Muluneh and Worku
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Carbon storages and sequestration potentials in remnant forests of different patch sizes in northern Ethiopia: an implication for climate change mitigation

Melese Genete Muluneh* and Belachew Bogale Worku

Abstract

Background: Forests provide various ecosystem services. They are natural capitals that enhance nature to regulate itself via carbon sinks. However, anthropogenic and natural factors have altered their CO_2 sequestration and carbon storage potentials. This study is aimed for examining the effect of patch size and biomass extraction on carbon stocks in northern Ethiopia. A total of 61 sample plots measuring 20 m × 20 m size each (0.04 ha) had been systematically assigned on patches classified into three size categories. However, the numbers of plots taken per patch were different with their sizes. Moreover, stump density has been computed at each plot to estimate the difference in the level of disturbance among patches. Carbon stocks had been estimated via models previously developed. One-way ANOVA was used to examine a variation in carbon stocks and sequestration potentials. Besides, a linear regression analysis was discretely done to examine the relationship between patch sizes, disturbance level, and carbon stocks.

Results: The overall aboveground biomass (ton ha^{-1}) for the studied patches was 2059.13. There was a statistically significant variation in carbon stocks (ton ha^{-1}) among patch size categories. The mean levels of disturbance ranges from 10.83% ± 1.30 to 30.8% ± 4.04. However, statistically significant difference in the level of disturbance was observed between large and small patch size categories, respectively ($p < 0.05$). Besides, a regression analysis confirmed a significant and negative relationship between patch size and patch disturbances ($R^2 = 0.65$, $p < 0.05$). However, significant positive relation between carbon stocks (ton ha^{-1}) and patch size ($R^2 = 0.53$, $p < 0.05$) had observed.

Conclusions: In general, patch size and biomass extinction significantly influenced carbon stocks and CO_2 sequestration potentials of forests. Consequently, with the pressing need to mitigate the effects of rising atmospheric CO_2, maximizing carbon storage in the forest ecosystem is increasingly considered a viable management strategy. Therefore, disturbed land restoration, increasing forest patch size, sustainable management, and conservation of the existing remnant forest patch is needed to enhance carbon stocks and CO_2 sequestration potentials.

Keywords: Aboveground biomass, Carbon stock, CO_2 emissions, Forest disturbances, Patch size categories, Wood density

Background

Forests provide various ecosystem services such as wood products, food, medicine, biodiversity conservation, erosion reduction, water purification, and carbon sinks [1–9]. Forests are also natural capitals that enhance nature to regulate itself and support economic growth for humans

*Correspondence: melesegenete2011@gmail.com; melese.genete@wu.edu.et

College of Agriculture, Department of Forestry, Wollo University, P.O. Box 1145, Dessie, Ethiopia

[10–12]. Accordingly, forests regulate nature via global carbon cycle, carbon dioxide sequestration, and climate change mitigations [13]. Besides, forest comprises greater carbon (C) than the entire atmosphere, contributing greatly to the worldwide terrestrial C sink [14] and consequently to the global climate regulation [15]. Therefore, forests have been considered as basins of global atmospheric carbon, storing more than 50% of atmospheric carbon in their aboveground vegetation [16]. Besides, forests store more than 80% of all terrestrial global aboveground C due to photosynthesis [17, 18].

Forests had been sequestered more than 20% of global fossil fuel emissions in the past periods [19] due to their high C sinking power [20]. Moreover, they have enormous possibilities in requisitioning and storing C and have been critical to the overall C sequence [21, 22]. However, recently anthropogenic and natural factors have been altered those ecosystem services and goods provided by forests [1, 23]. Furthermore, forests have been cleared and forced to remain only as small patches by agricultural activities. This leads to the destruction of ecosystem services such as carbon storage, climate regulation, and will give to the loss of global biodiversity [15, 22]. Accordingly, it has been well understood that forest destruction, disturbance, degradation, burning, and deforestation could lead to discharging of CO_2 into the global atmosphere [23–25]. This in turn changes atmospheric greenhouse gases (GHGs) accumulation, impacted global climate change, ecosystem biomasses, ecosystem productivities, and atmospheric global C cycle [26]. Therefore, global atmospheric C storage has been increasing due to fossil fuel burning and forest conversion recently [27]. For example, in tropics forest degradation and removal have been donated for 15–25% of the yearly global GHGs releases [28]. Besides, lumber production, fuel-wood, and charcoal, uninhibited fire, and grazing annually release 52%, 31%, 9%, & 7% of GHGs, respectively [29, 30]. Therefore, a minor distraction of the forest ecosystem could bring a major alteration in the overall C cycle. In this regard, forest dynamics and the related C storage, play an important role in atmospheric CO_2 concentrations [31, 32]. Conversely, little is understood about the effect of biomass removal and patch size on carbon stock of dry Afromontane forests (DAF) in Ethiopia at large and specifically in northern Ethiopia.

To quantify the C stocks, the amount, and changes of total woody biomass need to be measured. C is accumulated both as living tree biomass and as dead organic matter in forest ecosystems [15]. The two largest C pools in the forest ecosystem are aboveground live tree biomass and mineral soil organic matter, with roots, and surface detritus [33]. Therefore, the sum of the changes in the various forest C ponds is a balance between C fixation through photosynthesis and CO_2 loss through respiration [18, 22, 34, 35]. This in turn regulates the rate at which ecosystem C accumulates [36]. Recently, accounting for C sequestration and storage in the forest ecosystem has been recognized and extensive attention has been given to its persistent role in regulating global climate change [37]. Besides, the extent of C sequestration and storage of a forest ecosystem is the principal approach to fight and quantify global climate crisis impacts [38, 39]. Therefore, there should be applicable conservation and management practices and plans within forests to have the overall goods and services provided [22, 40, 41].

Although there are scientific studies on C stocks and storages in forest ecosystems of Ethiopia, the effects of patch size and biomass removal (disturbance) on C storage and sequestration potential are poorly understood in the DAF of northern Ethiopia. Besides, it is not clearly understood that whether small forest patches act the same as large patch-sized forests or not in regarding C storage and sequestration [42, 43]. Moreover, the influence of disturbance levels on carbon stocks of remnant forest patches with different patch size has been poorly understood. Therefore, there is a need of estimating and comparing C storage among patches [39, 44]. Besides, little is known about changes in C stocks, their sequestration potential, and climate change regulation roles at forests with different patch sizes in northern Ethiopia [45]. Furthermore, there is a growing global interest to conserve forest ecosystems for C sequestration, storage, and climate change mitigation [22, 46] and reduction of emissions from deforestation and forest degradation [47]. Therefore, scientific information on C sequestration and storage potentials among patches with different patch sizes would be helpful to establish management and conservation plans for those remnant forest patches [15, 22, 48]. Moreover, it could be intended to provide scientific information for administration bodies (governmental and non-governmental organizations), policymakers, researchers, academicians, and other concerned stakeholders. Therefore, the capacities of patches with different size to C storage and climate change regulation need further examination. Accordingly, the present study had been accompanied to examine the linkage between patch sizes, biomass removal (patch disturbance), C storages, and sequestration potentials. Hence, this study is aimed to (1) estimate the aboveground biomass carbon stocks of woody species; (2) examine the effect of patch size and patch biomass extraction on aboveground biomass carbon stocks in northern Ethiopia.

Materials and methods

Study site description

The study was conducted in the DAF [49] remnant state forest patches of northern Ethiopia [50]. *Lepidotrichilia volkensii*, *Albizia gummifera*, and *Pavetta abyssinica* had been reported as dominant species in the area [51]. The area is located between latitudes of 11°1′00″ N—11°37′00” N and longitudes 37°3′00” E—37°13′00” E (Fig. 1). The altitude of the study site ranges from 1800 to 2350 m above sea level (Table 1). The temperature of the

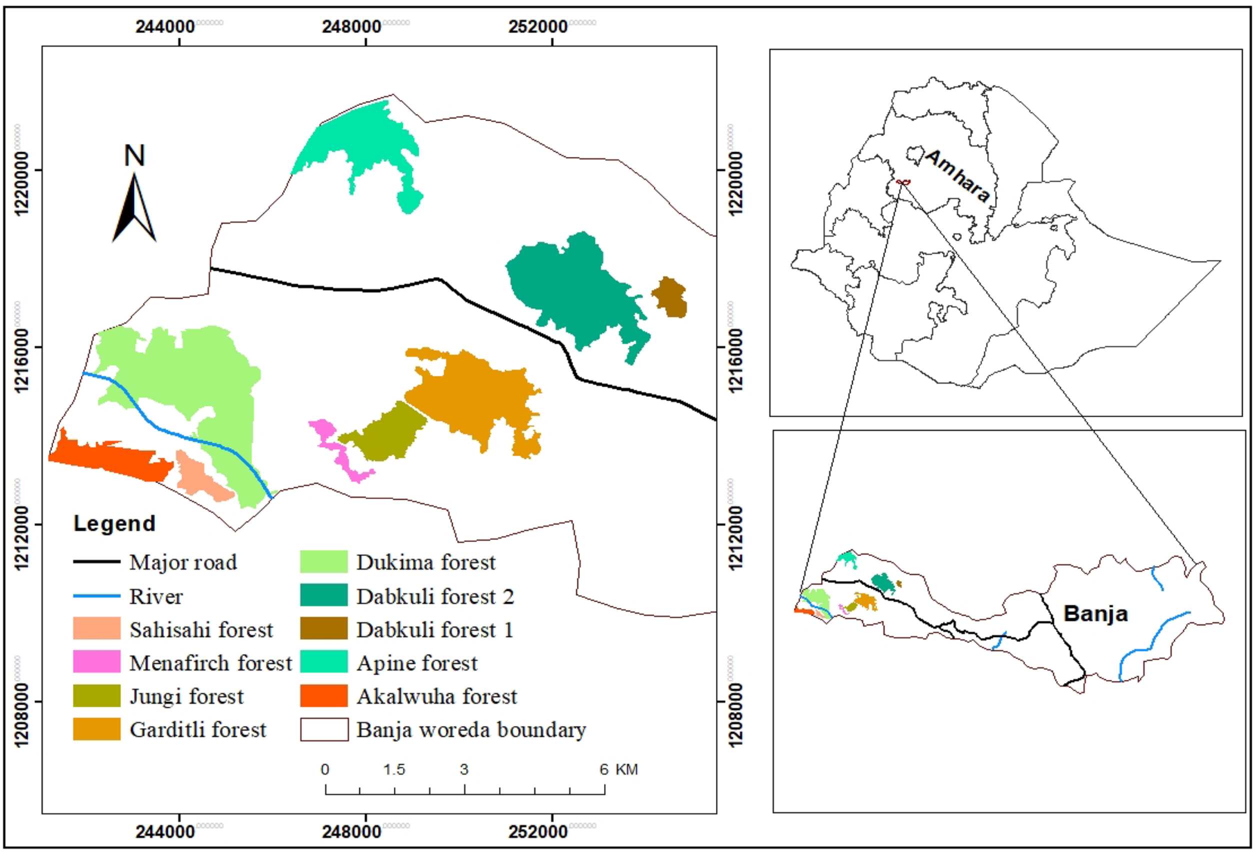

Fig. 1 Location map of the studied remnant forest patches in northern Ethiopia

Table 1 Forest patch size category, elevation range, and number of transects laid in northern Ethiopia

Patch size category	Patch size in ha	Patch name	Transect laid	Number of plot taken	Orientations of transects	Elevation range (m.a.s.l)
Small	35	Menafirch	1	2	NW	1870–2000
	40	Sahisahi	1	2	NW	1875–2045
	45	Dabkuli 1	1	2	NW	1985–2001
Medium	120	Zungi	2	3	NW	1870–2051
	175	Akalwuha	2	4	NW	1800–2037
	325	Apine	3	8	EW	1981–2350
Large	480	Garditili	4	10	NW	1924–2161
	525	Dabkuli 2	4	12	EW	1985–2267
	747	Dukima/Absakitem	5	18	NW	1805–2100
Total	2492		23	61		1800–2350

NW stands for Northwest, *EW* stands for East West and m.a.s.l stands for meter above sea level.

study area ranges from 9.4 °C to 29.4 °C with an average temperature of 18.7 °C. The rainfall distribution is unimodal with substantial rainfall from June to September (2241 mm) [50]. Based on data (from 1984 to 2015) from Ethiopian national meteorological service agency, the mean annual rainfall of the study area was 1300 mm. The major soil types of the study area are Andisols, Vertisols, Nitosols, and Cambisols [52].

Patch selection and sampling

Based on their sizes, the remnant forest patches were classified into three patch size categories (PSC): small (5–45 ha), medium (120–325 ha), and large (480–747 ha). Such patch size classifications have been used in other Biological study [53]. Forest patches used for this study are owned by government and legal approval had been gained before data gathering. A total of 61 sample plots measuring 20 m × 20 m size each (0.04 ha) had been systematically assigned on each patch following Sutherland [54], Laurance et al.[44], and Magurran and Mcgill [55]. Identification of plants was made in the field. For plants that were difficult to identify in the field, identification was made at the National Herbarium, Addis Ababa University, Ethiopia, and corresponding scientific names were followed [56]. At each plot, DBH (Diameter at Breast Height ≥ 5 cm or (at 1.3 m above ground) and height of woody species had been measured using Caliper and Hypsometer, respectively. Diameter Tape was used to measure the DBH of woody species whose DBH is too big for Calipers. Those woody species with several stalks or trunks at 1.3 m height above ground have been reflected as a single individual. While for those woody plants that bear many trunks below 1.3 m, DBH measurement had been carried out as separate individuals. Moreover, woody plants had been measured when ≥ 50% of their basal area fall within the plot [57]. Woody plants whose stems are located inside the sampling plot and branches outside had also been measured. The sample size was determined based on patch area coverage and time setting effort [58, 59]. Moreover, plot number and transects in forest patch, biological or ecological studies could be determined based on patch area coverage, time setting, available budget, and personal [1, 55, 60]. Conversely, the number of plots taken per patch was varied with their sizes [61]. Therefore, overall transect numbers and plots had been estimated based on the patch size (Table 1). Accordingly, an overall 2.44 ha of forest patches proportional to 0.12% of the study area was sampled. Moreover, 0.20%, 0.10%, and 0.09% of small, medium, and large patch size categories were sampled, respectively. The sampling intensity used in this study is greater than the compulsory standard minimum sampling amount suggested to study forest patches (0.01%) [62]. To remove edge or border effects, plots had been laid at 50 m inwards. Stump number or stump density has been documented at each plot to estimate the difference in the level of biomass removal (disturbance levels) among patches. Besides, the density of woody species (living woody species) had been computed following Mishra et al. [63] and Picard et al.[58].

Data analysis

The aboveground biomass (AGB) and C stock of trees had been estimated following the recently developed allometric model by Chave et al. [64]. The model was chosen among others because it had been developed using tree parameters such as tree Height and wood density with DBH instead of using only DBH or Height. Besides, it is an appropriate model developed to estimate AGB and C stocks of trees in dry tropics and pan-tropical forest types of Africa with extensive climatic varieties [65]. Moreover, Chave allometric model is recommend in delivering midway values for the broadest choice of trees in tropics. Therefore, it shows precise estimates away from sites where it has been developed and advisable to be used in the absence of site-specific allometric equations [66]. So that DBH of trees (DBH, cm), height (m), and wood density (g cm^{-3}) had been used to estimate the aboveground biomass and C stock of woody species using Eq. 1:

$$\mathrm{AGB_{est}}\left(\mathrm{kg}\right) = 0.0673\mathrm{x}\left(\rho \mathrm{D}^2\mathrm{H}\right)^{0.976}, \tag{1}$$

where AGB_{est} is the aboveground biomass of trees (kg), ρ is the specific wood density (g cm^{-3}), *D* is the diameter at breast height (cm), and *H* is the height (m). DBH and height of woody species had been obtained from measurement, while densities of definite woody plants were gained from wood density of tropical tree species database [67]. For woody species whose wood density is unknown, the middling values (0.612 g cm^{-3}) of the known species' family or genus of tropical tree species were used following Reyes et al. [67]. However, the generic equation developed for shrub species by Mokria et al. [68] was used to estimate the AGB of shrub species (Eq. 2). Moreover, the equation developed by Putz [69] was used to estimate the AGB of Lianas or climbers (Eq. 3):

$$y = 0.2451\left(\mathrm{DSH}^2\mathrm{x}\,H\right)^{0.7038}, \tag{2}$$

where Y = aboveground biomass (kg), *DSH* diameter at stump height, and *H* height.

$$\mathrm{AGB}\ (\mathrm{kg}) = \exp\ (0.12 + 0.91\log\left(\mathrm{BAcm}^2\right), \tag{3}$$

where *AGB* aboveground biomass (kg), *log* logarithm base 10, *BA* basal area.

The overall AGB at each plot had been estimated by adding AGB of all woody species. Besides, biomass carbon had been estimated following IPCC [70] where 47% of AGB comprise C. Biomass C stocks of woody species had been estimated for each plot per patches and generalized to hectares (ton ha^{-1}). Belowground biomass of woody species (BGB) had been estimated following IPCC [58] where belowground biomass is 27% of aboveground biomass (Eq. 4), and 47% of the BGB is below ground carbon (BGC):

$$\mathrm{BGB} = \mathrm{AGB} \times 0.27, \tag{4}$$

where BGB is below ground biomass and AGB is aboveground biomass.

Patch disturbance level (patch biomass extraction) had been estimated as a proportion of the addition of the stumps density to overall density (stump density plus live individuals' density) following Sagar et al. [71]:

$$\text{Patch disturbance level(PDL)} = \frac{\text{Stump density}}{\text{Total density}} * 100, \tag{5}$$

where the total density is the summations of the density of stumps and density of live woody plants. Stumps are the remnants of the removed stems of woody plants measuring diameter at stump height (DSH) of ≥ 5 cm. Density represents the number of individuals per hectare. Stump density or the number of stumps per area was determined by counting old and new cut stumps (DSH ≥ 5 cm) in each plot. Therefore, stump density ha^{-1} of cut stumps were calculated and determined for each patch. while density of live woody species (DBH ≥ 5 cm) was computed by converting the count from each plot to hectare basis. The total density was determined after summation of stump density and density of live or standing woody plants (DBH ≥ 5 cm).

Data of DBH, height, and abundance were tested using Kolmogorov–Smirnov[a] and Shapiro–Wilk test, and normally distributed ($P > 0.05$) (Appendix Table 10). The C stock data from transects of each patch were combined to estimate the C stock and sequestration potentials of patches. Accordingly, one-way ANOVA was used to examine if there is a variation in aboveground biomass, carbon stocks, and sequestration potentials across patches [72]. Post hoc comparisons were conducted for significant interactions using the Tukey honestly significant difference (HSD) test. A linear regression analysis was discretely carried out to examine the relationship between patch sizes and patch biomass extraction on C stocks and sequestration potentials. Therefore, the aboveground biomass was used as the dependent variable, whereas the patch size and patch disturbance level were used as independent variables [73]. Data were analyzed with SPSS software (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.) and Microsoft excel 2013.

Results

Aboveground biomass and carbon stocks along with patch size categories

A total of 2841 individuals (DBH ≥ 5 cm), representative of 80 species, 68 genera, and 43 families have been identified, documented, and measured in the studied remnant forest patches (Appendix Table 5). The highest number of species, genera, and families has been recorded at low disturbed large patch size categories (Appendix Table 5). Accordingly, the number of species decreased as patch disturbance increased. Moreover, mean woody species density for small, medium, and large patch size categories ranged from 992 individuals/ha, 1111 individuals/ha, and 1411 individuals/ha, respectively. The overall aboveground biomass for the studied forest patches was 2059 ton ha^{-1}.

The highest and the lowest aboveground biomass and carbon stocks at species level were recorded in large and small patch size categories, respectively (Table 2). Moreover, the highest and the lowest aboveground biomass (ton ha^{-1}) at small patch size categories was retained by *Albizia gummifera* (J. F. Gmel.) (9.77) and *Rytigynia neglecta* (Hiern) Robyns (0.093), respectively (Table 3). Similarly, the highest and the lowest aboveground biomass (ton ha^{-1}) at medium patch size categories was reserved by *Prunus africana* (Hook. f.) Kalkm. (495.6) and *Clausena anisata* (Willd.) Benth. (0.041), respectively. Besides, *Prunus africana* (Hook. f.) Kalkm. (551.57) and *Entada abyssinica* Steud. ex A. Rich. (0.047) has the highest and the lowest aboveground biomass (ton ha^{-1}) at large patch size categories (Appendix Table 6, Table 3). *P. africana*, and *A. gummifera* retained the highest aboveground biomass (ton ha^{-1}) and carbon stock values due to their big DBH and height values reaching up to 43 m in height and 170 and 157 cm in DBH, respectively (Fig. 2). Consequently,

Table 2 Biomass and C stocks in northern Ethiopia

Mean biomass and C stocks (ton ha^{-1})	Patch size categories		
	Small	Medium	Large
Aboveground biomass	$5.45^{a} \pm 0.201$	$309.16^{b} \pm 59.59$	$371.76^{b} \pm 59.16$

The means with different superscript letters in a column are significantly different statistically [(Honestly Significance Difference test)], $P < 0.05$ (Appendix Table 12)

The ANOVA table had been presented only for patch size and mean aboveground biomass. This is because belowground biomass, aboveground C, belowground C, $AGCO_2$, belowground CO_2, aboveground biomass and carbon stocks are dependent on aboveground biomass values.

Table 3 Woody species with high mean aboveground biomass and carbon stocks of patch size categories in the northern Ethiopia

Woody species	AGB (ton ha^{-1})		AGC (ton ha^{-1})			
	Small	Medium	Large	Small	Medium	Large
Albizia gummifera	9.77	41.7	49.3	4.6	19.6	23.2
Rosa abyssinica Lindle	1.03	0.11	0.2	0.5	0.1	0.1
Acacia abyssinica Hochst. Ex Benth	0.72	0.48	0.1	0.3	0.2	0.1
Croton macrostachyus Hochst. Ex Del	0.69	0.47	0.1	0.3	0.2	0.1
Prunus africana	–	495.6	551.6	–	232.9	259.2
Erythrococca trichogyne (Muell Arg.) Prain	–	119.21	0.2	–	56.0	0.1
Allophylus abyssinicus (Hochst.) Radlk	–	84.53	47.7	–	39.7	22.4
Celtis africana Burm. f	–	69.16	73.2	–	32.5	34.4
Apodytes dimidiata E.Mey.Ex Benth	–	12.93	79.1	–	6.1	37.2
Ficus vasta Forssk	–	19.10	118.4	–	9.0	55.7

AGB stands for aboveground biomass and AGC for aboveground carbon

large stem sizes donated more for aboveground biomass and carbon stocks while small size stems contributed less. Likewise, stem number or high stem density ha^{-1} contributed more for aboveground biomass and carbon stocks. In this regards, low aboveground biomass for woody species such as *Solanum marginatum*, *Clausena anisata*, and *Lippia adoensis* was because of low stem density, low DBH, and height values (Appendix Table 6).

Both aboveground biomass and carbon stocks were higher in large patch size categories than small. Accordingly, there was statistically significant variation in mean aboveground biomass, mean belowground biomass, mean aboveground C, mean below ground C, and mean $AGCO_2$ (ton ha^{-1}) among patch size categories in the studied forest patches ($p < 0.05$) (Table 2). The result indicated that the removal of large-sized woody species (trees) and biomass removal particularly at small patch size categories had resulted in carbon stocks and biomass reduction in the study area (Fig. 3). Accordingly, the aboveground biomass decreased from the high disturbed (5.45 ± 0.201 ton ha^{-1}) small patches to low disturbed (371.76 ± 59.16 ton ha^{-1}) large patches. Therefore, biomass removal or patch disturbance level links to a 56.7% reduction in aboveground biomass and carbon stocks from high disturbed to low disturbed patches. Similarly, the highest mean CO_2 sequestered was high in large-sized patch categories compared to small patches (Table 2). Consequently, the highest amount of stems with greater DBH at medium and large patch size categories have contributed a lot for aboveground mass and carbon stocks (Fig. 2). On the other hand, biomass removal of more woody species (trees) that have big stems particularly in the small patches has resulted in low aboveground biomass, carbon stock values and, carbon dioxide sequestration (Fig. 3).

As indicated in Table 3, most woody species that have high aboveground biomass values in the small patch size categories have low biomass values in medium and high patch size categories. Similarly, most woody species with high biomass values in medium patches have low biomass in large patch sizes. Furthermore, woody species with greater biomass values at medium and large patch size categories such as *Prunus africana*, *Celtis africana*, *Ficus vasta*, and *Allophylus abyssinicus* were absent at small patch size categories.

Distributions of aboveground biomass among DBH classes

Though 83.3% of woody species were located in the lower DBH classes (5–25 cm) (Fig. 4a), in each patch size categories, respectively, their contribution to AGB was low (Fig. 4b). Besides, a decreasing trend of individuals was observed with increasing DBH size. Accordingly, the highest AGB (ton ha^{-1}) was observed at a greater DBH classes ($DBH \geq 50$ cm) (Fig. 4b). Though the AGB increased with increasing DBH classes, this was not observed in DBH classes ranged from 30 to 35 and 45–50 cm due to intensive removal (selective logging) of trees in these DBH ranges. According to forest guards, trees in these DBH classes are highly removed illegally for the purpose of house construction and timber production.

Carbon stocks along with patch disturbance levels

The mean level of disturbance ranges from $30.80\% \pm 4.04$ at high disturbed small patches to $10.83\% \pm 1.30$ at low disturbed large patches. Consequently, the highest and the lowest disturbance levels were recorded in small and

Fig. 2 Trees with highest DBH and height in remnant forests of northern Ethiopia (**a**–**f**). Photo by Melese Genete 2018

Fig. 3 Biomass removal by anthropogenic means in remnant forests of northern Ethiopia (**a**–**f**). Photo by Melese Genete 2018

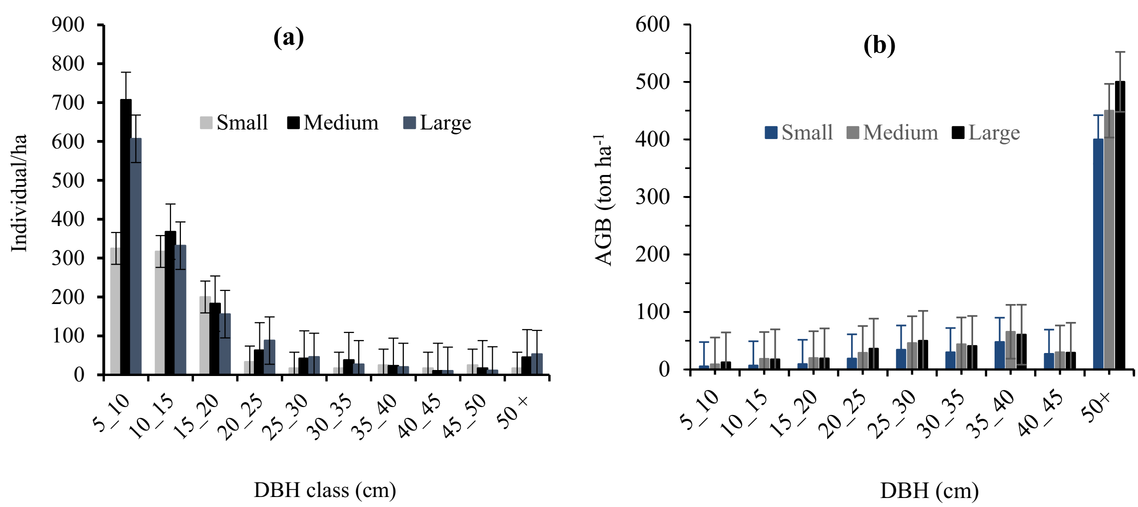

Fig. 4 The mean (mean ± SE) distribution of **a** number of woody species (individuals ha^{-1}) and **b** aboveground biomass (ton ha^{-1}) in relation to DBH classes in northern Ethiopia

Table 4 Patch disturbance levels across patch size categories and carbon stock in northern Ethiopia

Patch size categories	Stem density ha^{-1}	Stump density ha^{-1}	Patch disturbance level (%)	Total carbon stock (ton ha^{-1})
Small	$992^b \pm 44$	$302^a \pm 27$	$30.80^a \pm 4.04$	$3.25^b \pm 0.12$
Medium	$1111^{ab} \pm 123$	$199^b \pm 12$	$18.13^b \pm 1.04$	$184.54^a \pm 35.57$
Large	$1411^a \pm 28$	$152^b \pm 16$	$10.83^b \pm 1.30$	$221.91^a \pm 35.32$
Overall	1171 ± 73	218 ± 24	19.92 ± 3.18	136.57 ± 36.73
F	7.888	15.643	16.027	16.333
P	0.021	0.004	0.004	0.004

large patch size categories, respectively. The highest disturbance levels at small patch size categories resulted from removal of the highest amount of woody biomasses or resulted from the presence of highest stump density ha^{-1} (Table 4). Similarly, low disturbance levels at large patch size categories were resulted from the prevailing low cut stem number ha^{-1} (Table 4). Accordingly, the level of disturbance in small patch size category was significantly ($P<0.05$) highest than the large and small patch size categories. Though there is a difference in stump density ha^{-1} among large and medium patch categories, there has been no statistically significant difference in the level of disturbance.

The result has shown that the highest and the lowest carbon stocks were recorded at low disturbed large patch size categories and high disturbed small patch categories, respectively (Table 4). Nevertheless, statistically, the significant difference in C stocks was observed in low disturbed (large patch size categories) and high disturbed (small patch size categories) only ($p<0.05$). Therefore, there have been no significant differences in biomass and C stocks at patches with medium disturbance levels (medium patch size categories) and low disturbance levels.

Relationship between patch size, patch disturbance, and carbon stocks

A significant negative relationship between patch size and patch disturbance ($R^2=0.72$, $p<0.05$) had confirmed in this study (Fig. 5). Accordingly, the disturbance levels of patches decreased as their size increased. Moreover, aboveground biomass, belowground biomass, aboveground C, belowground C, $AGCO_2$, and $BGCO_2$ (ton ha^{-1}) decrease as the level of patch disturbance increase ($R^2=0.68$, $p<0.05$) (Appendix Table 6). Therefore, disturbance or biomass removal reduced the C sequestration capacity of remnant forest patches.

On the other hand, there has been significant positive relation between aboveground biomass, belowground biomass, aboveground C, BGC, $AGCO_2$, and belowground CO_2 (ton ha^{-1}), and patch size ($R^2=0.92$, $p<0.05$) (Fig. 6). In this regard, large size forest patches stored more amount of C compared to small-sized patches. Therefore, biomass removal or forest disturbance did not only shrink patch area or sizes, it also declines the aboveground biomass and carbon stocks. Though there has been a significant reduction in aboveground biomass with patch size in the present findings, patch size was not the only cause for the drop of

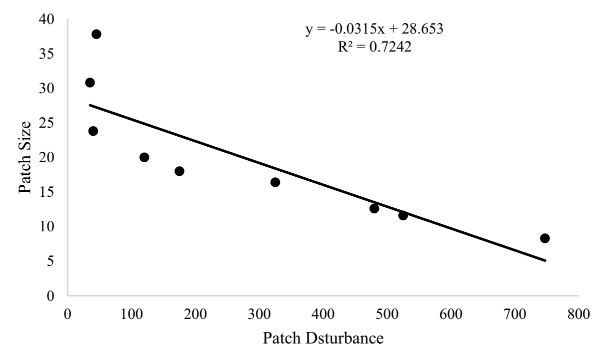

Fig. 5 Relation between patch size patch and disturbance in northern Ethiopia

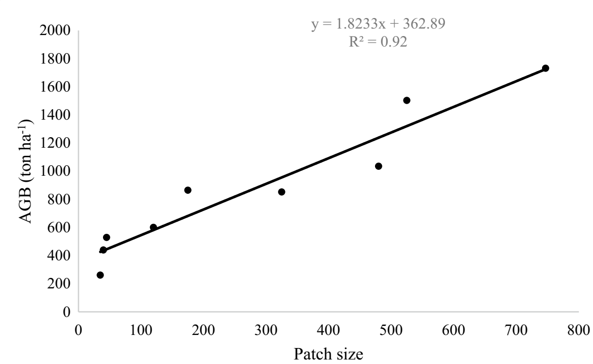

Fig. 6 Relation between patch size and above ground biomass in northern Ethiopia

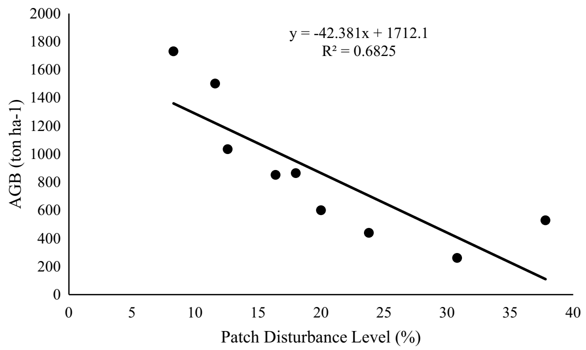

Fig. 7 Relation between patch disturbance and above ground biomass in northern Ethiopia

aboveground biomass, disturbance intensity was the other reason too (Fig. 7).

Note that the regression graph was presented only for patch size and aboveground biomass. This is because the relation between patch size and belowground biomass, aboveground carbon, belowground carbon, $AGCO_2$, and belowground CO_2 shown a similar trend with a trend in aboveground biomass. Note that the regression graph was presented only for patch disturbance and aboveground biomass. This is because the relation between patch disturbance and belowground biomass, aboveground carbon, belowground carbon, $AGCO_2$, and belowground CO_2 shown a similar trend with a trend in aboveground biomass.

Discussion

Aboveground biomass and carbon stocks along with patch size categories

Patch size affects aboveground biomass and number of individuals by altering the stand dynamics and level of disturbance across forest patches [74, 75]. Results showing low number of woody species at disturbed small patches were reported by Sagar et al. [71] similar to the results of the present study. Similarly, Shen et al. [75] reported a low number of species at smaller and disturbed patches consistent with this study. According to Kumar et al. [39] fragmented forest patches have lower species and donate to the lowest C stocks. However, [76] reported a different result from this study, reporting an increasing trend of the number of species with increased disturbance. The numbers of individuals reported in this study is greater than 1655 individuals reported in five patches of northwestern Ethiopia by Gebeyehu et al. [77]. More individuals in this study might be due to more number of patches taken and their size differences.

The total carbon stock values in the present study are comparable with the carbon stock value reported by Abere et al. [52] at Banja forests of northwestern Ethiopia. However, there was a variation in contribution of trees for aboveground biomass and carbon stocks across patches due to difference in size and stem density ha^{-1}. For example, tree species such as *Albizia gummifera*, *Croton macrostachyus*, *Prunus africana*, *Allophylus abyssinicus*, and *Apodytes dimidiata* had been reported as dominant species which have high mean aboveground biomass and carbon stocks in northwestern Ethiopia [77] in line with the result of this study. However, Abere et al. [52] reported the largest portion of the carbon stocks for *Juniperus procera* and *Ekebergia capensis* which this study did not. Moreover, Peng et al. [76] and Shen et al. [75] agreed that trees with the higher DBH contributed a lot for aboveground biomass and carbon stocks in line with the results of these findings. Therefore, there is a differences in carbon socks and sequestration potentials among trees with different size and number [61, 77, 78]. Besides, the variation in the aboveground biomass and the carbon stocks among patches were also due to the difference in the level of biomass removal or patch disturbance level [23, 74, 75, 79]. Accordingly, proper management, conservation, forest restoration, and utilization of woody species might improve biomass, carbon stocks, and CO_2 sequestration potentials of those remnant forest patches [22, 35].

Previous studies revealed that forest fragmentation affects carbon stocks and the sequestration potential of forests [39, 66]. Similarly, according to Lamarque et al. [4] carbon storage and sequestration of forests are different based on their patch sizes. Moreover, Paula et al. [80] reported variation of AGB across patches where large-sized patches store more amount of AGB. Therefore, small-sized forest patches store and sequester a small amount of ecosystem carbon compared to the large-sized forest patches [22, 23, 25, 32, 39]. However, [15] confirmed that connected small patches may store and sequester a high amount of carbon and CO_2, in reverse to the finding of this study. Therefore, variations among patches in mean biomass, C stocks, and Carbon dioxide sequestration in the present study were because of patch size, the difference in the level of biomass removal (patch disturbance), stem size, and height of woody species. An earlier study revealed that forest disturbances reduced C stocks of forests by 81% [39]. Wekesa et al. [61] and Houghton [81] reported similar results that there is a variation in C stocks between forests of different patch sizes and levels of disturbance. Moreover, C stocks of trees and live biomass in undisturbed forests /closed canopy/ were only 8 and 15% greater, respectively, than those in the moderately closed canopy [39].

This study revealed the variation of C stocks across remnant forest patches and determined which woody species store more carbon. Accordingly, woody species with greatest density and DBH stored more C stocks [39]. However, woody species that contributed more for C stocks at large patch categories were absent at small patch size categories because of high disturbances. Besides, those small patches are close to human settlement areas and are not frequently supervised by forest guards [82]. Therefore, the absence of ecologically important species in the small patch size categories has resulted in low aboveground biomass and carbon stock values. Besides, aboveground biomass is a resolute of species abundance, number, density, and size. Shen et al. [75] suggested that large-sized trees above 40 cm in DBH stowed a greater amount of carbon than smaller trees. Therefore, the removal of a small number of large-sized tree species in the small patch size categories may lead for a low amount of aboveground biomass and C stocks. According to Wekesa et al. [83] forest disturbance affected forest carbon stocks and CO_2 sequestrations. Moreover, extraction or removal of large-sized trees affected biomass and carbon stocks too [78]. Therefore, frequent biomass removal highly influences forest biomass, forest structure, and carbon sequestrations [23]. Besides, biomass removal and forest disturbance increase atmospheric carbon emissions [22, 84]. In this regard, frequent forest supervision and preparation of forest management plan greatly enhance aboveground biomass and carbon stocks [22]. Similarly, a previous study by Kumar et al. [39] reported that undisturbed or closed canopy donated 40% of the total forest C stocks.

Distributions of aboveground biomass among DBH classes

The variation of number of individuals and aboveground biomass among DBH classes was reported in northwestern DAF of Ethiopia with similar agro-ecologies to the current study [77]. Moreover, in line to the results of the present study, [85] reported decreasing trends of stem number with DBH size from Afromontane tropical forest of southwestern Rwanda. The highest number of individuals in DBH classes from 5 to 19 cm and the decreasing trends of individuals with increasing DBH were reported by Kumar et al. [39]. Senbeta et al. [56] also reported that selective logging of trees in Afromontane forests of Ethiopia is taking place based on tree size for the purpose of construction and income generation. Furthermore, studies conducted elsewhere indicated that though lower stem classes covered 50% of the stems in a forest [60], only 8% of the carbon increment was contained [86]. Moreover, [77] reported that those lower numbers of individuals at higher DBH classes have higher values of AGB. Preece et al. [66] also reported an increment of AGB with tree age and size.

Relationship between patch size, patch disturbance, and carbon stocks

The present study examined that biomass removal or selective cutting had major consequences on biomass and C stocks of woody species. Scientific studies reported the influence of disturbance or biomass removal on carbon stocks in line with the result of present study [23, 25, 61]. Moreover, [61, 77, 80] reported high disturbed and degraded small patch forest ecosystems store a low amount of carbon compared to low disturbed forests. Similarly, [87] reported a reduction in forest C stocks with different harvesting intensities. Simard et al. [88] agrees that harvesting intensity affects the aboveground and live tree C stocks in a forest. Accordingly, forest disturbances significantly reduce biomasses and C stocks [39]. Besides, [89] argues that clear-cutting, forest harvesting, disturbance, and forest conversion to other land uses such as agricultural crops had been responsible for up to 40% of global anthropogenic CO_2 emissions universally.

According to Williams et al. [90] C stocks declined as patch disturbance intensity increased. Besides, [91] find out that decreases in the aboveground biomass of Neotropical forests patches as forest loss and disturbance increased. The result of this study is also in line with [92] conveyed that disturbance alters the biomass and C stock patterns of remnant forest patches. Conversely, [93] reported positive roles of forest disturbance for C stocks which this study did not. Likewise, Hume et al. [94] argues that C stocks and aboveground tree biomass decrease linearly with cutting intensity. Moreover, [76] reported an increase in aboveground biomass from moderately disturbed site to the seriously disturbed site in reverse to the results of these findings. On the other hand [94], stated that losses in aboveground C storage declined linearly with reduced tree cutting intensity. Therefore, the level of harvesting reduces C stocks.

Total live biomass C reported in the undisturbed forest stands is higher than disturbed stands [39]. The highest biomass in the large size patches in the present study was due to low disturbance levels and high stem numbers at those patches than smaller patches. Similar results were reported by Ziter et al. [15]. Moreover, [95] confirmed the influence of patch size and disturbance on C stocks in Afromontane forest patches in line with the results of this study. Besides, [13, 66] reported that a C density in the forest fragments was significantly influenced by patch size similar to the results of the present study. According to Shen et al. [75] forest fragmentation or patch size declined aboveground biomass in subtropical forests of China. Therefore, it had frequently stated that biomass removal or forest disturbance did not only shrink patch area or sizes, it also declines the aboveground biomass and carbon stocks [39].

As a result, reduction of forest patch size and forest disturbance or selective removal of biomasses largely affects C stocks and sequestration potentials of forests [22, 23, 25, 35, 39]. Accordingly, variations in the amount of carbon storage and sequestration in the forests might be because of variations in the level of disturbances, patch size, number, and size of species among patches [25, 32]. For example, low C stock values at the small patch size categories compared to large-sized patches in the present study are because of frequent removal of large trees at small patches. Similar results were reported [46, 78, 96, 97]. Shen et al. [75] agrees with quick drops in aboveground biomass with decreasing patch size at subtropical forests.

Implications of carbon sequestration potentials for global climate change mitigation

Carbon storage and sequestration in a forest have been significant concerns to fight global climate change in recent decays. Therefore, there is a straight connection between carbon storage, sequestration, and climate change mitigation. However, forest disturbance, degradation, and patch size affect the carbon storage and sequestration potential of forests. Therefore, if the remnant forest patches are selectively harvested or cut their climate change mitigation potential will significantly decline [88]. For example, the variation in the biomass and carbon stocks in the studied forest patches with their sizes and disturbance implied the linkages of C stocks and storages with patch sizes. Conversely, increasing forest patch size or area might not be the only solution to improve climate change mitigation potentials of remnant forests. In this regard, in the rising interest of mitigating a changing climate due to increased CO_2, increasing sustainable forest conservation and management is significant. Furthermore, restoration and rehabilitation of disturbed forest patches will bring positive results to compact future climate change impacts via C storage and sequestration [35]. Sintayehu [98] find out that forests are a means to store atmospheric C and mitigate a changing climate. Therefore, enriched reforestation and rehabilitation had been reflected as actual tactics to mitigate a changing global climate [18, 84, 89, 92].

Forests are wonderful tools to cut off the global warming effects and accumulation of the greenhouse gases such as CO_2 through their physiological process (photosynthesis) [61, 83, 99]. However, the carbon sequestration and storage capacity of forests varied with their level of disturbance and patch size. In this regard, scientific studies and information on carbon stocks have been useful to solve global problems such as a global climate crisis, risks, and atmospheric sequence. According to FOA [100], declining a forest cover /area/ or patch size leaded to an annual reduction of global carbon stocks and biomass by 50% Gigaton (Gt) from 2005 to 2010. Besides, biomass removal leads to the reduction of forest patches and enhances CO_2 emission. Moreover, scientific findings stated that the conversion of forests to smaller patches donated 6–17% of anthropogenic CO_2 emissions [91, 96, 101]. Therefore, forest distractions, degradation, encroachment, fragmentation, and disturbance impacted the global climate change mitigation roles of forests.

The confirmed 2059.13 overall aboveground biomass (ton ha^{-1}) and sequestered overall CO_2 (1503.46) (ton ha^{-1}) for the studied forest patches in this study showed the potential of forests to mitigate climate change. Hence, CO_2 added to the atmosphere could be shunned by forests. Accordingly, sustainable management and conservation are important to increase C storage and sequestration potentials of forests sustainably. Similarly, [18, 73, 102–105] reported that appropriate forest management and restoration is a way to display the forest ecosystem C cycle. Therefore, clear consideration of the impact of sustainable forest management and conservation on C storage and sequestration could deliver clear evidence for climate change mitigation via well-managed forests. In contrast, disturbed, fragmented, and degraded forest patches would probably donate more carbon loss to the global atmosphere. In this regard, recently, humans through forest disturbance and fragmentation had positively contributed to forest loss, climate change impact aggravation, and atmospheric CO_2 emissions.

Conclusions

In general, the result confirmed the variation in the level of disturbance among patches with different size categories. Besides, the studied remnant forest patches stored and sequestered extensive biomass and CO_2. However, both the stored biomass and the sequestered CO_2 varied with the size and types of woody species. Accordingly, most of the woody species that have high aboveground biomass values in the small patches have low biomass values in medium and high patch size categories. Besides, patch size and biomass extinction or level of disturbance had a significant influence on carbon stocks and CO_2 sequestration potentials of forests. In this regard, low disturbed forest patches with large patch sizes stored and sequestered high amounts of C stocks and CO_2. Conversely, small patch size categories with high disturbance levels stored a low amount of carbon. Accordingly, significant variation in mean aboveground biomass, mean belowground biomass, mean aboveground C, mean belowground C and mean $AGCO_2$ (ton ha^{-1}) had been observed among patch size categories. Moreover, a regression analysis confirmed a significant negative relationship between patch size and patch disturbance ($R^2 = 0.8$, $p < 0.05$). However, there has been significant positive relation between mean aboveground biomass, mean belowground biomass, mean aboveground C, mean belowground C, mean $AGCO_2$, and mean belowground CO_2 (ton ha^{-1}) and patch size ($R^2 = 0.53$, $p < 0.05$).

With the pressing need to mitigate the effects of rising atmospheric CO_2, maximizing C storage in the forest ecosystem is increasingly considered a viable management strategy. Moreover, disturbed land restoration, increasing forest patch size, sustainable management, and conservation of the existing remnant forest patch is needed to enhance C stocks and CO_2 sequestration potentials. Besides, proper forest management, conservation, and utilization are required to improve biomass, carbon stocks, and carbon dioxide sequestration, and climate change mitigation of studied remnant forest patches.

Appendix

See Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, 14

Table 5 Woody species found in the study area

Scientific names of species	Family
Acacia abyssinica Hochst. Ex Benth	Fabaceae
Acacia lahai [Steud. & Hochst. Ex] Benth	Fabaceae
Acanthus eminens C. B. Clarke	Acanthaceae
Acokanthera schimperi (A. DC.)	Apocynaceae
Albizia gummifera (J. F. Gmel.) C. A. Sm	Fabaceae
Albizia schimperiana Oliv	Fabaceae
Allophylus abyssinicus (Hochst.) Radlk	Sapindaceae
Apodytes dimidiata E.Mey.Ex Benth	Icacinaceae
Bersama abyssinica Fresen	Melianthaceae
Brucea antidysenterica J. F. Mill	Simaroubaceae
Buddleja polystachya Fresen	Loganiaceae
Calpurnia aurea (Ait.) Benth	Fabaceae
Capparis tomentosa Lam	Capparidaceae
Carissa spinarum L	Apocynaceae
Cassipourea malosana (Baker) Alston	Rhizophoraceae
Celtis africana Burm. F	Ulmaceae
Cissus petiolata Hook. f	Vitaceae
Clausena anisata (Willd.) Benth	Rutaceae
Clematis simensis Fresen	Ranunculaceae
Combretum paniculatum Vent	Combretaceae
Cordia africana Lam	Boraginaceae
Croton macrostachyus Hochst. Ex Del	Euphorbiaceae
Discopodium penninervium Hochst	Solanaceae
Dombeya torrida (D. goetzenii)	Sterculiaceae
Dovyalis abyssinica (A. Rich.) Warb	Flacourtiaceae
Dovyalis verrucosa (Hochst.) Warb	Flacourtiaceae
Dracaena steudneri Engler	Dracaenaceae
Ehretia cymosa Thonn	Boraginaceae
Ekebergia capensis Sparrm	Meliaceae
Embelia schimperi Vatke	Myrsinaceae
Entada abyssinica Steud. ex A. Rich	Fabaceae
Erythrina brucei Schweinf	Fabaceae
Erythrococca trichogyne (Muell Arg.)	Euphorbiaceae
Euphorbia abyssinica Gmel	Euphorbiaceae

Table 5 (continued)

Scientific names of species	Family
Ficus sur Forssk	Moraceae
Ficus Thonningii Blume	Moraceae
Ficus vasta Forssk	Moraceae
Galiniera saxifraga (Hochst. Bridson)	Rubiaceae
Gouania longispicata Engl	Rhamnaceae
Grewia ferruginea Hochst. ex A. Rich	Tiliaceae
Hibiscus macranthus Hochst. ex A. Rich	Malvaceae
Hippocratea africana (Willd.) Loes	Celastraceae
Hippocratea goetzei Loes	Celastraceae
Jasminum abyssinicum Hochst. ex DC	Oleaceae
Juniperus procera Hochst	Cupracea
Justicia schimperiana (Hochst. ex Nees)	Acanthaceae
Landolphia buchananii (Hall.f.) Stapf	Apocynaceae
Lepidotrichilia volkensii (Gurke) Leroy	Meliaceae
Lippia adoensis Hochst	Verbenaceae
Maesa lanceolata Forssk	Myrsinaceae
Maytenus arbutifolia (A.Rich.) Wilczeck	Celastraceae
Maytenus obscura (A. Rich.) Cuf	Celastraceae
Maytenus undata (Thunb.) Blakelock	Celastraceae
Millettia ferruginea (Hochst.) Bak	Fabaceae
Mimusops kummel A. DC	Sapotaceae
Ocimum lamiifolium Hochst. Ex Benth	Lamiaceae
Olea capensis L	Oleaceae
Olea europaea L	Oleaceae
Pavetta abyssinica Fresen	Rubiaceae
Phytolacca dodecandra L 'Herit	Phytolaccaceae
Pittosporum viridiflorum Sims	Pittosporaceae
Prunus africana (Hook. f.) Kalkm	Rosaceae
Pterolobium stellatum (Forssk.)	Fabaceae
Rhus glutinosa Hochst. Ex. A. Rich	Anacardiaceae
Rosa abyssinica Lindle	Rosaceae
Rothmannia urcelliformis (Hiern) Robyns	Rubiaceae
Rubus apetalus Poir	Rosaceae
Rytigynia neglecta (Hiern) Robyns	Rubiaceae
Salix mucronata Thumb.(Willd.)	Salicaceae
Satureja abyssinica Benth. Briq	Lamiaceae
Schefflera abyssinica (Hochst)	Araliaceae
Sericostachys scandens Gilg & Lopr	Amaranthaceae
Solanecio gigas (Vatke) C	Asteraceae
Solanum giganteum Jasq	Solanaceae
Solanum marginatum L	Solanaceae
Syzygium guineense (Wild.) DC	Myrtaceae
Urera hypselodendron A. Rich	Urticaceae
Vepris dainellii (Pich. Serm.) Kokwaro	Rutaceae
Vernonia amygdalina Del	Asteraceae
Vernonia auriculifera Hiern	Asteraceae

Table 6 Wood density and C stocks of woody species in the study area

Scientific name	Mean DBH (cm)	Mean Ht.(m)	WD (wood density)	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Acacia abyssinica	9.75	5.13	0.826	9	35.12	16.51	60.58	9.48	4.46	16.36	44.61	20.96	76.94
Acacia lahi	6.00	3.31	0.769	10	6.54	3.07	11.28	1.77	0.83	3.04	8.30	3.90	14.32
Acanthus eminens	5.00	2.75	0.592	4	0.50	0.24	0.86	0.14	0.06	0.23	0.64	0.30	1.10
Acokanthera schimperi	22.50	13.00	0.784	5	72.67	34.15	125.34	19.62	9.22	33.84	92.29	43.37	159.19
Albizia gummifera	23.40	15.13	0.58	550	46358.92	21788.69	79964.50	12516.91	5882.95	21590.42	58875.83	27671.64	101554.92
Albizia schumparina	20.00	9.00	0.53	9	24.10	11.33	41.57	6.51	3.06	11.22	30.61	14.39	52.80
Allophylus abyssinicus	37.50	21.20	0.58	24	3172.66	1491.15	5472.51	856.62	402.61	1477.58	4029.27	1893.76	6950.09
Apodytes dimidiata	33.25	20.88	0.71	27	2485.38	1168.13	4287.04	671.05	315.40	1157.50	3156.44	1483.53	5444.54
Bersama abyssinica	9.00	4.60	0.671	65	145.85	68.55	251.57	39.38	18.51	67.92	185.22	87.06	319.49
Brucea antidysenterica	9.71	6.60	0.64	23	681.92	320.50	1176.24	184.12	86.54	317.58	866.03	407.04	1493.82
Buddleja polystachya	9.80	4.70	0.4	12	19.19	9.02	33.10	5.18	2.43	8.94	24.37	11.45	42.03
Calpurnia aurea	6.00	3.25	0.612	3	0.33	0.15	0.56	0.09	0.04	0.15	0.41	0.19	0.71
Capparis tomentosa	5.50	2.50	0.691	13	4.41	2.07	7.60	1.19	0.56	2.05	5.60	2.63	9.66
Carissa spinarum	9.00	4.00	0.65	4	1.25	0.59	2.15	0.34	0.16	0.58	1.58	0.74	2.73
Cassipourea malosana	12.75	7.00	0.673	22	97.89	46.01	168.85	26.43	12.42	45.59	124.32	58.43	214.44
Celtis africana	32.20	20.60	0.745	31	4412.98	2074.10	7611.95	1191.50	560.01	2055.23	5604.49	2634.11	9667.18
Cissus petiolata	5.00	2.50	0.612	1	0.06	0.03	0.10	0.02	0.01	0.03	0.07	0.04	0.13
Clausena anisata	5.00	2.71	0.482	10	0.50	0.24	0.87	0.14	0.06	0.23	0.64	0.30	1.10
Clematis simensis	7.00	4.00	0.526	1	0.16	0.07	0.27	0.04	0.02	0.07	0.20	0.09	0.34
Combretum paniculatum	5.85	5.20	0.612	28	22.80	10.72	39.33	6.16	2.89	10.62	28.96	13.61	49.94

Table 6 (continued)

Scientific name	Mean DBH (cm)	Mean Ht.(m)	WD (wood density)	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Cordia africana Lam	12.00	3.00	0.41	4	1.05	0.49	1.82	0.28	0.13	0.49	1.34	0.63	2.31
Croton macrostachyus	17.11	11.00	0.518	127	4415.69	2075.37	7616.62	1192.24	560.35	2056.49	5607.92	2635.72	9673.10
Discopodium penninervium	5.40	3.17	0.482	9	1.93	0.91	3.34	0.52	0.25	0.90	2.46	1.15	4.24
Dombeya torrida	10.00	5.00	0.451	8	5.53	2.60	9.54	1.49	0.70	2.57	7.02	3.30	12.11
Dovyalis abyssinica	8.50	4.00	0.579	6	4.04	1.90	6.97	1.09	0.51	1.88	5.13	2.41	8.85
Dovyalis verrucosa	7.25	3.63	0.612	10	7.59	3.57	13.09	2.05	0.96	3.54	9.64	4.53	16.63
Dracaena steudneri	21.00	9.00	0.418	4	9.35	4.39	16.12	2.52	1.19	4.35	11.87	5.58	20.47
Ehretia cymosa	16.00	8.70	0.484	38	320.27	150.53	552.43	86.47	40.64	149.16	406.74	191.17	701.59
Ekebergia capensis	26.83	14.25	0.58	18	778.23	365.77	1342.37	210.12	98.76	362.44	988.35	464.53	1704.81
Embelia schimperi	5.00	3.25	0.775	3	0.29	0.14	0.50	0.08	0.04	0.13	0.37	0.17	0.63
Entada abyssinica	5.00	2.00	0.612	4	0.38	0.18	0.65	0.10	0.05	0.18	0.48	0.23	0.83
Erythrina brucei	8.34	4.33	0.314	2	0.57	0.27	0.99	0.15	0.07	0.27	0.73	0.34	1.26
Erythrococca trichogyne	15.33	8.78	0.58	62	7405.20	3480.44	12773.22	1999.40	939.72	3448.77	9404.60	4420.16	16221.99
Euphorbia abyssinica	14.00	6.00	0.471	2	1.60	0.75	2.76	0.43	0.20	0.75	2.03	0.96	3.51
Ficus sur	25.40	14.00	0.441	16	473.68	222.63	817.05	127.89	60.11	220.60	601.57	282.74	1037.65
Ficus Thonningii	25.25	12.00	0.432	5	48.03	22.57	82.84	12.97	6.09	22.37	61.00	28.67	105.21
Ficus vasta Forssk	72.50	18.50	0.441	3	412.57	193.91	711.65	111.40	52.36	192.15	523.97	246.27	903.80
Galiniera saxifraga	6.50	3.30	0.399	12	2.33	1.10	4.02	0.63	0.30	1.09	2.96	1.39	5.10

Table 6 (continued)

Scientific name	Mean DBH (cm)	Mean Ht.(m)	WD (wood density)	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Gouania longispicata	5.00	8.00	0.612	3	0.55	0.26	0.95	0.15	0.07	0.26	0.70	0.33	1.21
Grewia fer-ruginea	6.80	3.20	0.583	20	18.61	8.74	32.09	5.02	2.36	8.67	23.63	11.11	40.76
Hibiscus macranthus	5.50	2.00	0.612	2	0.23	0.11	0.40	0.06	0.03	0.11	0.29	0.14	0.50
Hippocratea africana	10.25	4.39	0.876	22	82.22	38.64	141.81	22.20	10.43	38.29	104.41	49.07	180.10
Hippocratea goetzei	7.78	4.51	0.7	74	259.45	121.94	447.52	70.05	32.92	120.83	329.50	154.86	568.35
Jasminum abyssinicum	7.00	2.60	0.58	4	0.45	0.21	0.77	0.12	0.06	0.21	0.57	0.27	0.98
Juniperus procera	20.00	5.00	0.54	5	7.68	3.61	13.25	2.07	0.98	3.58	9.76	4.59	16.83
Justicia schimperi-ana	5.00	4.40	0.58	77	37.30	17.53	64.34	10.07	4.73	17.37	47.37	22.26	81.71
Landolphia buchananii	7.60	5.00	0.612	58	79.52	37.38	137.17	21.47	10.09	37.04	100.99	47.47	174.20
Lepi-dotrichilia volkensii	8.92	5.42	0.58	503	1326.31	623.36	2287.74	358.10	168.31	617.69	1684.41	791.67	2905.44
Lippia adoensis	4.00	2.67	0.7	5	0.85	0.40	1.46	0.23	0.11	0.40	1.08	0.51	1.86
Maesa lanceolata	5.50	3.30	0.676	2	0.43	0.20	0.74	0.12	0.05	0.20	0.54	0.26	0.94
Maytenus arbutifolia	5.00	2.55	0.713	68	4.74	2.23	8.18	1.28	0.60	2.21	6.03	2.83	10.39
Maytenus obscura	8.00	4.35	0.713	9	5.56	2.61	9.59	1.50	0.71	2.59	7.06	3.32	12.18
Maytenus undata	5.00	2.50	0.732	5	0.70	0.33	1.21	0.19	0.09	0.33	0.89	0.42	1.54
Millettia fer-ruginea	17.40	10.10	0.738	41	850.02	399.51	1466.19	229.50	107.87	395.87	1079.52	507.37	1862.06
Mimusops kummel	14.50	9.50	0.88	5	34.70	16.31	59.85	9.37	4.40	16.16	44.07	20.71	76.01
Ocimum lamiifolium	5.00	2.00	0.612	2	0.09	0.04	0.16	0.03	0.01	0.04	0.12	0.06	0.21

Table 6 (continued)

Scientific name	Mean DBH (cm)	Mean Ht.(m)	WD (wood density)	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Olea capensis	14.33	8.00	0.99	57	392.40	184.43	676.86	105.95	49.80	182.75	498.35	234.23	859.61
Olea europaea	18.00	12.00	0.807	5	26.108849	12.271159	45.035153	7.0493891	3.313213	12.159491	33.158238	15.584372	57.1946442
Pavetta abyssinica	7.08	4.12	0.612	167	379.89	178.55	655.28	102.57	48.21	176.93	482.47	226.76	832.20
Phytolacca dodecandra	6.25	2.88	0.612	6	1.26	0.59	2.17	0.34	0.16	0.59	1.60	0.75	2.76
Pittosporum viridiflorum	8.00	4.50	0.633	8	5.92	2.78	10.21	1.60	0.75	2.76	7.52	3.53	12.97
Prunus africana	69.67	32.92	0.85	104	18150.79	8530.87	31308.30	4900.71	2303.34	8453.24	23051.50	10834.21	39761.54
Pterolobium stellatum	5.00	2.00	0.58	4	0.36	0.17	0.62	0.10	0.05	0.17	0.46	0.21	0.79
Rhus glutinosa	8.75	4.42	0.62	22	45.64	21.45	78.72	12.32	5.79	21.25	57.96	27.24	99.97
Rosa abyssinica	10.00	3.50	0.612	8	11.43	5.37	19.72	3.09	1.45	5.32	14.52	6.82	25.05
Rothmannia urcelliformis	7.50	4.25	0.642	3	1.52	0.71	2.61	0.41	0.19	0.71	1.93	0.90	3.32
Rubus apetalus	5.00	2.13	0.612	10	2.01	0.95	3.47	0.54	0.26	0.94	2.56	1.20	4.41
Rytigynia neglecta	12.14	5.21	0.612	46	290.34	136.46	500.82	78.39	36.84	135.22	368.74	173.31	636.04
Salix mucronata	5.00	4.00	0.612	2	0.19	0.09	0.32	0.05	0.02	0.09	0.24	0.11	0.41
Satureja abyssinica	5.00	2.50	0.612	2	0.12	0.06	0.20	0.03	0.01	0.05	0.15	0.07	0.26
Schefflera abyssinica	35.00	19.00	0.491	3	46.10	21.66	79.51	12.45	5.85	21.47	58.54	27.51	100.98
Sericostachys scandens	5.00	5.00	0.612	5	1.16	0.55	2.00	0.31	0.15	0.54	1.47	0.69	2.54
Solanecio gigas	5.00	3.00	0.612	6	1.27	0.59	2.18	0.34	0.16	0.59	1.61	0.76	2.77
Solanum giganteum	5.00	2.00	0.612	2	0.09	0.04	0.16	0.03	0.01	0.04	0.12	0.06	0.21

Table 6 (continued)

Scientific name	Mean DBH (cm)	Mean Ht.(m)	WD (wood density)	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Syzygium guineense	5.00	2.00	0.612	7	1.66	0.78	2.86	0.45	0.21	0.77	2.11	0.99	3.64
Urera hypseloden-dron	19.13	9.63	0.74	9	33.37	15.68	57.56	9.01	4.23	15.54	42.38	19.92	73.11
Vepris dainellii	13.40	7.20	0.7	89	709.54	333.48	1223.89	191.58	90.04	330.45	901.12	423.53	1554.34
Vernonia amygdalina	10.00	4.50	0.413	8	4.55	2.14	7.84	1.23	0.58	2.12	5.77	2.71	9.96
Vernonia auriculifera	6.91	3.56	0.413	77	82.52	38.79	142.35	22.28	10.47	38.43	104.81	49.26	180.78

Table 7 Carbon stock of different species in the small patch size category of northern Ethiopia

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Acacia abyssinica Hochst. Ex Benth	7.00	4.00	0.826	5	1.21	0.57	2.08	0.33	0.15	0.56	1.53	0.72	2.64
Acacia lahi [Steud. & Hochst. Ex] Benth	5.00	3.00	0.769	6	0.53	0.25	0.91	0.14	0.07	0.25	0.67	0.32	1.16
Albizia gummifera (J. F. Gmel.) C. A. Sm	17.21	13.57	0.58	22	71.64	33.67	123.56	19.34	9.09	33.36	90.98	42.76	156.93
Brucea antidysenterica J. F. Mill	5.00	3.00	0.64	6	0.44	0.21	0.76	0.12	0.06	0.21	0.56	0.26	0.97
Buddleja polystachya Fresen	8.00	4.50	0.4	9	1.56	0.73	2.68	0.42	0.20	0.72	1.98	0.93	3.41
Croton macrostachyus Hochst. Ex Del	9.00	3.67	0.518	17	3.90	1.83	6.73	1.05	0.50	1.82	4.96	2.33	8.55
Erythrina brucei Schweinf	8.34	4.33	0.314	2	0.29	0.13	0.49	0.08	0.04	0.13	0.36	0.17	0.63
Grewia ferruginea Hochst. ex A. Rich	5.00	2.50	0.583	5	0.28	0.13	0.49	0.08	0.04	0.13	0.36	0.17	0.62
Mimusops kummel A. DC	7.00	8.00	0.88	1	0.50	0.24	0.87	0.14	0.06	0.23	0.64	0.30	1.11
Pavetta abyssinica Fresen	7.90	4.54	0.612	6	1.55	0.73	2.67	0.42	0.20	0.72	1.96	0.92	3.39
Rhus glutinosa Hochst. Ex. A. Rich	7.00	3.50	0.62	9	1.44	0.68	2.48	0.39	0.18	0.67	1.83	0.86	3.15
Rosa abyssinica Lindle	12.00	4.00	0.612	4	2.06	0.97	3.55	0.56	0.26	0.96	2.62	1.23	4.51
Rytigynia neglecta (Hiern) Robyns	5.00	4.00	0.612	5	0.47	0.22	0.80	0.13	0.06	0.22	0.59	0.28	1.02
Solanecio gigas	5.00	5.00	0.612	2	0.23	0.11	0.40	0.06	0.03	0.11	0.29	0.14	0.51

Table 7 (continued)

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO_2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO_2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO_2 (ton ha^{-1})
Solanum marginatum L	5.00	2.00	0.612	3	0.14	0.07	0.25	0.04	0.02	0.07	0.18	0.08	0.31
Vernonia auriculifera Hiern	8.22	4.11	0.413	20	3.37	1.58	5.82	0.91	0.43	1.57	4.28	2.01	7.39

Table 8 Carbon stock of different species in the medium patch size category of northern Ethiopia

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Acanthus eminens C. B. Clarke	5.00	3.00	0.6	3	0.20	0.10	0.35	0.06	0.03	0.10	0.26	0.12	0.45
Acokanthera schimperi (A. DC.)	25.00	14.00	0.8	2	18.67	8.78	32.21	5.04	2.37	8.70	23.72	11.15	40.91
Albizia gummifera (J. F. Gmel.) C. A. Sm	20.67	13.50	0.6	219	1766.05	830.04	3046.26	476.83	224.11	822.49	2242.88	1054.15	3868.75
Allophylus abyssinicus (Hochst.) Radlk	44.00	25.50	0.6	5	281.11	132.12	484.89	75.90	35.67	130.92	357.01	167.80	615.81
Apodytes dimidiata E.Mey.Ex Benth	27.00	18.50	0.7	2	25.86	12.15	44.60	6.98	3.28	12.04	32.84	15.43	56.65
Bersama abyssinica Fresen. subsp. Abyssinica	10.00	5.00	0.7	20	7.85	3.69	13.53	2.12	1.00	3.65	9.97	4.68	17.19
Brucea antidysenterica J. F. Mill	20.00	15.25	0.6	6	58.36	27.43	100.66	15.76	7.41	27.18	74.11	34.83	127.84
Buddleja polystachya Fresen	16.00	6.00	0.4	2	1.77	0.83	3.06	0.48	0.22	0.83	2.25	1.06	3.88
Capparis tomentosa Lam	5.00	2.50	0.7	2	0.13	0.06	0.23	0.04	0.02	0.06	0.17	0.08	0.29
Carissa spinarum L	9.00	4.00	0.7	4	1.25	0.59	2.15	0.34	0.16	0.58	1.58	0.74	2.73
Cassipourea malosana (Baker) Alston	11.00	7.00	0.7	4	3.29	1.55	5.68	0.89	0.42	1.53	4.18	1.97	7.22
Celtis africana Burm. f	32.00	18.50	0.7	18	164.89	77.50	284.41	44.52	20.92	76.79	209.40	98.42	361.20
Cissus petiolata Hook. f	5.00	2.50	0.6	1	0.06	0.03	0.10	0.02	0.01	0.03	0.07	0.04	0.13

Table 8 (continued)

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Clausena anisata (Willd.) Benth	5.00	2.20	0.5	5	0.21	0.10	0.36	0.06	0.03	0.10	0.26	0.12	0.45
Combretum paniculatum Vent	6.00	4.50	0.6	5	0.71	0.33	1.22	0.19	0.09	0.33	0.90	0.42	1.55
Croton macrostachyus Hochst. Ex Del	15.33	13.00	0.5	54	187.76	88.25	323.87	50.70	23.83	87.44	238.46	112.07	411.31
Discopodium penninervium Hochst	5.00	2.75	0.5	3	0.16	0.07	0.27	0.04	0.02	0.07	0.20	0.09	0.35
Dovyalis abyssinica (A. Rich.) Warb	5.00	3.00	0.6	4	0.27	0.13	0.46	0.07	0.03	0.12	0.34	0.16	0.58
Dovyalis verrucosa (Hochst.) Warb	7.00	3.00	0.6	5	0.58	0.27	1.00	0.16	0.07	0.27	0.73	0.35	1.27
Ehretia cymosa Thonn	17.33	9.33	0.5	11	23.26	10.93	40.12	6.28	2.95	10.83	29.54	13.88	50.95
Ekebergia capensis Sparrm	18.33	7.00	0.6	2	3.86	1.81	6.66	1.04	0.49	1.80	4.90	2.30	8.46
Entada abyssinica Steud. ex A. Rich	5.00	2.00	0.6	2	0.09	0.04	0.16	0.03	0.01	0.04	0.12	0.06	0.21
Erythrococca trichogyne (Muell Arg.) Prain	25.33	14.57	0.6	16	239.25	112.45	412.69	64.60	30.36	111.43	303.85	142.81	524.11
Ficus sur Forssk	27.50	15.50	0.4	3	19.84	9.32	34.22	5.36	2.52	9.24	25.19	11.84	43.46
Ficus thonningii Blume	23.00	9.00	0.4	1	2.88	1.35	4.97	0.78	0.37	1.34	3.66	1.72	6.31
Ficus vasta Forssk	45.00	16.00	0.4	2	38.22	17.96	65.92	10.32	4.85	17.80	48.53	22.81	83.72

Table 8 (continued)

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Gouania longispicata Engl	5.00	8.00	0.6	3	0.55	0.26	0.95	0.15	0.07	0.26	0.70	0.33	1.21
Grewia ferruginea Hochst. ex A. Rich	7.00	3.50	0.6	10	1.51	0.71	2.60	0.41	0.19	0.70	1.91	0.90	3.30
Hibiscus macranthus Hochst. ex A. Rich	5.00	2.00	0.6	1	0.05	0.02	0.08	0.01	0.01	0.02	0.06	0.03	0.10
Hippocratea africana (Willd.) Loes	8.25	4.17	0.9	7	2.58	1.21	4.46	0.70	0.33	1.20	3.28	1.54	5.66
Hippocratea goetzei Loes	6.67	5.33	0.6	13	2.47	1.16	4.26	0.67	0.31	1.15	3.14	1.47	5.41
Hippocratea pallens Planch ex Oliver	15.00	6.00	0.9	1	1.68	0.79	2.90	0.45	0.21	0.78	2.13	1.00	3.68
Justicia schimperiana (Hochst. ex Nees)	5.00	5.25	0.6	17	1.19	0.56	2.05	0.32	0.15	0.55	1.51	0.71	2.60
Landolphia buchananii (Hall.f.) Stapf	8.00	5.00	0.6	11	3.74	1.76	6.44	1.01	0.47	1.74	4.74	2.23	8.18
Lepidotrichilia volkensii (Gurke) Leroy	7.67	4.34	0.6	107	38.09	17.90	65.71	10.29	4.83	17.74	48.38	22.74	83.45
Lippia adoensis Hochst. ex Walp. var. adoensis	5.00	3.00	0.7	2	0.16	0.08	0.28	0.04	0.02	0.07	0.20	0.10	0.35
Maesa lanceolata Forssk	6.00	4.00	0.7	1	0.15	0.07	0.25	0.04	0.02	0.07	0.19	0.09	0.32
Maytenus arbutifolia (A.Rich.) Wilczeck	5.00	2.75	0.7	39	3.12	1.47	5.39	0.84	0.40	1.45	3.97	1.86	6.84

Table 8 (continued)

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Maytenus obscura (A. Rich.) Cuf	9.00	5.00	0.7	2	0.85	0.40	1.46	0.23	0.11	0.40	1.08	0.51	1.86
Maytenus undata (Thunb.) Blakelock	5.00	2.00	0.7	1	0.06	0.03	0.10	0.02	0.01	0.03	0.07	0.03	0.12
Millettia ferruginea (Hochst.) Bak	12.00	7.25	0.7	14	18.64	8.76	32.15	5.03	2.37	8.68	23.67	11.13	40.83
Olea capensis L. (C.A.Wright) Verdc	14.00	8.00	1	43	94.15	44.25	162.40	25.42	11.95	43.85	119.57	56.20	206.25
Pavetta abys-sinica Fresen	7.67	4.33	0.6	73	16.22	7.62	27.98	4.38	2.06	7.55	20.60	9.68	35.53
Phytolacca dodecandra L 'Herit	6.00	2.75	0.6	4	0.37	0.17	0.64	0.10	0.05	0.17	0.47	0.22	0.81
Pittosporum viridiflorum Sims	5.00	3.00	0.6	3	0.22	0.10	0.38	0.06	0.03	0.10	0.28	0.13	0.48
Prunus afri-cana (Hook. f.) Kalkm	67.67	32.50	0.9	37	4587.80	2156.27	7913.50	1238.71	582.19	2136.65	5826.51	2738.46	10050.15
Rhus gluti-nosa Hochst. Ex. A. Rich	11.00	5.00	0.6	11	6.36	2.99	10.97	1.72	0.81	2.96	8.08	3.80	13.93
Rosa abys-sinica Lindle	5.00	3.00	0.6	2	0.14	0.07	0.24	0.04	0.02	0.07	0.18	0.08	0.31
Rothmannia urcelliformis (Hiern) Robyns	7.50	4.25	0.6	3	0.89	0.42	1.53	0.24	0.11	0.41	1.13	0.53	1.95
Rubus apeta-lus Poir	5.00	2.00	0.6	3	0.14	0.07	0.25	0.04	0.02	0.07	0.18	0.08	0.31
Rytigynia neglecta (Hiern) Robyns	11.00	4.17	0.6	15	7.02	3.30	12.10	1.89	0.89	3.27	8.91	4.19	15.37

Table 8 (continued)

Species name	Mean DBH (cm)	Mean Ht.(m)	WD	Abundance	AGB (ton ha^{-1})	AGC (ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Syzygium guineense (Wild.) DC	20.75	8.25	0.7	3	11.82	5.56	20.39	3.19	1.50	5.51	15.01	7.06	25.89
Urera hypseloden-dron A. Rich	7.33	5.00	0.3	4	0.54	0.26	0.94	0.15	0.07	0.25	0.69	0.32	1.19
Vepris dainellii (Pich. Serm.) Kokwaro	12.00	6.50	0.7	21	22.20	10.44	38.30	6.00	2.82	10.34	28.20	13.25	48.64
Vernonia amygdalina Del	9.00	4.00	0.4	4	0.80	0.38	1.38	0.22	0.10	0.37	1.02	0.48	1.75
Vernonia auriculifera Hiern	6.50	3.50	0.4	35	2.94	1.38	5.07	0.79	0.37	1.37	3.73	1.75	6.44

Table 9 Carbon stock of different species in the large patch size category of northern Ethiopia

Species name	Abundance	Mean DBH (cm)	Mean Ht.(m)	WD	AGB (ton ha^{-1})	AGC(ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Acacia abyssinica Hochst. Ex Benth	18.00	8.50	0.826	4	12.72	5.98	21.94	3.43	1.61	5.92	16.15	7.59	27.86
Acacia lahi [Steud. & Hochst. Ex] Benth	9.00	4.25	0.769	4	1.56	0.73	2.69	0.42	0.20	0.73	1.98	0.93	3.41
Acanthus eminens C. B. Clarke	5.00	2.50	0.592	1	0.06	0.03	0.10	0.02	0.01	0.03	0.07	0.03	0.13
Acokanthera schimperi (A. DC.)	20.00	12.00	0.784	3	15.59	7.33	26.89	4.21	1.98	7.26	19.80	9.31	34.15
Albizia gummifera (J. F. Gmel.) C. A. Sm	32.33	18.33	0.58	309	3965.75	1863.90	6840.52	1070.75	503.25	1846.94	5036.50	2367.15	8687.46
Albizia schumparina	20.00	9.00	0.53	9	24.10	11.33	41.57	6.51	3.06	11.22	30.61	14.39	52.80
Allophylus abyssinicus (Hochst.) Radlk	33.17	18.33	0.58	19	300.86	141.40	518.95	81.23	38.18	140.12	382.09	179.58	659.07
Apodytes dimidiata E.Mey. Ex Benth	35.33	21.67	0.71	25	562.12	264.20	969.60	151.77	71.33	261.79	713.89	335.53	1231.39
Bersama abyssinica Fresen	8.33	4.33	0.671	45	18.09	8.50	31.20	4.88	2.30	8.42	22.97	10.80	39.62
Brucea antidysenterica J. F. Mill	6.50	3.35	0.64	11	1.62	0.76	2.79	0.44	0.21	0.75	2.05	0.97	3.54
Buddleja polystachya Fresen	9.00	4.00	0.4	1	0.19	0.09	0.33	0.05	0.02	0.09	0.25	0.12	0.43
Calpurnia aurea (Ait.) Benth	6.00	3.25	0.612	3	0.33	0.15	0.56	0.09	0.04	0.15	0.41	0.19	0.71
Capparis tomentosa Lam	5.67	2.50	0.691	11	1.12	0.53	1.94	0.30	0.14	0.52	1.43	0.67	2.46
Cassipourea malosana (Baker) Alston	13.33	7.00	0.673	18	22.66	10.65	39.08	6.12	2.88	10.55	28.77	13.52	49.63
Celtis africana Burm. f	32.33	22.00	0.745	13	333.74	156.86	575.67	90.11	42.35	155.43	423.85	199.21	731.10
Clausena anisata (wild.) Hook.F.ex Benth	5.00	3.21	0.482	5	0.30	0.14	0.51	0.08	0.04	0.14	0.38	0.18	0.65
Clematis simensis Fresen	7.00	4.00	0.526	1	0.16	0.07	0.27	0.04	0.02	0.07	0.20	0.09	0.34

Table 9 (continued)

Species name	Abundance	Mean DBH (cm)	Mean Ht.(m)	WD	AGB (ton ha^{-1})	AGC(ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Combretum paniculatum Vent	5.75	5.67	0.612	23	4.04	1.90	6.96	1.09	0.51	1.88	5.12	2.41	8.84
Cordia africana Lam	12.00	3.00	0.41	4	1.05	0.49	1.82	0.28	0.13	0.49	1.34	0.63	2.31
Croton macrostachyus Hochst. Ex Del	27.00	16.33	0.518	56	489.94	230.27	845.10	132.28	62.17	228.18	622.22	292.45	1073.28
Discopodium penninervium Hochst	6.20	4.00	0.482	6	0.67	0.32	1.16	0.18	0.09	0.31	0.86	0.40	1.48
Dombeya torrida (D. goetzenii)	10.00	5.00	0.451	8	2.50	1.18	4.32	0.68	0.32	1.17	3.18	1.49	5.49
Dovyalis abyssinica	12.00	5.00	0.579	2	1.21	0.57	2.09	0.33	0.15	0.57	1.54	0.72	2.66
Dovyalis verrucosa (Hochst.) Warb	7.50	4.25	0.612	5	1.33	0.63	2.29	0.36	0.17	0.62	1.69	0.79	2.91
Dracaena steudneri Engler	21.00	9.00	0.418	4	9.35	4.39	16.12	2.52	1.19	4.35	11.87	5.58	20.47
Ehretia cymosa Thonn	14.00	7.75	0.484	27	28.77	13.52	49.62	7.77	3.65	13.40	36.53	17.17	63.01
Ekebergia capensis Sparrm	29.67	16.67	0.58	16	240.72	113.14	415.21	64.99	30.55	112.11	305.71	143.68	527.32
Embelia schimperi Vatke	5.00	3.25	0.775	3	0.29	0.14	0.50	0.08	0.04	0.13	0.37	0.17	0.63
Entada abyssinica Steud. ex A. Rich	5.00	2.00	0.612	2	0.09	0.04	0.16	0.03	0.01	0.04	0.12	0.06	0.21
Erythrococca trichogyne (Muell Arg.) Prain	5.33	3.00	0.58	46	3.25	1.53	5.60	0.88	0.41	1.51	4.12	1.94	7.11
Euphorbia abyssinica Gmel	14.00	6.00	0.471	2	1.60	0.75	2.76	0.43	0.20	0.75	2.03	0.96	3.51
Ficus sur Forssk	24.00	13.00	0.441	13	67.25	31.61	116.00	18.16	8.53	31.32	85.41	40.14	147.32
Ficus Thonningii Blume	27.50	15.00	0.432	4	26.90	12.64	46.39	7.26	3.41	12.53	34.16	16.05	58.92
Ficus vasta Forssk	100.00	21.00	0.441	1	118.42	55.66	204.26	31.97	15.03	55.15	150.39	70.68	259.41

Table 9 (continued)

Species name	Abundance	Mean DBH (cm)	Mean Ht.(m)	WD	AGB (ton ha^{-1})	AGC(ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Galiniera saxifraga (Hochst. Bridson	6.50	3.30	0.399	12	1.51	0.71	2.60	0.41	0.19	0.70	1.91	0.90	3.30
Grewia ferruginea Hochst. ex A. Rich	12.00	5.00	0.583	5	3.05	1.44	5.27	0.82	0.39	1.42	3.88	1.82	6.69
Hibiscus macranthus Hochst. ex A. Rich	6.00	2.00	0.612	1	0.07	0.03	0.12	0.02	0.01	0.03	0.09	0.04	0.15
Hippocratea africana (Willd.) Loes	11.25	4.50	0.876	15	10.82	5.09	18.67	2.92	1.37	5.04	13.75	6.46	23.71
Hippocratea goetzei Loes	6.00	3.87	0.612	52	7.62	3.58	13.14	2.06	0.97	3.55	9.68	4.55	16.69
Hippocratea pallens Planch ex Oliver	8.50	3.50	0.876	8	2.05	0.96	3.54	0.55	0.26	0.96	2.61	1.23	4.50
Jasminum abyssinicum Hochst. ex DC	7.00	2.60	0.58	4	0.45	0.21	0.77	0.12	0.06	0.21	0.57	0.27	0.98
Juniperus procera Hochst	20.00	5.00	0.54	5	7.68	3.61	13.25	2.07	0.98	3.58	9.76	4.59	16.83
Justicia schimperiana (Hochst. ex Nees)	5.00	3.83	0.58	60	4.18	1.96	7.21	1.13	0.53	1.95	5.31	2.49	9.16
Landolphia buchananii (Hall.f.) Stapf	7.33	5.00	0.612	47	10.10	4.75	17.42	2.73	1.28	4.70	12.83	6.03	22.13
Lepidotrichilia volkensii (Gurke) Leroy	10.17	6.50	0.58	396	300.36	141.17	518.10	81.10	38.12	139.89	381.46	179.29	657.99
Lippia adoensis Hochst. ex Walp. var. adoensis	3.50	2.50	0.7	3	0.17	0.08	0.29	0.05	0.02	0.08	0.22	0.10	0.37
Maesa lanceolata Forssk	5.00	2.60	0.676	1	0.07	0.03	0.12	0.02	0.01	0.03	0.09	0.04	0.15
Maytenus arbutifolia (A.Rich.) Wilczeck	5.00	2.42	0.713	29	1.90	0.90	3.29	0.51	0.24	0.89	2.42	1.14	4.17

Table 9 (continued)

Species name	Abundance	Mean DBH (cm)	Mean Ht.(m)	WD	AGB (ton ha^{-1})	AGC(ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Maytenus obscura (A. Rich.) Cuf	7.00	3.70	0.713	7	1.35	0.64	2.34	0.37	0.17	0.63	1.72	0.81	2.97
Maytenus undata (Thunb.) Blakelock	5.00	3.00	0.732	4	0.34	0.16	0.58	0.09	0.04	0.16	0.43	0.20	0.74
Millettia ferruginea (Hochst.) Bak	21.00	12.00	0.738	27	187.85	88.29	324.03	50.72	23.84	87.49	238.57	112.13	411.51
Mimusops kummel A. DC	22.00	11.00	0.88	4	25.74	12.10	44.40	6.95	3.27	11.99	32.69	15.37	56.39
Ocimum lamiifolium Hochst. Ex Benth	5.00	2.00	0.612	2	0.09	0.04	0.16	0.03	0.01	0.04	0.12	0.06	0.21
Olea capensis L. (C.A.Wright) Verdc	14.50	8.00	0.99	14	33.49	15.74	57.77	9.04	4.25	15.60	42.54	19.99	73.37
Olea europaea L	18.00	12.00	0.807	6	26.11	12.27	45.04	7.05	3.31	12.16	33.16	15.58	57.19
Pavetta abyssinica Fresen	5.67	3.50	0.612	88	10.22	4.81	17.64	2.76	1.30	4.76	12.99	6.10	22.40
Phytolacca dodecandra L 'Herit	6.50	3.00	0.612	2	0.24	0.11	0.41	0.06	0.03	0.11	0.30	0.14	0.52
Pittosporum viridiflorum Sims	11.00	6.00	0.633	5	3.34	1.57	5.76	0.90	0.42	1.55	4.24	1.99	7.31
Prunus africana (Hook. f.) Kalkm	71.67	33.33	0.85	67	11694.75	5496.53	20172.28	3157.58	1484.06	5446.52	14852.34	6980.60	25618.80
Pterolobium stellatum (Forssk.) Brenan	5.00	2.00	0.58	4	0.18	0.08	0.31	0.05	0.02	0.08	0.23	0.11	0.39
Rhus glutinosa Hochst. Ex. A. Rich	9.50	6.00	0.62	2	0.98	0.46	1.69	0.27	0.12	0.46	1.25	0.59	2.15
Rosa abyssinica Lindle	11.00	3.00	0.612	2	0.66	0.31	1.13	0.18	0.08	0.31	0.83	0.39	1.44
Rubus apetalus Poir	5.00	2.17	0.612	7	0.37	0.17	0.63	0.10	0.05	0.17	0.47	0.22	0.80
Rytigynia neglecta (Hiern) Robyns	15.67	6.67	0.612	26	33.50	15.75	57.79	9.05	4.25	15.60	42.55	20.00	73.40
Salix mucronata Thumb. (Willd.)	5.00	4.00	0.612	2	0.19	0.09	0.32	0.05	0.02	0.09	0.24	0.11	0.41

Table 9 (continued)

Species name	Abundance	Mean DBH (cm)	Mean Ht.(m)	WD	AGB (ton ha^{-1})	AGC(ton ha^{-1})	AG CO2 (ton ha^{-1})	BGB (ton ha^{-1})	BGC (ton ha^{-1})	BG CO2 (ton ha^{-1})	TB (ton ha^{-1})	TC (ton ha^{-1})	TCO2 (ton ha^{-1})
Satureja abyssinica Benth. Briq	5.00	2.50	0.612	2	0.12	0.06	0.20	0.03	0.01	0.05	0.15	0.07	0.26
Schefflera abyssinica (Hochst. ex A.Rich.) Harms	35.00	19.00	0.491	3	46.10	21.66	79.51	12.45	5.85	21.47	58.54	27.51	100.98
Sericostachys scandens Gilg & Lopr	5.00	5.00	0.612	5	0.58	0.27	1.00	0.16	0.07	0.27	0.74	0.35	1.27
Solanecio gigas	5.00	2.00	0.612	4	0.19	0.09	0.33	0.05	0.02	0.09	0.24	0.11	0.42
Solanum giganteum Jasq	5.00	2.00	0.612	2	0.09	0.04	0.16	0.03	0.01	0.04	0.12	0.06	0.21
Solanum marginatum L	5.00	2.00	0.612	4	0.19	0.09	0.33	0.05	0.02	0.09	0.24	0.11	0.42
Syzygium guineense (Wild.) DC	17.50	11.00	0.74	6	15.89	7.47	27.40	4.29	2.02	7.40	20.18	9.48	34.80
Urera hypselodendron A. Rich	6.67	5.00	0.324	33	3.62	1.70	6.25	0.98	0.46	1.69	4.60	2.16	7.94
Vepris dainellii (Pich. Serm.) Kokwaro	14.33	7.67	0.7	68	128.49	60.39	221.64	34.69	16.31	59.84	163.19	76.70	281.48

Table 10 Test of normality on DBH, height and abundance data

Tests of normality						
	Kolmogorov–Smirnov[b]			Shapiro–Wilk		
	Statistic	**df**	**Sig**	**Statistic**	**df**	**Sig**
DBH	0.260	9	0.082	0.847	9	0.068
Height	0.191	9	0.200[a]	0.920	9	0.396
Abundance	0.216	9	0.200[a]	0.848	9	0.071

[a] This is a lower bound of the true significance

[b] Lilliefors significance correction

Table 11 Descriptive statistics of biomass, carbon and CO2equivalent of different patch size categories in northern Ethiopia

Descriptives

	N	Mean	Std. deviation	Std. error	95% confidence interval for mean		Minimum	Maximum
					Lower bound	Upper bound		
AGB_(ton/ha)								
Small	3	5.4507	0.35095	0.20262	4.5789	6.3225	5.22	5.85
Medium	3	309.1610	103.21174	59.58932	52.7688	565.5532	207.29	413.66
Large	3	371.7642	102.47464	59.16376	117.2031	626.3253	276.92	480.46
Total	9	228.7920	184.61188	61.53729	86.8867	370.6972	5.22	480.46
AGC_(ton/ha)								
Small	3	2.5618	0.16494	0.09523	2.1521	2.9716	2.45	2.75
Medium	3	145.3057	48.50952	28.00698	24.8013	265.8100	97.43	194.42
Large	3	174.7292	48.16308	27.80697	55.0855	294.3729	130.15	225.82
Total	9	107.5322	86.76758	28.92253	40.8368	174.2277	2.45	225.82
AGCO2_(ton/ha)								
Small	3	9.4019	0.60535	0.34950	7.8981	10.9057	9.00	10.10
Medium	3	533.2718	178.02993	102.78563	91.0209	975.5226	357.56	713.53
Large	3	641.2561	176.75851	102.05157	202.1636	1080.3486	477.66	828.75
Total	9	394.6433	318.43704	106.14568	149.8709	639.4156	9.00	828.75
BGB_(ton/ha)								
Small	3	1.4717	0.09476	0.05471	1.2363	1.7071	1.41	1.58
Medium	3	83.4735	27.86717	16.08912	14.2476	152.6994	55.97	111.69
Large	3	100.3763	27.66815	15.97422	31.6448	169.1078	74.77	129.72
Total	9	61.7738	49.84521	16.61507	23.4594	100.0882	1.41	129.72
BGC_(ton/ha)								
Small	3	0.6917	0.04454	0.02571	0.5811	0.8023	0.66	0.74
Medium	3	39.2325	13.09757	7.56189	6.6964	71.7687	26.31	52.49
Large	3	47.1769	13.00403	7.50788	14.8731	79.4807	35.14	60.97
Total	9	29.0337	23.42725	7.80908	11.0259	47.0415	0.66	60.97
BGCO2_(ton/ha)								
Small	3	2.5385	0.16344	0.09436	2.1325	2.9445	2.43	2.73
Medium	3	143.9834	48.06808	27.75212	24.5757	263.3911	96.54	192.65
Large	3	173.1391	47.72480	27.55392	54.5842	291.6941	128.97	223.76
Total	9	106.5537	85.97800	28.65933	40.4651	172.6422	2.43	223.76
TB_(ton/ha)								
Small	3	6.9224	0.44570	0.25733	5.8152	8.0296	6.62	7.43
Medium	3	392.6345	131.07891	75.67844	67.0164	718.2525	263.26	525.35
Large	3	472.1405	130.14279	75.13798	148.8479	795.4332	351.69	610.19
Total	9	290.5658	234.45709	78.15236	110.3461	470.7855	6.62	610.19
TC_(ton/ha)								
Small	3	3.2535	0.20948	0.12094	2.7331	3.7739	3.11	3.49
Medium	3	184.5382	61.60709	35.56887	31.4977	337.5787	123.73	246.92
Large	3	221.9061	61.16711	35.31485	69.9585	373.8536	165.29	286.79
Total	9	136.5659	110.19483	36.73161	51.8627	221.2692	3.11	286.79
TCO2_(ton/ha)								
Small	3	11.9404	0.76879	0.44386	10.0306	13.8502	11.42	12.82
Medium	3	677.2552	226.09801	130.53774	115.5966	1238.9137	454.10	906.18
Large	3	814.3952	224.48331	129.60550	256.7478	1372.0427	606.63	1052.51
Total	9	501.1969	404.41504	134.80501	190.3360	812.0578	11.42	1052.51

Table 12 One-way analysis of variance (ANOVA) result of biomass, carbon and CO2equivalent of different patch size category in northern Ethiopia

ANOVA					
	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
AGB_(ton/ha)					
Between groups	230344.700	2	115172.350	16.334	0.004
Within groups	42307.676	6	7051.279		
Total	272652.376	8			
AGC_(ton/ha)					
Between groups	50883.144	2	25441.572	16.334	0.004
Within groups	9345.766	6	1557.628		
Total	60228.910	8			
AGCO2_(ton/ha)					
Between groups	685339.982	2	342669.991	16.334	0.004
Within groups	125877.183	6	20979.530		
Total	811217.165	8			
BGB_(ton/ha)					
Between groups	16792.129	2	8396.064	16.334	0.004
Within groups	3084.230	6	514.038		
Total	19876.358	8			
BGC_(ton/ha)					
Between groups	3709.381	2	1854.691	16.334	0.004
Within groups	681.306	6	113.551		
Total	4390.688	8			
BGCO2_(ton/ha)					
Between groups	49961.285	2	24980.642	16.334	0.004
Within groups	9176.447	6	1529.408		
Total	59137.731	8			
TB_(ton/ha)					
Between groups	371522.967	2	185761.484	16.334	0.004
Within groups	68238.051	6	11373.008		
Total	439761.018	8			
TC_(ton/ha)					
Between groups	82069.423	2	41034.712	16.334	0.004
Within groups	15073.785	6	2512.298		
Total	97143.209	8			
TCO2_(ton/ha)					
Between groups	1105384.857	2	552692.429	16.334	0.004
Within groups	203027.308	6	33837.885		
Total	1308412.165	8			

Table 13 Descriptive statistics of stem density/ha, stump density/ha and patch disturbance levels of different patch size categories in northern Ethiopia

Descriptives								
	N	Mean	Std. deviation	Std. error	95% confidence interval for mean		Minimum	Maximum
					Lower bound	Upper bound		
Stem density/ha								
Small	3	991.67	76.376	44.096	801.94	1181.40	925	1075
Medium	3	1110.67	212.590	122.739	582.56	1638.77	875	1288
Large	3	1411.33	48.439	27.966	1291.00	1531.66	1357	1450
Total	9	1171.22	220.065	73.355	1002.07	1340.38	875	1450
Stump density/ha								
Small	3	302.00	47.032	27.154	185.17	418.83	256	350
Medium	3	198.67	20.502	11.837	147.74	249.60	175	211
Large	3	152.33	27.301	15.762	84.51	220.15	121	171
Total	9	217.67	72.440	24.147	161.98	273.35	121	350
Patch disturbance level (%)								
Small	3	30.8000	7.00000	4.04145	13.4110	48.1890	23.80	37.80
Medium	3	18.1333	1.80370	1.04137	13.6527	22.6140	16.40	20.00
Large	3	10.8333	2.25019	1.29915	5.2436	16.4231	8.30	12.60
Total	9	19.9222	9.53307	3.17769	12.5945	27.2500	8.30	37.80

Table 14 One-way analysis of variance (ANOVA) result of stem density/ha, stump density/ha and patch disturbance levels of different patch size category in northern Ethiopia

ANOVA					
	Sum of squares	df	Mean square	F	Sig
Stem density/ha					
Between groups	280681.556	2	140340.778	7.888	0.021
Within groups	106748.000	6	17791.333		
Total	387429.556	8			
Stump density/ha					
Between groups	35224.667	2	17612.333	15.643	0.004
Within groups	6755.333	6	1125.889		
Total	41980.000	8			
Patch disturbance level (%)					
Between groups	612.402	2	306.201	16.027	0.004
Within groups	114.633	6	19.106		
Total	727.036	8			

Abbreviations
GHGs: Greenhouse gases; DAF: Dry Afromontane forests; ANOVA: Analysis of variance; HSD: Honestly significant difference; ENMA: Ethiopian National Meteorological Agency; PDL: Patch disturbance level; PSC: Patch size category; UTM: Universal Transverse Mercator.

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Author contributions
All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by MGM and BBW. The first draft of the manuscript was written by MGM and BBW. Both authors read and approved the final manuscript.

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Data availability
The authors declare that data supporting the findings of this study are available within the article and its supplementary information files.

Declarations

Ethics approval and consent to participate
The authors have no ethical or conflicts of interest to declare that are relevant to the content of this article. Informed consent was obtained from all individual participants included in the study.

Consent for publication
The authors affirm that human research participants provided informed consent for publication of the images in Figure(s) 2 def and 3 cd.

Competing interests
The authors have no conflicts of interest to declare that are relevant to the content of this article.

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