) was calculated using the formula

$$\mathrm{BA} = \pi\frac{\mathrm{DBH2}}{4} \tag{11}$$

where BA = basal area, DBH = diameter at breast height.

Basal area and volume increment were calculated as:

$$V_tI = V_{t,2017} - V_{t,2012} \tag{12}$$

$$BAI = BA_{2017} - BA_{2012} \tag{13}$$

where V_tI is the volume increment (m^3 ha^{-1} year^{-1}) and BAI basal area increment (m^2 ha^{-1} year^{-1}). The volume and basal area were calculated for each tree in the plot; then, volume and basal area of each tree were summed up to give total plot volume and basal area and converted into hectare(s). Growth and yield data analyses were made for trees measured in both times and cut trees not used for calculation.

Statistical analysis

The carbon stock, growth, and yield variation among the tree species were considered as fixed factors and each tree was considered as a random factor because the environmental variables such as slope and altitude had no significant impact to be considered as covariant variables. The analyses were analyzed using RStudio (R-Development Core team 2017). To analyze the equality of means, we used ANOVA for multiple comparisons among elevation classes at α = 0.05. The carbon stock variation among soil depth and land use types was analyzed using Proc mixed model and mean separation performed using Tukey Kramers test.

Results

Aboveground biomass, basal area, and number of stems for plantation forests

Dendrometry and tree data measurements of height, diameter at breast height, and diameter at stump height were made for 385 trees of *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula* plantations in Chilimo dry Afromontane plantation forest in 2012. Thereof, 254 trees have been reassessed in 2017. The remaining 128 trees (33.2%) had been cut in the 5-year interval between the two sets of measurements. The number of stems in the second measurement was 483.33, 508.33, and 1133.33 N ha^{-1} for *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula*, respectively (Table 2). In the first measurement (2012), the aboveground and belowground biomass, volume, and basal area of the *Cupressus lusitanica* plantation was higher than that of the *Eucalyptus saligna* and *Pinus patula* plantations, while in the second measurement (2017) the *Pinus patula* plantation showed the highest aboveground biomass, volume, and basal area. *Eucalyptus saligna* had the lowest aboveground biomass, volume, and basal area in all the measurement times in all the sampled plots (Table 2). The stem number of *Pinus patula* was always higher than other planted species. The highest aboveground biomass 184.80 t ha^{-1} was measured for *Cupressus lusitanica* followed by 165.91 t ha^{-1} *Pinus patula*. Moreover, the aboveground biomass showed a slight increase in 2017 due to a greater number of trees cut (Table 2). The highest aboveground and total carbon density was also found for *Cupressus lusitanica* followed by *Pinus patula* for all the sampled plots in all the measurement times. The lowest aboveground and carbon density was found for *Eucalyptus saligna* for all the sampled plots in all the measurement times (Table 2).

Soil organic carbon and nitrogen stock and concentration for the planted forests

The summarized results of SOC and SON stock of plantation forests, cultivated land, and degraded land are presented under Tables 3 and 4. The highest SOC and SON stock was found under plantation forests followed by cultivated land, while the lowest stock was found under degraded land (Fig. 1). There was also significant difference for SOC and SON stock among the species and soil depths at $P < 0.05$ (Table 3). The amount of soil organic carbon stock slightly increased under plantations in 2017, whereas SON stock density highly increased in the same measurement period. The SOC and SON stock were the highest under *Eucalyptus saligna* plantation followed by *Cupressus lusitanica* plantation for all the sampled soil depths in 2012, whereas, they were lowest under *Pinus patula* in the same measurement year for all the soil depths. The SOC stock in the deepest soil was the highest under *Pinus patula* plantation followed by *Eucalyptus saligna* plantation in the second sampling period (i.e., 2017). The lowest stock was found under *Cupressus lusitanica* plantation in the same sampled year. To a depth of 1 m, the mean SOC stock stored under plantations was 130.13 ± 14.59 t C $\mathrm{ha}^{-1}$for *Pinus patula*, 156.09 ± 61.22 t C ha^{-1} for *Cupressus lusitanica*, and 234.26 ± 59.17 t C ha^{-1} for *Eucalyptus saligna*. In the same line, the mean SON stock stored was also 11.21 ± 0.40 t N ha^{-1} under *Pinus patula*, 13.54 ± 4.33 t N ha^{-1} under *Cupressus lusitanica* and 17.28 ± 4.4.58 t N ha^{-1} under *Eucalyptus saligna* plantations in the same sampled year (Table 4).

Number of illegally cut stumps inside plantation forests

The number of stumps ranged from 550 to 50 N ha^{-1}, while the stump carbon density was ranged 3.02 to 0.06 t C ha^{-1} inside plantation forests. The analysis of variance revealed that the stump carbon density and number of stumps were non-significant among the species at $P <$ 0.05. In addition, the stump carbon density and number of stumps did not show A similar pattern among the plantations, for example, the number of stumps was the highest under *Cupressus lusitanica*, while the stump carbon density was the highest under the *Pinus patula* plantation (Table 5). The highest number of stumps was found for *Cupressus lusitanica* followed by *Pinus patula* in 2012, but the number of stumps was the highest for *Eucalyptus saligna* followed by *Pinus patula* in 2017.

Total ecosystem carbon density for planted forests

The total ecosystem carbon stock density for the planted forests ranged from 354.53 to 192.81 t C ha^{-1} and the summary of results is presented in Table 6. The highest total ecosystem carbon stock density was found for *Eucalyptus saligna* followed by *Cupressus lusitanica* plantations, whereas the lowest value was found under the *Pinus patula* plantation (Table 6; Fig. 2a and b). In addition, the mean total ecosystem carbon stock density of the plantation forest was 308.05 and 256.82 t C ha^{-1} in

Table 2 Number of stems, basal area, volume, aboveground biomass, aboveground carbon density and total carbon density of the plantation

Plot No	Species	N		N.cut	G		G.cut	V		V.cut	AGB		ACD		TCD		AGB.cut	ACD.cut	TCD. cut
		2012	2017		2012	2017		2012	2017		2012	2017	2012	2017	2012	2017			
01	*C. lusitanica*	750	750	0	29.20	32.96	0.00	227.78	272.77	0.00	159.90	194.93	75.15	91.62	93.19	113.61	0	0.00	0.00
02		550	375	175	23.42	24.47	7.41	187.31	233.38	7.41	134.06	164.93	63.01	77.52	78.13	96.12	42.40	19.93	24.71
03		400	325	75	23.89	24.92	4.20	231.38	277.54	4.20	163.55	194.55	76.87	91.44	95.32	113.38	24.43	11.48	14.24
Mean ± SE CL		566±175.59	483.33±232.29	83.33±87.80	25.50±3.21	27.45±4.78	3.87±3.72	215.49±24.47	261.23±24.24	3.87±3.72	152.50±16.07	184.80±17.21	71.67±7.56	86.86±8.10	88.88±9.37	107.70±10.03	22.28±21.28	10.47±10.00	12.98±12.40
04	*E. saligna*	1450	525	950	21.12	15.37	13.10	150.67	139.99	13.10	172.37	157.03	81.02	73.80	100.47	91.52	108.88	51.17	63.45
05		800	500	300	14.49	15.07	5.74	115.65	153.11	5.74	131.71	171.67	61.90	80.68	76.76	100.05	52.69	24.77	30.71
06		700	500	200	8.38	10.82	1.67	63.85	101.78	1.67	73.20	114.99	34.41	54.05	42.66	67.02	12.19	5.73	7.10
Mean ± SE ES		983.33±407.23	508.33±14.4	483.33±407.23	14.66±6.37	13.75±2.55	6.84±5.79	110.06±43.68	131.63±26.68	6.84±5.79	125.76±49.85	147.90±29.42	59.11±23.43	69.51±13.82	73.30±29.06	86.20±17.15	57.92±48.57	27.22±22.82	33.75±28.30
07	*Pinus patula*	1100	1100	0	25.55	29.67	0.00	205.79	257.05	0.00	155.96	185.53	73.30	87.20	90.90	108.13	0.00	0.00	0.00
08		1500	1375	150	19.07	24.00	2.36	143.01	194.59	1.90	109.88	142.02	51.64	66.75	64.04	82.77	13.98	6.57	8.15
09		925	925	0	19.19	22.75	0.00	191.19	236.44	0.00	144.43	170.19	67.88	79.89	84.17	99.19	0.00	0.00	0.00
Mean ± SE PP		1175±294.75	1133.33±226.84	50±86.60	21.27±3.70	25.47±3.69	0.79±1.36	180.00±32.85	229.36±31.83	0.63±1.10	136.76±23.98	165.91±22.07	64.27±11.27	77.95±10.36	79.70±13.98	96.70±12.86	4.66±8.07	2.19±3.79	2.72±4.71

N number of stems (N ha^{-1}), *G* basal area (m^2 ha^{-1}), *V* volume (m^3 ha^{-1}), *ACD* aboveground carbon density (t C ha^{-1}), *TCD* total carbon density (t C ha^{-1}), *SE* standard error of the mean, *CL Cupressus lusitanica*, *ES Eucalyptus saligna*, *PP Pinus patula*

Table 3 Analysis of variance result for carbon concentration of mineral soil along altitudinal gradient

Variable	Factor	DF	Sum square	Mean Square	F value	Pr > F value
SOCD (t C ha^{-1})	Species	2	10676	5338	8.223	**0.000648 *****
	Depth	3	124349	41450	63.852	**< 2e-16 *****
	Residuals	66	42844	649		
SOND (t N ha^{-1})	Species	2	89.6	44.82	4.225	**0.0188 ***
	Depth	3	879.5	293.16	27.630	**1.08e-11 *****
	Residuals	66	700.3	10.61		

SOCD soil organic carbon density (t C ha^{-1}), *SOCD* soil organic nitrogen stock density (t N ha^{-1})
***Highly significant at $P < 0.01$
*Significant at $P < 0.05$

2012 and 2017, respectively (Fig. 2a, b). The current plantation area was 450 ha; then, the total carbon stock density of the plantation was 508,740.9 CO_2 eq, based on these results the total annual carbon sequestration potential of the plantation forest is 3426.48 carbon or 12,575.18 tonne CO_2 eq.

Growth and yield of planted forests

The growth and yield of *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula* plantations were calculated in two measurement periods (2012 and 2017). The age of plantation was 25 years for *Eucalyptus saligna* and *Pinus patula* and 30 years for *Cupressus lusitanica*. The measured height, basal area, and volume ranged from 4 to 30 m, 0.001 to 0.025 m^2 tree^{-1}, and 0.002 to 1.24 m^3 tree^{-1}, respectively, and the basal area and volume increment from 0.001 to 0.044 m^2 and 0.001 to 0.484 m^3 per tree, respectively. The total volume in 2017 was 261.24 ± 24.23 m^3 ha^{-1} for *Cupressus lusitanica*, 229.36 ± 31.8 m^3 ha^{-1} for *Pinus patula*, and 131.63 ± 26.66 m^3 ha^{-1} for *Eucalyptus saligna*. At the same time, the total basal area was 27.45 ± 4.77 m^2 tree^{-1}for *Cupressus lusitanica*, 25.47 ± 3.69 m^2 tree^{-1}for *Pinus patula* and 13.75 ± 2.55m^2 tree^{-1} for *Eucalyptus saligna* (Table, 7). The highest mean annual basal area and volume increment were found for *Cupressus lusitanica* followed by *Eucalyptus saligna* plantations, while the lowest basal area and volume increment were found for *Pinus patula* plantations (Table 7).

Treatment mean differences for growth parameters

The treatment means of different dendrometric parameters varied significantly among the species. The treatment means of differences of total height varied significantly among the species. However, the total volume was non-significant among the species. This was also true for basal area. The treatment mean differences for height and diameter increment were also statistically significant among the studied species, however, non-significant among *Pinus patula* and *Eucalyptus saligna*.

Discussion

This aboveground biomass and carbon and nitrogen stock study under plantation forests in the surroundings of Chilimo dry Afromontane forest is also the first of its kind for understanding the temporal variation of carbon and nitrogen stock and concentration for two consecutive periods for the study site and nearby areas. Soil carbon study knowledge for forest growth, mean annual increment, and rotation period are important for forest managers to fix the amount of total harvest in each year for a species. The mean annual increment (MAI) indicates the amount of wood that the plantation will produce annually. We found variation in growth, yield, and aboveground biomass among the planted forests, soil depth, and time. Results revealed that higher carbon and nitrogen stock was found under *Eucalyptus saligna* plantation in 2012. This might be due to higher litter fall and low soil erosion. The second soil sampling pit was made in the nearby area and showed an increase and a decrease of carbon and nitrogen stocks. The reduction in carbon stock in the last 5-year interval (from 2012 to 2017) is also attributed to illegal cuttings of trees and frequent removal of litter fall and twigs by fuelwood collectors. In line with that, a lot of illegal tree cutting, new stumps (up to 550 N ha^{-1}) were measured inside the *Eucalyptus saligna* plantation, the highest figure of the three plantations. The higher disturbance for this species is likely due to shortage of forest products in the study area and its higher market value. On the contrary, the low disturbance inside *Pinus patula* is likely due to a lack of knowledge for utilization and the site is located near by the main road and resulted in being easily seen by the guards and passers-by. Another plausible assumption is that prohibition of cutting the natural forests is likely to increase pressure on plantations. In comparison with other land use types, the carbon and nitrogen stock under plantation was higher than degraded and cultivated land. This may be due to better input turn over through addition of litter fall. Moreover, the lower soil organic carbon and nitrogen stock density in the cultivated and degraded land is likely due to higher erosion

Table 4 Summarized result for soil organic carbon and nitrogen carbon density output for each soil depth

Plot	Species	LUT	SOCD.10.2012	SOCD.10.2017	SOCD.30.2012	SOCD.30.2017	SOCD.50.2012	SOCD.50.2017	SOCD.100.2012	SOCD.100.2017	SOND.10.2012	SOND.10.2017	SOND.30.2012	SOND.30.2017	SOND.50.2012	SOND.50.2017	SOND.100.2012	SOND.100.2017
01	Cropland	CU	26.40	64.80	51.10	112.03	66.40	142.23	90.90	223.15	2.20	4.32	4.10	10.76	5.80	14.54	9.30	24.06
02			30.00	5.98	76.17	11.68	103.71	15.68	156.21	81.68	2.00	0.69	7.13	4.49	10.37	8.49	14.12	16.74
03			28.80	24.48	74.97	54.12	108.99	107.42	156.24	187.29	1.80	2.88	5.22	7.82	8.46	15.43	11.61	26.84
Mean ± SE (CU)			28.4±1.83	31.75±30.08	67.41±14.14	59.28±50.27	93.03±23.22	88.44±65.37	134.45±37.72	164.04±73.55	2±0.2	2.63±1.83	5.48±1.53	7.69±3.14	8.21±2.30	12.82±3.78	11.68±2.41	22.55±5.22
01	Bare land	DL	14.94	13.39	34.83	21.95	48.33	38.99	58.83	57.05	1.07	2.23	2.60	5.08	3.95	7.22	5.45	7.22
02			6.37	3.13	16.27	7.81	21.88	9.30	26.68	12.10	1.06	0.00	3.04	4.68	3.04	6.18	3.04	6.18
03			18.24	0.96	26.16	4.92	29.68	6.84	33.28	8.79	0.96	1.92	2.94	3.90	2.94	3.90	2.94	3.90
Mean ± SE (DL)			13.18±6.13	5.83±6.63	25.75±9.29	11.56±9.11	33.30±13.60	18.38±17.89	39.60±16.98	25.98±26.96	1.03±0.06	1.38±1.21	2.86±0.23	4.55±0.60	3.31±0.56	5.77±1.70	3.81±1.42	5.77±1.70
O1	*C.lusitanica*	PF	46.20	44.20	98.64	111.23	133.20	142.01	157.20	209.21	3.30	6.12	7.86	15.43	10.02	19.53	14.82	29.13
02			74.48	63.60	160.59	84.58	184.35	118.24	216.75	141.82	4.70	8.10	11.33	10.89	13.49	17.01	17.09	20.94
03			24.29	38.30	50.21	88.92	67.10	123.33	94.33	162.96	2.11	5.47	4.27	10.80	5.68	14.85	8.71	22.05
Mean ± SD (*C. lusitanica*)			48.32±25.16	48.7±13.24	103.15±55.33	94.91±14.30	128.22±58.78	127.86±12.52	156.09±61.22	171.33±34.47	3.37±1.30	6.56±1.37	7.82±3.53	12.37±2.65	9.73±3.91	17.13±2.34	13.54±4.33	24.04±4.44
04	*E. saligna*	PF	71.20	71.82	141.40	155.12	186.17	187.84	228.42	222.94	4.00	2.28	9.40	5.48	11.53	8.93	15.76	12.83
05			53.00	47.30	106.46	96.80	135.32	146.00	178.22	209.00	4.00	9.90	7.96	15.84	9.76	18.30	13.66	22.50
06			59.00	43.46	188.96	108.36	246.08	143.04	296.13	164.74	4.00	5.30	13.12	14.57	17.88	20.35	22.43	24.69
Mean ± SE (*E. saligna*)			61.07±9.27	54.19±15.39	145.61±14.41	120.09±30.88	189.19±55.44	158.96±25.06	234.26±59.17	198.89±30.39	4±0.00	5.83±3.84	10.16±2.66	11.96±5.65	13.06±4.27	15.86±6.09	17.28±4.58	20.01±6.31
07	*P. patula*	PF	40.80	71.24	88.30	111.72	104.50	138.63	122.00	195.33	2.40	4.11	7.31	9.17	8.93	13.31	11.43	17.36
08			42.40	6.72	82.14	109.76	99.42	119.42	121.42	186.03	3.20	3.36	6.51	3.36	7.95	5.78	10.70	15.29
09			40.16	27.16	80.66	70.72	111.98	160.50	146.98	247.50	2.62	3.88	5.86	9.82	8.99	16.08	11.49	22.08
Mean ± SE (*P. patula*)			41.12±1.15	35.04±32.97	83.7±4.05	97.4±23.13	105.3±6.32	139.52±20.55	130.13±14.59	209.62±33.13	2.74±0.41	3.78±0.38	6.56±0.73	7.45±3.56	8.62±0.58	11.72±5.33	11.21±0.44	18.24±3.48

CU cultivated land, *DL* degraded land, *PF* plantation forest, *C Cupressus*, *E Eucalyptus*, *P Pinus*, *SOCD* soil organic carbon density (t C ha^{-1}), *SOND* soil organic nitrogen stock density (t N ha^{-1}), *SE* standard error of the mean

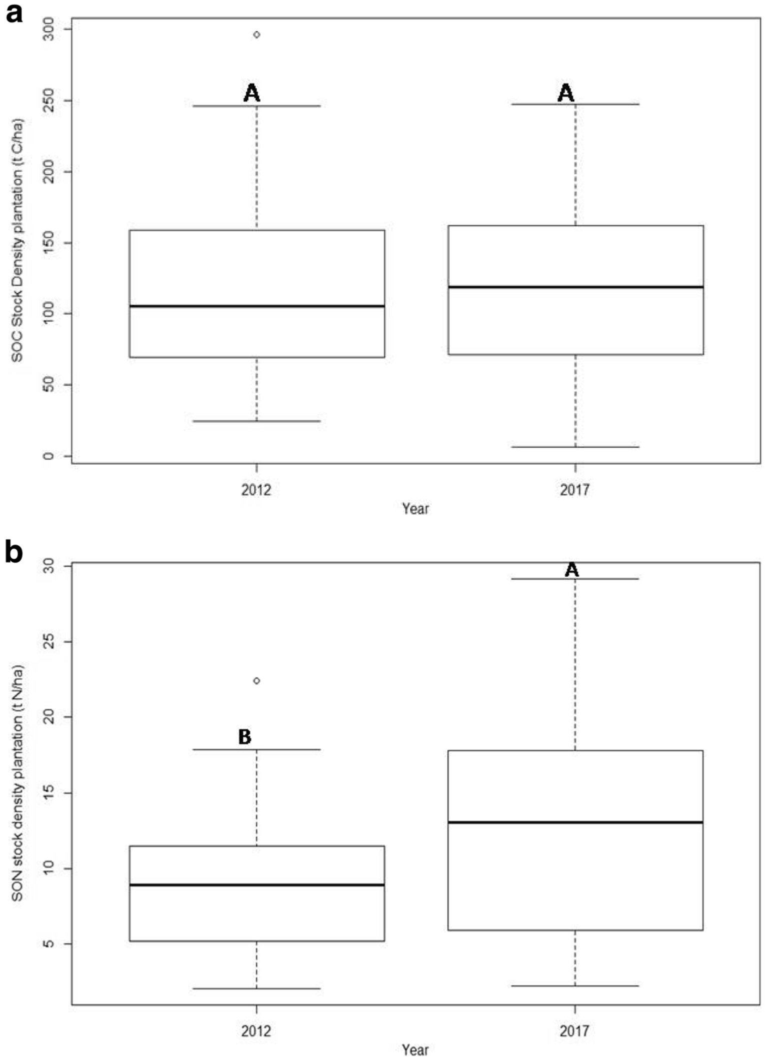

Fig. 1 **a** SOC density (Mg C ha^{-1}) for plantation, letters within the same letter superscript are not statistically significant at $P < 0.05$. **b** SON (Mg ha^{-1}) for plantation 2012 vs 2017). Letters within different superscript are statistically significant at $P < 0.05$

rate, surface crusting, frequent tilling, and lack of inputs. The positive impact of plantations on degraded land and the negative impact of substitution and conversion of degraded and cultivated land into plantations are inconsistent with findings by other authors (Tesfaye et al. 2015 and 2016).

Feyissa and Sormessa (2017) found higher carbon stock density in aboveground and belowground biomass, litter biomass, and soil organic carbon along lower altitudes of planted dry Afromontane forests in Ethiopia. Lemma et al. (2006) studied SOC stock under *E. grandis*, *C. lusitanica*, and *P. patula* plantation in southern Ethiopia and found a net SOC increase of 69.9 t C ha^{-1} under *C. lusitanica* and 29.3 t C ha^{-1} under *Pinus patula* of 20 years after plantation and their findings used to strengthen studies related to these species. The soil carbon pool is also affected by soil properties, forest management practices, litter fall, and root turnover (Jandl et al. 2006; Zhu et al. 2010). The SOC stock found in this study is also in line with the SOC stock reported in China (193.6 t C ha^{-1}) (Zann et al. 2009). The SOC stock was highest at 0–10 cm soil depth and decreased with increasing in soil depth. Soil organic matter content is the main source of soil C and is higher in topsoil (Seely et al. 2010). Our SOC stock values in the upper 50 cm is much higher than SOC stock stored in *Pinus koraiensis* plantations (Li et al. 2012). The slight increase in carbon stock in 2017 is likely due to increasing disturbance (illegal cutting) and litter fall removal.

The SOC stock stored under planted forests was 173.49 ± 44.99 t C ha^{-1} (2012) and 193.28 ± 32.66 t C ha^{-1} (2017); this result is higher than the reports by Du et al. (2015) for *Eucalyptus* plantation 162.7 t C $ha^{-1}$and other studies in different regions (Twongyirwe et al.

Table 5 Summarized stump carbon density for the plantation forest

No plot	Species	Nstumps.2012	Nstumps.2017	StCD.2012	StCD.2017
01	*Cupressus lusitanica*	225	200	0.73	0.43
02		375	75	1.21	0.06
03		225	300	0.85	0.94
Mean ± SE CL		275 ± 86.60	191.67 ± 112.73	0.93 ± 0.25	0.48 ± 0.44
04	*Eucalyptus saligna*	250	100	1.01	0.30
05		50	100	0.19	0.37
06		50	550	0.29	3.02
Mean ± SE ES		116.67 ± 115.47	250 ± 259.81	0.50 ± 0.45	1.23 ± 1.55
07	*Pinus patula*	100	100	0.36	0.53
08		225	350	0.97	1.80
09		250	250	1.16	0.83
Mean ± SE PP		191.67 ± 80.36	233.33 ± 125.83	0.83 ± 0.42	1.05 ± 0.66

N number, *StCD* stump carbon density, *SE* standard error of the mean, *CL Cupressus lusitanica*, *ES Eucalyptus saligna*, *PP Pinus patula*

2013). This calls for the restoring of a forest cover on abandoned crop lands and degraded lands to prevent tree cutting in the natural forests. Moreover, continuous and well-planned carbon and nitrogen stock, monitoring and assessment work should be made. In Ethiopia, conversion from a natural forest into agricultural land resulted in a significant loss of SOC which ranged from 17 to 83% (Girmay et al. 2008). In a field study carried out in the South-Western highlands of Ethiopia, Lemenih et al. (2006) found that plantations of *Cupressus lusitanica* and *Pinus patula* established on former arable land resulted in an increase of SOC over a 20-year period. A different study, which also found an increase of SOC, was conducted by Grunzweig et al. (2007) in Israel. Plantations of *Pinus halepensis* were established under semi-arid shrublands which resulted in an increase of SOC stock by 75% in SOC after 35 years. Similarly, Del Galdo et al. (2003) assessed and compared the amount of carbon stored among farm land, grass land, and mixed plantation of *Quercus robur* established on former agricultural land after 20 years. He reported significantly higher SOC under plantation than under other land use types. Garten (2002) reported a net C-accumulation of 40–170 g cm^{-3} year^{-1} over a 10-year period under plantations of *Pinus taeda* established on abandoned farmlands in the USA. Pooltouchidou (2013) reported that the SOC stock increased under forest plantations and natural forest in 10 years' time, however, decreased under farmlands in the same period. According to Laganive et al. (2010) the SOC stock was also increased when pasture lands are converted into plantation by 3% and when a farmland is converted into plantation increased by 18%. In addition, the differences in SOC stock among *Cupressus lusitanica* and *Eucalyptus saligna* plantation is due to the nature of the species. This is also confirmed by Lemma et al. (2007) who found that over a 20-year period, *Cupressus lusitanica* had the highest SOC (32.8 t C ha^{-1}) followed by *P. patula* (26.3 t C ha^{-1}) and *Eucalyptus grandis* (18.1 t C ha^{-1}). This attributed due to higher litter and debris from tree cut under

Table 6 Ecosystem carbon stock density of planted forest 2012

Plot N0	Patch	Species	ACD (t C ha)		BCD (t Cha)		StCD (t C ha $^{-1)}$		SOCD (t C ha^{-1}) up to 1m depth		TECD (t C ha^{-1})	
			2012	2017	2012	2017	2012	2017	2012	2017	2012	2017
01	Chilimo	CL	75.15	91.62	20.29	24.74	0.73	0.43	157.2	209.21	253.37	326
02			63.01	77.42	17.01	20.90	1.21	0.06	216.75	141.82	297.98	240.2
03			76.87	9.14	20.76	2.47	0.85	0.94	94.33	162.96	192.81	280.03
04		ES	81.02	73.80	21.88	19.93	1.01	0.30	228.42	222.94	332.33	316.97
05			61.90	80.68	16.71	21.78	0.19	0.37	178.22	209	257.02	311.83
06			34.41	54.05	9.29	14.60	0.29	3.02	296.13	164.74	340.12	236.41
07		PP	73.30	87.20	19.79	23.54	0.36	0.53	122.00	195.33	215.452	311.63
08			51.64	66.75	13.94	18.02	0.97	1.80	121.42	186.03	187.97	276.45
09			67.88	79.99	18.33	21.60	1.16	0.83	146.98	247.50	234.35	354.53

CL Cupressus lusitanica, *ES Eucalyptus saligna*, *PP Pinus patula*, *G* basal area, *ACD* aboveground carbon density, *BCD* belowground carbon density, *PF* plantation forest, *StCD* stump carbon density, *SOCD* soil organic carbon density, *TECD* total ecosystem carbon density

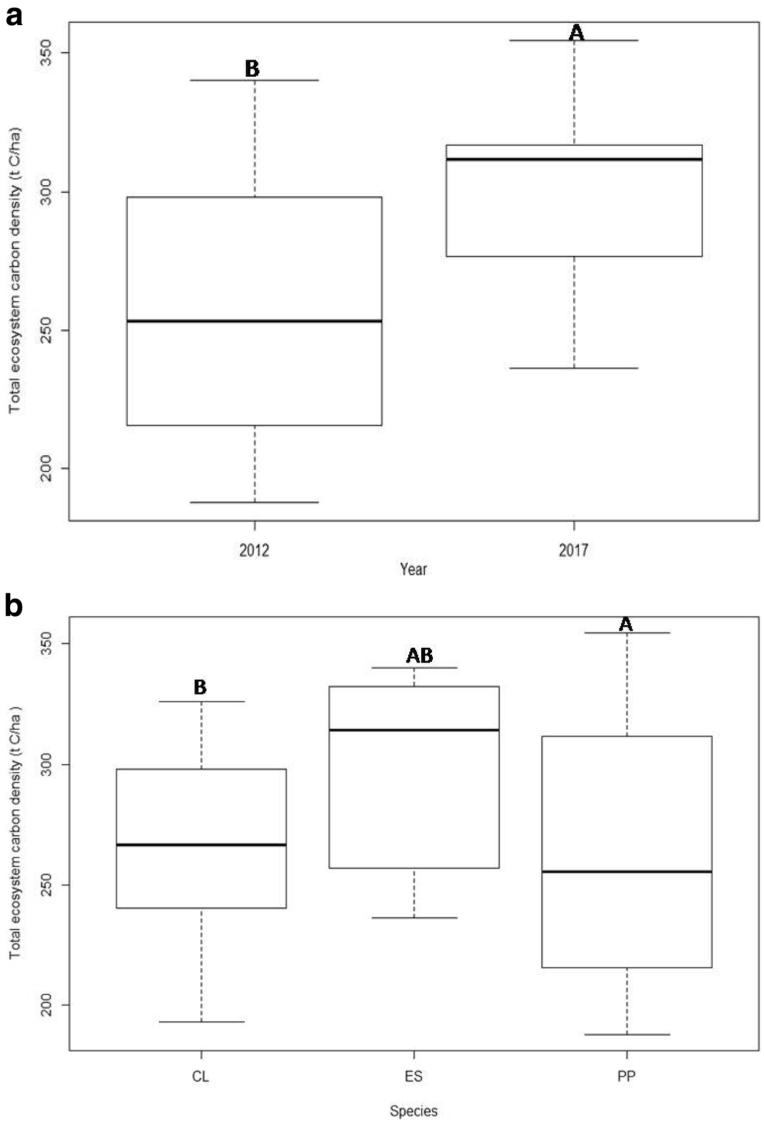

Fig. 2 a Total ecosystem carbon density (t C ha^{-1}) along a time period. Letters within different superscript are statistically significant at $P < 0.05$. **b** Total ecosystem carbon density (t C ha^{-1}) along time species. CL, *Cupressus lusitanica*; ES. *Eucalyptus saligna*; PP, *Pinus patula*. Letters within the same superscript are statistically significant at $P < 0.05$

Cupressus lusitanica and better decomposition rate. They concluded that the litter quality and the differences in microclimatic conditions contributed to a small extent to the differences observed in SOC among the tree species.

In the current study, total SOC increased by 25% under *Cupressus lusitanica* and 20% under *Eucalyptus saligna* within a 5-year period. Similarly, Lemma et al. (2007) found an increase of 14% in SOC under *Cupressus lusitanica* accompanied by an 8% increase in total biomass within 2 years.

The number of stems for *Cupressus lusitanica* and *Eucalyptus saligna* was lower than for *Pinus patula* plantation. This might be due to *Cupressus lusitanica* plantation is found to be overmature due to lack of forest management plan. These attract more illegal cutters in the nearby areas and the same for *Eucalyptus saligna*. *Cupressus lusitanica* and *Pinus patula* are the best industrial plantations in Ethiopia with higher market price and demand. Moreover, due to illegal cutting in the study area because of higher market demand, poverty, fuel wood, and construction wood shortage.

The mean annual increment of *Cupressus lusitanica* was higher than those of *Eucalyptus saligna* and *Pinus patula*. This might be due to better fertility status of the planting site, because *Eucalyptus saligna* and *Pinus patula* were planted on barren land. The mean annual increment for the studied species was found to be 16.22

Table 7 Mean ± standard deviation of the different growth parameters for plantation forest

Plot No	Species	Mean Dbh (cm)		Mean height (m)		No (N ha^{-1})		Basal area (m^2 ha^{-1})		Volume (m^3 ha^{-1})		Average Diameter increment (cm)	Average Height (m)	Vincrement (m^{3}ha^{-1}yr^{-1})	G increment (m^2 ha^{-1} yr^{-1})	Vincrement (m^{3}tree yr)	BA increment (m^{-2} tree year)
		2012	2017	2012	2017	2012	2017	2012	2017	2012	2017						
01	*C. lusitanica*	21.73	23.22	17.50	19.32	750	750	29.20	32.96	222.78	272.77	1.49	1.82	10.00	0.76	0.0133	0.001
02		23.01	28.47	18.54	22.33	375	375	16.01	24.47	128.06	233.40	5.45	3.79	21.06	1.69	0.0562	0.0045
03		27.44	31.08	23.44	26.39	325	325	19.68	24.92	197.02	277.54	3.64	2.95	16.11	1.047	0.0496	0.0032
Mean ± SE CL		24.06± 2.99	27.59± 4.00	19.83± 3.17	22.68± 3.55	483.33± 232.29	483.33± 232.29	21.63± 6.81	27.45± 4.77	182.62± 48.98	261.24± 24.23	2.53±1.98	2.85± 0.99	15.72±5.54	1.17±0.48	0.04±0.02	0.003± 0.002
04	*E. saligna*	12.70	18.48	13.96	19.87	525	525	8.02	15.37	55.62	139.99	5.77	5.91	16.88	1.471	0.0321	0.0028
05		14.21	19.18	17.75	23.27	500	500	8.75	15.07	69.35	153.11	4.97	5.52	16.78	1.265	0.0335	0.0025
06		12.06	15.95	16.65	20.96	500	500	6.71	10.82	53.34	101.80	3.89	4.31	9.69	0.823	0.0194	0.0017
Mean± SE ES		12.99± 1.10	17.87± 1.70	16.12± 1.95	21.37± 1.74	508.33± 14.43	508.33± 14.43	7.83± 1.03	13.75± 2.55	59.44± 8.66	131.63± 26.66	4.88±0.94	5.25± 0.83	14.45±4.12	1.19±0.33	0.03±0.008	0.0023± 0.0006
07	*Pinus patula*	16.80	18.19	18.43	20.08	1100	1100	25.55	29.67	205.79	257.05	1.40	1.65	10.25	0.824	0.0093	0.0008
08		12.02	14.55	16.26	18.34	1375	1375	17.17	24.00	128.33	194.59	2.53	2.07	13.25	1.366	0.0096	0.0010
09		15.67	17.27	22.58	23.87	925	925	19.19	22.75	191.19	236.44	1.60	1.29	9.05	0.710	0.0096	0.0008
Mean± SE PP		14.83± 2.50	16.67± 1.89	19.00± 3.21	20.76± 2.83	1133.33± 226.84	1133.33± 226.84	20.64± 4.37	25.47± 3.69	175.10± 41.16	229.36± 31.83	1.84±0.60	1.67± 0.39	10.85±2.16	0.97±0.35	0.0095± 0.0002	0.001± 0.00012

DBH Diameter at breast height, *N* number of stems, *ha* hectare, *CL Cupressus lusitanica*, *ES Eucalyptus saligna*, *PP Pinus patula*, *SE* standard error of the mean

$m^3\,ha^{-1}\,year^{-1}$ for *Cupressus lusitanica*, 14.34 $m^3\,ha^{-1}\,year^{-1}$ for *Eucalyptus saligna*, and 10.79 $m^3\,ha^{-1}\,year^{-1}$ for *Pinus patula* plantations. This result is in line with the findings reported by Bekele (2011), Moges et al. (2010). and Nune et al. (2012) which state that the mean annual increment estimates for the three most common plantation species, i.e., eucalyptus, pine, and cypress, is 5 to 20 $m^3\,ha^{-1}\,year^{-1}$ in the country. In addition, it is also in line with the mean annual increment (MAI) 10–20 $m^3\,ha^{-1}\,year^{-1}$ reported for *Eucalyptus* woodlots in Ethiopia (Moges et al. 2010). Generally, the growth and productivity of these species is good, in case in the absence of proper management.

These species are widely grown in the tropics and subtropics in general and in Ethiopia, in particular (Moges et al. 2010; Bekele 2001 and 2011; FAO 2001). The results showed that the mean annual increment of *E. saligna* in Chilimo areas was also found to be 14.34 $m^3\,ha^{-1}\,year^{-1}$ which is in line with the figures in the range of 10–15 $m^3\,ha^{-1}year^{-1}$ reported by Jacobs (1981), Eldridge et al. (1993), and FAO (2001). The mean annual increment of *Pinus patula* was 10.79 $m^3\,ha^{-1}\,year^{-1}$in lines with the mean annual volume increments 8 and 40 $m^3\,ha^{-1}year^{-1}$ reported for the same species with 30–40-year rotation period by FAO (2001). The mean annual increment of *Cupressus lusitanica* found in this study was 6.22 $m^3\,ha^{-1}\,year^{-1}$ which is in line with other research findings in the range of 8–15 $m^3\,ha^{-1}\,year^{-1}$as reported by Lamprecht (1990) and FAO (2001).

The growth, total biomass production, and changes in soil organic carbon density under *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula* plantation after 30 years provide an indication of species suitability in the study area. These tree species were found to be more adaptable and grow faster in the sampled site conditions and nearby areas. In another study in Central Highlands of Ethiopia, *Eucalyptus* species had faster diameter and height growth and produced maximum biomass production than other tested species (Mekonnen et al. 2006; Tesfaye et al. 2015). Buffer zone plantation of these tree species under Chilimo dry Afromontane forest play a vital role for livelihood improvement of the farmers and reduce pressure on the natural forests. Moreover, *Eucalyptus* is one of the most popular species widely planted in Ethiopia (Lemenih and Kassa, 2014). It 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). Socioeconomic studies on *Eucalyptus* species in the country showed that planting these fast-growing species increases household income more than agricultural crops do (Jagger and Pender 2000; Zerihun 2002; Holden et al. 2003; Tesfaye 2009). Therefore, integration of *Eucalyptus* in the afforestation and or re-afforestation programs of farmers' fields can represent a convenient solution for both protection of the natural forests and livelihood improvement. The major drivers for planting these species are income generation, household energy, and construction purposes. According Lemenih (2010), smallholder farmers in Ethiopia are being spurred to establish and expand eucalyptus plantations because of the scarcity of fuelwood and construction wood and market access is also true for Chilimo area. *Eucalyptus* plantations can serve as an insurance or be life-saving of farmers because they can be cut and generate income to meet their needs. Moreover, in some communities planting of eucalyptus is a privilege and obligation of all households not only for meeting household wood requirements and generating cash revenue but also for preserving social pride and reputation (Achalu 2004). *Eucalyptus* plantations contribute from 25 to 72% total household income (Lemenih and Kassa 2014). In other parts of Ethiopia, a study found that the income from trees and related products has become the third most important source of household income in some parts of the Amhara Regional State, North Western Ethiopia (Sandewall et al. 2015). Tree farming by private farm households and entrepreneurs is a growing area of small investment throughout rural and urban Ethiopia (Lemenih 2010). As tree growing requires less labor than annual crop production, the observed shift from annual crops to tree-growing facilitates diversification of livelihood options (Sandewall et al. 2015). In general, this study showed that the aforementioned trees species can be promoted as buffer plantation, homestead, and farm lands in the study area to minimize pressure on the existed natural forest. Moreover, it can serve to open forest processing industries.

Conclusions

The analysis of carbon and nitrogen stock of the planted forests showed significant difference of carbon storage among soil depth and time. The planted forests store more carbon and nitrogen stock than crop lands and degraded lands in all the measurement times. Hence, unproductive croplands and degraded lands should be converted into plantations. The growth and yield of the planted forests under Chilimo forest area was also higher than nearby sites, even though there is no proper management and silviculture operations to increase productivity and yield of the plantations. Thus, appropriate forest management practices and options should be devised in these regards to increase biomass and yield. We recommend that forest carbon-related awareness should be made for local people and promotion of the local knowledge be regarded as a possible option for sustainable forest management of the adjacent chilimo dry Afromontane forest. This will enhance the capacity of the existing forests for climate change mitigation and adaptation and other provision from the forest. A local bylaw should be also formulated to avoid illegal logging and equitable and fair distribution of the planted forest.

Abbreviations

ACD: Accumulated aboveground carbon density; AGB: Aboveground biomass; ANOVA: Analysis of variance; BCD: Belowground carbon density; C: Carbon; CFW: Coarse fragmented matter; CL: *Cupressus lusitanica*; cm: Centimeter; CO_2 eq: Carbon equivalent; CO_2: Carbon dioxide; CRGE: Climate resilience green economy; CU: Cultivated land; DBH: Diameter at breast height; DL: Degraded land; ES: *Eucalyptus saligna*; G: basal area; *G*: basal area ($m^2\ ha^{-1}$),; H: Height; ha: Hectare; N: Nitrogen; *N*: Number of stems ($N\ ha^{-1}$)g; PF: Plantation forest; PP: *Pinus patula*; SD: Standard deviation; SOCD: Soil organic carbon density; StCD: Stump carbon density; t $C\ ha^{-1}$: Tonne carbon per hectare; *V*: Volume; ρ: Basic wood density

Acknowledgements

The authors thank Genene Tesfaye, Central Ethiopia Environment and Forest Research Centre, for assisting us in field data collection and preparation of plant and soil samples and Mossissa Kebede, from Oromiya Forest and Wildlife Enterprise, and Ginch Branch and Mekonnen Gemechu from Chilimo village for their assistance in fieldwork and soil pit digging. The Swiss Government Excellent Scholarship programme is also highly acknowledged for funding Mehari A. Tesfaye's fellowship and the Ethiopian Environment and Forest Research Institute (EEFRI) headquarters for covering the cost of field work and laboratory analyses.

Declaration

All the authors declared that this manuscript is our original work and no competing claims among the authors. The authors also confirmed that availability of raw data and all the necessary materials are based on the interest of the publisher.

Authors' contributions

MAT contributed to the design of the experiment, data collection and analysis, and writing of the manuscript. OG contributed to the data analysis and commented and edited the manuscript. TB commented and edited the manuscript. JB contributed to the overall supervision of the work and commented and edited the manuscript. All authors read and approved the final manuscripts.

Funding

The Ecosystem Management Research Directorate and Ethiopian Environment and Forest Research Institute (EEFRI) funded the research grant and the Swiss Government Scholarship programme gave full scholarship for funding to Mehari A. Tesfaye's fellowship.

Availability of data and materials

The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This research was performed in accordance with the laws, guidelines, and ethical standards of Ethiopia and Switzerland, where the research was performed.

Consent for publication

All the co-authors gave their consent for publication.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Central Ethiopia Ethiopian Environment and Forest Research Centre, Box 30708, Addis Ababa, Ethiopia. [2]Bern University of Applied Sciences School of Agriculture, Forest and Food Sciences HAFL, CH-3052 Zollikofen, Switzerland. [3]Ethiopian Environment and Forest Research Institute (EEFRI), Code 1000, Gurd Shola, Box 24536, Addis Ababa, Ethiopia.

Received: 2 July 2019 Accepted: 12 December 2019

References

Achalu N. 2004. Farm forestry decision - making strategies of the Guraghae households, Southern-Central Highlands of Ethiopia, PhD Dissertation, Technische University Dresden. Agriculture Natural Resource Extension.

Adimassu Z, Kessler A, Stroosnijder L. 2012. Exploring co – investments in sustainable land management in Central Rift Valley of Ethiopia, International Journal of Sustainable Development and World Ecology.

Alebachew M. 2012. Traditional Agroforestry Practices, Opportunities,Threats and Research Needs in the Highlands of Oromia, Central Ethiopia. *International Research Journal of Agricultural and Soil Science* (ISSN: 2251 - 0044) Vol. 2 (5): 194 - 206. http://www.intersjournals.org.IRRJAS. Copy right@2012 International Research Journal.

Yosef Ameha, Teshome Mindaye, Alebachew Mehari, KassaZigjit, Eshet Negash and Derero Abayneh. 2017. Edited by Mehari Alebachew, Wubalem Tadesse, AgenaAnjulo, Fassile Kebede (eds), Early survival and growth performance of trees and shrubs on degraded midlands of Ethiopia. Proceedings of the 1st technology dessimination workshop, 26th - 27th November 2015, TokumaHotela, Adama, Ethiopia.

Anderson J.M. and Ingram J.S. 1996. Tropical soils biology and fertility. A hand book of methods. 2nd edn. CAB, International: Wallingford, UK.

Atta-Boateng J. and Moser J.R. 1998. A Method for classifying commercial tree species of uneven- aged mixed species tropical forest doe growth and yield construction. Forest Ecology and Management Vol. 104, pp. 89-99. http://www.fao.org/forestry/25518/en/.

Azene Bekele, Birnie A. and Tengias B. 1993. Useful trees and shrubs of Ethiopia, identification and management: Department of Agronomy and Land Management: University of Florence, Piazzale DelleCvascince and Florence-18- b50144-Italy.

Million Bekele. 2001. Forestry out look studies in Africa (FOSA), Ethiopia. http://www.fao.org/13/a-ab582e.pdf.

Million Bekele. 2003. Forest property rights, the role of the state and institutional exigency: the Ethiopian Experience. Doctoral Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Million Bekele. 2011. Forest plantations and woodlots in Ethiopia. AF. For. Forum, Work, Pap. Ser. 2011: 1-51.

Blake G.R. 1965. Bulk density. In: Methods of soil analysis, (Ed. C. A. Black), American Society of Agronomy, Wisconsin, Pp. 374-390.

Brown C. 1998. Global forest products study: thematic study on plantations. Consulting Report for: Food and Agriculture Organization of the UnitedNations. Rome. Mimeo.

Carnus J. M, Parrotta J, Brockerhoff E.G, Arbez M, Jactel H, Kremer A, Lamb D, O'Hara K. and Walters B. 2003. Planted forests and biodiversity. IUFRO Occasional Paper No. 15: 33 - 49.

Chamshama S.A.O, Nwonwu F.O.C, Lundgren B. and Kowero G.S. 2009. Plantation forestry in Sub - Saharan Africa: silvicultural, ecological and economic aspects. Discov. Innov. 2009; 21 http://www.afforum.org/sites/default/files/English/English-59.pdf.

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan M S, Delitti W.B.C. and Vieilledent G. 2014. Improved allometric models to estimate the above - ground biomass of tropical trees. Global Change Biology, 3177 - 3190. Doi: https://doi.org/10.1111/gcb.12629.

Cossalter C, Pye-Smith C (2003), Fast-wood forestry: myths and realities. Centre for International Forestry Research, Bogor, Indonesia.

CRGE. 2011. Ethiopian climate resilinece, green economy strategy, MEFCC, Strategeic Document, 2011,Addis Ababa.

Del Galdol, Six J, Peressotti A. and Cotrufo M.F. 2003. Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable Cisotopes. Global Change Biology, 9, 204 - 1213.

Desalegn G, Abega M, Teketay D, Gezahgne A. Commercial timer species in Ethiopia: characteristics and uses - a handbook for forest industries, construction and energy sectors, foresters and other stakeholders. Addis Ababa: Addis Ababa University Press; 2012.

Du H, Zeng Fuping Peng W, Kelin W, Hau Z, Li L, Tongging S. Carbon storage in a *Eucalyptus plantation* chrono - sequence in Southern China. Forest. 2015;6: 1763–78. https://doi.org/10.3390/f6061/763.

Eldridge K, Davidson J, Hardwood C. and van Wyk G. 1993. *Eucalyptus* domestication and breeding. Oxford Science Publications. USA. 288 p.

EMA. 1988. National atlas of Ethiopia. Ethiopian Mapping Authority, Addis Ababa, Ethiopia. Pp. 76.

Environmental Protection Authority of Ethiopia (EPA). 1998. Democratic Republic of Ethiopia National action programme to combat desertification. Addis Ababa, Ethiopia. Pp. 17-87.

Ethiopian Forest Sector Review (EFSR). 2015. MEFCC, Technical Report, Addis Ababa,Ethiopia

FAO. 2001. Mean annual volume increment of selected industrial forest plantation species by L Ugalde and O., Pérez. Forest Plantation Thematic Papers, *Working Paper 1*. Forest Resources Development Service, Forest Resources Division. FAO, Rome.

FAO. 2009. State of world's forests 2009. FAO, Rome, Italy.

Fayolle A, Doucet JL, Gillet JF, Bourland N, Lejeune P. Tree Allometry in Central Africa: testing the validation of pantropical multi-species allometric equations for estimation biomass and carbon stock. For Ecol Mgt. 2013;304:29–37.

Feyissa A. and Soromessa T. 2017. Variation in forest carbon stocks along environmental gradients in Egdu Forest of Oromiya Region, Ethiopia, Implications for Sustainable Forest Management. *American Journal of Environmental Protection Special issues*, Forest Ecosystem Carbon Stock Variation along altitudinal and slope gradient Vol (6); 1 pp 1- 8.

Garten, C.T. (2002). Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA, Biomass and Bioenergy, 23;2:93–102.

Gartner BL, North EM and Singleton R. 2002. Effect of live crown on vertical patterns of wood density and growth in Douglas fir Can. J.For.Res 32;439–447. https://doi.org/10.1139/XO1-218.

Getahun A. 2010. Eucalyptus farming in Ethiopia: the case for *Eucalyptus* woodlots in the Amhara Region. *In* Proceedings of the conference on Eucalyptus species management, history, status and trends in Ethiopia, Addis Ababa, Ethiopia,15 - 17 Sep 2010 : Gil, L., Tadesse, W., Tolosana, E., Lope, R., (Eds.). Ethiopian Institute of Agricultural Research (EIAR), Addis Ababa, Ethiopia. Pp. 206-221.

Gibbs H.K, Brown S, Niles J.O. and Foley J.A. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD$^+$ a reality. *Environmental Research Letters 2*: 045023.

Gil L, Tadesse W, Tolosona E. and López R (eds.), 2010. Eucalyptus species management, history and trends in Ethiopia, EIAR, UPM, ENCE, Madrid. Pp .409.

Girmay G, Singh B. R, Mitiku H., Borresen T. and Lal R. 2008. Carbon stocks in Ethiopian soils in relation to land use and soil management." Land Degradation and Development 19 (4): 351-367.

Grunzweig J.M, Gelfand I, Fried Y. and Yakir D. 2007. Biochemical factors contributing to enhanced carbon storage following afforestation of a semi - arid shrubland. *Biogeosciences 4* (*5*): 891- 904.

Hills WE, and Brown A.G. 1978. Eucalyptus for Wood Production, Division of Building Research, CsiRio, Melbourne, Australia.

Holden S, Benin S, Bekele S. and Pender J. 2003. Tree planting for poverty reduction in less favoured areas of the Ethiopian Highlands. Small - scale forest economics. *Management and Policy*, *2* (*1*): 63-80.

IPCC. 2006. Guidelines for national green gas inventories, Chapter 4, forest land.

Islam K.R. and Weil R.R. 2000. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agr. Eco. Env. *79*: 9-16.

Jacobs M. R. 1981. Eucalypts for planting. FAO Forestry Series No. 11. FAO, Rome.

Garten, C.T. (2002). Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA, Biomass and Bioenergy, 23 (2): 93–102.

Jagger P. and Pender J. 2000. The role of trees for sustainable management of less - favoured lands: the case of *Eucalyptus* in Ethiopia. International, food policy research institute. EPTD Discussion paper 65, Washington, D.C, U.S.A.

Jagger P. and Pender J. 2014. The role of trees for sustainable management of less-favored lands: the case of Eucalyptus in Ethiopia. *For. Pol. Econ. 2003*, 5, 83 - 95. Available online: http://www.sciencedirect.com/science/article/pii/S1389934101000788 (accessed on 15 Jan 2014).

Jandl R, Rasmussen K, Tume M. and Johnson D.W. 2006. The role of forests in carbon cycles, sequestration and storage, Vienna Austria: Forest management and carbon sequestration.

Jenbere D, Lemenih M, Kassa H. 2011. Expansion of Eucalypt farm forestry and its determinants in ArsiNegelle District, South Central Ethiopia. Small - Scale For. *2011*, 11, 389 - 405. Available online: http://link.springer.com/article/10.1007/s11842-011- 9191-x (accessed on 23 Oct 2013).

Keeney D.R. and Nelson D.W. 1982. Nitrogen - inorganic forms. In: page A. L. (ed.), Methods of soil analysis. Agron.9, part 2: Chemical and microbiological properties, 2nd ed., Am. Soc. Agron. Madison Wisc., USA. Pp. 643-698.

Laganivee, J., Angers, D.A. and Pare, D. (2010). Carbon accumulation in agricultural soils after afforestation: A meta analisyis. Global Change Biology 16 (1): 439–453.

Lamprecht H. 1990. Silviculture in theTropics: Tropical forest ecosystems and their tree species-possibilities and methods for their long-term utilization. GTZ, Eschborn. Germany. 296 p.

Lemenih M. Expediting ecological restoration with the help of foster tree plantations in Ethiopia. J Drylands. 2006;1(1):72–84.

Lemenih M. 2010. Growing eucalypts by smallholder farmers in Ethiopia. In: Gil, L. , Tadesse, W., Tolosana, E., Lopez, R. (Eds.). Proceedings of the conference on eucalyptus species management, history, status and trends in Ethiopia 15 - 17 Sep 2010. EIAR, Addis Ababa, Ethiopia. Pp. 91 - 103.

Lemenih M. and Kassa H. 2014. Re - greening Ethiopia: History, challenges and lessons. Forests 5: 1896-1909. Doi: 3390/f5081896.

Lemenih M, Teketay D. Restoration of native forest flora in the degraded highlands of Ethiopia: constraints and opportunities. SINET Ethiop J Sci. 2004; 27(1):75–90.

Lemenih M. and Teketay D. 2004b. Restoration of native forest flora under plantation forests established on abandoned de-graded agricultural sites in Ethiopia. Environmental Management.

Lemma B, Kleja DB, Olsson M, Nilsson I. Factors controlling soil organic carbon sequestration under exotic tree plantations: a case study using the CO_2Fix model in Southwestern Ethiopia. Forest Ecol Manag. 2007;252(1-3):124–31.

Li D, Niu S. and Luo Y. 2012. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: a meta-analysis. The New Phytologist 195 (1): 172 - 81.

Little EC. 1985. Common fuel wood crops, a hand book for their identification: Communi - Tech Associates Morgatown, Westverginia, US.PP.354.

Lugo AE. Comparison of tropical tree plantations with secondary forests of similar age. Ecol Monogr. 1992;62:1–41.

Mekonnen K, Tadesse Y, Gerhard G, Yossef A. Performance of eight tree species in the highland vertisols of Central Ethiopia: growth, foliage nutrient concentration and effect on soil chemical properties. New Forests. 2006;32(3):285–98.

Mekonnen Z, Kassa H, Lemenih M, Campbell B. 2007. The role and management of eucalyptus in Lode Hetosa district, Central Ethiopia. For. Trees Livelihoods 17, 309 - 323.

Moges Y. 2015. The experiances of REDD$^+$ for Ethiopian condition. Proceedings of the 1st technology dessimination workshop, 26th - 27th November 2015, Tokuma Hotel, Adama, Ethiopia.

Moges Y, Eshetu Z. and Nune S. 2010. Ethiopian forest resources: status and future management options in view of access to carbon finances. Ethiopian Climate Research and Networking Report, UNDP, Addis Ababa, Ethiopia.

Mussa M, Hashim H. and Teha M. 2016. Rangeland degradation: Extent, impact and alternative restoration technologies in the rangelands of Ethiopia. Tropical and Subtropical Agroecosystems 19, 305-318.

Ngomanda A, Engone-Obiang NL, Lebamba J, Moudounga-Mavouroulou Q, Gomat H, Mamkou GS, Loumeto R, Midoko ID, Kossi DR, Zinga KR, BKH B, Mikala OC, Nyangadouma R, Lépengué N, Mbatchi B, Picard N. Site specific versus pantropical allometric equations: which option to estimate the biomass of a moist central Africa forest? For Ecol Mgt. 2014;312, 1:–9.

Nicholas P, Saint-André L and Henry M. 2012. Manual for building tree volume and biomass allometric equations, from field measurement to prediction. FAO, Rome, CIRAD, Montpellier. Pp. 215.

Nune S, Kassie M and Mungatana E. 2012. Forest resources accounting for Ethiopia. in Book: Accounts, Rashid et al. (eds,), Netherlands, DOI: https://doi.org/10.1007/1978-94-007-5323-5-5, Pp:103-142.

Page-Dumroese D, Harvey A and Jurgensen M. 1995. A guide to soil sampling and analysis on the national forests of the Inland Northwest. USDA - FS, INT GTR-326 (11 pp.).

Pearson T, Brown S, Birdsey R. 2007. Measurement guidelines for the sequestration of forest carbon. Northern Research Station, Department of Agriculture, Washington, D.C.

Pearson T, Walker S. and Brown S. 2005. Source book for land use, land-use change and forestry projects.

Ponce-Hernandez R. 2004. Assessing carbon stocks and modeling win–win scenarios of carbon sequestration through land-use changes. FAO, UN, Rome.

Pooltouchidou A. 2013. Effects of forest plantation on soil carbon sequestration and farmers livelihoods. A case study in Ethiopia, MSc Thesis in Biology, Swedish University of Agricultural Sciences, Department of soil and Environment, Uppsala, Sweden.

Pukkala T. and Pohjonen V. 1989. Forest inventory planning on fuelwood plantations of Ethiopia. *Silvicultura 13*: 1-20.

R-Development Core Team., 2017. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Ruiz-Peinado R, Bravo-Oviedo A. Senespleda, López-Senespleda E, Montero G and Río M. 2013. Do thinning influence biomass and soil carbon stocks in Mediterranean Maritime pine wood? Eur.J. Forest Res *132*: 252-262; Doi https://doi.org/10.1007/s10342-012-0672-2.

Sandewall M, Kassa H, Wu S, Khoa PV, He Y. and Ohlsson B. 2015. Policies to promote household-based plantation forestry and their impacts on livelihoods and the environment: cases from Ethiopia, China, Vietnam and Sweden, International Forestry Review Vol.17 (1).

Sedjo R, Botkin D. Using forest plantations to spare natural forests. Environment. 1997;39(10):14–20.

Seely B, Weldham C, Blanco JAT. Towards the application of soil organic matter as an indicator of forest ecosystem productivity deriving thresholds, developing monitoring systems and evaluating practices. Ecol India. 2010;10:999–1008.

Girma Shumi. 2009. The structure and regeneration status of tree and shrub species of Chilimo forest-Ecological sustainability indicators for participatory forest management (PFM) in Oromia, Ethiopia. MSc Thesis, University of Dresden, Germany.

Siry J, A. Malmquist and Cubbage F. 1999. Potential impacts of increased management intensities on planted pine growth and yield and timber supply modeling in the South. In: Proceedings of the 1999 Southern Forest Economics Workshop, April 18 - 20, 999. Pp. 236 - 242.

Tesfaye K, Walker S. 2004. Matching of crop and environment for optimal water use: the case of Ethiopia. Physics and Chemistry of the Earth, 29 (15-18):1061-1067.

Tesfaye MA, Bravo F, Ruiz-Peinado R, Pando V and Bravo-Oviedo A. 2016. Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands. Geoderma 261:70-79. 0016-7061/© 2015 Elsevier B.V. All Rights Reserved.

Tesfaye T. 2009. Is Eucalyptus ecologically hazardous tree species? Ethiopian e-journal for Research and Innovation Foresight vol.1 (1): 128-134.

Twongyirwe R, Sheil D, Majaliwa JGM, Ebanyat P, Tenywa MM, Van Heist M. and Kumar L. 2013. Variability of soil organic carbon stocks under different land uses: a study in an Afromontane landscape in South-Western Uganda. Geoderma 193 - 194, 282 - 289. Doi: https://doi.org/10.1016/j.geoderma.2012.09.005.

Vanclay J.K. 1994. Modelling forest growth and yield: *Applications to mixed tropical forests*, CAB International Wallingford, UK.

Woldeyohannes F. 2005. Above ground biomass allometric equations and fuel wood supply properties of six species growth in Ethiopia. PhD Thesis, University of Putra, Malaysia.

Yin R. 1998. Forestry and the environment in China: the current situation and strategic choices. World Development 26 (12): 2152 - 2167.

Young A. 1997. Agroforestry for soil conservation. CAB International, Wallingford, UK.

Zanne A, Lopez-Gonzalez G, Coomes D, Ilic J, Jansen S, Lewis L, Miller B, Swenson G, Wiemann C and Chave J. 2009. Global wood density database [http://hdl.handle.net/10255/dryad.235

Zerfu H. 2002. Ecological impact evaluation of Eucalyptus plantations in comparison with grazing land use types in the highlands of Ethiopia. PhD Thesis, Institute of Forest Ecology, Vienna University of Agricultural sciences, Vienna.

Zerihun K. 2002. Profitability and household income contribution of growing Eucalyptus globulus (Labill.) to small holder farmers. The case of Central Highlands of Oromia, Ethiopia. MSc Thesis, in Forestry Program, Thesis Report No.2002; 69. Swedish Uni.Agri.Sci., Sweden.

Zewdie M, Olsson M. and Vewijst T. 2009. Above ground biomass production and allometric relations of *Eucalyptus globulus* Labill. Coppice plantations along a chronosequence in central Highland of Ethiopia. Biomass and Bioenergy 33 (3): 421-428.

Zhou Y.R, Yu Z.L. and Zhao S.D. 2010. Carbon storage and budget of major Chinese forest types, Acta Phytoeco. Sin 24, 518-522.

Publisher's Note