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Carbon Stock Density of the Different Carbon Pools in Tulu Lafto Forest and Woodland Complex: Horo Guduru Wollega Zone, Oromia Region, Ethiopia

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Abstract: Forest contains one of the world's largest terrestrial C pools and play vital role in combating climate change through carbon sequestration. This study was conducted on Tulu Lafto Forest and woodland complex (here after named as TLF) with the objective of investigating carbon stock density of the different carbon pools and its variation between vegetation units. Data were collected from a total of 75 nested plots. Diameter at breast height and total height were measured for all woody individuals (trees, shrubs and lianas) that attained a DBH of 2.5 cm and above. Woody plants that did not attained a DBH of 2.5 cm and herbaceous plants were destructively harvested from subplots of 1 m^2 within the main plot. All dead woods were also measured for their length and diameter and samples were taken to determine its specific wood density and decomposition class. Above and below ground biomass was estimated using allometric equation, while the litter carbon was determined by loss on ignition (LOI) method. Soil samples were also collected in order to determine soil organic carbon. The mean above and below ground C stocks were 218.4 and 43.49 t C ha^{-1}, respectively while, C stocks in soil organic matter, dead wood and litter were 128.95, 6.15 and 2.43 t C ha^{-1}, respectively. The total C stock density of TLF was found to be 399.42 ± 265.15 t C ha^{-1} of which 54.68 and 32.28% was kept in the aboveground biomass and soil, respectively. Result indicated that there is significant C stock density variation between vegetation units in the study area.

Keywords: Tulu Lafto Forest and Woodland Complex, Aboveground Carbon, Forest Carbon Pools, Carbon Stock Density Variation

1. Introduction

Climate change is a widespread and growing concern of the global community. As a result, the role of tropical forests in mitigating the impact of climate change through increased CO_2 uptake has got global recognition [42]. Thus, determining forest biomass and its C content is essential to understand the global C budget and the amount of C that would be released from converting a forest to cleared land (and vice versa) [38]. While plants are absorbing atmospheric CO_2 to make their food, enormous amount of carbon is sequestered and stored in forest biomass [44, 55]. This made forests key component in the processes of mitigating the impacts climate change [24, 29, 41]. Recently, international communities are working towards reducing greenhouse gas emissions while increasing their sinks, especially that of CO_2 [31]. As a result, the forest area designated for C storage purpose in the world is increasing from time to time mainly due to their low cost. For example, the forest area designated for similar purpose has increased from 1.3% in 1990 to 5.3% in 2015 [51]. However, the C storage potential of forests is deteriorating from time to time due to human induced deforestation and forest degradation especially in Africa and South America [42]. Although net annual emissions from deforestation is decreasing from annual average of 4.68 Gt CO_2 in 1990s to 2.94 Gt CO_2 from 2011 to 2015, emissions from forest degradation is increasing three-fold, from 0.35 Gt during 1990s to 0.99 Gt in 2011–2015 [23] suggesting a sudden shift in CO_2 emission from deforestation to forest degradation.

As deforestation and forest degradation are continuing to be significant sources of CO_2, documenting forest C stock and measuring its change through time is among the crucial steps in mitigating the impact of climate change. This could support regulatory frameworks such as the United Nations REDD program on the one hand and national policies that could enhance forest C stock on the other hand. Reducing emission from deforestation and forest degradation and increasing forest area through afforestation and carbon management in the existing forests could offset as much as 10–20% of fossil fuel-based emissions [48]. Thus, accurate and timely monitoring of forest biomass and its carbon content is vital for investigating changes in forest C stocks at global level. But these are not comprehensive in developing countries mainly Africa [8, 17, 59]. Like other African countries, measurement of forest biomass and its C stock is at its early stage in Ethiopia with only few efforts started recently [3, 4, 9, 33, 34, 53, 64, 66, 67].

Ethiopia consists of 12.3 million ha of forest land [20] which provide important C sink. But, regular forest resource assessment is absent and forest C stock estimation is fragmentary and showed wide variation in the country. Insufficient biomass and C storage data in Ethiopian forests makes it difficult to evaluate the C sequestration potential of forests in the overall climate change mitigation efforts. In Ethiopia, the mean C stock in the living biomass showed huge variation, ranging from 25 ton ha^{-1} (for *Acacia-Commiphora* woodland) to 125 ton ha^{-1} (for Moist Afromontane forest) [22]. Available literature also revealed inconsistency in total forest C stock at national level. Yitebitu Moges *et al.* [67] reported about 2.76 billion tons of C while FAO [22] reduced it to only 219 million tons. This variation could be due to differences in sampling method and the allometeric models used in biomass estimation.

TLF is one of the few remnant forest patches with natural vegetation cover in Ethiopia. It plays key ecological roles including biodiversity conservation and C sequestration, but no detailed scientific study was made to document the C stock density of the different carbon pools in TLF. So, this research was conducted with the following objectives in mind: (1) to estimate the amount of carbon accumulated in all carbon pools, (2) to investigate the C stock variation among the different vegetation units and (3) to provide base line data for C monitoring on a regular basis.

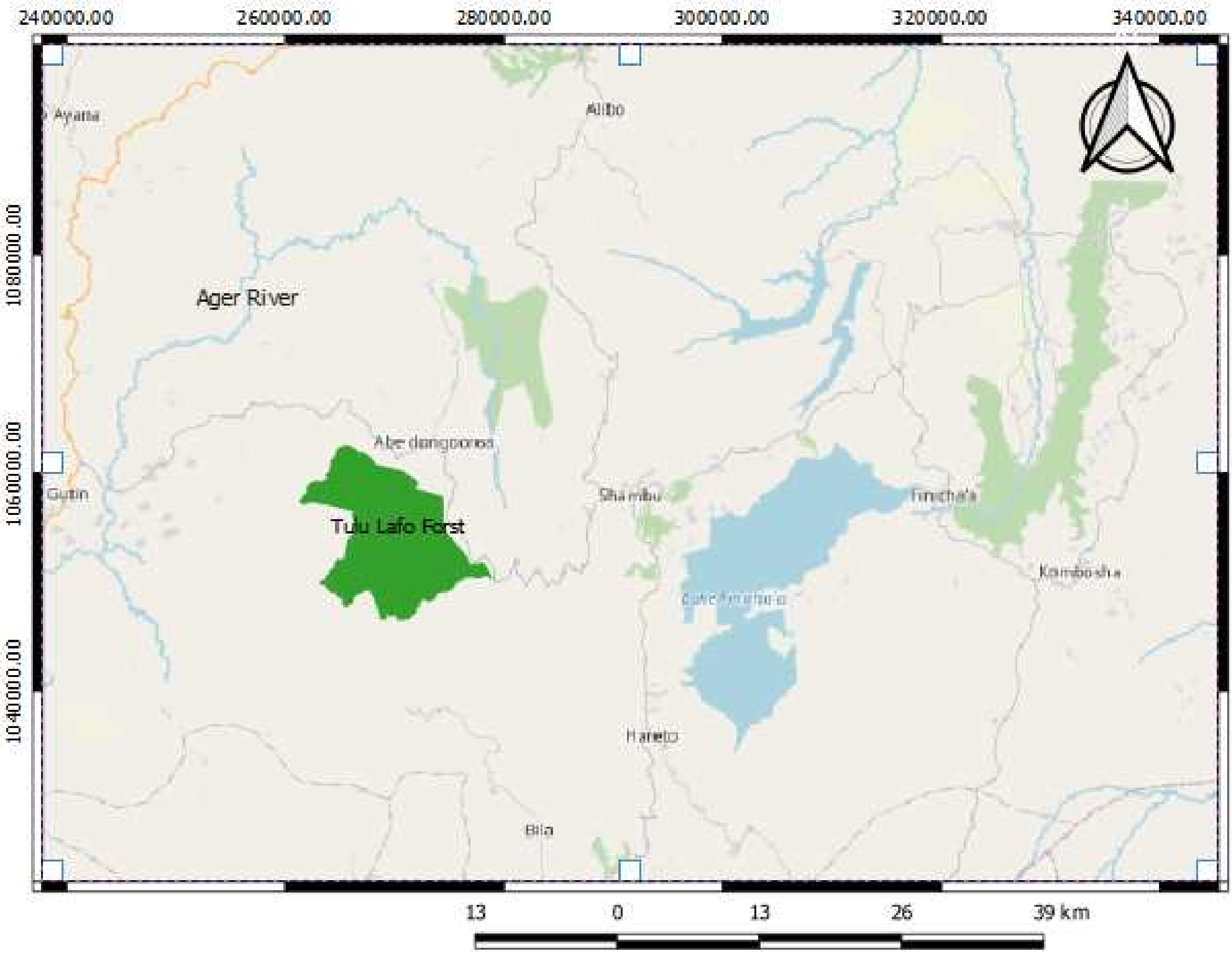


Figure 1. *Map of Study area (TLF).*

2. Materials and Methods

2.1. Study Area

TLF is located at a distance of 378 km west of Addis Ababa and 59 km from Shambu (Horo Guduru Wollega zone capital) in Abe Dongoro district of Horro Guduru Wollegga zone, western Ethiopia between 9°27′ to 9°37′ N and 36°47′ to 37°00′ E (Figure 1). The study area is found on a steep and isolated mountain that is surrounded by lowland plains. The forest boundary covers an area of more than 10,000 ha with a wide gradient in elevation.

As the study area falls in the western highlands of Ethiopia, the rainfall pattern is unimodal. Climate data was obtained from two nearest meteorological stations, Shambu and Anger Gutin (Figure 2). Shambu (2460m), in the east, has an average annual rainfall of 1540 mm and an average annual temperature of 17.3°C. Angar Gutin (1350m), in the west, has a mean annual rainfall of 1596 mm and an average annual temperature of 22.1°C. TLF is dissected by numerous rivers and small streams that permanently feed Anger River. The forest is thus among the headwater sources of the Anger-Didessa watershed which is the main tributary to the Blue Nile River. Tulu Lafto forest consists of different vegetation units with rich floristic diversity. The tall savanna grasses mixed with short and medium sized trees predominate the elevation below 1500 m while dense canopy forests dominate the hill and far down stream areas.

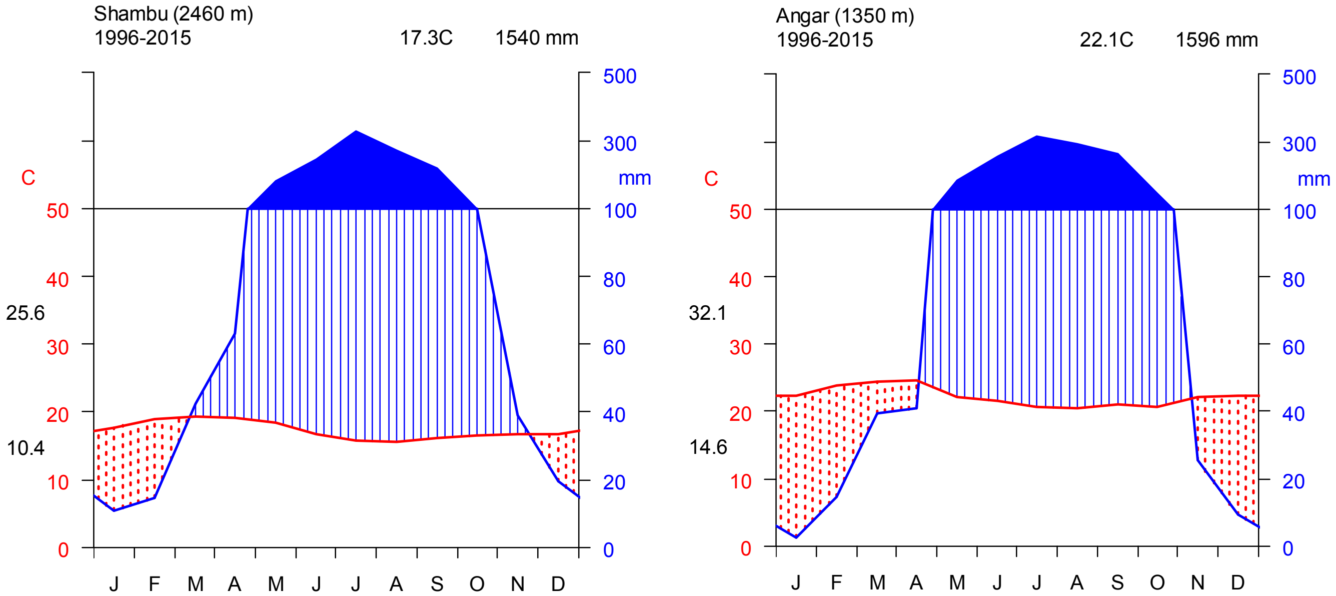


Figure 2. *Climatic diagram of the study area.*

2.2. Data Collection

In order to increase the accuracy and precision of measuring and estimating C, it is useful to divide the study area into sub-populations or "strata" that form relatively homogenous units. TLF was divided into 3 vegetation units (*Combretum-Terminalia woodland type, Riverine type and Afromontane type*) based on the dominant tree species and elevation in order to facilitate field data collection and increase the accuracy and precision of measuring C stock following Pearson *et al.* [56]. Nested plots of 400 m^2 (20 m x 20 m), 100 m^2 (10 m x 10 m) and 25 m^2 (5 m x 5 m) were set to record trees with dbh ≥ 30cm, dbh range of 10-30 cm and dbh range of 2.5-10 cm, respectively [56]. Trees and shrubs were marked, mapped and identified to species level. Height and diameter at breast height (dbh) were measured at 1.3 m for all trees and shrubs with dbh ≥ 2.5 cm including Liana. Liana diameter was measured at 130 cm above the highest root [28]. Leaf litter, defined as all non-living biomass with a size greater than the limit for soil organic matter (suggested 2 mm) and less than the minimum diameter chosen for dead wood (10 cm diameter in this study), was collected from a 1 m^2 sub plot established in the 25 m^2 subplots following Pearson *et al.* [56]. Total fresh weight was measured in the field; and a well-mixed sample of 100 g was placed in a marked plastic bag and taken to laboratory to determine moisture content and the total dry mass [56, 61]. Herbs, grasses and woody species that did not attain a dbh of 2.5 cm were destructively harvested by clipping all of them down to ground level within the 1 m^2 subplots. Total fresh weight was recorded in the field and a 100 g well-mixed sample was taken to laboratory to determine total dry weight and moisture content [61].

Dead woods are important carbon sources and sinks [61]. Downed dead wood census was made using line-intersect methods [35]. Length and diameter of all downed dead woods with diameter ≥ 10 cm were recorded in a 5 m wide transect established in the main plot (400 m^2). Downed dead woods were divided into sections of roughly 1 m and the exact length and diameter at the middle of each section were measured. For wood fragments that are less than 1 m long, the total length and diameter at the middle was measured [61]. Dead woods were grouped into decomposition classes following Pearson *et al.* [56] and samples were collected from each decomposition class for density (dry weight per volume) determination. Downed dead wood with a diameter < 10 cm were included to the litter layer. Soil samples were collected from the top 30 cm depth in the $1m^2$ sub plots and composite samples were taken to laboratory. The soil samples were then ground to determine soil organic carbon concentration. In addition, a 30 cm depth core sampler with a diameter of 5 cm was used to take soil samples for bulk density determination.

2.3. Estimation of Biomass and Carbon Stock

Live Trees

The data obtained from tree measurement, litter, herb and grasses (LHG), dead wood and soil was recorded and organized on the excel data sheet. Trees were categorized into diameter classes (≥ 5 cm and between 2.5 and 5 cm) in order to apply appropriate biomass estimation models. As site-specific multi species equations were not available, aboveground biomass of trees with dbh ≥ 5 cm was estimated using the biomass equation formulated to estimate the aboveground biomass of tropical trees [15].

$$Y = 0.0673 \times (\varrho D^2 H)^{0.976}$$

Where, Y is aboveground biomass (Kg), ϱ: wood specific density (g/cm^3), D: Diameter at Brest Height (cm) and H: height (m)

Estimates of wood specific density were obtained from FDRE [22]. According to this source, the average wood density for woody species in Ethiopia was 0.612 g cm^{-3}. This is comparable with the global average value and that of tropical Africa [58, 14, 37]. For a species whose wood specific density is missing, the genus average was used.

The above-ground biomass of small trees and shrubs with 2.5 cm ≤ dbh < 5 cm was determined using the biomass model developed by Ali *et al.* [5].

$$\mathrm{Ln}(AGB) = -3.50 + 1.65 \times \ln(D) + 0.842 \times \ln(H)$$

Where, *AGB = above-ground biomass [kg] of shrub and small trees;* ln, natural logarithm; H, total height (m); D, basal diameter of the longest stem (cm)

This model was preferred because it was formulated in similar climatic conditions with the current study area (warm and humid subtropical climate with a temperature ranging from 4.2 to 28.1°C, and an average annual precipitation of 1374.7 mm, most of which occurs between May and August) [5].

Palms possess very distinct growth pattern and internal anatomy from the common dicot trees [30]. Thus, a biomass model developed by Frangi and Lugo [25] was used in this study.

$$B_{palm} = 4.5 + (7.7 \times H)$$

Where: B_{palm}: palm aboveground biomass (kg) and H: Palm stem height

Lianas are important structural component of tropical forests, and contribute a lot to forest biomass, especially in liana infested forests [2]. Thus, liana aboveground biomass was estimated by the equation developed by Schnitzer *et al.* [60].

$$AGB = \exp[1.484 + 2.657 \times \ln(D)]$$

Where, AGB: aboveground dry weight (kg); D: diameter at 1.3m; ln: natural logarithm.

As belowground biomass estimation is difficult, time consuming and destructive [26], it was estimated based on the root to shoot ratio, assuming BGB constitutes 20% of the aboveground biomass [46].

$$BGB = AGB \times 0.2$$

Where, BGB: Belowground biomass, AGB: Aboveground biomass, 0.2: conversion factor (or 20% of AGB).

Above and belowground biomass was computed for each individual tree and sample plot, and presented on a hectare basis. The living biomass of trees was converted to C stock by multiplying it with the IPCC default fraction of 0.47 [39]. Carbon stock distribution pattern across size classes were computed and presented by d-d curve diagram based on 10 cm DBH intervals for trees with a DBH of 5 cm and above.

Dead wood

The biomass of downed dead wood was estimated as a product of volume and wood density for each decomposition class by the equation given below [56]:

$$B_{DDW} = \sum_{i=0}^{n} \Sigma V_i \times \varrho$$

Where, B_{DDW}: Biomass of downed dead wood, ΣV_i: Sum of volume of the i^{th} dead wood and ϱ: specific density per decomposition class.

The volume of downed dead wood was estimated as follows.

$$V_i = \Pi * \frac{Di^2}{4} \times L_i$$

Where, V_i: volume of dead wood; D_i: diameter of the dead wood; and L_i: length of the dead wood.

The C stock of dead woods was obtained by multiplying the total dead wood biomass by the IPCC [39] default carbon fraction of 0.47.

Leaf litter, herbs and grasses (LHG)

Biomass of leaf litter, herbs, and grasses (LHG) was calculated using the following formula [56, 61].

$$B = (\frac{Total\ fresh\ Wt}{A} \times \frac{Sample\ Dry\ Wt}{Sample\ Fresh\ Wt}) \times 1/10{,}000$$

Where B: LHG Biomass (t ha^{-1}), A: Subplot area, W_t: weight

The loss on ignition (LOI) method was used to determine percent carbon in LHGs [6]. This method is a fast and inexpensive means of determining carbonate and organic contents. Accordingly, fresh weights of vegetative samples were dried at 70°C in the oven for 48 hours. Oven dried samples were placed on pre-weighted crucibles (W_1) and weighed together (W_2) and placed in the furnace at 550°C for ignition. The sample was removed from the furnace after one hour. The crucibles with ash were weighed after cooling (W_3) and then the percentage of carbon was calculated according to [6].

$$\text{Ash}(\%) = (W_3 - W_1)/(W_2 - W_1) \times 100$$

C (%) = (100 – Ash (%)) × 0.58 (58% carbon in ash-free litter material) [65].

Where: C (%): *Carbon fraction in LHG biomass*, W_1: *weight of crucible*, W_2: *weight of the oven-dried sample and crucible*, W_3: *weight of ash and crucible*.

The carbon stock of LHGs was calculated by multiplying biomass of LHGs per unit area with C (%).

$$C_{LHG} = B_{LHG} \times C(\%)$$

Where, C_{LHG}: carbon stock in the leaf litter, herbs and grasses, B_{LHG}: Biomass in the leaf litter, herbs and grasses, C (%): carbon fraction determined in the laboratory [56].

Soil carbon

Soil organic carbon was calculated as recommended by Pearson *et al.* [56] from the depth, bulk density and C (%).

$$SOC = BD * d * C\ (\%)$$

Where: SOC: soil organic carbon stock per unit area (t/ha); BD: soil bulk density (g/cm); d: the depth at which the sample was taken (30cm) and C (%): Carbon concentration (%) was determined in the laboratory.

Bulk density of the soil sample was calculated as follows:

$$BD = \frac{D_{wt}}{V}$$

Where: BD: bulk density of the soil sample; D_{Wt}: dry weight of soil sample; V: is volume of the soil sample in cm^3.

Volume of the soil was computed using the following formula.

$$V = h * \pi r^2$$

Where, V: volume of the soil in the core sampler in cm^3, h: height of core sampler in cm, and r: radius of core sampler in cm.

Total C stock of the forest was obtained by summing the C stocks of all carbon pools following Pearson *et al.* [56].

$$C_t = AGC + BGC + C_{LHG} + C_{DW} + SOC$$

Where: C_t: total carbon stock for all pools (ton/ha); AGC: Aboveground Carbon (ton/ha); BGC: Belowground Carbon (ton/ha); C_{LHG}: Carbon in leaf litter, herb and grasses (ton/ha); C_{DW}: Carbon in dead wood (ton/ha); SOC: Soil organic carbon (ton/ha).

3. Result and Discussion

3.1. Carbon Stock Density in Different C pools

This study investigated C stock densities of the 5 forest carbon pools, namely above and belowground biomass, dead wood, leaf litter, herbs and grasses (LHGs) and soil organic matter. Biomass C was calculated for 93 woody species including trees, shrubs and lianas in TLF. Result indicated that the total carbon stock density of TLF was 399.42 ± 188.01 t ha^{-1} (range: 145.37-886.23 t C ha^{-1}) (Table 1).

Table 1. *Biomass and carbon stock (t ha^{-1}) summary in various carbon pools of TLF. (AGB: Aboveground biomass; BGB: Belowground biomass; AGC: Aboveground carbon; BGC: Belowground carbon; C_{LHG}: Leaf, herbs and grass carbon; DW_B: Dead wood biomass; DW_C: Dead wood carbon; SOC: Soil organic carbon; TC: Total carbon).*

	AGB	BGB	AGC	BGC	C_{LHG}	DW_B	DW_C	SOC	TC
Min	26.19	4.835	42.31	8.27	1.13	0.000	0.000	46.39	145.37
Mean	464.69	92.54	218.40	43.49	2.43	13.08	6.149	128.95	399.42
sd	303.44	60.69	142.63	28.53	0.68	34.38	16.16	40.32	188.01
Max	3258.68	651.25	631.58	126.13	3.59	211.26	99.29	263.3	886.23

Among the 5 carbon pools, aboveground biomass stored the largest (54.68%) portion of C in the forest out of which 214.86 t C ha^{-1} was accumulated in trees with dbh ≥ 5 cm (Table 2). This is in agreement with Mckinley *et al.* [48] in which they indicated aboveground tree biomass stored the majority of C in tropical forests. The aboveground C (AGC) stock of TLF is within the range reported for closed tropical forests, i.e. less than 50 to 360 Mg C ha^{-1} [12, 13, 43] and other similar studies in Ethiopia (30.8–414.7 t C ha^{-1}) [4, 52].

Table 2. *Proportion of carbon in various carbon pools of TLF.*

S/No	Forest carbon pool		Carbon content	
			t ha^{-1}	Percent
1	Aboveground Biomass	Tree with dbh ≥ 5 cm	214.86	54.68
		Shrub and small tree 2.5 ≤ dbh < 5 cm	0.99	
		Liana Carbon	1.20	
		Palm Carbon	1.35	
2	Belowground Biomass		43.49	10.89
3	Leaf litter, herbs and grass (LHG)		2.42	0.61
4	Dead wood		6.15	1.54
5	Soil		128.95	32.28
Total			399.42	100

Although the proportional contribution of small trees depends on the successional stage of the stand, their contribution to the total forest carbon stock was little and thus are often neglected in forest C stock assessments [11]. Similarly, small trees and shrubs (2.5 cm ≤ dbh <5 cm) in the current study area consists of large number of individuals (132.33 stems ha^{-1}), but their share to the total AGC was only 0.99 t ha^{-1} (0.46%). Other studies in Ethiopia and elsewhere also revealed that saplings, shrubs and other understory plants contributed only small fraction to the total forest C stock [13, 53]. The abundance of saplings and smaller trees suggest that TLF is in a secondary state of development. Sustainable management of small trees and saplings in secondary forests increase the amount of living biomass and C stock in subsequent years as trees and saplings grow [50]. As the proportion of secondary forests in the tropics is projected to increase due to increasing anthropogenic pressure, they are becoming important in global carbon cycle. Therefore, TLF can be recommended as a potential site for $REDD^+$ project in Ethiopia.

Palms are important components of tropical rainforest and present in all forest strata [62]. Out of ca. 2400 species of palms known in the world [32], 9 species exist in Ethiopia [19]. In this study area, however, only one species (*Phoenix reclinata* Jacq.) is recorded. Its AGC stock density was 1.35 t ha^{-1}. This value is greater than the value obtained for *Eugeissona tristis* (Palm) in Ayer Hitam Forest Reserve (Malaysia) with only 0.44 t ha^{-1} [62]. The overall result, however, is in agreement with the studies of de Castilho *et al.* [16]. The input of lianas to the total AGC of TLF was much lower (0.55%) than that of tropical lowland forests where liana comprises 1-14% of the total live AGC [7, 27, 45]. The low proportion of liana C in this study area might be due to anthropogenic exploitation of lianas as these are widely used for fencing and house construction by the local people.

Compared to other forests in Ethiopia and elsewhere, TLF stored more C in its AGB than Humbo [4] and Anbessa forests [63] from Ethiopia; and Secondary and Gallery forests of Congo [18], Natural forests of Bangladesh [65] and Collaborative Forests in Nepal [47] (Table 3). But AGC stock density of TLF is much lower than Garjeda [63], Tara Gedam [52], Adaba-Dodola [53], Egdu [3], Low land areas of Simen Mountain National park [64], Arbaminch ground water forest [9] (all in Ethiopia), and Usambra and Uluguru forests [54] from Tanzania. The variation in AGC stock density between the current study area and other forests can be attributed to species composition, disturbance history, successional stage, climate, topography, edaphic factors and the allometric models used to calculate the AGB [54, 55, 16, 29]. For instance, higher C stock density of Tara Gedam forest was associated to strict conservation through religious regulations [52] while that of Adaba-Dodola forest could be due to participatory forest management [53]. On the other hand, the higher AGC of Usambra and Uluguru forests was due to computational and sampling procedures [54].

Table 3. *Comparison of TLF and other forests in Ethiopia and elsewhere with respect to Carbon stock (t ha^{-1}).*

S/N	Forest	AGC	BGC	SOC	DWC	LHGC	Total	Source
1	Garjeda	466.1	93.2	155.8	-	2.51	717.6	Tamene Yohannes [63]
2	Anbessa	169.0	33.8	149.6	-	1.15	353.6	
3	Adaba-Dodola community forest	278.0	41.8	186.4	-	1.06	507.3	Muluken Nega *et al.* [53]
4	Egdu	278.1	55.6	277.6	-	3.47	614.7	Adugna Feyisa *et al.* [3]
5	Natural forests of Bangladesh	111.4	-	168.2	-	4.21	283.8	Ullah & Al Amin [65]
6	Collaborative Forests in Terai (Nepal)	116.7-178.9	-	-	-	-	-	Mandal *et al.* [47]
7	Secondary and Gallery forests of Congo	131.0	-	-	-	-	-	Ekoungoulou *et al.* [18]
8	Lowland Area of Simien Mountains National Park	270.9	54.2	242.5	0.7	0.02	568.3	Tibebu Yelemfrhat *et al.* [64]
9	Humbo	30.8	14.5	168.2	-	12.6	225.9	Alefu Chinasho *et al.* [4]
10	Arba Minch Ground Water Forest	414.7	83.5	83.8	-	1.3	583.2	Belay Melese *et al.* [9]
11	Tara Gedam forest	306.4	61.5	274.3	-	0.9	643.1	Mohammed Gedefaw *et al.* [52]
12	Mount Zequalla Monastery forest	237.8	47.6	57.6	-	6.5	349.5	Abel Girma *et al.* [1]
13	Tropical seasonal forest in Southwestern China	163.0	38.8	91.1	9	1.4	303.3	Lu *et al.* [45]
14	Usambra	427	90	418	-	-		Munishi [54]
15	Uluguru	318	70	295	-	-		
16	Tulu Lafto	218.4	43.5	128.9	6.2	2.4	399.4	Current study

In TLF, soil was the 2nd largest C pool with 128.95 t C ha^{-1} (32.28%) stored in the upper 30 cm depth. This is within the range estimated for tropical moist and seasonal forests [13]. TLF stored more carbon in its soil than other forests such as Mount Ziquala [1] and Arbaminch Ground water forests [9] but much lower than Usambra and Uluguru forests [54] may be due to the difference in vegetation types, topography, natural and anthropogenic disturbances, soil type, and land use history [40]. Though most studies outside Ethiopia included the upper 1 m layer of the soil profile and comparison is not feasible, soil C in the present study area is higher than that of Tropical seasonal forest in Southwestern China [45].

Belowground biomass, dead wood and leaf litter, herbs and grasses (LHGs) contributed the remaining 13% C in TLF (Table 2). Dead wood accounts for 10–20% of AGC in mature forests [36, 57, 49], but it contributed only 2.82% of the AGC and 1.54% of the total C in the current study area.

In terms of dead wood C stock, TLF is less than other tropical forests [45, 55, 57] except the Lowland area of Simien Mountains National Park in Ethiopia [64]. The low dead wood carbon in the study area could be attributed to fuel wood collection by the surrounding people, forest fire that convert all the dead wood into ashes and the rapid decomposition rate associated to tropical climate.

Leaf litter, herbs and grasses (LHG) comprised the least proportion of carbon stock (0.56%) in TLF. It is comparable to the value reported for Garjeda forest [63]; but greater than that of Tropical seasonal forest in Southwestern China [45], Tara Gedam [52], Arbaminch ground water [9], Low land areas of Simen Mountain [64], Adaba Dodola [53] and Anbessa forests [63].

Carbon stock density along DBH classes

Size class distributions such as diameter class are considered as an important indicator of forest dynamics and determine a number of ecosystem functions in a forest. This study revealed that total stem density (trees with a diameter ≥5cm) decreased with increasing diameter asserting an *inverted-J* population curve (Figure 3a). Such population structure indicates good reproduction and healthy regeneration. The distribution of C stock along dbh classes, however, revealed an irregular shape with maximum C accumulated in the middle (from 35-55 cm) and last (>105 cm) dbh classes (Figure 3b) which is due to abundance of medium sized trees typical of *Combretum-Terminalia* woodland vegetation type (CTW) and large tree size in the last diameter classes. This asserts that higher diameter trees are important reservoirs of biomass C and removal of these trees from the forest would release large amount of C to the atmosphere in the form of CO_2.

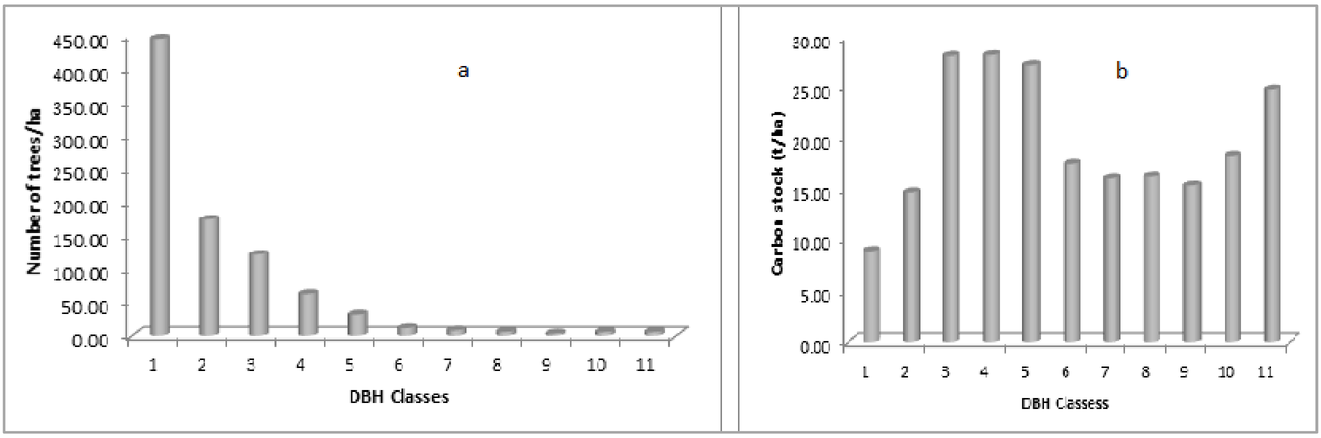


Figure 3. *Stem density (a) and C stock distribution (b) along DBH Classes in TLF.*

DBH Classes: 1: 5.00-15.00 cm; 2: 15.01-25.00 cm; 3: 25.01-35.00 cm; 4: 35.01-45.00 cm; 5: 45.01-55.00 cm; 6: 55.01-65.00 cm; 7: 65.01-75.00 cm; 8: 75.01-85.00 cm; 9: 85.01-95.00 cm; 10: 95.01-105.00 cm and 11: >105 cm.

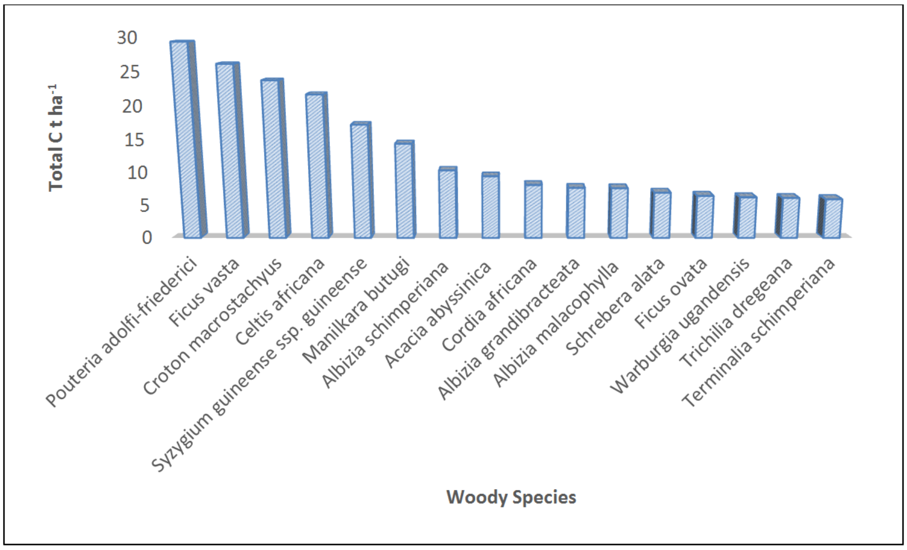


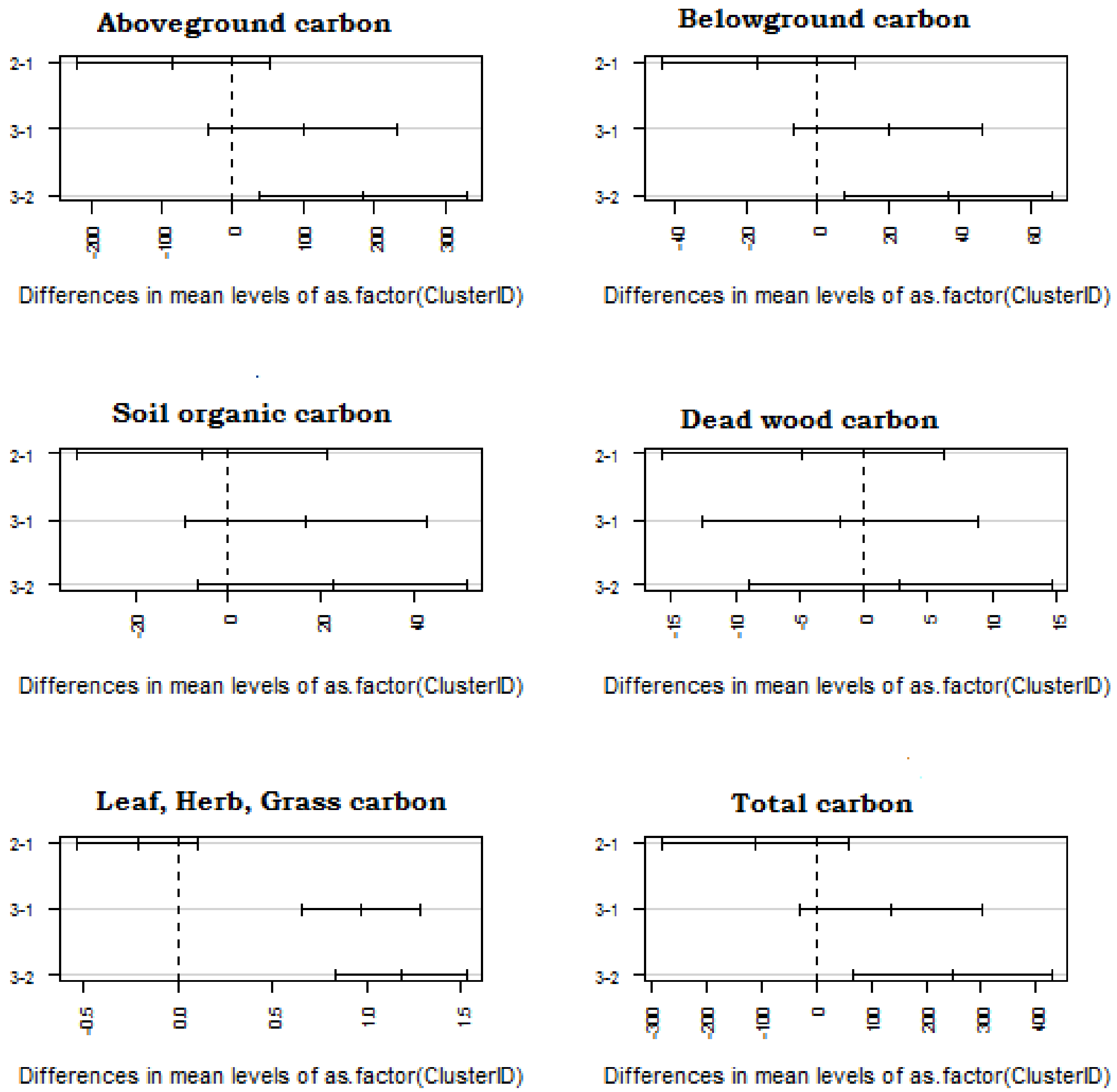
Figure 4. *Carbon stock (t ha^{-1}) of tree species in Tulu Lafto Forest.*

3.2. Carbon Stock density of Tree Species in Tulu Lafto Forest

Tree species differ in terms of their carbon content. Out of the 93 woody species in TLF, ca. 80% of the living C was stored in only 16 tree species (Figure 4) indicating interspecific variation in C stock. Two tree species that were well represented by large sized individuals namely, *Pouteria adolfi-friederici* (with larger mean height) and *Ficus vasta* (larger mean diameter), stored more than 20% of biomass C in the forest. *Croton macrostachyus, Celtis africana* and *Syzyguim guineense* ssp. *guineense* with 9.16, 8.36 and 6.65%, respectively are also important C reservoirs in TLF. Previous studies in Ethiopia and elsewhere also confirmed the dominance of few tree species in terms of above and belowground C stock. For example, 90% of the total C in the living biomass of Adaba Dodola community forest was stored in only two tree species (*Juniperus procera* and *Podocarpus falcatus*) [53]. Similarly, *Dipterocarpus turbinatus* was indicated to dominate both above and belowground C stock of natural forests in Bangladesh [65]. Thus, conservation of tree species with larger biomass C in the forest would contribute to the efforts of reducing emission from deforestation and forest degradation.

3.3. Carbon Stock Variation Among Vegetation Units

Vegetation units in TLF showed significant difference in total C, aboveground C, belowground C and C stock of leaf litter, herbs and grasses (LHG), but not in soil and dead wood carbon (Figure 5). Clusters on the opposite sides of the dotted line and not overlapping it are significantly different from one another. The Afromontane type vegetation unit occupying higher altitude accumulated significantly higher C than the remaining two vegetation units. The *Riverine* and *Combretum-Terminalia* woodland types did not show significant difference with respect to total C.



Numbers on the left indicate vegetation units 1: *Riverine type*; 2: *Combretum-Terminalia* woodland type; 3: *Afromontane forest* type vegetation units.

Figure 5. *Pairwise comparison of vegetation units in terms of carbon stock density.*

Documenting within forest C stock variation is vital in monitoring change in global C stock. C stock varies within sites due to variation in topographic features and floristic composition, disturbance history, successional stage and soil fertility [55]. The variation in C stock density between vegetation units of this study area could be attributed to a number of interacting environmental factors, including: topography, edaphic factors and species composition. For instance, the higher C stock density of the *Afromontane type* vegetation unit in this study area is due to minimal human impact at higher elevation that maintained abundant big sized trees.

Results of this study showed the highest dead wood C stock density in *Riverine type* vegetation unit may be because of: (1) moist microclimate around river valley that protected dead woods from the devastating effect of forest fire; (2) the steep slope around rivers that hindered the surrounding people from collecting dead woods for fuel and other purposes; and (3) increased rate of tree fall on steep slope of riverine areas [10]. In contrast, dead wood carbon stock was the lowest in Combretum-*Terminalia type vegetation units* which might be due to forest fire that consumes the dead wood, or fuelwood collection by the local people as this vegetation unit is easily accessible. Fuelwood constitutes the only available source of energy for household utilization by the surrounding people. Fuelwood constitute the largest component of biomass loss in many developing countries [39].

4. Conclusion and Recommendation

Forests sequester and store more carbon than any other terrestrial ecosystems [29]. Hence, conserving remnant forest patches and maintaining its C stocks while promoting greater CO_2 uptake has gained much attention as an option to mitigate the impact of climate change [21]. Though the C stock of TLF is lower than some other forests in Ethiopia, substantial amount of carbon is stored in its aboveground biomass and soil. However, increasing frequency of disturbances due to farmland expansion, livestock grazing, logging and other anthropogenic activities will likely threaten the sustainability of TLF and its C stock. As per this study, more than 60% of trees in TLF are less than 15 cm DBH asserting that the forest is in a secondary state of development. The abundance of young trees in the forest indicates a high potential of C sequestration as they rapidly grow and accumulate more C in the future. Hence, appropriate forest conservation strategies including enrichment planting should be done in order to conserve the existing C stock and enhance further C sequestration in the forest. In addition, integrating the C sequestration potential of this forest with the international initiatives such as REDD$^+$ could supplement the national forest conservation efforts in the future. Finally, site-specific C stock studies should be promoted than using regional and national average values that fail to account local variability. Regional and national average data tend to underestimate forest C stocks as compared to site specific studies.

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