Environment, Development and Sustainability
https://doi.org/10.1007/s10668-019-00483-5

Factors affecting woody carbon stock in Sirso moist evergreen Afromontane forest, southern Ethiopia: implications for climate change mitigation

Befkadu Mewded[1] · **Debissa Lemessa**[1]

Received: 14 July 2018 / Accepted: 30 September 2019

Abstract

Among the many other factors that would be taken as one of the most important options for climate change mitigation is forest wood carbon stock. Hence, the aim of this study was to examine the carbon stock potential of woody species and how it varies by community types and topographic aspects, along altitudinal and slope gradients in Sirso moist evergreen Afromontane vegetation ecosystem of southern Ethiopia. To collect data, a systematic sampling procedure was employed. Five transects were laid out across altitudinal gradients which aligned parallel at 2 km intervals, and 50 sample plots (20 m × 20 m) were laid along transects at 100 m altitudinal interval. Carbon stock was estimated based on the equations and conversion factors formulated for tropical forest carbon stock measurement. The results showed that the total carbon stock of woody species in Sirso moist evergreen Afromontane forest was 384.44 ton/ha. The carbon stock of woody species varied among community types, along altitudinal and slope gradients, while topographic aspect had no significant effect. The carbon stock was higher for the community type of *Dracaena fragrans–Rytigynia neglecta*, for mid-altitude (1934–2319 m.a.s.l.), and upper slope class (58–75%). *Schefflera abyssinica*, *Syzygium guineense*, and *Ficus sur* contributed 49% of the total carbon stock. Our study suggests that selecting a certain forest as the mitigation option for climate change needs to consider the determinants including vegetation composition and topographic features such as altitude and slope gradients.

Keywords Biomass · Carbon stock · Climate change mitigation · Determinant

✉ Befkadu Mewded
mewded2013@gmail.com

Debissa Lemessa
lemdeb@yahoo.com

[1] Forest and Rangeland Biodiversity Directorate, Ethiopian Biodiversity Institute, P.O. Box 30726, Addis Ababa, Ethiopia

1 Introduction

Global warming is one of the major environmental issues of the world (Kassahun et al. 2015). Increasing earth's temperature due to increasing of CO_2 release is the major phenomenon affecting global climate (Pittock 2005). Deforestation and forest degradation are major contributors to rising levels of CO_2 in the atmosphere and induce changes in the earth's climate (Yohannes et al. 2015). From a variety of forests provided ecosystem services, tackling climate change by storing and sequestering carbon is one of the most important roles (Yohannes et al. 2015). Forests have more potential for sequestering and storing carbon than any other terrestrial ecosystems (Gibbs et al. 2007; Chaturvedi et al. 2008). Particularly, tropical forests are globally important carbon sinks that currently sequestering CO_2 and are critical to future climate stabilization (Millar et al. 2007). However, tropical forests are being degraded and deforested alarmingly at an average rate of 8–15 million hectares per year (Yohannes et al. 2015). These directly affect the living biomass which is the main carbon pool of tropical forest ecosystems (Gibbs et al. 2007; Gairola et al. 2011; Vashum and Jayakumar 2012; Sharma and Chaudhry 2015).

Understanding the carbon balance of forest ecosystems is vigorous to minimize the impact of climate change, offer adaptation needs and strategies, and explore mitigation options (Moss et al. 2010; Gairola et al. 2011; Halofsky et al. 2014; Mensah et al. 2016a). Currently, the conservation and sustainable management of forests for carbon stocks enhancement is one of the most important agenda in climate negotiations. This is supported by financial mechanisms of clean development mechanism (CDM) and reducing emission from deforestation and forest degradation; and conservation and sustainable management of forests, and enhancement of forest carbon stocks (REDD+).

The other important indicator for estimation and selection of forest ecosystems to mitigate climate change is understanding the factors affecting carbon stock potential of forests. This is because of many altitude-induced environmental factors such as temperature, precipitation, atmospheric pressure, and solar radiation; geographical factors such as aspect and slope; disturbance factors, species composition and distribution affect the growth and productivity of forest ecosystems. Consequently, these factors affect the biomass and carbon stock of forests positively or negatively. Considerate determinants and quantifying carbon stock along different ecosystem components and environmental factors will support for better prediction of regional and global carbon balance and effective conservation and management plan (Pregitzer and Euskirchen 2004; Zhu et al. 2010).

However, Ethiopia's forest ecosystems and their potential to combat climate change are not yet well understood. Studies of carbon stock variation across different vegetation community composition, topographic features such as altitude, slope gradients, and aspect positions of forest ecosystems are still lacking. Similarly, in the study area, Sirso moist evergreen Afromontane forest, no studies were done on the carbon stock of woody species and determinant factors. From our scoping exploration of the studied forest, we have expected that woody biomass would vary by the differences in species composition, structure, and topographic gradients. Hence, we hypothesized that woody carbon stock varies among community types and by the topographic gradients including altitude, slope, and aspect. Moreover, we hypothesized that woody carbon stock is affected by the variation in species richness among community types and along topographic gradients. This study is therefore aimed to (1) estimating the carbon stock of woody species in Sirso moist evergreen Afromontane forest and (2) identifying the determinant factors that affect the carbon stock of woody species in Sirso moist evergreen Afromontane forest. The study will have a further role for future management decision and plan.

2 Materials and methods

2.1 Description of study area

The study was conducted at Sirso natural forest of Melokoza district which is located between 6°18′–6°42′N and 36°00′–37°00′E in Gamo Gofa Zone of South Nations, Nationalities, and Peoples' Regional State, Ethiopia (Fig. 1). Sirso natural forest is one of the moist evergreen Afromontane forests found in Melokoza district (Friis et al. 2010). It has area coverage of 3501 ha and rich in plant diversity. It contains economically important plants, for example, coffee (*Coffea arabica*), spices (*Aframomum corrorima*), honey (*Schefflera abyssinica*), food (*Ensete ventricosum*), and medicine (*Vepris dainellii* and *Hagenia abyssinica*). The elevation of Sirso moist evergreen Afromontane forest ranges from 1547 to 2707 m.a.s.l. with mountainous, undulate and flat landscapes and slope range of 5–75%. The annual average temperature of the district is 22 °C, and annual rainfall ranges 1200–1300 mm (Denu and Desissa 2013).

2.2 Sampling design

A systematic sampling technique was employed to collect vegetation data. Five transects were laid out across the altitudinal gradients from lower to upper altitudes. Transects were aligned parallel at 2 km intervals. The length of the transects extended from 1.7 to 5.7 km. Fifty 20 × 20 m sample plots were systematically laid down at 100 m altitudinal intervals along the transect lines for recording and measuring the diameter at breast height/diameter at stump height (DBH/DSH ≥ 2.5 cm), and height ≥ 1.5 m. The number of sample plots taken from each transect varied between 5 and 19. Altitude indirectly affects the species

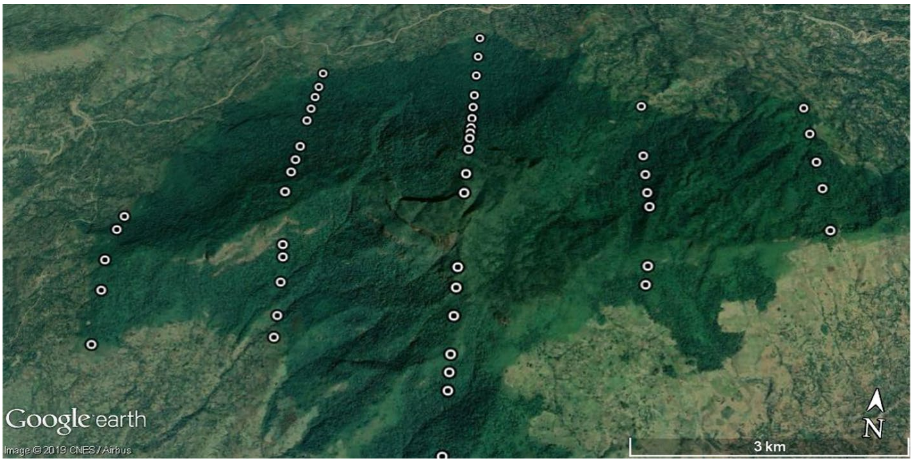

Fig. 1 Map of the study area, Sirso moist evergreen Afromontane forest and sample plots

distribution of vegetation by influencing temperature, rainfall, and incoming radiation, and hence, these factors may affect the biomass and carbon stock of certain vegetation (Gemechu 1988; Gairola et al. 2011; Yirdaw et al. 2015).

2.3 Data collection

2.3.1 Woody species data

All woody stems with a DBH ≥ 2.5 cm and height ≥ 1.5 m were measured, and their growth habits were recorded. The DBH (at 1.3 m) and tree height were measured using diameter tape and hypsometer (Forestry Pro), respectively. Geographical location, altitude, and aspect of sample plots were recorded using GPS (Garmin 72). The slope of the sample plots also recorded using Suunto Clinometer. The plant specimens were collected, labeled, pressed, dried, and identified at Ethiopian Biodiversity Institute (EBI) and National Herbarium (ETH), Addis Ababa, Ethiopia. Identified plant specimens were mounted and deposited at EBI.

2.3.2 Above-ground biomass and estimation of above-ground carbon stock (AGC)

Above-ground biomass was estimated according to tropical county forests field carbon stock measurement guideline (Pearson et al. 2005). The carbon content was estimated from above-ground biomass by multiplying 0.47 which is default carbon fraction (Kandel 2015). To estimate the amount of CO_2 sequestered in the above-ground biomass, the above-ground carbon has to be multiplied by the conversion factor 3.67 (Pearson et al. 2005; Kauffman and Donato 2012):

$$\mathrm{AGB} = 34.4703 - 8.0671(\mathrm{DBH}) + 0.6589\left(\mathrm{DBH}^2\right)$$

$$\mathrm{AGC} = \mathrm{AGB} \times 0.47$$

where AGB is the above-ground biomass (kg), DBH is the diameter at breast height (cm) and AGC is the above-ground carbon.

2.3.3 Below-ground biomass and estimation of below-ground carbon stock (BGC)

Roots play an important role in the carbon sequestration and cycle (Kassahun et al. 2015). However, below-ground biomass estimation is difficult and time consuming (Geider et al. 2001). Root biomass is typically estimated to be 20% of the above-ground forest biomass (MacDicken 1997; Houghton 2001; Achard et al. 2002; Ramankutty et al. 2007; Gibbs et al. 2007; Sharma and Chaudhry 2015). Accordingly, below-ground biomass (BGB) was estimated as AGB × 0.2, where 0.2 is the conversion factor. The amount of below-ground carbon (BGC) of below-ground biomass (BGB) was estimated as:

$$\mathrm{BGC} = \mathrm{BGB} \times 0.47$$

2.3.4 Importance value index (IVI)

According to Kent and Coker (1992), IVI reflects the extent of the dominance and abundance of a given species in relation to other species in vegetation. IVI is the sum-up of the relative frequency, relative density, and relative abundance:

$$\mathrm{IVI} = \mathrm{RD} + \mathrm{RF} + \mathrm{RDO}$$

where RD is the relative density, RF is the relative frequency and RDO is the relative dominance.

$$\text{Relative density} = \frac{\text{number of individuals of species}}{\text{number of individual of all species}} \times 100$$

$$\text{Relative frequency} = \frac{\text{Number of occurrence of the species}}{\text{Number of occurrence of all the species}} \times 100$$

$$\text{Relative dominance} = \frac{\text{Total basal area of the species}}{\text{Total basal area of all the species}} \times 100$$

$$\text{Basal area} = \frac{\pi d^2}{4}$$

where d is the diameter of the tree/shrub.

2.4 Data analysis

To explore the factors that affect the carbon stock of woody species, firstly, the vegetation was stratified into five community types using R version 3.4.3 vegan package (Oksanen et al. 2013). Hierarchical agglomerative cluster analysis technique using similarity ratio was used for stratification. These communities were (1) *Maesa lanceolata–Dombeya torrida*, (2) *Galineria saxifraga–Cyathea manniana*, (3) *Vepris dainellii–Triumfetta tomentosa*, (4) *Dracaena fragrans–Rytigynia neglecta,* and (5) *Arundinaria alpina*. Secondly, the mean and total carbon stock of species were calculated using Microsoft Excel, and thirdly, these data were arranged with respective to the altitudinal classes: lower (1547–1933 m.a.s.l.), mid (1934–2319 m.a.s.l.), and upper (2320–2707 m.a.s.l.); slope classes: lower (5–28%), mid (29–57%), and upper (58–75%); and topographic aspects: north, northeast, east, west, south, and southwest. The effects of these factors on the carbon stock of woody species were statically tested using one-way analysis of variance (ANOVA) with R statistical program (version: 3.4. 3).

3 Results

A total of 74 woody species representing 70 genera and 34 families were recorded. The total carbon stock of woody species in Sirso moist evergreen Afromontane forest was 384.44 ton/ha. The highest carbon stock was recorded in ton/ha for *Schefflera abyssinica* (81.38) followed by *Syzygium guineense* (66.34) and *Ficus sur* (40.58) (Table 1). Indigenous species for which the least carbon storage recorded were *Pycnostachys abyssinica, Guizotia arborescens, Senecio myriocephalus, Allophylus abyssinicus, Ocimum urticifolia, Erica arborea, Lippia adoensis, Flacourtia indica, Coffea arabica, Lepidotrichilia volkensii, Solanecio mannii, Aspilia africana,* and *Pittosporum viridiflora*.

Table 1 Estimated carbon stock of top ten woody species in Sirso moist evergreen Afromontane forest

Species	*D*	A_{DBH} (cm)	A_H (m)	*C* (ton/ha)
Schefflera abyssinica	27	92	40	81.38
Syzygium guineense	148	47	33	66.34
Ficus sur Forssk	61	54	33	40.58
Allophylus spp.	74	33	22	36.56
Croton macrostachyus	99	28	26	18.38
Albizia gummifera	18	49	34	12.36
Macaranga capensis	127	20	22	11.33
Polyscias fulva	13	55	32	11.31
Ficus vasta Forssk	4	125	43	10.72
Arundinaria alpina	175	19	12	9.60
Total *C* (ton/ha)				298.54

D stem density, A_{DBH} average DBH, A_H average height, *C* carbon stock

3.1 Carbon stock by community types

The result of carbon stock analysis by vegetation community types showed that the mean value of carbon stock was higher for *Dracaena fragrans–Rytigynia neglecta* community (536.27 ton/ha) followed by *Galineria saxifraga–Cyathea manniana* community (198.26 ton/ha). The lowest mean value of carbon stock was recorded for *Arundinaria alpina* community (81.64 ton/ha). The carbon stock value of *Dracaena fragrans–Rytigynia neglecta* community was significantly higher than the other communities at $P \leq 0.001$, whereas the carbon stock value between community one, two, three, and five was not significant (Fig. 2). The species richness and individuals of species of the community

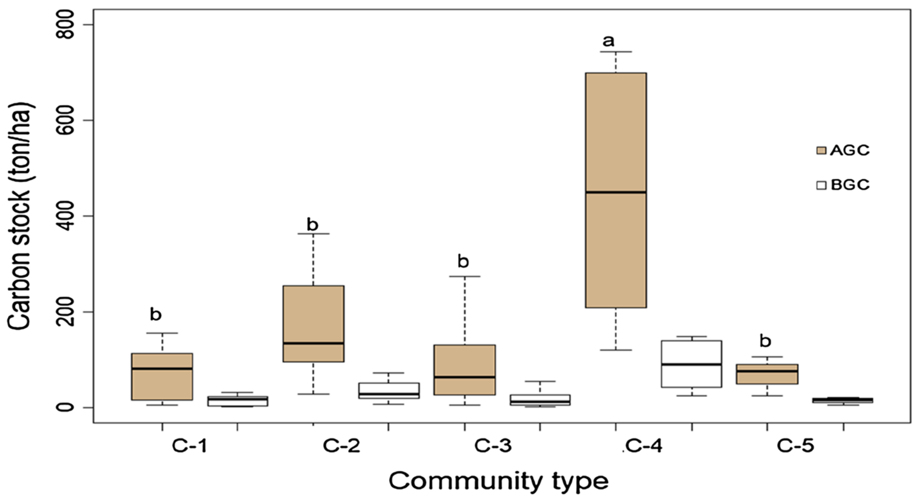

Fig. 2 Carbon stock of community types. The different letters on the boxplots show the significant differences in carbon stocks between the community types at $P \leq 0.001$, (C-1 *Maesa lanceolata–Dombeya torrida*, C-2 *Galineria saxifraga–Cyathea manniana*, C-3 *Vepris dainellii–Triumfetta tomentosa*, C-4 *Dracaena fragrans–Rytigynia neglecta*, and C-5 *Arundinaria alpina* community)

Dracaena fragrans–Rytigynia neglecta were 29 and 407, respectively. Dominant species in this community were *Dracaena fragrans*, *Galineria saxifrage*, and *Hippocratea africana*. Although community one had 46 species and 548 individuals of species, community two had 51 species and 828 individuals of species, community three had 46 species and 592 individuals of species, and community five had seven species and 185 individuals of species.

3.2 Environmental factors affecting carbon stock

3.2.1 Altitudinal gradient

The carbon stock of mid-altitude (1934–2319 m.a.s.l.) was significantly higher (296.36 ton/ha) when compared to either at upper (2320–2707 m.a.s.l.) altitude carbon stock (143.6 ton/ha) or lower (1547–1933 m.a.s.l.) altitude carbon stock (85.48 ton/ha) ($P \leq 0.001$, Fig. 3). The carbon stock difference between lower and upper altitudes was not significant. In mid-altitude, 51 species and 1121 individuals of species were recorded. The number was greater than that of recorded in lower (46 species and 652 individuals of species) and upper (44 species and 757 individuals of species) altitudes. The dominant species in the mid-altitude were *Dracaena fragrans*, *Galineria saxifrage*, and *Syzygium guineense*.

3.2.2 Slope gradient

Significantly, higher mean carbon stock (427.61 ton/ha) was recorded for upper slope (58–75%) than either with the mean carbon stock of mid-slope (29–57%) or lower slope

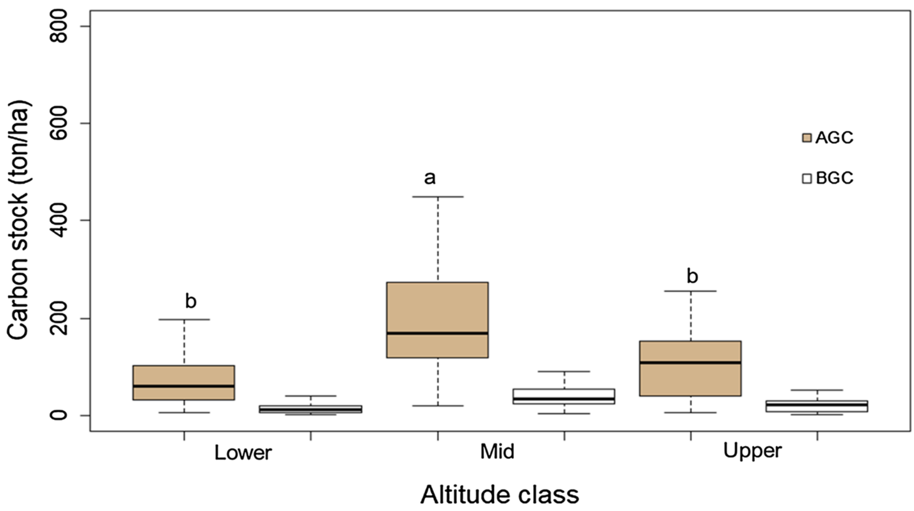

Fig. 3 Carbon stock of woody species along altitudinal classes. The different letters on the boxplots show the significant differences in carbon stocks between the altitudinal classes ($P \leq 0.001$), (lower 1547–1933 m.a.s.l., mid 1934–2319 m.a.s.l., upper 2320–2707 m.a.s.l.)

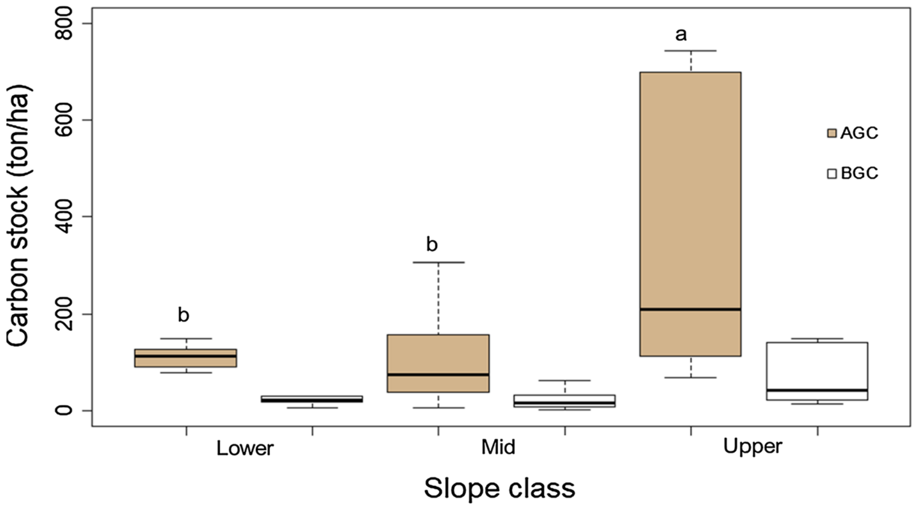

Fig. 4 Carbon stock of woody species along slope classes. The different letters on the boxplots show the significant differences in carbon stocks between the slope classes at $P \leq 0.001$, (lower 5–28%, mid 29–57%, upper 58–75%)

of less than 29% ($P \leq 0.001$), whereas the carbon stock difference between mid and lower slopes was not statically significant (Fig. 4). In the upper slope class, 33 species and 379 individuals of species were recorded. The number is lower than that of recorded in mid (69 species and 1429 individuals of species) and lower (54 species and 722 individuals of species) slopes. The dominant species in upper slope were *Dracaena fragrans*, *Galineria saxifrage*, and *Hippocratea africana* similar to community four.

3.2.3 Aspect position

Based on the result of our study, the mean carbon stock was highest in the north aspect of the study forest (249.19 ton/ha) followed by the northeast aspect (148.64 ton/ha). The lowest carbon stock was recorded for southwest aspect (5.5 ton/ha). But, the difference was not statistically significant (Fig. 5).

4 Discussion

4.1 Carbon stock by community types

The dominant indigenous tree species that contributed about 49% to the total carbon stock (384.44 ton/ha) of Sirso moist evergreen Afromontane forest ecosystem were

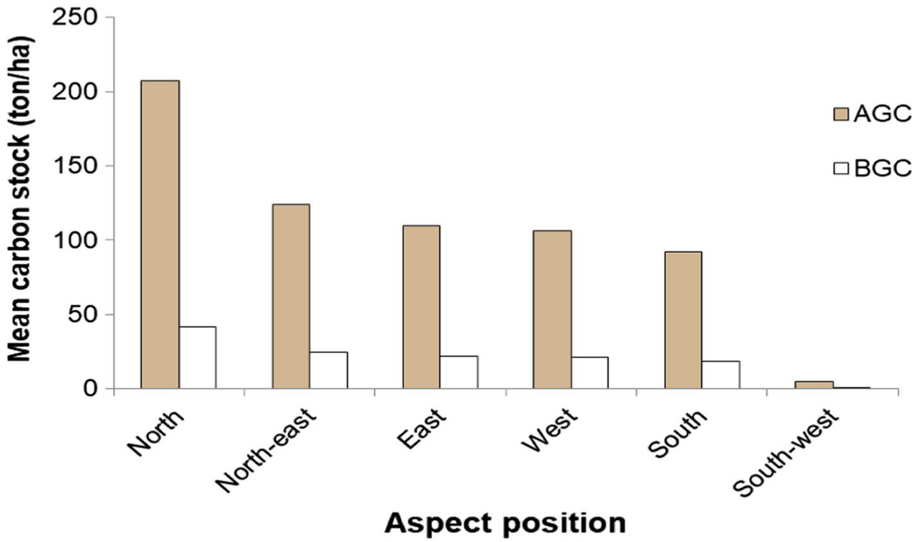

Fig. 5 Carbon stock of woody species along different aspects

Schefflera abyssinica (81.38 ton/ha), *Syzygium guineense* (66.34 ton/ha), and *Ficus sur* (40.58 ton/ha). These species were higher in density, DBH, and height. According to Lung and Espira (2015), tree stems larger than 50 cm have the greatest impact on forest biomass and carbon stock. The principal contribution of few species to the total carbon stock is probably as a result of selection effects, and conversion of such species could provide a better long-term guarantee of ecosystem services (Mensah et al. 2016a). However, the carbon stock of the forest varied among the community types. In this regard, the *Dracaena fragrans–Rytigynia neglecta* community had higher carbon sock when compared to the other community types. This variation may emanate from the differences in species composition among the community types. The presence of large-sized woody species such as *Schefflera abyssinica, Syzygium guineense*, and *Ficus sur* was the reason for the higher carbon stock recorded in *Dracaena fragrans–Rytigynia neglecta* community type than other communities. Woody species such as *Dracaena fragrans*, *Galineria saxifrage*, and *Hippocratea africana* also found abundantly in this community. This indicated plant community composition is an important determinant of carbon stock of woody species in moist evergreen Afromontane forest ecosystem (Jonsson and Wardle 2009; Neupane and Sharma 2014). The least carbon stock of *Arundinaria alpina* community is because the community is dominated by *Arundinaria alpina* (Poaceae) which is characterized by lower DBH (< 25 cm) and height (< 20 m). Regarding the species richness and carbon stock relation of the communities, community *Dracaena fragrans–Rytigynia neglecta* had lower richness than the other three communities while higher carbon stock indicated that the communities' species richness could not matter the carbon stock rather than the size and abundance of the species found in the community. The weak effect of tree species richness on living biomass and carbon stock suggests that dominance patterns are likely to be stronger (Mensah et al. 2016a). In line with the present study, earlier studies found that the dominant species can determine carbon storage in the forest ecosystem (Bunker et al. 2005; Ruiz-Jaen and Potvin 2010). *Schefflera abyssinica* species was reported as species with the second highest carbon stock in Ades forest of eastern Ethiopia (Yohannes et al. 2015). According to this report, the highest carbon stored in *Podocarpus falcatus* species (58.08 ton/ha) followed by *Schefflera abyssinica* (42.51 ton/ha) which is lower than the current study result. Indigenous species which had least carbon stock were found with few individual numbers, lower DBH, and height classes.

4.2 Environmental factors affecting carbon stock

4.2.1 Altitudinal gradient

The carbon stock difference in woody species in different altitude classes indicated that altitudinal variation could determine the carbon stock of moist evergreen Afromontane forest. The higher carbon stock of mid-altitude (1934–2319 m.a.s.l.) forest was supported by the highest species richness in this altitudinal range. The species richness could positively affect the carbon stocks of the forest in altitudinal classes. Higher species richness of mid-altitude relates with the suitability of altitudinal gradient and environmental conditions such as temperature, humidity, and soil characteristics (Rosenzweig 1995). These environmental characteristics in turn positively affect growth, and size (DBH and height), and carbon stock. Hence, the carbon stock of species in this altitudinal range could be higher than others. In the other side, in lower and upper altitudes, environmental factors are less suitable for species richness, growth, and size and subsequently affect living biomass and carbon stock. The higher species richness probably leads to higher stem density and higher forest productivity (Mensah et al. 2016a, b). Tree biomass was highest at intermediate elevation in the montane zones, and an increasing of biomass with elevation did not extend higher than the tropical tree line (2500 m.a.s.l.), due to precipitation which is the main determinant of biomass variation in elevation (Ensslin et al. 2015). Soil and topography of the altitudinal ranges are also the other factor for carbon stock variation (Castilho et al. 2016). Kassahun et al. (2015) showed higher carbon stock at the mid-altitudinal zone of Ades forest, eastern Ethiopia, than the rest of the altitudinal classes due to the presence of higher DBH class of individuals. However, our study is also inconsistence with the study result of Zhu et al. (2010), which reported that living biomass and comprised carbon stock were significantly and negatively correlated with altitude in mountain Changbai temperate forest, China. Positive correlation of tree carbon stock with altitude reported from moist temperate valley slopes of the Garhwal Himalaya, India (Gairola et al. 2011), and tropical Atlantic moist forest of Brazil (Alves et al. 2010). The variation in the study result on the relationship between altitude and forest biomass is perhaps due to the variation in the altitudinal range sampled among studies.

4.2.2 Slope gradient

The slope is one of the determinant factors of carbon stock in Sirso moist evergreen Afromontane forest. However, the species richness cannot affect the carbon stock in slope gradients. Consistent with our results, the slope has been identified as a potential environmental variable that affects tree carbon (Kassahun et al. 2015; Mensah et al. 2016b). However, the study results of Mensah et al. (2016b) showed that the carbon stock is lower at steeper sites and species richness had a positive relationship with carbon stock along slope gradients. Inconsistently, Castilho et al. (2016) also reported that the carbon stock is insensitive to slope gradients. In our case, the significantly higher carbon stock of the upper slope (58–75%) was due to disturbance and slopes are negatively correlated with the studied forest (Mewded et al. 2019). In this regard, steeper sites are inaccessible for extraction by local people and positively affect the carbon stock potential of woody species. This is supported by Alves et al. (2010), in which disturbance and associated changes in light and nutrient supply probably control biomass and carbon stocks distribution in the forest.

4.2.3 Aspect position

The insignificant difference in carbon stocks of woody species across different aspects of Sirso moist evergreen Afromontane forest indicated rough similarity of moisture, solar radiation, temperature, and natural and anthropogenic disturbances between them. Contradictorily, Sharma et al. (2011) and Kassahun et al. (2015) reported topographic aspect could affect biomass and carbon stock of living biomass. A statistically higher value of woody species biomass and carbon stocks were recorded in northern aspects of mountain Changbai temperate forest of China by Sharma et al. (2011) and in the northeast aspect of Ades forest, eastern Ethiopia, by Kassahun et al. (2015).

4.3 Moist forest management implications for climate change mitigation

The study of carbon stock relationship with plant community composition, altitude, slope, and aspect could improve the predictions of the responses of moist forests to climate change. The community types, altitude, and slope gradients are the potential factors determining woody biomass and carbon stock in moist forests. Therefore, it is of paramount importance to consider the carbon sink potential of woody species in relation to the forest structure and environmental factors to give priority in designing management and conservation plans for climate change mitigation (Mensah et al. 2016a). The conservation of forests with larger-sized dominant tree species at mid-altitude and steeper slope in moist forests could be a strategy to increase carbon storage and thereby mitigating climate change. Conservation of dominant woody species plays a vigorous role for a better long-term guarantee of ecosystem services of climate change mitigation (Tilman et al. 1997; Mensah et al. 2016a).

5 Conclusions

Sirso moist evergreen Afromontane forest has a significant contribution to carbon sequestration and climate change mitigation and could generate carbon credits in Ethiopia. The highest total carbon stock was recorded for *Schefflera abyssinica* tree species followed by *Syzygium guineense* and *Ficus sur.* These species were among the dominant indigenous tree species with larger DBH, height, and stem density. The carbon stock of woody species in Sirso moist evergreen Afromontane forest was differing among community types, along altitudinal and slope gradients, while topographic aspect had no significant effect. This confirms community composition, altitude, and slope are important determinant factors of carbon stock potential of woody species in moist forest ecosystem. The carbon stock of *Dracaena fragrans–Rytigynia neglecta* community was significantly higher with compared to other community types. At mid-altitude class (1934–2319 m.a.s.l.), higher carbon stock was recorded when compared with other lower and upper altitudinal classes. Moreover, higher carbon stock was measured at upper slope class (58–75%). Although woody species richness mediated the carbon stock along altitudinal gradient, the effect was not observed by community types and slope gradient. By summing up, our results suggest that selecting a certain forest for carbon sequestration and thereby for mitigating climate change needs considering the determinant factors such as forest community types, structure, and topographic features mainly altitude and slope gradients.

Acknowledgements We are grateful to thank Kedir Erbo, Gorfu Goshu, Gido Gigo, and Habtamu Chanko for their unreserved assistance during data collection. We would like to thank Melokoza District Office for its allowing experts, local community's communication, and work facilities. Finally, we would like to acknowledge Ethiopian Biodiversity Institute (EBI) for its financial support and logistic facilities.

Funding This study was funded by Ethiopian Biodiversity Institute.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

See Table 2.

Table 2 List of woody species and estimated carbon stock of Sirso moist evergreen Afromontane forest

Species	AGC	BGC	TC
Schefflera abyssinica (Hochst. ex A. Rich.) Harms	67.82	13.56	81.38
Syzygium guineense (Wild.) DC.	55.29	11.06	66.34
Ficus sur Forssk	33.82	6.76	40.58
Allophylus spp.	30.46	6.09	36.56
Croton macrostachyus Del.	15.32	3.06	18.38
Albizia gummifera (J. F. Gmel.) C. A. Sm	10.30	2.06	12.36
Macaranga capensis (Baill.) Benth. ex Sim	9.44	1.89	11.33
Polyscias fulva (Hiern) Harms	9.43	1.89	11.31
Ficus vasta Forssk	8.93	1.79	10.72
Arundinaria alpina K. Schum	8.00	1.60	9.60
Millettia ferruginea (Hochst) Baker	5.84	1.17	7.01
Maesa lanceolata Forssk	5.14	1.03	6.17
Rhus glutinosa A. Rich subsp. *glutinosa*	4.96	0.99	5.95
Galineria saxifraga (Hochst.) Bridson	4.88	0.98	5.85
Bersama abyssinica Fresen	4.50	0.90	5.40
Nuxia congesta K. Br. ex Fresen.	4.10	0.82	4.92
Trichilia dregeana Sond	4.08	0.82	4.89
Sapium ellipticum (Krauss) Pax	3.76	0.75	4.51
Ehretia cymosa Thonn. var. cymosa	3.71	0.74	4.45
Ilex mitis (L.) Radlk	3.67	0.73	4.40
Vernonia myriantha Hook.f.	3.61	0.72	4.34
Trilepisium madagascariense DC	2.97	0.59	3.57
Dracaena fragrans (L.) Ker Gawl	2.65	0.53	3.18
Hippocratea africana (Willd) Loes.	2.13	0.43	2.55
Vepris dainellii (Pichi-Serm.) Kokwaro	1.75	0.35	2.10
Dombeya torrida (J. F. Gmel.) P. Bamps	1.74	0.35	2.09
Erythrina brucei Schweinf	1.40	0.28	1.68
Prunus africana (Hook.f.) Kalkm.	1.22	0.24	1.46
Hagenia abyssinica (Bruce) J.F.Gmelin	1.03	0.21	1.24
Ficus spp.	0.74	0.15	0.88
Cordia africana Lam.	0.66	0.13	0.79
Dracaena steudneri Engl.	0.66	0.13	0.79
Cyathea manniana Hook.	0.62	0.12	0.75
Rytigynia neglecta (Hiern) Robyns	0.62	0.12	0.75
Rothmannia urcelliformis (Hiern) Bullock ex Robyns	0.57	0.11	0.69
Bridelia micrantha (Hochst.) Baill.	0.56	0.11	0.67
Hypericum revolutum Vahl	0.50	0.10	0.59
Canthium oligocarpum Hiern	0.48	0.10	0.57
Agarista salicifolia (Comm. ex Lam.) Hook.	0.34	0.07	0.40
Myrsine melanophloeos (L.) R. Br.	0.33	0.07	0.39
Triumfetta tomentosa Boj.	0.32	0.06	0.38
Teclea nobilis Del.	0.28	0.06	0.34
Oxyanthus speciosus DC. subsp. *stenocarpus*	0.24	0.05	0.29
Pentas schimperiana (A. Rich.) Vatke subsp. *schimperiana*	0.21	0.04	0.25

Table 2 (continued)

Species	AGC	BGC	TC
Olea spp.	0.16	0.03	0.19
Alangium chinense (Lour.) Harms	0.15	0.03	0.18
Phoenix reclinata Jacq.	0.15	0.03	0.18
Euphorbia amplyphylla Pax	0.14	0.03	0.17
Coelospermum paniculatum F.Muell.	0.12	0.02	0.15
Rubus apetalus Poir.	0.09	0.02	0.11
Maytenus gracilipes (Welw. ex Oliv.) Exell	0.09	0.02	0.10
Terminalia laxiflora Engl. & Diels.	0.07	0.01	0.08
Brucea antidysenterica J.F.Mill	0.04	0.01	0.05
Clausena anisata (Willd.) Benth.	0.04	0.01	0.05
Vernonia amygdalina Del.	0.04	0.01	0.05
Buddleja polystachya Fresen	0.03	0.01	0.04
Embelia schimperi Vatke	0.03	0.01	0.04
Erythrococca trichogyne (Muell Arg.) Prain	0.02	0.00	0.03
Aspilia africana (Pers) Adams	0.01	0.00	0.02
Coffea arabica L.	0.02	0.00	0.02
Lepidotrichilia volkensii (Gurke) Leroy	0.02	0.00	0.02
Solanecio mannii (Hook. f.) C.Jaffrey	0.02	0.00	0.02
Acanthus pubescens (Thomson ex Oliv.) Engl	0.01	0.00	0.01
Allophylus abyssinicus (Hochst) Radkofer	0.01	0.00	0.01
Guizotia arborescens Friis	0.01	0.00	0.01
Pittosporum viridiflora Sims	0.01	0.00	0.01
Pycnostachys abyssinica Fresen.	0.01	0.00	0.01
Senecio myriocephalus Sch.Bip.ex A. Rich.	0.01	0.00	0.01
Senna septemtrionalis (Viv.) Irwin & Barneby	0.01	0.00	0.01
Dalbergia lactea Vatke	0.00	0.00	0.00
Erica arborea L.	0.00	0.00	0.00
Flacourtia indica (Burm. f) Merr.	0.00	0.00	0.00
Lippia adoensis Hochst. ex Walp.	0.00	0.00	0.00
Ocimum urticifolia Roth	0.00	0.00	0.00
Total	320.36	64.07	384.44

AGC above-ground carbon, *BGC* below-ground carbon, *TC* total carbon stock

References

Achard, F., Eva, H. D., Stibig, H. J., Mayaux, P., Gallego, J., Richards, T., et al. (2002). Determination of deforestation rates of the world's humid tropical forests. *Science, 297*(5583), 999–1002.

Alves, L. F., Vieira, S. A., Scaranello, M. A., Camargo, P. B., Santos, F. A., Joly, C. A., et al. (2010). Forest structure and live aboveground biomass variation along an elevational gradient of tropical Atlantic moist forest (Brazil). *Forest Ecology and Management, 260*(5), 679–691.

Bunker, D. E., DeClerck, F., Bradford, J. C., Colwell, R. K., Perfecto, I., Phillips, O. L., et al. (2005). Species loss and aboveground carbon storage in a tropical forest. *Science, 310*(5750), 1029–1031.

Castilho, C. V., Magnusson, W. E., de Araújo, R. N. O., Luizao, R. C., Luizao, F. J., Lima, A. P., et al. (2006). Variation in aboveground tree live biomass in a central Amazonian Forest: Effects of soil and topography. *Forest Ecology and Management, 234*(1–3), 85–96.

Chaturvedi, R. K., Tiwari, R., & Ravindranath, N. H. (2008). Climate change and forests in India. *International Forestry Review, 10*(2), 256–268.

Denu, D., & Desissa, D. (2013). Abundance and use of Vepris dainellii (Pichi-Serm.) Kokwaro, an Ethiopian endemic plant, in Melokoza woreda, Southern Ethiopia. *Ethiopian Journal of Education and Sciences, 8*(2), 1–10.

Ensslin, A., Rutten, G., Pommer, U., Zimmermann, R., Hemp, A., & Fischer, M. (2015). Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro. *Ecosphere, 6*(3), 1–15.

Friis, I. B., Sebsebe, D., & Breugel, P. V. (2010). *Atlas of the potential vegetation of Ethiopia*. Copenhagen: Biologiske Skrifter, Royal Danish Academy of Sciences and Letters.

Gairola, S., Sharma, C. M., Ghildiyal, S. K., & Suyal, S. (2011). Live tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India). *Current Science, 100,* 1862–1870.

Geider, R. J., Delucia, E. H., Falkowski, P. G., Finzi, A. C., Grime, J. P., Grace, J., et al. (2001). Primary productivity of planet earth: Biological determinants and physical constraints in terrestrial and aquatic habitats. *Global Change Biology, 7*(8), 849–882.

Gemechu, D. (1988). Some patterns of altitudinal variation of climatic elements in the mountainous regions of Ethiopia. *Mountain Research and Development, 8*(2), 131–138.

Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/2/4/045023.

Halofsky, J. E., Peterson, D. L., Joyce, L. A., Millar, C. I., Rice, J. M., & Swanston, C. W. (2014). Implementing climate change adaptation in forested regions of the United States. In S. V. Alaric (Ed.), *Forest conservation and management in the Anthropocene* (pp. 229–243). Fort Collins: Rocky Mountain Research Station.

Houghton, R. A. (2001). *Carbon flux to the atmosphere from land-use changes: 1850–1990 (No. ORNL/CDIAC-131)*. Oak Ridge, TN: Oak Ridge National Lab.

Jonsson, M., & Wardle, D. A. (2009). Structural equation modeling reveals plant-community drivers of carbon storage in boreal forest ecosystems. *Biology Letters*. https://doi.org/10.1098/rsbl.2009.0613.

Kandel, P. N. (2015). Estimation of above ground forest biomass and carbon stock by integrating LiDAR, satellite image and field measurement in Nepal. *Journal of Natural History Museum*. https://doi.org/10.3126/jnhm.v28i0.14191.

Kassahun, K., Soromessa, T., & Belliethathan, S. (2015). Forest Carbon Stock in Woody Plants of Ades Forest, Western Hararghe Zone of Ethiopia and its variation along environmental factors: Implication for climate change mitigation. *Journal of Natural Sciences Research, 5*(21), 96–109.

Kauffman, J. B., & Donato, D. C. (2012). *Protocols for the measurement, monitoring and reporting of structure, biomass, and carbon stocks in mangrove forests*. Bogor: CIFOR.

Kent, M., & Coker, P. (1992). *Vegetation description and analysis: A practical approach*. London: Belhaven Press.

Lung, M., & Espira, A. (2015). The influence of stand variables and human use on biomass and carbon stocks of a transitional African forest: Implications for forest carbon projects. *Forest Ecology and Management, 351,* 36–46.

MacDicken, K. G. (1997). *A guide to monitoring carbon storage in forestry and agroforestry projects*. Arlington: Winrock International Institute for Agricultural Development.

Mensah, S., Veldtman, R., Assogbadjo, A. E., Glèlè Kakaï, R., & Seifert, T. (2016a). Tree species diversity promotes aboveground carbon storage through functional diversity and functional dominance. *Ecology and Evolution, 6*(20), 7546–7557.

Mensah, S., Veldtman, R., Du Toit, B., Glèlè Kakaï, R., & Seifert, T. (2016b). Aboveground biomass and carbon in a South African mistbelt forest and the relationships with tree species diversity and forest structures. *Forests, 7*(4), 1–17.

Mewded, B., Negash, M., & Awas, T. (2019). Woody species composition, structure and environmental determinants in a moist evergreen Afromontane forest, southern Ethiopia. *Journal of Forestry Research*. https://doi.org/10.1007/s11676-019-00894-0.

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). Climate change and forests of the future: Managing in the face of uncertainty. *Ecological Applications, 17*(8), 2145–2151.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature, 463*(7282), 747–756.

Neupane, B., & Sharma, R. P. (2014). An assessment of the effect of vegetation size and type, and altitude on above ground plant biomass and carbon. *Journal of Agricultural and Crop Research, 2*(3), 44–50.
Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H., Wagner, H., & Oksanen, M. J. (2013). Package 'vegan'. *Community Ecology Package, 2*(9), 1–295.
Pearson, T. R., Walker, S., & Brown, S. (2005). *Source book for land-use, land-use change and forestry projects*. Arlington: Winrock International and the Bio-carbon fund of the World Bank.
Pittock, A. B. (2005). *Climate change: Turning up the heat*. Milton Park: Taylors & Francis.
Pregitzer, K. S., & Euskirchen, E. S. (2004). Carbon cycling and storage in world forests: Biome patterns related to forest age. *Global Change Biology, 10*(12), 2052–2077.
Ramankutty, N., Gibbs, H. K., Achard, F., Defries, R., Foley, J. A., & Houghton, R. A. (2007). Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biology, 13*(1), 51–66.
Rosenzweig, M. L. (1995). *Species diversity in space and time*. Cambridge: Cambridge University Press.
Ruiz-Jaen, M. C., & Potvin, C. (2010). Can we predict carbon stocks in tropical ecosystems from tree diversity? Comparing species and functional diversity in a plantation and a natural forest. *New Phytologist, 189*(4), 978–987.
Sharma, C. M., Gairola, S., Baduni, N. P., Ghildiyal, S. K., & Suyal, S. (2011). Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. *Journal of Biosciences, 36*(4), 701–708.
Sharma, V., & Chaudhry, S. (2015). An evaluation of existing methods for assessment of above-ground biomass in forests. *International Journal of Engineering, Science and Technology, 4*(2), 1–18.
Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., & Siemann, E. (1997). The influence of functional diversity and composition on ecosystem processes. *Science, 277,* 1300–1302.
Vashum, K. T., & Jayakumar, S. (2012). Methods to estimate above-ground biomass and carbon stock in natural forests—A review. *Journal of Ecosystem and Ecography, 2*(4), 1–7.
Yirdaw, E., Starr, M., Negash, M., & Yimer, F. (2015). Influence of topographic aspect on floristic diversity, structure and treeline of afromontane cloud forests in the Bale Mountains. *Ethiopia. Journal of Forestry Research, 26*(4), 919–931.
Yohannes, H., Soromessa, T., & Argaw, M. (2015). Estimation of carbon stored in selected tree species in Gedo forest: Implications to forest management for climate change mitigation. *Journal of Environment and Waste Management, 2*(4), 102–107.
Zhu, B., Wang, X., Fang, J., Piao, S., Shen, H., Zhao, S., et al. (2010). Altitudinal changes in carbon storage of temperate forests on Mt Changbai, Northeast China. *Journal of Plant Research, 123*(4), 439–452.