Temporal variation of ecosystem carbon pools along altitudinal gradient and slope: the case of Chilimo dry afromontane natural forest, Central Highlands of Ethiopia

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Abstract

Quantifying the amount of carbon pools in forest ecosystems enables to understand about various carbon pools in the forest ecosystem. Therefore, this study was conducted in the Chilimo dry afromontane forest to estimate the amount of carbon stored. The natural forest was stratified into three forest patches based on species composition, diversity, and structure. A total of 50 permanent sample plots of 20 m × 20 m (400 m^2) each were established, laid out on transects of altitudinal gradients with a distance of 100 m between plots. The plots were measured twice in 2012 and 2017. Tree, deadwood, mineral soil, forest floor, and stump data were collected in the main plots, while shrubs, saplings, herbaceous plants, and seedling data were sampled inside subplots. Soil organic carbon (SOC %) was analyzed following Walkely, while Black's procedure and bulk density were estimated following the procedure of Blake (Methods of soil analysis, 1965). Aboveground biomass was calculated using the equation of Chave et al. (Glob Chang Biol_20:3177–3190, 2014). Data analysis was made using RStudio software. To analyze equality of means, we used ANOVA for multiple comparisons among elevation classes at $a = 0.05$. The aboveground carbon of the natural forest ranged from 148.30 ± 115.02 for high altitude to 100.14 ± 39.93 for middle altitude, was highest at 151.35 ± 108.98 t C ha^{-1} for gentle slope, and was lowest at 88.01 ± 49.72 t C ha^{-1} for middle slope. The mean stump carbon density 2.33 ± 1.64 t C ha^{-1} was the highest for the middle slope, and 1.68 ± 1.21 t C ha^{-1} was the lowest for the steep slope range. The highest 1.44 ± 2.21 t C ha^{-1} deadwood carbon density was found under the middle slope range, and the lowest 0.21 ± 0.20 t C ha^{-1} was found under the lowest slope range. The SOCD up to 1 m depth was highest at 295.96 ± 80.45 t C ha^{-1} under the middle altitudinal gradient; however, it was lowest at 206.40 ± 65.59 t C ha^{-1} under the lower altitudinal gradient. The mean ecosystem carbon stock density of the sampled plots in natural forests ranged from 221.89 to 819.44 t C ha^{-1}. There was a temporal variation in carbon pools along environmental and social factors. The highest carbon pool was contributed by SOC. We recommend forest carbon-related awareness creation for local people, and promotion of the local knowledge can be regarded as a possible option for sustainable forest management.

Keywords: Carbon stock density, Dry afromontane natural forest, Deadwood, Humus, Herbaceous, Mineral soil and stump carbon

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Background

Forest provides goods, such as wood and non-wood forest products (NWFP), and ecosystem services, such as biodiversity protection, fresh water supply, soil protection, and climate regulation, which are important for the well-being of the people at local, national, and global levels. Forests mitigate atmospheric CO_2 as sinks in its carbon pools (C sequestration). IPCC (2013) reported that the global forest cover is 4 billion hectares and represents over 50% of global greenhouse gas mitigation potential (IPCC 2007). Tropical, humid, and dry forests spread over 2.1 billion hectare area worldwide, store 180 Gt C stock in biomass, and have a turnover of 915 Gt of carbon each year (Millennium Ecosystem Assessments 2005; Baccini et al. 2008; FRA 2015). Tropical dry forests cover over 840,000,000 ha, constitute a net terrestrial primary production of 40% of all tropical forests, and store 60% carbon which contain half of the world's tree species (Miles et al. 2006; Chidumayo et al. 2011).

The major carbon pools in forest ecosystems are aboveground and belowground biomass, deadwood, litter, and soil organic carbon (FAO 2005; IPCC 2003, 2006). Aboveground biomass (AGB) includes all living biomass above the soil, while belowground biomass (BGB) includes all biomass of live roots excluding fine roots (< 2 mm diameter) (Brown 1997; IPCC 2003). Deadwood organic carbon includes coarse and fine deadwood found in the form of logged, standing and lying deadwood (Takahashi et al. 2010; Kassa 2015). Litter carbon is found in the form of fallen leaves, twigs, and undecomposed litter (Lemma et al. 2007). The soil is the largest carbon reservoir of the terrestrial carbon cycle storing 1500–1550 Gt of organic carbon. About three times more carbon is contained in soils than in the world's vegetation 560 Gt, and soils hold more than twice the amount of carbon, i.e., present in the atmosphere 720 Gt (Post et al. 2001; Lal 2004). Forest soil is part of any forest ecosystem and stores about 40% of the total SOC of the global soils (Baker 2007; Rooney 2013).

The carbon pools in forest ecosystems are affected by altitude, slope, and land-use types (Diawei et al. 2006). Bhat et al. (2013) indicated that land use, land-use changes, soil erosion, and deforestation are the most important factors affecting the carbon stock density in the forest ecosystem. According to Feyissa et al. (2013), forest carbon is affected by altitude and slope. Altitude has a significant effect on temperature and precipitation. This strongly affects the species composition, the diversity, the quantity, and the turnover of forest ecosystem (Sheikh and Bussmann 2009). Hamere et al. (2015) assessed the impact of slope in above and belowground biomass, soil organic carbon, and total ecosystem carbon, in which east slope aspect showed the highest, whereas south slope aspect showed the lowest total

carbon stock. In the tropics, land use affects the global carbon cycle by increasing the rate of carbon emissions (Silver et al. 2000). Conversion of forest land use type into agricultural land use types reduced SOC stock density by 20–50% (Solomon et al. 2002; Lemenih and Itanna 2004; Lal 2005).

Ethiopia is endowed with various landscape types. Accordingly, the vegetation types are diverse and vary from tropical humid forests and cloud forests located in the southwest to desert scrubs in the east and northeast (Bongers and Tenngkeit 2010). The natural high forests of Ethiopia are mainly found in the highlands where annual rainfall distribution and amount is better, with a maximum mean annual rainfall of more than 1000 mm year^{-1}. Around 90% of the total population live in the highlands, which covers 44% of the country's land mass. Moreover, the great majority (93%) of the cultivated land and the country's livestock population (75%) is found in the highlands.

The national carbon stock of Ethiopia was estimated to be 153 teragram (Tg) of C by Houghton (1998), 867 Tg of C by Gibbs et al. (2007), and 2.5 Gt of C by Sisay (2010). The natural high forest carbon stock ranges from 101 to 200 Mg C ha^{-1} (Brown 1997; Moges et al. 2010; Temam 2010; Tsegaye 2010). The discrepancy between these values sees to be the different methods and tools used by the authors and the variability in soil, topography, and forest types. Thus, localized carbon stock assessment studies should have been done (IBC 2005; Moges et al. 2010). However, relatively little is currently known about the intersite and temporal variability of forest biomass when compared to a large amount of information available in other continents (Chave et al. 2001; Girma et al. 2014; Hassen 2015). Periodic forest inventories and continuous monitoring and assessment works in the country are lacking, even though they are most useful in order to evaluate the magnitude of carbon fluxes between AGB and the atmosphere (Girma et al. 2014). According to Adugna et al. (2013), information on carbon stocks of forest is limited in Ethiopia. Similarly, Meles et al. (2014) also noted that, although the carbon pool varies between vegetation types and soil types, there is a limited number of studies except few works by Hassen (2015), Gebre (2015), Tesfaye (2015), Yahya (2015), and Wodajo (2018).

Chilimo forest is composed of mixed broad-leaved *Podocarpus falcatus*, *Olea europea* 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 of Tesfaye et al. (2016)

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 2533 stems per hectare found in Chilimo to 848 stems per hectare found in Gallessa patch. Like in many parts of Ethiopia, Chilimo forest was previously a closed dense forest before the Italian occupation (1936–1941) (Shumi 2009). However, the Italians had established a camp and introduced seven saw mills inside Chilimo forest for timber extraction. This resulted in intensive exploitation of high value timber native tree species under Chilimo dry afro montane forest since long years ago. 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 overgrazing and agricultural expansion in the forest radically reduced the forest area from 22,000 ha in 1982, 11,000 ha in 1984, 6000 ha in 1991, and 4500 ha in 2016 (Shumi 2009; Teshome 2017). It has also been reported that some plant species are becoming endangered due to deforestation (Soromessa and Kelbessa 2014).

Some years ago, participatory forest management approach was established by non-governmental organization, i.e., Farm Africa (Negassa and Wiersum 2006), where all parts of Chilimo forest was managed by the community. However, Farm Africa had left its engagement, and then, in 2005, the forest was transferred to Oromia Wildlife and Forest Enterprise. Currently, the Chilimo forest is jointly managed by 12 Forest User Groups (FUGs) under the umbrella of Oromia Wildlife and Forest Enterprise (OFWE). In and around the forest, there are more than 4000 households with a total population of about 20,000 people who are living (Tesfaye et al. 2016). The forest was divided into nine forest compartments (patches), and each compartment is managed by each kebele administration. Forest in Chilimo has the highest share for the livelihood of people, i.e., it contributes almost an equal amount to agriculture for livelihoods (Negassa and Wiersum 2006; Kassa et al. 2008).

The Chilimo forest is characterized by different altitudinal gradient, slope range, forest patch, and land-use types, and given that the temporal variation in carbon pools along these factors are not yet known, we therefore hypothesized that there is a temporal variation in carbon pools along environmental variables, forest patch, and land-use types. The main purpose of this study is therefore to determine temporal variation in carbon pools along environmental gradient and slope in Chilimo dry afromontane forest. The specific research questions to be addressed are as follows: (i) Is there a temporal variation in carbon pools along the altitudinal gradient, slope, and forest patch? (ii) Does temporal variation occur in humus and litter carbon pools? (iii) Is there any temporal variation in the SOC stock across land-use categories and soil depth? (iv) Is there any correlation among carbon pools in the natural forest? (v) Do environmental factors and forest patch affect the total ecosystem carbon?

Material and methods
Description of the study site
The Chilimo forest contains a total of 4500 ha. For administrative purposes, the forest has been partitioned into nine compartments (forest patches) as a part of the management scheme of Oromia Forest and Wildlife Enterprise (Fig. 1). This study was conducted in the largest forest patches of the forest which are Chilimo, Galless, and Gaji. The sampled plots are geographically located at 038° 08′ 679′′ to 038° 10′ 283′′ E latitude and 09° 04′ 038′′to 09°05′765′′ N longitude, at an altitude of 2470 to 2900 m above sea level (Fig. 1) in Dendi District, Western Shewa Zone, Oromia Administrative Region, and Central Highlands of Ethiopia. Chilimo forest is one of the few remnant of dry afromontane forests located in the Central Highlands of Ethiopia. This forest is characterized by a small enclave in the western section of a chain of hills and ridges that stretch over 200 km from north of Addis Ababa westwards up to the Ghedeo highlands in the west, and local river valleys and gorges cut through the chain. Awash river, one of the longest river in the country, originates from this forest and is the home of over 180 species of birds and 21 species of mammals (Woldemariam 1998). Chilimo forest is composed of mixed broad-leaved *Podocarpus falcatus*, *Olea europaea*, *Scolopia theifolia*, *Rhus glutinosa*, *Olinia rochetiana*, and *Allophylus abyssinicus*, and *Juniperus procera* are the major species in the forest (Bekele 2004; Kelbessa and Soromessa 2004; Kassa et al. 2008). While Shumi (2009) investigated 42 species composed of 27 tree and 15 shrub species in the forest, Tesfaye (2015) reported for Chilimo 33 different native woody species (22 tree species and 11 shrub species) in three forest patches. On their part, Soromessa and Kelbessa (2014) reported 213 different plant species which belong to 83 families, and 18 plant species are recorded as endemic, from which one was endangered and three were evaluated as vulnerable to the Chilimo forest (Kelbessa and Soromessa 2004).

For over a century, Chilimo forest was owned and controlled by the State. Nevertheless, the State control had weakened from 1991 to 1996. This resulted in an increasing conversion of the forest into agricultural land and illegal cutting of trees for timber, construction wood, and fuelwood. Thus to minimize deforestation of the remaining forest, the government classified 58 natural forests as National Forest Priority Areas NFPAS including Chilimo forest was one of them (Shumi 2009). The
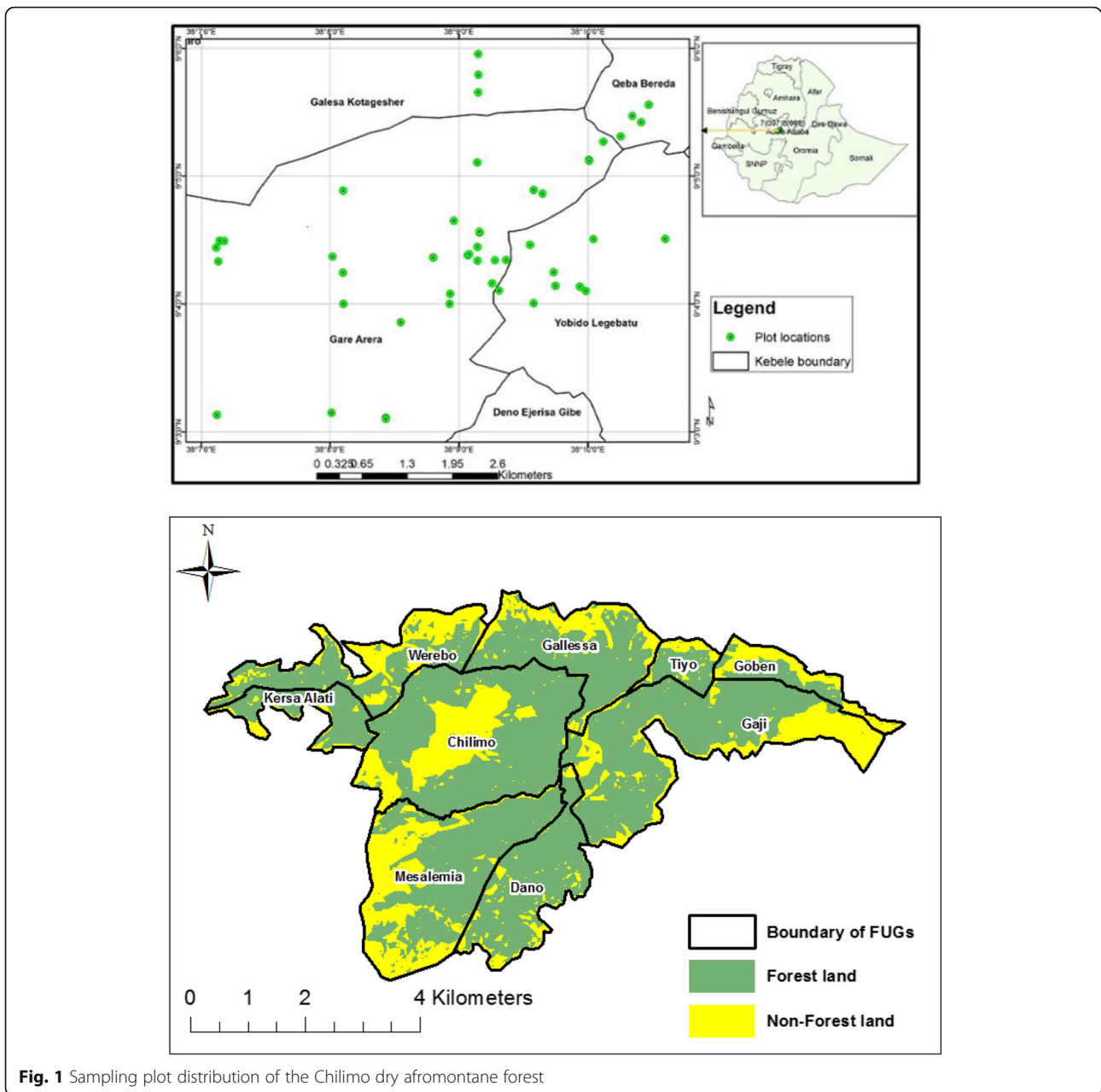
Fig. 1 Sampling plot distribution of the Chilimo dry afromontane forest

mean annual temperature of the area ranges between 15 and 20 °C, and the mean annual precipitation ranges from 1000 to 1264 mm (Shumi 2009). Following Köppen's classification, the climate of Chilimo forest could be classified as warm temperate climate I (CWB) type (EMA 1988).

Field sampling
Reconnaissance survey
Discussions were held with Oromia Wildlife and Forest Enterprise office in Addis Ababa for awareness creation and issuance of authorizations to work in this forest. Subsequently, after the permit, a reconnaissance survey

was conducted through a field visit and a physical observation across the forest. Three forest patches were selected for further in-depth study based on their accessibility, species composition, and representativeness. Then an inventory was conducted in Chilimo, Gallessa, and Gaji forest patches. The survey also covered the adjacent land-use types, which include plantation forests, cultivated land, and degraded lands.

Sampling design
A systematic sampling approach was used to carry out the inventory. A total of 35 20 m × 20 m (400 m^2) squared sampled plots (20 plots in Chilimo, 11 plots in

Gallessa, and 4 plots in Gaji forest patches) were established, based on Neyman's optimal proportional allocation formula in the natural forest (Kangas and Maltamo 2006; Köhl et al. 2006) (Fig. 2). In addition, nine sample plots of 20 m × 20 m were established in the plantation of *Cupressus lusitanica*, *Eucalyptus saligna*, and *Pinus patula* forests (three in each) along an altitudinal gradient. Additionally, six plots under cultivated land and degraded land (three in each) were laid out for soil sampling. The total number of plots was 50 in natural and plantation forests and cultivated and degraded lands. The center of the first plot was laid out systematically using Silva compass, 150 m away from the outer edge following north direction to avoid edging effect. To attain a 90°corner of the main plots, the Pythagoras theorem was applied. Then, four sharpened wooden pegs were stalked in the four corners of the main plot. The plots were laid out along 100 m ground distance, starting from the highest to the lowest ridges of the mountains using a measuring tape, GPS, and compass. A total of ten transect lines (four in Chilimo, four in Gallessa, and two in Gaji) were made along the center of the natural forest. The distance between two consecutive transect lines was 300 m and 1 km, respectively, depending on the accessibility of the next transect. A first inventory was conducted in 2012, and remeasurements were conducted within the same established sampling plots and for the same numbered trees in 2017. Soil samples were also taken from adjacent land-use types (cultivated land and degraded land) 1 km away from the outer edge of the natural forest. The horizontal distance between sampling plots in these land-use types was also 100 m, and transect lines were made from bottom to top parts of the gradient.

Fig. 2 Design of the sampling plots of the Chilimo dry afromontane forest
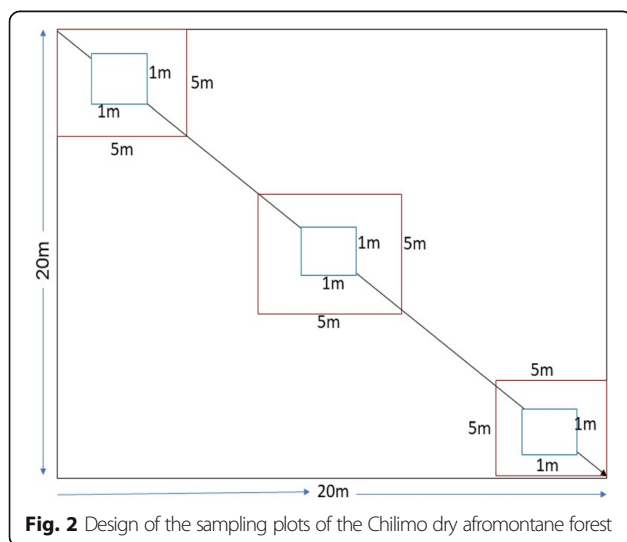
Field data collection

Before the actual measurements started, all trees and shrubs found in the border of each plot were marked, and then, all trees in the main plot were numbered. 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). Tree measurements were conducted in the 20 m × 20 m main plot, while shrubs and saplings were measured in 3.5 m × 5 m subplots and seedling measurements were made in 3.1 m × 1 m subplots. Tree diameter (cm) was measured using a metallic caliper for small- and medium-sized trees, while diameter tape was used for bigger tree measurements. Height was measured to the nearest two digits using Vertex III digital electronics tree height measurement instruments. In cases where trees branched at below the breast height, the diameter was measured separately for each branch and was the square root of diameter squared ($\sqrt{Dbhi2 + Dbhii2}$). Likewise, the diameter at each stem was measured separately for trees with multiple stems connecting near to the ground. For irregularities and/or buttresses on large trunks, measurements were taken at the nearest lower points. Height and diameter measurements for shrubs and saplings were done using graduated wooden bars and metallic caliper. Counting and average height measurement for seedlings were made using a wooden ruler.

Data analysis

For the purpose of analysis, environmental factors and forest patches were categorized into three discrete classes: the altitudinal gradient as class 1 (low elevation) ≤ 2599 m, class 2 (middle elevation) 2600–2699 m, and class 3 (high elevation) ≥ 2700 m and slope class as slope 1 (gentle slope) ≤ 25%, slope 2 (middle slope) 26–50%, and slope 3 (steep slope) 51–70%; data for the different carbon pools both in the natural forest and other land uses 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 $\alpha = 0.05$.

Aboveground biomass

Aboveground biomass was calculated using the equation of Chave et al. (2014) (Eq. 1)

$$AGB = 0.0673(\rho HDbh2)^{0.976} \tag{1}$$

where AGB is the above ground biomass (in kg), Dbh is the diameter at breast height (in cm), H is the height (in m), and ρ is the basic wood density (in g cm^{-3}). The wood density data information were obtained from the

Global Wood Density Database (Zanne et al. 2009), ICRAF Wood Density Database (www.worldagroforestry. org), and Wood Technology Research Centre, Addis Ababa (Desalegn et al. 2012). In addition, wood densitity for *Allophyllus abyssinicus, Olea europea subspp cuspidiata, Olinia rochetiana, Rhus glutinous,* and *Scolopia theifolia* was used from Tesfaye (2015).

Accumulated aboveground and total carbon density was calculated following Eqs. 2 and 3:

$$ACD = AGB \times 0.47 \tag{2}$$

(IPCC 2006)

$$BCD = ACD \times 0.24 \tag{3}$$

(Gibbs et al. 2007; Ponce-Hernandez 2004)
where ACD is the aboveground carbon density (t C ha^{-1}) and BCD is the belowground carbon density (t C ha^{-1}).

The accumulated aboveground and total carbon densities for each tree were calculated separately in each plot, and then, figures for the carbon density of each tree were summed up to give a plot accumulated carbon density and converted to per hectare. The plots were stratified along altitudinal gradient, slope percent, forest patch, and land-use types using R software (R-Development Core Team 2017).

Herbaceous biomass sampling and analysis

Sampling at the herbaceous layer was made in the interior of three subplots for the inventory of herbs and grasses in 2017. Harvesting of herbs and grasses was made using sickles, and fresh weight of all samples was recorded in the field using string balance. Then, 500 g of fresh sample was taken to the laboratory to determine the water content and dry biomass.

The samples were oven dried at 70 °C for 24 h and weighed again to obtain the dry matter of the sample, and these data were used for the calculation of Eq. 4:

$$\begin{aligned} HbCD = &\left(W_{sample}\,(dry) \right) / \left(W_{sample}(fresh) \right) \\ &\times W_{field}/3 \times 0.47 \times 10000/10^6 \end{aligned} \tag{4}$$

where HbCD is the herbaceous carbon density (t C ha^{-1}), W_{sample} (dry) is the sample oven-dried weight, W_{sample} (fresh) is the sample fresh weight, and W_{Field} is the total fresh weight of the samples collected.

Coarse wood debris sampling

Deadwood was sampled in 11, 6, and 1 plots in Chilimo, Gallessa, and Gaji forest patches, respectively. Coarse wood debris (logs and cut stumps) were inventoried within the 20 m × 20 m plots. All fallen branches and/or twigs of 2 cm diameter and above were collected and measured in the field using string balance. The weight of big logs was estimated in the field manually. For fallen

branches and twigs, subsamples were taken into the laboratory. All fallen branches/twigs of 2 cm diameter and above were oven dried at 102 °C for 24 h.

Stump biomass

Stumps were sampled inside the 20 m × 20 m plots. Diameter measurements for all the stumps were made in the main plots in their bases and at the top using a metallic caliper and diameter tape, while height measurements were done using a measuring tape. To calculate the stump carbon, first, the volume was calculated using Smalian's formula (Nicholas et al. 2012) (Eq. 5):

$$V = \pi/8L\left(D_1{}^2 + D_2{}^2\right) \tag{5}$$

where V is the volume (cm^3), L is the length of the trunk (cm), $D_1{}^2$ is the diameter of the narrow end of the trunk (cm), and $D_2{}^2$ is the diameter of the large end of the trunk (cm). Once the volume was determined, the mass was calculated as follows (Eq. 6):

$$m_i = \rho_i \times V_i \tag{6}$$

where m_i is the mass in kilograms, ρ_i is the density (g cm^{-3}), and V_i is the volume.

Forest floor and litter sampling and analysis

Litter, intermediate, and humus samples were taken within a 0.25 m × 0.25 m (0.0625 m^2) metallic frame in the center of the main plot where available, while depth of the forest floor was measured using a metallic ruler. The collected materials were taken into the laboratory for analysis for water content and dry weight.

The sampled litter, intermediate, and humus layers were oven dried at 70 °C for 24 h in the laboratory and weighed using sensitive balance. Chemical analysis for the humus and intermediate layer was performed using the loss-on-ignition method (Ben-Dar and Banin 1989). Then, soil organic matter was converted into organic carbon following Eq. 7 and Eq. 8:

$$SOM = (w105-w400)/w105 \times 100 \tag{7}$$

$$\%C = \%SOM \times 0.58 \tag{8}$$

where SOC is the soil organic carbon concentration, SOM is the soil organic matter, $w105$ is the weight of dry soil sample at 105 °C, $w400$ is the weight of ground soil sample at 400 °C, and 0.58 is the carbon concentration in the soil organic matter which has been found to be the most convenient conversion factor from organic matter to carbon content in forest floor (De Vos et al. 2005). Although Pribyl (2010) recommended a value of 0.5, we retained the 0.58 value in forest floor as it has been commonly used and it allows comparisons with other studies.

The forest carbon density was calculated using the conversion of humus carbon stock density (HuCD, in $t\,C\,ha^{-1}$) in the sampled plot following Eq. 9:

$$HuCD\left(t\,C\,ha^{-1}\right) = \frac{HODweight}{0.0625} \times \frac{c_p}{100} \times 10000/10^{\wedge}6 \quad (9)$$

where HuCD is the humus carbon density, HOD is the humus oven dry weight, and Cp is the carbon percentage.

Soil organic carbon sampling and analysis

Mineral soil samples were collected in 18 out of 50 sampled plots in natural forest, 9 in plantations, 3 in cultivated lands, and 3 in degraded lands. Sampling was made layer by layer with 1-m-long × 0.60-m-wide dug pit at the center of the main plot. Five hundred grams each of four mineral soil layers (0–10, 10–30, 30–50, and 50–100) was sampled and handled with plastic bags. Separate samples were taken at four soil depths for bulk density with a 5-cm-high cylinder that was introduced vertically in the corresponding depth. Resamplings were made in both cases by digging new sample pits 10 cm away from the older pit following an appropriate direction. A total of 264 (132 mineral soil + 132 cores) were collected and transported into the laboratory for organic C % and bulk density analyses.

Mineral soil sampled was air dried and passed through a 2-mm sieve to obtain the fine fraction for chemical analysis. The coarse fragments (2 mm) were removed from the sample, and their percentage of stoniness and
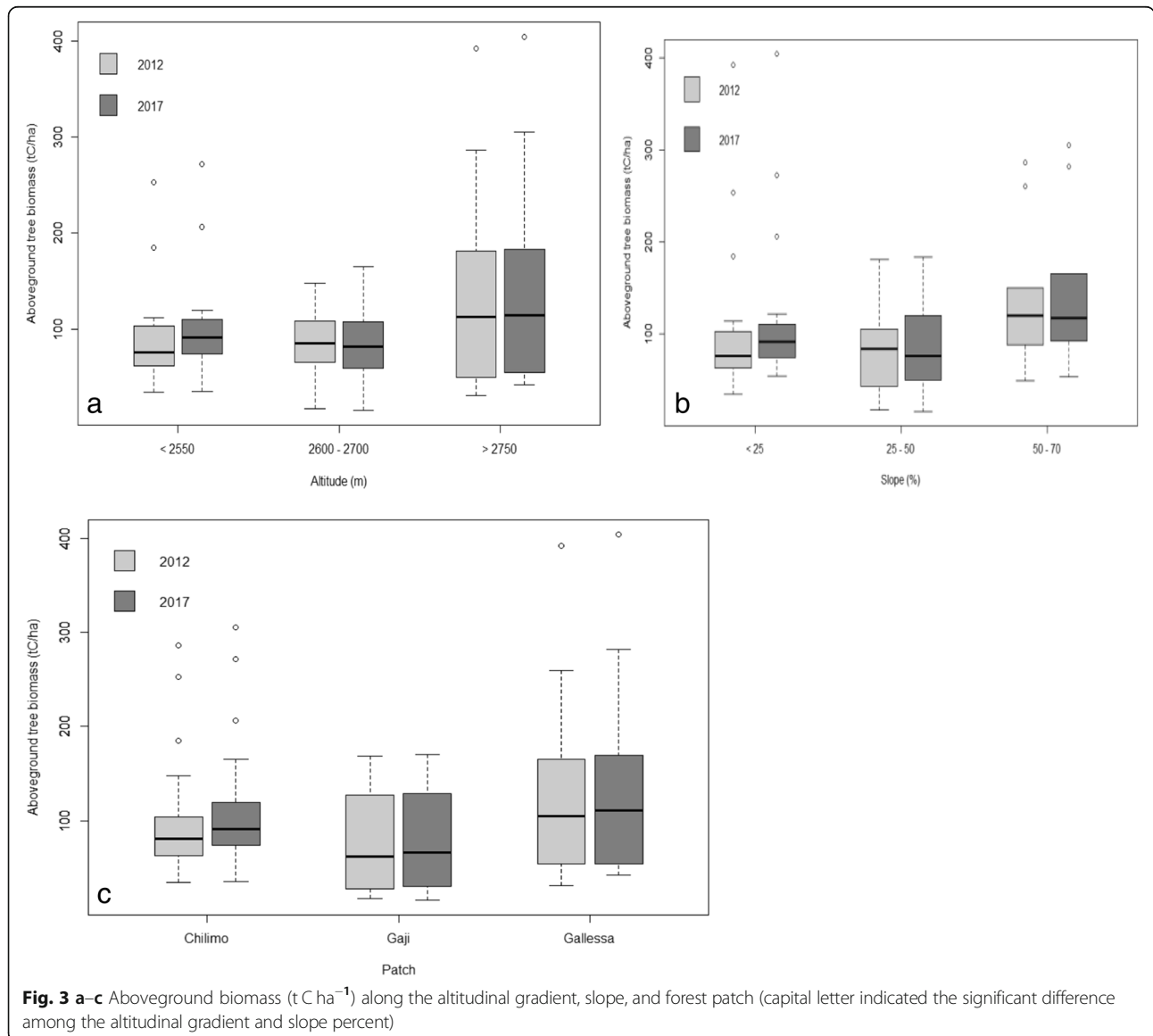
Fig. 3 a–c Aboveground biomass (t C ha^{-1}) along the altitudinal gradient, slope, and forest patch (capital letter indicated the significant difference among the altitudinal gradient and slope percent)

or rockiness was calculated by comparing their mass with the total weight of the oven dried samples at 67 °C for 24 h (Eq.10):

$$\mathrm{CFW\%} = \frac{\text{weight coarse fraction}}{\text{weight of total soil}} \times 100 \qquad (10)$$

where CFW is the percentage of coarse fragments by weight (Page-Dumroese et al. 1995). Then, the total organic carbon (C %) was analyzed following Walkley-Black's method described by the Anderson and Ingram (1996) procedure. Bulk density was estimated following the procedure of Blake (1965). The oven-dried soil was weighed and divided by the volume of the metallic cylinder.

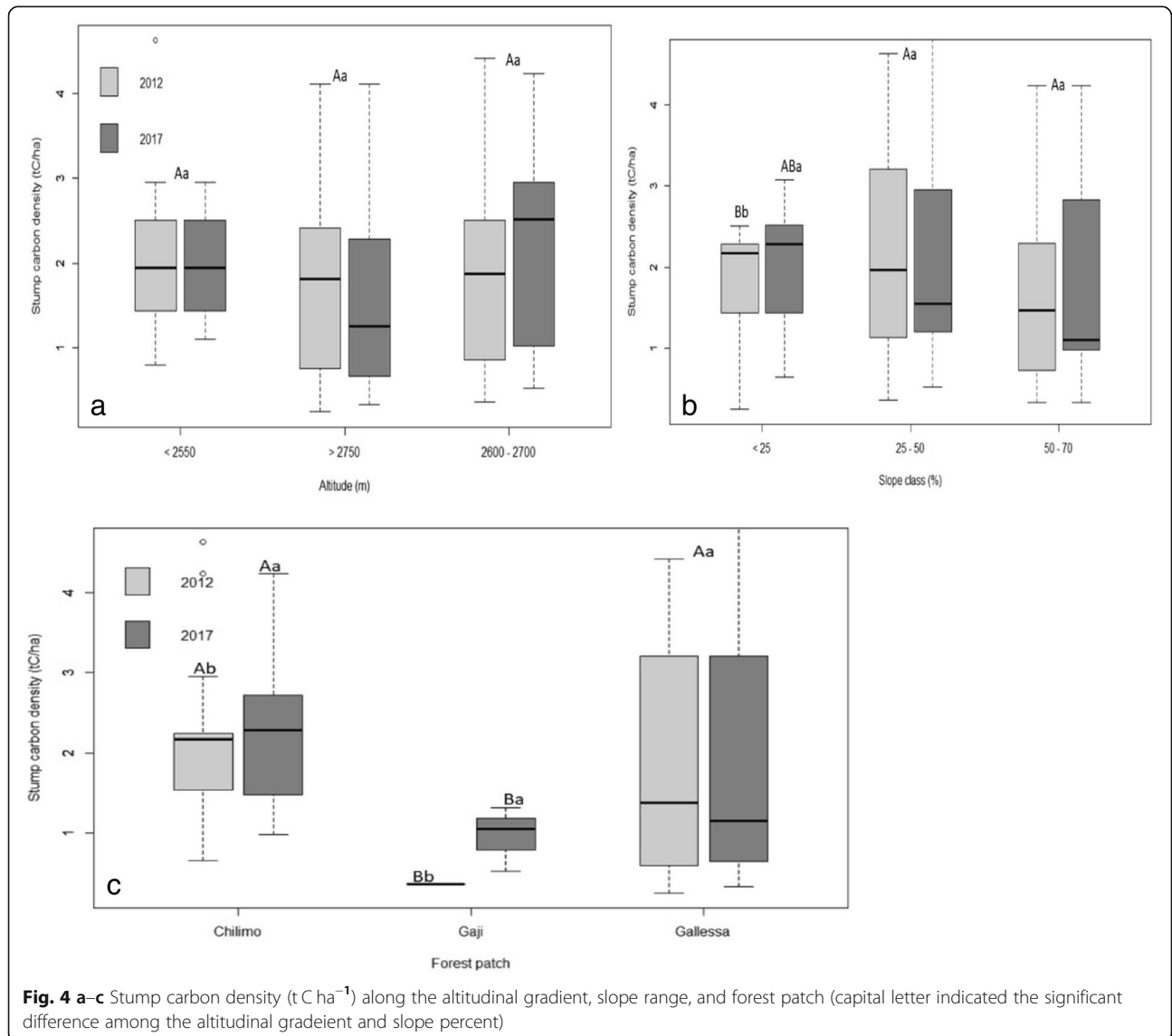The SOC stock density in mineral soil was calculated based on fixed depth method using carbon concentration, thickness of each layer, soil bulk density, and coarse fragmented matter at each depth, according to Eq. 10 (Ruiz-Peinado et al. 2013) (Eq. 11):

$$\mathrm{SOC\ stock} = \mathrm{SOC\ con}.BD.L\,(1{-}\mathrm{CFM}) \times 10 \qquad (11)$$

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

Total forest ecosystem carbon estimation

The total carbon stock (carbon density) was calculated by summing up all the seven carbon stocks of each

Fig. 4 a–c Stump carbon density (t C ha^{-1}) along the altitudinal gradient, slope range, and forest patch (capital letter indicated the significant difference among the altitudinal gradeient and slope percent)

carbon pools of the forest ecosystem following Pearson et al. (2005), then converted into tonnes of CO_2 equivalent by multiplying it by 3.67 as developed by Pearson et al. (2007). Carbon stock density of the study area was calculated using (Eq. 12):

$$TECD = ACD + BCD + DWCD + StCD \\ + HbCD + LCD + HuCD + SOCD \quad (12)$$

where TECD is the total ecosystem carbon density (t C ha^{-1}), ACD is the aboveground carbon density (t C ha^{-1}), BCD is the belowground carbon density (t C ha^{-1}), DWCD is the deadwood carbon density (t C ha^{-1}), StCD is the stump carbon density (t C ha^{-1}), LCD is the litter carbon density (t C ha^{-1}), HuCD is the humus carbon density (t C ha^{-1}), HbCD is the herbaceous carbon density (t C ha^{-1}), and SOCD is the soil organic carbon density (t C ha^{-1}).

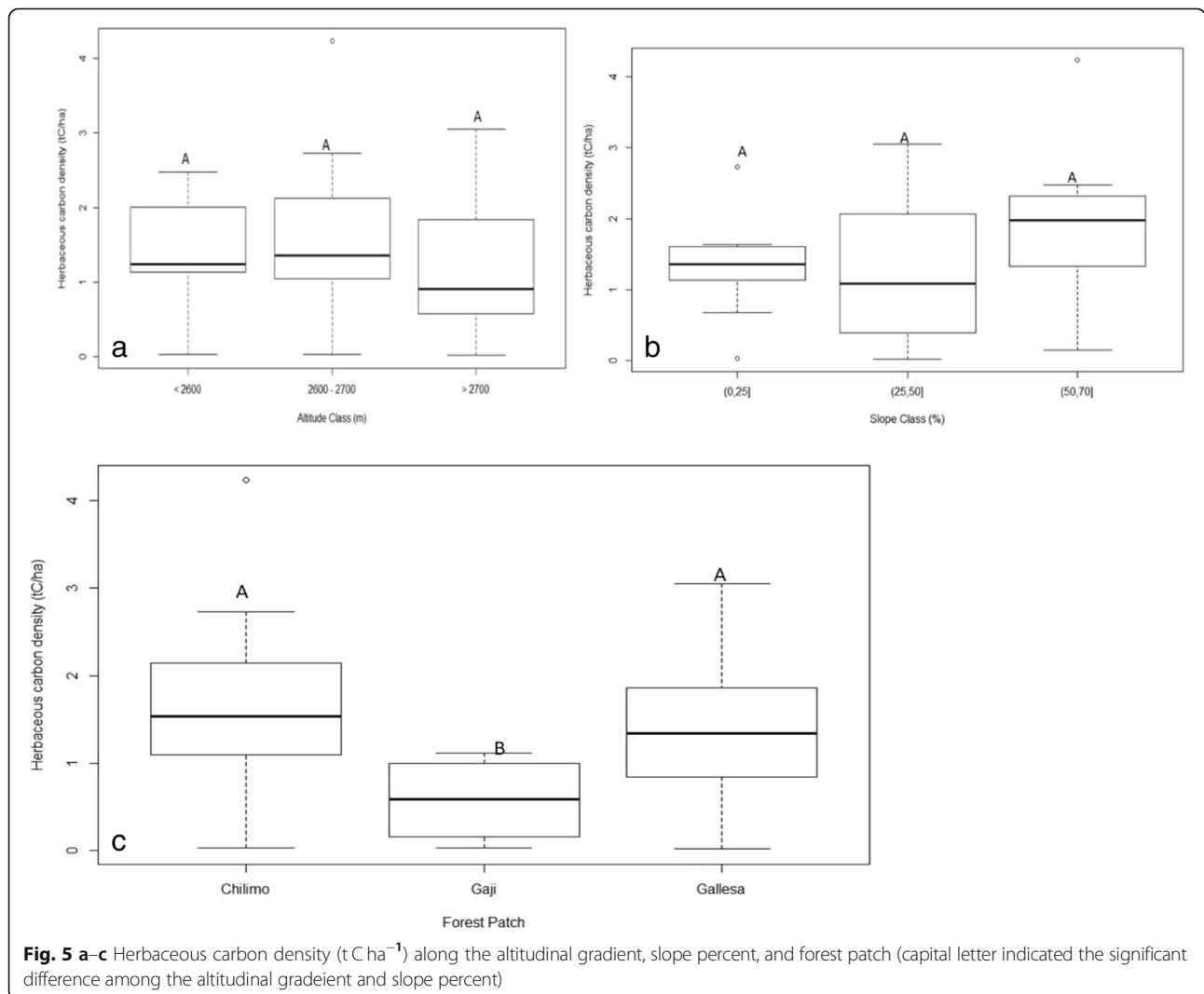### Correlation and regression analyses

A multiple regression correlation analysis was performed using R software (R-Development Core Team 2017). Then, a multiple regression correlation matrix graph was developed. Highly correlated carbon pools were selected and further evaluated. A linear correlation analysis graph and a linear equation model were developed, evaluated, and fitted. The best linear models were selected based on the MRES (mean residual for evaluating bias) and the RMSE (root mean square error for evaluating precision).

Results

Aboveground biomass and belowground carbon biomass

The aboveground and belowground biomass varied significantly among the altitudinal gradient and slope percent $P \leq 0.05$. However, there was non-significant among time and forest patch (Table 2; Fig. 3a–c). The aboveground and belowground biomass was the highest for

Fig. 5 a–c Herbaceous carbon density (t C ha^{-1}) along the altitudinal gradient, slope percent, and forest patch (capital letter indicated the significant difference among the altitudinal gradeient and slope percent)

Table 1 The different carbon pools of Chilimo dry afromontane forest natural forest along the altitudinal gradient, slope, and forest patch (mean ± SD)

Factors	Level	ACD (t C ha⁻¹)		BCD (t C ha⁻¹)		StCD (t C ha⁻¹)		Deadwood (t C ha⁻¹)		HbCD (t C ha⁻¹)	Litter + HUCD (t C ha⁻¹)		SOCD (100 cm depth) (t C ha⁻¹)	
		2012	2017	2012	2017	2012	2017	2012	2017	2017	2012	2017	2012	2017
Altitudinal gradient	High	139.66 ± 111.44	148.30 ± 115.02	37.71 ± 30.09	40.03 ± 31.06	1.76 ± 1.31	1.68 ± 1.21	1.58 ± 0.98	0.40 ± 0.38	1.35 ± 0.88	15.36 ± 13.38	6.92 ± 6.55	268.98 ± 80.45	224.7 ± 63.45
	Medium	97.49 ± 31.10	100.14 ± 39.93	26.32 ± 8.40	27.04 ± 10.78	1.87 ± 1.37	2.33 ± 1.64	0.37 ± 0.21	0.23 ± 0.21	1.27 ± 0.94	17.33 ± 17.35	8.14 ± 8.41	267.2 ± 102.13	295.96 ± 80.45
	Low	113.73 ± 67.39	125.92 ± 72.06	30.71 ± 18.19	34.00 ± 19.46	2.14 ± 1.15	2.32 ± 1.40	0.41 ± 0.50	0.27 ± 0.12	1.56 ± 1.08	9.67 ± 4.97	4.84 ± 2.58	206.40 ± 65.59	287.20 ± 112.63
Slope gradient	High	140.90 ± 81.48	150.78 ± 88.40	38.04 ± 22.00	40.71 ± 23.87	1.7 ± 1.26	2.03 ± 1.28	0.79 ± 1.20	0.37 ± 0.47	1.85 ± 1.17	7.39 ± 3.97	3.54 ± 1.90	271.14 ± 60.22	263.41 ± 65.16
	Medium	82.08 ± 49.05	88.01 ± 49.72	22.16 ± 13.24	23.76 ± 13.43	1.96 ± 1.51	2.11 ± 1.76	1.44 ± 2.21	0.34 ± 0.22	1.19 ± 0.95	24.64 ± 18.73	11.62 ± 9.14	245.48 ± 83.25	219.09 ± 56.65
	Low	151.35 ± 108.98	158.62 ± 115.08	40.86 ± 29.43	42.83 ± 31.07	1.79 ± 0.80	2.1 ± 0.74	0.51 ± 0.50	0.21 ± 0.20	1.4 ± 0.70	12.07 ± 6.38	5.33 ± 3.17	251.10 ± 113.28	311.91 ± 104.97
Forest patch	Chilimo	111.92 ± 64.96	121.60 ± 70.21	30.22 ± 17.54	32.83 ± 18.96	2.6 ± 1.0	2.32 ± 1.1	0.61 ± 0.80	0.26 ± 0.19	1.58 ± 1.01	10.67 ± 5.87	4.95 ± 2.85	257.34 ± 96.14	283.65 ± 92.62
	Gallessa	134.37 ± 109.21	139.1 ± 113.84	36.28 ± 29.48	37.56 ± 30.74	1.6 ± 1.7	1.8 ± 1.9	0.61 ± 0.64	0.44 ± 0.46	1.39 ± 0.88	21.67 ± 22.26	11.00 ± 10.96	265.22 ± 87.64	248.81 ± 69.86
	Gaji	77.28 ± 67.10	79.66 ± 67.20	20.86 ± 18.12	21.51 ± 18.15	0.7 ± 0.97	0.68 ± 0.3	5.88	0.06	0.71 ± 0.59	21.17 ± 15.02	9.71 ± 6.92	227.02 ± 52.16	213.85 ± 70.49

ACD accumulated aboveground carbon density, BCD belowground carbon density, StCD stump carbon density, HbCD herbaceous carbon density, HUCD humus carbon density, SOCD soil organic carbon density

Table 2 ANOVA for the five carbon pools of the Chilimo dry afromontane forest along the altitude, slope, and forest patch

Parameters	Factor	DF	Sum square	Mean square	F value	Pr > F
Aboveground biomass						
ACD (t C ha^{-1})	Forest patch	2	10,257	10,128	1.97	0.1480
	Altitude class	2	33,432	16,716	3.25	0.0454*
	Slope class	2	97,753	48,877	9.51	0.0025***
	Time	1	930	930	0.18	0.67211
	Residuals	62	318,701	5140		
Belowground biomass						
BCD (t C ha^{-1})	Forest patch	2	1477	739	1.97	0.1480
	Altitude class	2	2438	1219	3.25	0.0454*
	Slope class	2	7126	3563	9.51	0.0025***
	Time	1	68	58	0.18	0.6721
	Residuals	62	23,233	375		
Stump biomass						
StCD (N ha^{-1})	Forest patch	2	8.31	4.16	2.83	0.0475
	Altitude class	2	6.13	3.06	2.09	0.1337
	Slope class	2	9.97	4.97	3.39	0.0405*
	Period	1	0.45	0.45	0.30	0.5834
	Residuals	57	83.77	1.47		
Deadwood biomass						
DWCD (C t ha^{-1})	Forest patch	2	11.88	5.94	6.88	0.00401**
	Altitude class	2	0.97	0.49	0.56	0.57642
	Slope class	2	0.26	0.13	0.15	0.86325
	Time	1	3.26	3.26	3.77	0.06314
	Residuals	26	22.46	0.86		
Herbaceous biomass						
HbCD (C t ha^{-1})	Forest patch	2	3.31	1.66	2.07	0.0146
	Altitude class	2	3.59	1.80	2.25	0.1250
	Slope class	2	2.50	1.25	1.57	0.2270
	Residuals	27	21.58	0.80		
Humus and litter biomass						
HUCD (t C ha^{-1})	Forest patch	2	765	382.4	4.007	0.02555*
	Altitude class	2	321	160.3	1.680	0.19870
	Slope class	2	607	303.3	3.178	0.055187
	Period	1	804	804.0	8.423	0.00588**
	Residuals	42	4009	95.4		
Soil organic carbon						
SOCD (t C ha^{-1})	Forest patch	2	76,044	38,022	13.992	1.67e−06***
	Altitude class	2	230,462	115,231	42.403	< 2e−16***
	Land-use type	3	330,301	110,100	40.515	< 2e−16***
	Slope class	2	11,857	5928	2.182	0.115
	Depth	3	860,002	286,007	105.489	< 2e−16***
	Time	1	538	538	0.198	0.657
	Residuals	266	722,855	2717		

Table 2 ANOVA for the five carbon pools of the Chilimo dry afromontane forest along the altitude, slope, and forest patch *(Continued)*

Parameters	Factor	DF	Sum square	Mean square	*F* value	Pr > *F*
Total ecosystem carbon						
TECD (t C ha⁻¹) NF	Forest patch	2	3867	1934	0.08	0.9255
	Altitude class	2	133,008	66,504	2.67	0.0775
	Slope class	2	588,092	294,046	11.79	4.59e−05***
	Time	1	1455	1455	0.06	0.8099
	Residuals	62	1,546,631	24,946		

Where: *ACD* Above ground carbon density, *DF* Degree of freedom, *HbCD* Herbaceous carbon density, *StCD* Stump carbon density, *DWCD* Dead wood carbon density, *NF* Natural forest, *HUCD* Humus carbon density, *SOCD* Soil organic carbon density, *tCha⁻¹* tone carbon per hectare, and *TECD* Total ecosystem carbon density

the highest altitudinal gradients and the lowest for the medium altitudinal gradients in all the measurement times. The mean aboveground and belowground biomass in 2012 for the natural forest was ranged from 139.66 ± 111.44 and 37.71 ± 30.09 for high altitude to 97.49 ± 31.10 and 26.32 ± 8.40 for middle altitude, and in 2017, it was ranged from 148.30 ± 115.02 and 40.03 ± 31.06 for high altitude to 100.14 ± 39.93 and 27.04 ± 10.78 for middle altitudinal gradient. The mean ACD and BCD was also highest at 151.35 ± 108.98 t C ha⁻¹ for gentle slope and lowest at 88.01 ± 49.72 t C ha⁻¹ for middle slope. In a similar way, the ACD and BCD were highest for Gallessa forest patch and lowest for Gaji forest patch in all the measurement times. Overall, the ACD and BCD affirmed temporal variations among altitudinal gradient and slope (Fig. 3b, c).

Stump carbon biomass

The stump carbon density of the natural forest varied significantly along slope range and forest patch at $P \le 0.05$. However, it was non-significant among the altitudinal gradient and time (Table 2). The mean stump carbon density 2.38 ± 1.45 was highest for the middle altitudinal gradient and 1.81 ± 1.03 tCha⁻¹ was lowest for the highest altitudinal gradient. Stump carbon density also decreased along with the increasing and decreasing altitudinal gradients and slope range. The mean stump carbon density 2.33 ± 1.64 t C ha⁻¹ was highest for the middle slope and 1.68 ± 1.21 t C ha⁻¹ was lowest for the steep slope range. The mean stump carbon density 2.32 ± 1.1 tCha⁻¹ for the Chilimo forest patch was always the highest, while 0.68 ± 0.3 tCha⁻¹ for the Gaji forest patch was the lowest. The stump carbon density was also higher in 2017 than in 2012. Moreover, stump carbon density was influenced by the altitudinal gradient, slope percent, and forest patch (Fig. 4a–c). The stump carbon density among the middle and highest altitudinal gradient was non-significant. The stump carbon density in the Gaji forest patch with others and gentle slope with other slopes were also significant (Fig. 4a, c).

Harbaceous carbon biomass

The analysis of variance for herbaceous carbon density revealed significant variations among the forest patch $P \le 0.05$; however, it was non-significant among the altitudinal gradient and slope percent (Table 2). The mean 1.56 ± 1.08 tCha⁻¹ herbaceous carbon density was the highest under the lowest altitudinal gradient, while 1.27 ± 0.94 t C ha⁻¹ was the lowest under the middle altitudinal gradient. Moreover, the herbaceous carbon density showed an increasing trend along with increasing slope percentage (Table 4). The highest herbaceous carbon density was found under the Chilimo forest patch, whereas the lowest was found under the Gaji forest patches (Table 4). The herbaceous carbon density along the altitudinal gradient, slope percent, and forest patch is also presented under Fig. 5a–c. There was also a significant variation among the Gaji forest patch with Chilimo and Gallessa; however, it was non-significant among the altitudinal gradient and slope percent (Fig. 5a–c).

Deadwood carbon pool

The analysis of variance for deadwood carbon density is presented in Table 1 and non-significant among altitudinal gradient and slope percent at $P \le 0.05$ (Table 2). The highest 1.58 ± 0.98 tCha⁻¹ deadwood carbon density was found under the highest altitudinal gradient, while the lowest 0.37 ± 0.21 t C ha⁻¹ was found under the lowest altitudinal gradient. Moreover, there was an increasing trend along with an increasing altitudinal gradient. The highest 1.44 ± 2.21 tCha⁻¹ deadwood carbon density was found under the middle slope range, and the lowest 0.21 ± 0.20 t C ha⁻¹ was found under the lowest slope range. Altitude, slope, and forest patch significantly influenced the deadwood carbon density of Chilimo dry afromontane forest at $P \le 0.05$. In line with, the highest 5.88 tCha⁻¹ deadwood carbon density was found under the Gaji forest patch; however, the lowest 0.26 ± 0.19 tCha⁻¹ was found under the Chilimo forest patch (Table 3; Fig. 6c).

Table 3 Soil organic carbon density (SOCD) (t C ha^{-1}) along land use types

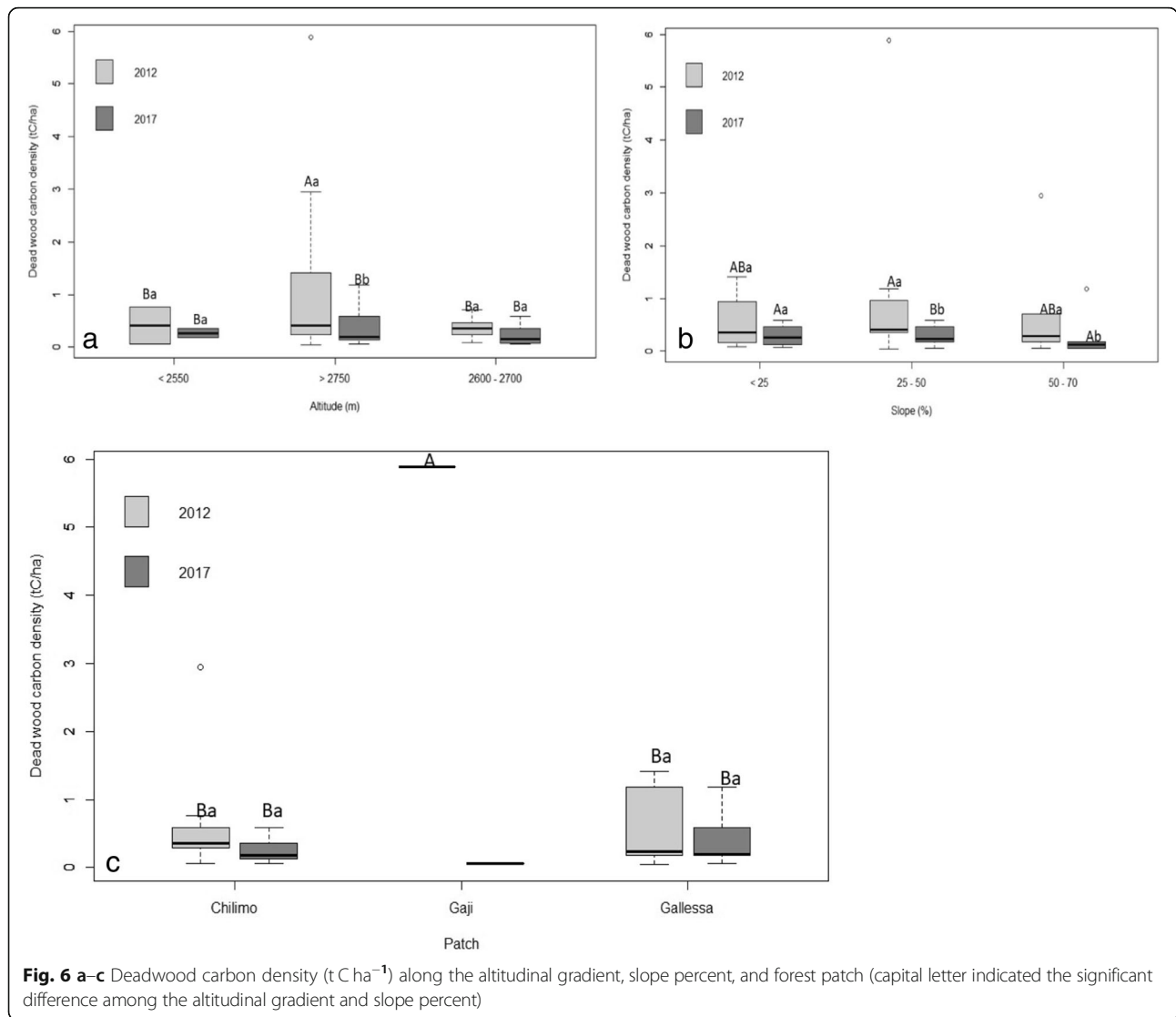| Plot no.	LUT	Patch	SOCD.10.2012	SOCD.10.2017	SOCD.30.2012	SOCD.30.2017	SOCD.50.2012	SOCD.50.2017	SOCD.100.2012	SOCD.100.2017
1	CU	Chilimo	26.4	64.8	51.1	112.03	66.4	142	90.9	223.15
2	CU	Chilimo	30	5.98	76.17	11.68	103.7	15.7	156.2	81.68
3	CU	Chilimo	28.8	24.48	74.97	54.12	109	107	156.2	187.29
Mean ± cultivated land			28.4 ± 1.8	31.75 ± 30.1	67.41 ± 14.1	59.28 ± 50.37	93.03 ± 23.2	88.44 ± 65.4	134.45 ± 37.7	164.04 ± 73.6
1	DL	Chilimo	14.94	13.39	34.83	21.95	48.33	39	58.83	57.05
2	DL	Chilimo	6.37	3.13	16.27	7.81	21.88	9.3	26.68	12.1
3	DL	Chilimo	18.24	0.96	26.16	4.92	29.68	6.84	33.28	8.79
Mean ± degraded land			13.28 ± 6.1	5.83 ± 6.6	25.75 ± 9.3	11.56 ± 9.1	33.30 ± 13.6	18.38 ± 17.9	39.60 ± 17	25.98 ± 7.0
1	PF	Chilimo	46.2	44.2	98.64	111.23	133.2	142	157.2	209.21
2	PF	Chilimo	74.48	63.6	160.59	84.58	184.4	118	216.8	141.82
3	PF	Chilimo	24.29	38.3	50.21	88.92	67.1	123	94.33	162.96
4	PF	Chilimo	71.2	71.82	141.4	155.12	186.2	188	228.4	222.94
5	PF	Chilimo	53	47.3	106.46	96.8	135.3	146	178.2	209
6	PF	Chilimo	59	43.46	188.96	108.36	246.1	143	296.1	164.74
7	PF	Chilimo	40.8	71.24	88.3	111.72	104.5	139	122	195.33
8	PF	Chilimo	42.4	6.72	82.14	109.76	99.42	119	121.4	186.03
9	PF	Chilimo	40.16	27.16	80.66	70.72	112	161	147	247.5
Mean ± plantation forest			50.17 ± 16	45.98 ± 21.2	110.82 ± 44.2	104.13 ± 23.8	140.90 ± 55.3	142.11 ± 22.07	173.49 ± 63.1	193.28 ± 33.1
1	NF	Chilimo	67.03	72.19	138.89	112.28	192.4	147	217.5	199.09
2	NF	Chilimo	87.12	26.75	207.86	90.11	283.4	132	372.6	194.35
3	NF	Chilimo	27.3	49.8	92.1	150.6	139.6	233	195.4	278.92
4	NF	Chilimo	83.79	64.98	135.89	137.67	148.7	195	167.9	222.09
5	NF	Chilimo	77.4	88.9	145.69	221.98	187.5	296	213.8	428.92
8	NF	Chilimo	100.35	86.44	273.15	184.36	357.5	235	451.5	256.68
11	NF	Chilimo	47.31	83.79	148.11	184.59	233.6	210	297.4	264.42
14	NF	Chilimo	44.8	102.4	87.49	279.04	112	358	150.5	452.45
17	NF	Chilimo	70.66	70.66	132.48	132.48	174.7	175	209.8	209.82
20	NF	Chilimo	62.3	131.67	176.6	209.28	226.8	275	297	329.78
Mean ± SD			66.81 ± 22.0	77.76 ± 28.6	153.83 ± 54.8	170.24 ± 56.9	205.62 ± 73.2	225.58 ± 69.9	257.34 ± 96.1	283.65 ± 92.6
21	NF	Gallessa	40.8	136.8	80.32	202.16	106.3	258	130.8	305.86
23	NF	Gallessa	78.38	99.81	215.18	225.81	272.3	245	313.1	301.51
25	NF	Gallessa	50	82.5	153.6	244.68	184	263	223.2	288.69
28	NF	Gallessa	83.3	46.4	171.46	79.84	228.6	112	316.3	192.76
30	NF	Gallessa	76.3	27.5	222.22	73.58	288.6	103	342.6	155.24
Mean ± SD NF Gallessa			65.76 ± 19.0	78.60 ± 43.3	168.56 ± 57.2	165.21 ± 82.2	215.97 ± 73.60	196.30 ± 81.33	265.22 ± 87.64	248.81 ± 69.86
32	NF	Gaji	85.4	47.6	182.68	98.37	208.6	122	235.6	160.1
34	NF	Gaji	50.4	85.2	151.2	141.36	211.4	178	274.4	293.66
35	NF	Gaji	48.55	60.09	117.67	134.39	142.3	160	171.1	187.78
Mean ± SD NF Gaji			61.45 ± 20.8	64.30 ± 19.15	150.52 ± 32.5	124.71 ± 23.17	187.42 ± 39.09	153.37 ± 28.85	227.02 ± 52.2	213.85 ± 70.5
Mean ± Natural forest			65.62 ± 19.97	75.75 ± 30.76	157.37 ± 50.3	161.25 ± 60.4	205.46 ± 66.16	205.41 ± 70.56	254.48 ± 84.8	262.34 ± 83.7

LUT land-use type, *SOCD* soil organic carbon density, *CU* cultivated land, *DL* degraded land, *PF* plantation forest, *NF* naturel forest, *SD* standard deviation

Humus and litter carbon pools

The humus carbon density of the forest floor along altitudinal gradients was ranged from 17.33 ± 17.35 to 4.84 ± 2.58 t C ha^{-1}. The analysis of variance also revealed that the humus carbon density was significantly influenced by the forest patch, year of data collected, and slope percent ($P \leq 0.05$) (Table 2). It was highest for the Gallessa forest patch, but lowest for the Chilimo forest patch (Table 1; Fig. 7c). The highest humus and litter carbon stock density was found

Fig. 6 a–c Deadwood carbon density (t C ha^{-1}) along the altitudinal gradient, slope percent, and forest patch (capital letter indicated the significant difference among the altitudinal gradient and slope percent)
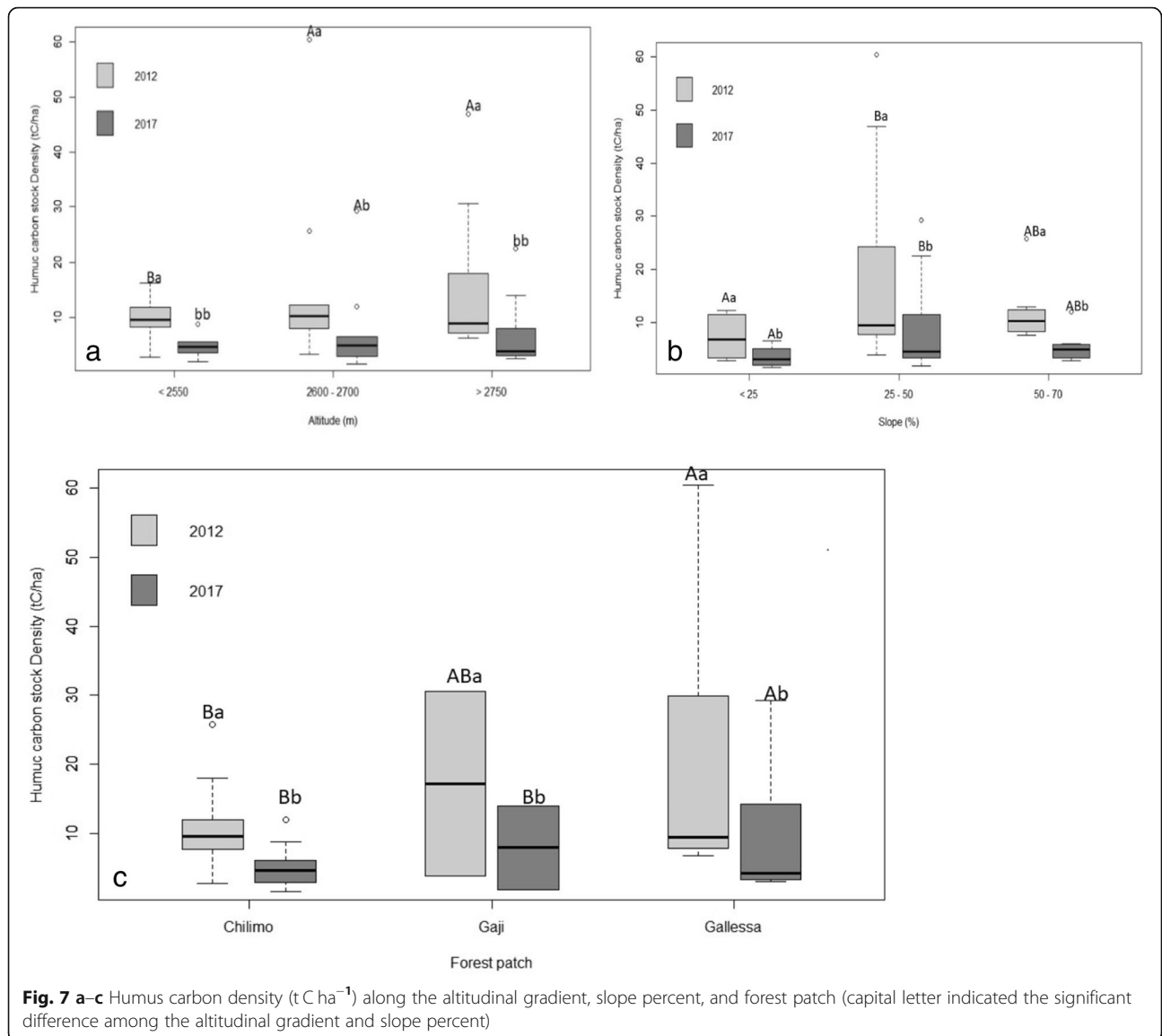
under the middle slope range and showed similar trends with gentle and steep slope ranges (Table 1; Fig. 7b). There was significant difference among middle slope with gentle slope and Gallessa forest patch with Chilimo forest patch; however, it was non-significant among altitudinal gradients and within the same altitudinal gradient (Fig. 7 a–c).

Soil organic carbon pool
The SOC stock is highly influenced by the altitudinal gradient, slope range, and forest patch. The analysis of variance of soil organic carbon is presented in Table 2. The SOCD was significantly different among the altitudinal gradient, slope, and land-use types at $P \le 0.05$. The SOCD up to 1 m depth was highest at 295.96 ± 80.45 t C ha^{-1} under the middle altitudinal gradient, but lowest at

206.40 ± 65.59 t C ha^{-1} under the lower altitudinal gradient (Additional file 1: Table S1; Fig. 9).

The SOCD up to 1 m depth of the forest patch ranged from 283.65 ± 92.62 for the Chilimo forest patch to 213.85 ± 70.49 t C ha^{-1} for the Gaji forest patch (Table 1; Fig. 10b). SOCD among the Chilimo and Gallessa forest patch was significant; however, SOCD among the same forest patches with time bound and Gaji forest patch with others was non-significant (Fig. 9b). The SOCD 271.14 ± 60.22 t C ha^{-1} in 2012 was the highest under the steep slopes; however, 245.48 ± 83.25 t C ha^{-1} was the lowest under the middle slope. In 2017, the SOCD 311.91 ± 104.97 was the highest under the gentle slope; however, 245.48 ± 83.25 t C ha^{-1} was the lowest under the middle slope. Moreover, the SOCD was also significant among steep slopes and middle slopes; however, it was non-significant among the same slope

Fig. 7 a–c Humus carbon density (t C ha^{-1}) along the altitudinal gradient, slope percent, and forest patch (capital letter indicated the significant difference among the altitudinal gradient and slope percent)

range with time bound and gentle slope with others, respectively (Fig. 8c).

The soil organic carbon stock density was highly influenced by land-use types and soil depth (Table 2). The SOCD up to 1 m depth was ranged from 254.48 ± 84.8 t C ha^{-1} for natural forests to 39.60 ± 17 t C ha^{-1} for degraded lands. Similarly, the SOCD in 2017 was ranged from 262.34 ± 83.7 for natural forests to 25 98 ± 7 t C ha^{-1} for degraded lands. The mean SOCD up to 1 m nominal depth of the natural forest was also 264.44 ± 84.81 and 277.77 ± 83.73 t C ha^{-1} in 2012 and 2017, respectively (Annex 1). the SOCD in the natural forest was always higher than other land-use types in all soil depth. On the contrary, the SOCD in

the degraded and cultivated land was the lowest in all soil depth in all the measurement times (Annex 1). Moreover, the SOCD of the natural forest was significantly different among other land-use types and always higher in all soil depth (Table 1 and Fig. 8d). On the contrary, SOCD for the degraded land was the lowest in all soil depth in all the measurement times (Annex 1). The SOCD between the cultivated land and plantation forest was non-significant, although the value of plantation forest was higher than cultivated land. In plantations, the carbon stock density at the same depth was one third less than natural forests but 35% and 77% higher than cropland and degraded lands, respectively (Annex 1).
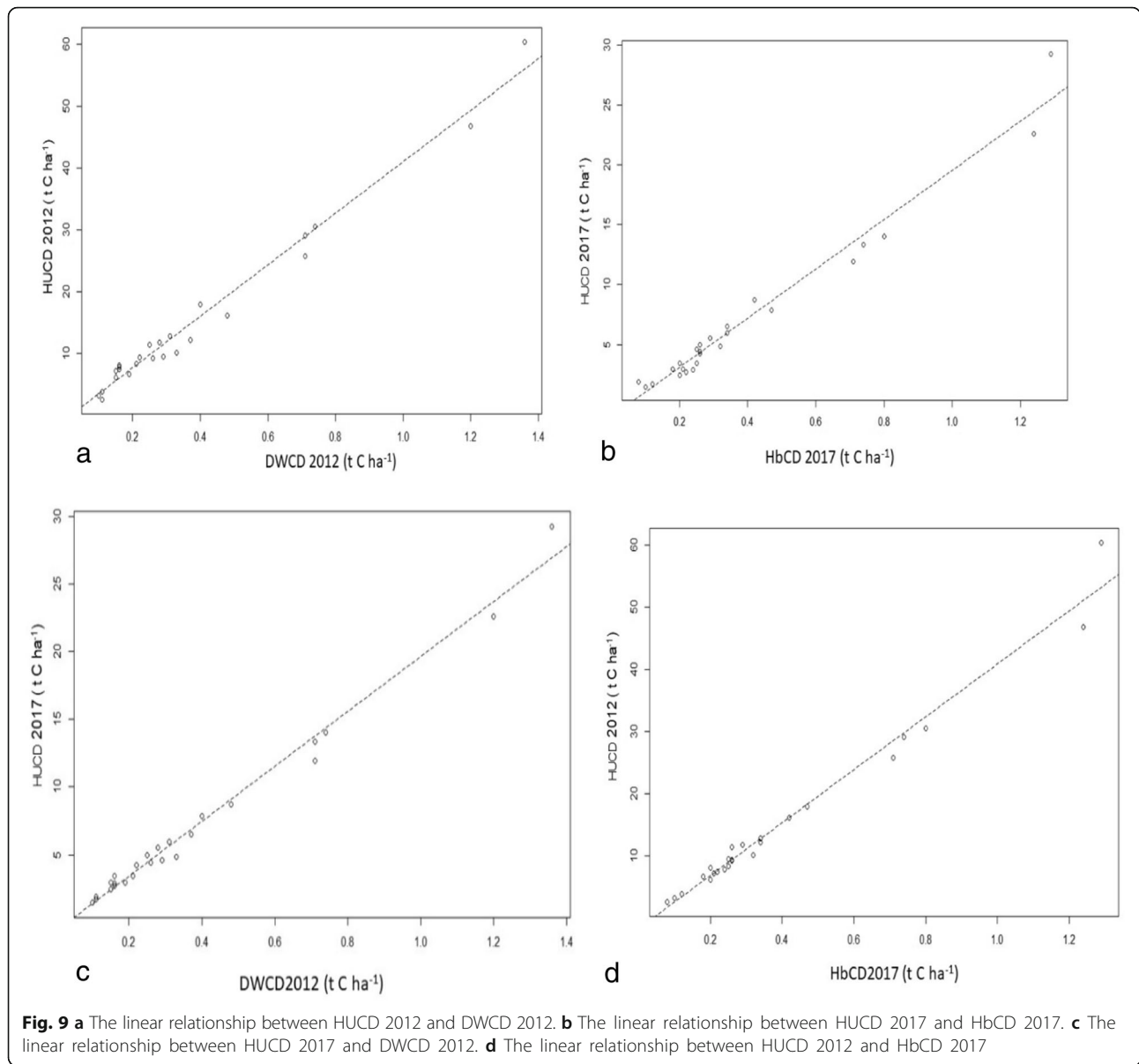
Fig. 8 a–c Soil organic carbon density (t C ha^{-1}) along the altitudinal gradient, slope percent, and forest patch (capital letter indicated the significant difference among the altitudinal gradient and slope percent)
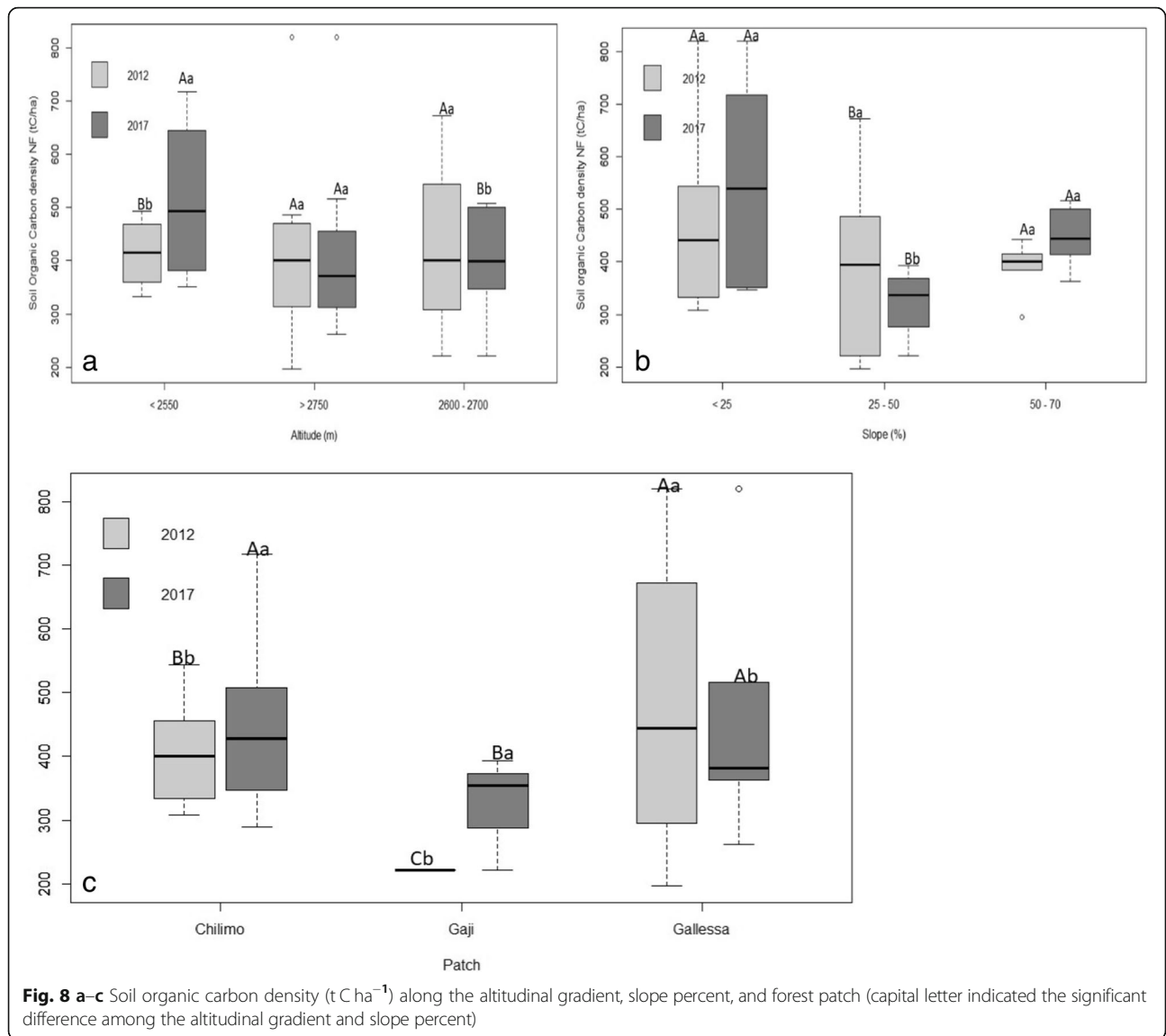
Table 4 The linear regression equation of the different carbon pools of Chilimo dry afromontane forest

SN	Equation	SE	*t* value	Pr > /*t*/	Adj. R^2
1	HUCD2012 = − 0.6563 + 41.6202DWCD2012	0.60	− 1.09	0.286	0.98
		0.21	34.36	< 2e−16***	
2	HUCD2017 = − 1.0623 + 20.5616HbCD2017	0.37	− 2.86	0.00887**	0.97
		0.74	27.85	< 2e−16***	
3	HUCD2017 = − 0.6336 + 20.2528DWCD2012	0.25	− 2.59	0.0166*	0.97
		0.49	41.00	< 2e−16***	
4	HbCD2017 = 0.0461198 + 0.0230173HUCD2012	0.01	3.29	0.00324**	0.98
		0.001	33.20	< 2e−16***	
5	HbCD2017 = 0.02648 + 0.97002 DWCD2012	0.01	2.15	0.0424*	0.99
		0.03	39.05	< 2e−16***	
6	StCD2012 = 0.25923 + 0.72541StCD2017	0.18	1.461	0.151	0.66
		0.08	9.152	1.4e−11***	

Where: *DWCD* Dead wood carbon density, *HbCD* Herbaceous carbon density, *HUCD* Humus carbon density, *StCD* Stump carbon density, *Pr* Probability, *S.N.* Series number, *SE* Standard error, *Adj. R^2* Adjusted R squared and /*t*/*t*-value

Fig. 9 a The linear relationship between HUCD 2012 and DWCD 2012. **b** The linear relationship between HUCD 2017 and HbCD 2017. **c** The linear relationship between HUCD 2017 and DWCD 2012. **d** The linear relationship between HUCD 2012 and HbCD 2017

Is there any correlation among carbon pools in the natural forest?

The multiple regression correlation matrix and linear relationship of various carbon pools in the Chilimo forest ecosystem are presented in Table 3 and affirmed the linear relationship among carbon pools. Based on the goodness-of-fit statistics and biological behavior of the model, there was a strong linear relationship between the weighted aboveground, humus, herbaceous, and deadwood carbon density which was highly correlated with the adjusted R^2 (> 0.97) (Tables 3 and 4). There was also a moderate linear relationship between the soil organic carbon stock density and the adjusted R^2 (> 0.60). However, there was a weak linear relationship between

stump carbon density and topsoil carbon density, aboveground carbon density and herbaceous carbon density, and aboveground carbon density and stump carbon density (Fig. 9a–d).

Do environmental factors and forest patch affect total ecosystem carbon?

The results affirmed that the total ecosystem carbon was significantly influenced by environmental factors and forest patch at $P \leq 0.05$. The highest total ecosystem carbon stock density was found under the highest altitudinal gradient, highest slopes, and Gallessa forest patch (Fig. 10 a–c). The total ecosystem carbon density was significant among the middle and highest altitudinal gradient, the middle slope with steep and gentle slopes, and

Fig. 10 a–c Total ecosystem carbon density (t C ha^{-1}) along the altitudinal gradient, slope percent, and forest patch (capital letter indicated the significant difference among the altitudinal gradient, slope percent, and forest patch)
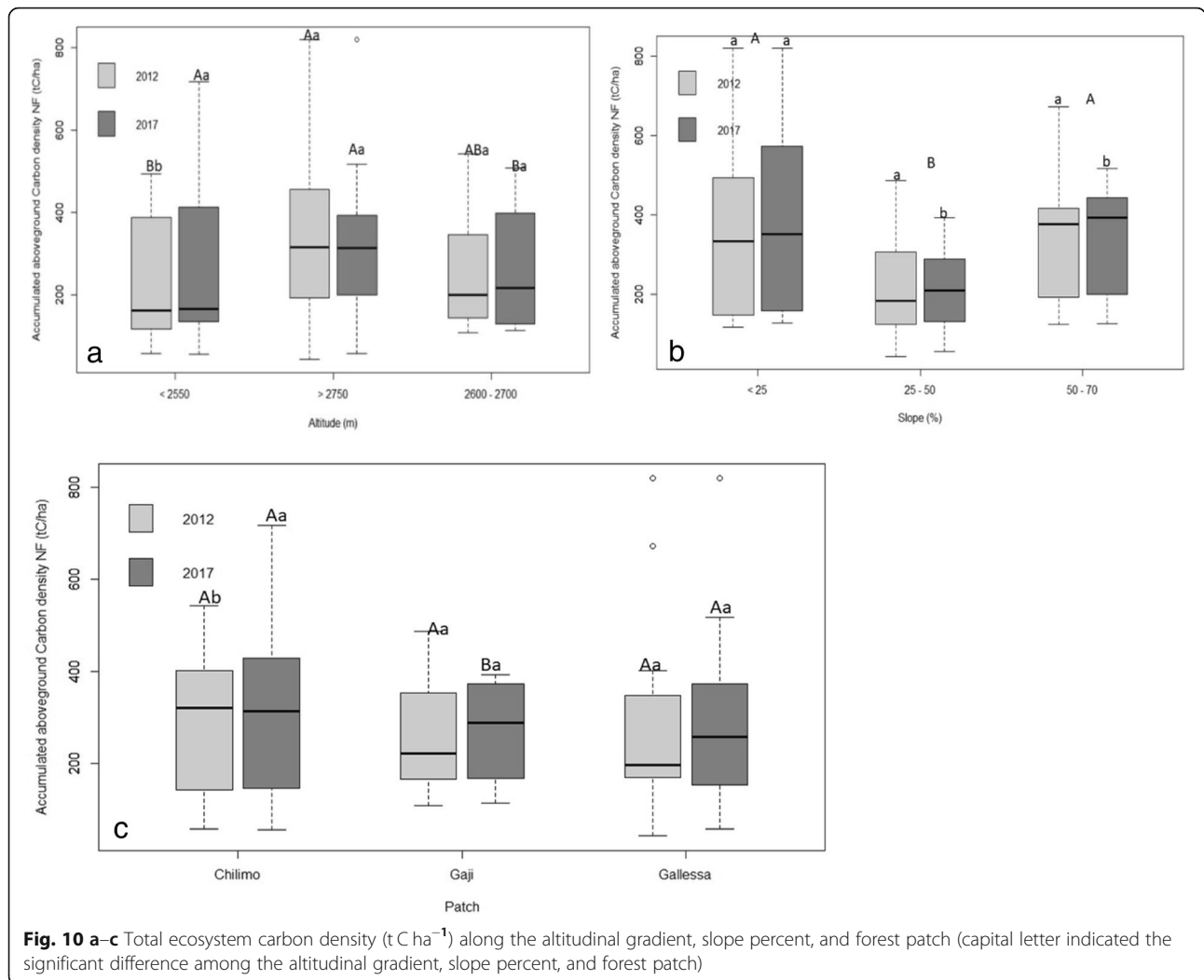
the Gaji forest patch with Chilimo and Gallessa forest patches (Fig. 10 a, b). The mean ecosystem carbon stock density of the sampled plots in natural forests was also ranged from 196.22 to 672.72 and 221.89 to 819.44 t C ha^{-1} in 2012 and 2017, respectively (Additional file 1). The total natural forest and plantation forest were estimated to be 5000 and 450 ha, respectively. The sum of the total ecosystem carbon stock density for the natural and planted forest was 1,564,847 (5,742,996.2 t CO$_2$ eq. in 2012 and 1,660,318 t C or 6,093,365 t CO$_2$ eq. in 2017). The combined carbon sequestration potential of the Chilimo natural forest and planted forest was also estimated to be 65,828.98 t CO$_2$ eq. year^{-1}. The carbon sequestration potential of the Chilimo natural and planted forest was estimated to be 65,828.98 CO$_2$ eq. year^{-1}.

Discussion

The present study has investigated the temporal variation in carbon pools of the Chilimo dry afromontane forest along the altitudinal gradient, slope, and forest patch. This study is also the first type in the study area conducted into two consecutive periods. There is a lower aboveground biomass in the middle altitudinal gradient, this is might be due to the intense anthropogenic effect, which resulted in few but big trees with higher above and belowground biomass. In addition, there is a higher stump carbon density in the middle and lower altitudinal gradient, this is might be due to the presence of higher number of stumps. In line with, similar reports were also reported by Shumi (2009), Hassen (20150, Tesfaye (2015), and Tesfaye et al. (2016).

The aboveground biomass carbon density reported (200 t C ha^{-1}) in the Chilimo forest is also higher than the Gara Mukitar dry afromontane forest in Eastern Ethiopia (156.60 t C ha^{-1}) (Wodajo 2018). However, it was less than by 142.47 and 174.02 t C ha^{-1} of the Arba Minch riverine forest, Egdu forest, and Gera moist afromontane forest (Hassen 2015; Meles et al. 2014; Feyissa

et al. 2013), Chato forest (301.86 t C ha^{-1}) (Iticha 2017) and Ades forest too (259.17 t C ha^{-1}) (Kassahun et al. 2015). The highest ACD (200 t C ha^{-1}) under the higher altitudinal gradient and slope range is might be due to lower disturbance. Similar findings are also reported for other Ethiopian forests too (Girma et al. 2004; Hassen 2015; Iticha 2017).

The mean accumulated biomass capacity of the Chilimo forest as mentioned above is also in line with the reports of Eticha et al. (2017). But, it was lower than the Zequala Monastery (475.51 t C ha^{-1}) and Semien Mountain National Park forest (994.16 t C ha^{-1}) in the Central and Northern Ethiopia, respectively (Abel Girma et al. 2014; Yelemfrhat et al. 2014). The highest deadwood carbon density at steep slopes and highest altitudinal gradients is might be due to the low disturbance. Moreover, the higher deadwood carbon density in the Gaji forest patch is also due to the presence of big fallen trees in the sampled site than others.

The herbaceous carbon density of the Chilimo forest is in line with other tropical seasonal rain forests (1.4), tropical secondary forests (1.9) (Lasco et al. 2006), and subtropical forest too (2.6–3.8 t C ha^{-1}) (Brown et al. 1989). The higher herbaceous carbon density under the lower and higher altitudinal gradients is also might be due to the low canopy cover. The higher herbaceous carbon density in steep slopes is also due to the low disturbance and better nutrient release. Swai et al. (2014) reported low tree density makes a suitable condition for undergrowth, vegetation, and higher precipitation. The reduction in litter and humus carbon is due to an increasing disturbance and excessive removal of litterfall.

The soil carbon stock density was conducted across the altitudinal gradient, land-use type, slope, and forest patch for the last 5 years except a study done by Tesfaye et al. (2016). In this study, the soil carbon stock was significant along the altitudinal gradient as suggested by other studies in African forests too (Zewdu et al. 2004; Twongyirwe et al. 2013), because altitudinal gradient is one of the environmental factors that affect the soil carbon stock density and it can be considered as a useful tool to predict the forest carbon stock (Mayaux et al. 2007). Results of the present study also revealed that higher soil organic carbon stock density was found under the middle altitudinal gradients. This was might be due to low soil erosion and higher number of inputs. However, the carbon stock in the forest floor showed a reduction in the last 5 years. This is might be due to frequent removal of litterfall and twigs by fuelwood collectors. At the same time, lower canopy cover might result in high sunlight to reach the forest floor that accelerates the litter decomposition. Similary, Hassen (2015) found higher carbon pools in Gera moist afromontane forest due to higher disturbance.

The higher carbon stock density in the middle altitudinal gradient is might be due to higher disturbance; this is also in line with Kassahun et al. (2015) who reported for a higher SOC density under a middle altitudinal gradient of Ades dry afromontane forest. The lower carbon stock density in the higher and middle elevation is might be due to the over sealing of soil by livestock movement and higher soil erosion. In addition, there is a continuous removal of fallen litter, deadwood, and twigs by fuelwood collectors. Tree cutting for firewood, charcoal making, illegal logging for timber and construction wood, forest clearing for agricultural land, and free livestock grazing are also frequently occurring in these areas.

Land use is a major factor in carbon stock, among the four land-use types studied in the Chilimo dry afromontane forest and adjacent land uses. The higher carbon stock in the natural and plantation forest in all the sampled period is might be due to higher litterfall, decomposition rate, and species composition. The low erosion rate in the natural and plantation forest was might be due to the interception of the raindrops by plants. The carbon stock density was slightly reduced in the forest floor in the last 5 years due to the lack of appropriate land management practices to improve land productivity and more tree cutting in the natural forest than previous years. The low carbon in the degraded and cultivated land is might be due to the low nutrient cycling, continuous tillage, and crop residue removal for livestock feed in the cultivated land. In addition, in the degraded land, there is an over sealing and surface crusting effect, which reduced the microbial activity and leads to a high runoff and soil erosion. In general, there is a slight increase in the carbon stock in the degraded land in the last 5 years; this is might be due to some exclosure activities done in these areas. Similar results were also reported by several authors; Girmay et al. (2008) reported the carbon stock in the topsoil (0–10 cm) is decreased after the conversion of native forest into croplands (– 63%) and plantations (– 83%). Solomon et al. (2002) indicated that the conversion of humid tropical forests for maize cultivation in Southern Ethiopia resulted in a 55–60% reduction in SOC stock. 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 into a eucalyptus plantation. In Brazil, Zinn et al. (2002) reported a 23–48% loss in SOC after a native wooded savannah was converted into a eucalyptus plantation. Rhoades et al. (2000) reported a 70% reduction in SOC in Ecuador in the upper 30 cm of the topsoil when the original forest was converted into a sugarcane plantation (*Saccharum* spp.). Berhangaray et al. (2013) investigated the impact of changes in land use on soil carbon stock found under trees than 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 lands and 56.4% more carbon than croplands. The C stock density under native natural forest and plantation forest in the Chilimo dry afromontane forest was higher than those reported in other regions (Beets et al. 2002; Harms et al. 2005; Twongyirwe et al. 2013) and suggests two management strategies for improving soil conditions. The first is to maintain and preserve the Chilimo natural forest as other African tropical forests do (Lewis et al. 2009), and the second is to recover abandoned croplands and degraded lands by establishing tree plantations.

There is a strong linear relationship between the humus and herbaceous carbon density due to the presence of higher humus content which is good for the growth of herbaceous plants and higher decomposition rate and open canopy cover. On the contrary, the presence of higher humus content results due to low soil erosion. The strong linear relationship between the humus and deadwood carbon density is might be due to a higher litterfall, better decomposition, and better twigs. The weak linear relationship between the stump and herbaceous carbon density is due to a higher number of stumps, low aboveground carbon density, and lower herbaceous plants.

The total area of Chilimo forest was 22,000 ha in 1982 and reduced to 4500 ha in 2016; as a result, the total carbon emission for Chilimo forest in the last 34 years was 5,218,850 t C. In general, the mean carbon stock density of Chilimo forest has increased from 289.86 to 298.22 t C ha^{-1}. In 2012, the total ecosystem carbon density was 56.12% in soil organic carbon, 31.21% aboveground biomass, 8.43% belowground biomass, 3.65% humus carbon, 0.47% stump carbon, and 0.12% deadwood carbon. In the same line in 2017, the highest share for ecosystem carbon density was soil organic carbon (59.64%), aboveground carbon (29.78%), belowground carbon (8.04%), humus carbon (1.69%), stump carbon (0.48%), herbaceous carbon (0.33%), and deadwood carbon (0.04%), respectively.

Conclusions

The aboveground and belowground biomass of the Chilimo natural forest was the highest for the highest altitudinal gradients and the lowest for the medium altitudinal gradients in all the measurement times. The stump carbon density was increased in 2017 than in 2012 due to the increasing number of illegal stumps. Deadwood and humus carbon density was reduced by 50% in the last 5 years due to a surplus increasing level of disturbance. The SOCD up to 1 m depth was the highest at 295.96 ± 80.45 tCha^{-1} under the middle altitudinal gradient; however, it was the lowest at 206.40 ± 65.59 t C ha^{-1} under the lower altitudinal gradient. The Chilimo natural forest stored more carbon than adjacent land-use categories, but degraded land stored the lowest soil organic carbon stock. The carbon stock density was weakly correlated among the stump carbon density and aboveground carbon density. The sum of total ecosystem carbon stock density and carbon sequestration potential for the natural and planted forest was 1,660,318 tC or 6,093,365 t CO$_2$ eq. and 65,828.98 CO$_2$ eq. year^{-1}, respectively. For maintaining a higher carbon stock density in the study area, other land use types such as degraded land and cultivated. Forest management options should be applied to improve productivity. We recommend a forest carbon-related awareness creation for local people, and promotion of the local knowledge can be regarded as a possible option for sustainable forest management.

Additional file

Additional file 1: Table S1. Ecosystem carbon accumulation potential of Chilimo dry afromontane forest 2012 and 2017. (DOCX 47 kb)

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 manuscript.

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