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RESEARCH

Carbon stocks of Humbo Farmer Managed Natural Regeneration forest along altitudinal gradients, Southern Ethiopia

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Background: Humbo Farmer Managed Natural Regeneration (FMNR) forest is managed through direct involvement of the local community and funded by the World Vision Australia through World Vision Ethiopia under framework of the Kyoto Protocol's Clean Development Mechanism on greenhouse gas emissions. Understanding the amount and distribution of carbon stored in forests across different elevations will enhance ability to anticipate how forests will react to future climate conditions and carbon levels. The aim of the study was to quantify the amount of carbon stocks along altitudinal gradients in the Humbo FMNR forest in southern Ethiopia. A total of 54 nested sample plots of 20 m × 20 m were established on transects of elevation gradients. Inventories of woody species and soil samples (0–10 cm and 10–20 cm depth) were collected within each nested sample plot. Carbon stocks in woody biomass and soil were compared by three elevation classes.
Results: The total carbon stocks significantly ($p < 0.05$) differed among the three altitudinal gradients. There is no significant difference in biomass carbon stocks between the middle (1,610–1,750 m above sea level [a.s.l.]) and lower (1,470–1,610 m a.s.l.) elevations. However, both of these elevations significantly differ ($p < 0.05$) from the higher (1,750–1,890 m a.s.l.) elevation, despite an increase in carbon stocks from lower to higher elevations. The highest ecosystem carbon stock was contributed by soil carbon. The higher proportion of C stocks at the higher elevations may be associated to the species composition and dominance with larger wood density.
Conclusions: It was concluded that even though soil carbon contributed higher carbon to the total carbon stock, biomass is stronger impact than soil carbon when it comes to carbon stock variation by altitudinal gradients. We recommend that carbon-related awareness creation on reducing emission for the local people and promotion of knowledge on carbon stock credits accounting and to be claimed in future for financing, which could be considered as additional possible option for sustainable forest management.

Keywords: altitudinal gradients, biomass, carbon stocks, Clean Development Mechanism, Humbo

Introduction

Governments in most industrialized countries have now committed to increasing funding for carbon sequestration and forest biodiversity conservation to reduce greenhouse gas (GHG) emissions (Anwar 2008). In particular, under the Kyoto Protocol's Clean Development Mechanism (CDM) on GHG emissions, investments in land and forest resources from developing countries have attracted the attention of developed countries. With the dual objective of reducing GHGs and promoting sustainable development in the host countries, CDM projects have been carried out in non-industrialized countries since 2005 (Streck et al. 2008; UNFCCC 2010).

In line with this, in 2006, the Afforestation and Reforestation CDM project for carbon sequestration in Humbo

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district in southern Ethiopia started when the region faced severe deforestation and land degradation due to unsustainable agricultural practices, population pressure, and climate change impacts (Brown et al. 2011). Initiated by World Vision Australia and World Vision Ethiopia, the initiative introduced a Farmer Managed Natural Regeneration (FMNR) technique to restore degraded natural forest and improve the livelihoods of the local communities and thereby generate carbon credits with the goal of sequestering CO_2 by regenerating native forest (Brown et al. 2011). It is a remarkable example of successful community-based forest restoration and management. Consequently, the woodland, long an open access resource, has been fenced off and protected (Aynalem 2012). FMNR is a low-cost and sustainable land restoration approach that involves the systematic regrowth and management of trees and shrubs from existing root systems.

The role and purpose of the Humbo FMNR forest are multi-faceted. Firstly, it serves as a crucial carbon sink, sequestering significant amounts of carbon dioxide from the atmosphere. The reforestation efforts in the Humbo FMNR forest have resulted in the restoration of approximately 2,700 hectares of degraded land, leading to the sequestration of an estimated 2.7 million tons of CO_2 by 2020 (Brown et al. 2011). Secondly, the Humbo FMNR forest plays a vital role in biodiversity conservation. The restoration of the forest has led to the recovery of various plant and animal species, including endemic and endangered ones. The increased vegetation cover has created a favorable habitat for wildlife, contributing to the overall ecological balance of the region (Donaldson 2009). Furthermore, the Humbo FMNR forest has significant socio-economic benefits for the local communities. The restored forest provides various ecosystem services, such as improved water regulation, soil fertility, and increased agricultural productivity. The communities also benefit from the sustainable use of forest resources, including timber, non-timber forest products, and fodder for livestock (Aynalem 2012; Donaldson 2009).

Ethiopia is blessed with different types of landscapes. Thus, vegetation types are diverse, varying from tropical moist forest and cloud forest in the southwest to desert scrub in the east and northeast (Bongers and Tennigkeit 2010). The majority of Ethiopia's natural highland forests are primarily situated in elevated regions characterized by favorable annual rainfall distribution and higher amounts, with an average annual rainfall exceeding 1,000 mm. Around 90% of the total population lives in the highlands that cover 44% of the country's landmass. The national carbon stock of Ethiopia was estimated at 153 teragrams (Tg) C by Houghton (1999) and by Gibbs et al. (2007) estimated at 867 Tg C. and 2.5 Gt C by Sisay (2010). The natural carbon stock in the high forest ranges from 101 to 200 Mg C ha^{-1} (Brown 1997; Moges et al. 2010; Temam 2010; Tsegaye 2010). Regular forest records and ongoing in-country monitoring and assessment work are lacking, although they are most useful for assessing the extent of carbon fluxes between the AGB and the atmosphere (Girma et al. 2014). According to Feyissa et al. (2013), information on forest carbon stocks in Ethiopia is limited. In the same way, Wolde et al. (2014) also noted that although carbon storage varies between vegetation types and soil types, there are only a limited number of studies, with the exception of some work by Hassen (2015), Gebre (2015), Tesfaye (2015), Yahya (2015), and Wodajo (2018).

In Ethiopia, dry areas cover about 71.5% of the landmass (Lemenih and Itanna 2004). Of this, the forest ecosystem covers 25.8%, which corresponds to a sequestration of 1,263.1 million tons of carbon (Yitebitu et al. 2010). However, dry forest loss in Ethiopia occurs through habitat destruction due to extensive deforestation and conversion of forests to agricultural land (Argaw et al. 1999). The recognition of these resources in mitigating climate change on the other hand, and also the influence of altitude differences on biomass and soil carbon stocks have hardly been studied (Aide et al. 2013; Gillespie et al. 2012; Houghton 2007). However, understanding forest carbon storage and distribution along elevation changes will help us to better predict the response of dry forests to future climate regional and global carbon balances (Girma et al. 2014). Also, communities dependent on dry forests would benefit from future payments for ecosystem services, particularly carbon finance programs through forest resource conservation (Alemu 2012). Carbon stocks in forest ecosystems are influenced by altitude, slope and land use (Liu et al. 2006). Bhat et al. (2013) point out that land use, land use change, soil erosion and deforestation are the most important factors affecting carbon storage density in forest ecosystems. According to Feyissa et al. (2013), forest carbon is affected by elevation and slope. Altitude has a significant impact on temperature and precipitation. This has a strong impact on the species composition, diversity, abundance and turnover of the forest ecosystem (Sheikh et al. 2009).

Increases in temperature and decreases in precipitation significantly impact the structure, function, dynamics, and distribution of forest vegetation, which in turn affects the carbon sequestration potential (CSP) of these forests (Guo et al. 2021; Hui et al. 2017). Various environmental factors, including temperature, precipitation, atmospheric pressure, solar radiation, and wind velocity, vary with altitude (Djukic et al. 2010; Takeuchi et al. 2011). Altitude is crucial in determining the temperature and rainfall patterns of a location (Schindlbacher et al. 2010; Swetnam et al. 2017; Kobler et al. 2019). Due to shorter growing seasons at higher altitudes, net primary production tends to decrease with altitude, leading to a reduction in living biomass carbon stock (Swetnam et al. 2017). However, soil organic carbon (SOC) tends to increase with altitude because slower decomposition of soil organic matter (SOM) occurs in colder temperatures at higher elevations (Tashi et al. 2016).

Moreover, topographic features such as altitude, slope, and aspect influence tree species distribution and forest carbon stock across different vegetation communities (Clark and Clark 2000; McEwan et al. 2011). Climate variations along altitudinal gradients affect vegetation composition and productivity, impacting the quantity and turnover of SOM (Quideau et al. 2001). These climatic changes also influence SOM by controlling soil water balance, erosion, and geological deposition processes (Tan et al. 2004). Nonetheless, the storage and spatial patterns of SOC in high-altitude ecosystems remain largely uncertain due to limited field observations and significant spatial heterogeneity (Garnett et al. 2001; Liu et al. 2006; Yang et al. 2007).

The carbon estimates have multiple applications in relation to carbon sequestration in forests and can contribute to achieving climate change responses such as mitigation and adaptation. The study is based on primary data collected from the FMNR forest across different altitudes, making the results more accurate and serving as an updated carbon estimate. These updated estimates can be utilized to assess the forestry's contribution to emission reduction in the region and serve as a default estimate for carbon sequestration at different altitudes in the FMNR forest. Additionally, these estimates can help in evaluating the trade-offs between altitude-wise carbon sequestration and the offsetting of polluting gases in forests. The estimation of biomass and soil carbon also enhances the value of forest-based incentive mechanisms for climate change mitigation, particularly the reducing emissions from deforestation and degradation plus (REDD$^+$) program. The precise carbon estimate encourages greater community participation in forest-based mitigation actions, as it provides a more comprehensive measurement of total carbon stored in forests, including soil carbon at greater depths. Furthermore, this study offers specific insights into the amount of soil carbon captured by forests at different altitudes. This information contributes to existing knowledge about species-specific data on tree carbon estimation at various altitudinal gradients, enabling the use of the Tier III approach for carbon estimation. Therefore, this study aimed to investigate the carbon stocks of the Humbo FMNR forest ecosystem for along altitudinal ranges.

Materials and Methods

Study area

This study was conducted in the Humbo Tabala District of southern Ethiopia, located 397 km southwest of the capital Addis Ababa (Murugan and Israel 2017). The city of Humbo, capital of the district, is geographically located at the approximate coordinates 6°46'48.47'' to 6°41'04.28'' north latitude and 37°48'35.44'' to 37°55'14.51'' east longitude (Fig. 1). From an agro-ecological point of view, 11% of the district falls under highland ('Dega'), 27% under middle highland ('Woina Dega') and the remaining 61% under lowland ('Kolla'). The average annual temperature of the district is 22°C and the average annual rainfall is 1,123 mm at an altitude of 1,100–2,335 m above sea level (a.s.l.) (Murugan and Israel 2017). The Humbo FMNR forest can be assigned to the dry forest type. It was covered by dense deciduous vegetation and afro-montane forests before they were cleared some fifty years ago. Moreover, within the forest ecosystem, the families of trees, specifically Fabaceae, Combretaceae, and Oleaceae, were found to be the most diverse in terms of species richness (Kuma and Shibru 2015).

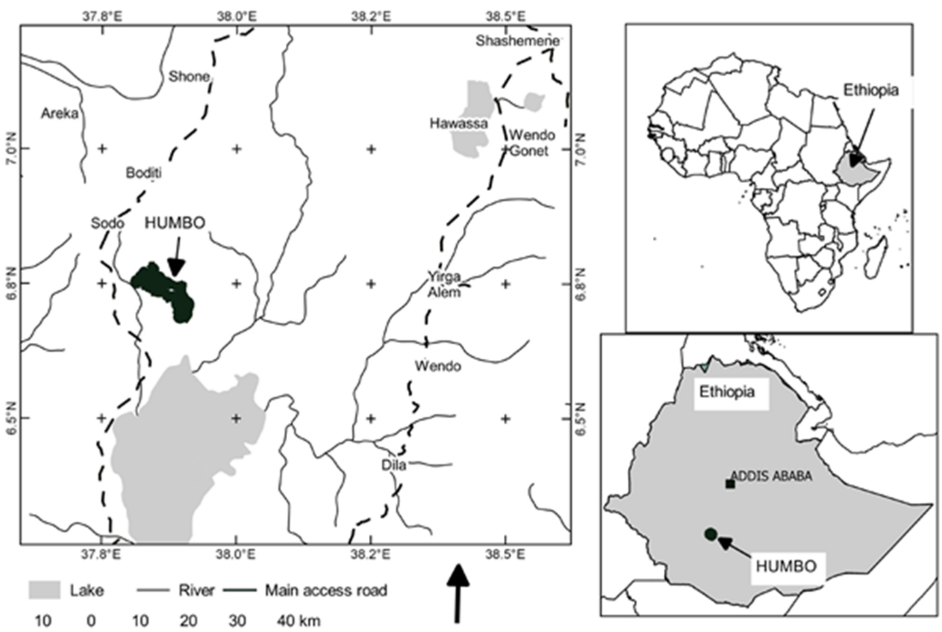

Fig. 1 Map of Humbo Farmer Managed Natural Regeneration forest in Southern Ethiopia. Reused from the article of Negewo et al. (Low Carbon Econ. 2016;7(2):88-105).

Sampling techniques

The Humbo landscape was categorized into three altitudinal gradients, namely higher (1,750–1,890 m a.s.l.), middle (1,610–1,750 m a.s.l.) and lower (1,470–1,610 m a.s.l.) based on its topographical settings. A systematic random sampling technique was employed to lay plots. A total of 54 nested sample plots (3 transects × 3 elevation ranges × 6 sample plots) sized 20 m × 20 m were systematically established for species inventory. Transects were laid using GPS and compass. A transect line in the context of forest inventory refers to a straight line or path that is systematically established and used to collect sample data on forest attributes. The sampling size and distribution were determined by laying out transects at 46-m intervals across three altitudinal gradients to capture the variation in the forestland. Along each transect, sampling plots were positioned at 150-m intervals. This systematic approach ensured that the sampling adequately represented the forestland by covering different altitudinal zones and providing a comprehensive assessment of the forest's characteristics across these gradients. The sample plots were used to collect biomass and soil carbon stocks data. In order to eliminate any influence of the edge effects on the forest biomass, all sample plots were laid at least 150 m away from nearest roads and agricultural lands.

Woody species inventory and composition

The study was carried out in 10–30 December 2017. All tree species in the nested sample plot were measured and recorded (diameter at breast height [DBH at 1.3 m] and total tree height). Besides, trees on the border of the plot were measured if ≥ 50% of their basal area fall wthin the plot. Trees with their trunks inside the sampling plot and branches outside were also considered (MacDicken 1997). In the occasion of multi-stemmed woody species, each stem was measured individually and the equivalent diameter of the plant was calculated as the square root of the sum of the diameters of all stems per plant (Snowdon et al. 2001) as below.

$$D_e = \sqrt{\sum_{i=1}^{n} d_i^{\,2}} \qquad (1)\ \text{Eq. 1}$$

where, d_e is diameter equivalent (at breast or stump height), d_i is diameter of the ith stem at breast or stump height (cm). When dealing with multi-stem woody species, where the main trunk divides into multiple stems, measuring the diameter of each stem individually may not fully represent the size or structure of the plant. In such cases, using the concept of equivalent diameter helps to summarize the overall size of the plant as if it had a single stem.

Plant species identification by their vernacular name was conducted through the help of the key informants and counter checked using floras of Ethiopia and Eritrea (Coppock 1994).

On other hands, the following structural parameters were determined according to standards set by Lamprecht (1989) and Wodemariam (1998):

- Total number species encountered in the entire forest ecosystem
- Abundance = number of individuals of species per total sampled area
- Absolute frequency of a species = percent of plots in which a given species was recorded
- Relative frequency = frequency of specific species/ total frequency of specie × 100
- Relative density = density of specific species/total density of specie × 100
- Basal area (m^2) = $(D/200)^2 \times \pi$, where D = diameter at breast height in cm, $\pi = 3.14$
- Dominance = total basal area per ha or total sampled area
- Relative dominance = dominance of specific species/ total dominance of all species × 100
- Importance value index (IVI) = the sum of relative density, relative frequency and relative dominance
- Tree stand density per hectare (tree/ha) = number of trees per plot area × 10,000.

Soil sampling

At each corner and center of the main plot laid for species inventory, five sub-plots were laid for soil samples. A total of 108 soil samples (3 transects × 3 elevation ranges × 6 sample plots × 1 composite soil sample × 2 – depths) were collected from soil depths of 0–10 and 10–20 cm. The soil samples for carbon analysis were collected using augur of 8 cm diameter while soil samples for bulk density were collected with soil core samplers of (5 cm diameter × 5 cm tall, 98.2 cm^3). All samples were placed in paper bags with appropriate label. The soil samples for carbon analysis were air dried and sieved with 2 mm sieve for SOC determination to mineral soil fraction of <2 mm. The carbon content (%) of the soil samples was determined using the Walkley–Black (Walkley and Black 1934).

The Walkley–Black method is a widely used technique for determining the carbon content of soil samples. It is based on the principle of oxidizing the organic carbon present in the soil to produce carbon dioxide (CO_2), which can then be quantified. The method involves the following steps: (1) sample preparation: a soil sample is first collected and dried to remove any moisture. It is then finely ground to increase the surface area and promote uniform oxidation; (2) oxidation with potassium dichromate: the dried and ground soil sample is mixed with a solution containing potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4). The potassium dichromate acts as an oxidizing agent, converting the organic carbon in the soil to CO_2; and (3) titration: after the oxidation reaction, the excess potassium dichromate that has not reacted with the organic carbon is determined by titration using a reducing agent, such as ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2$ $6H_2O$). The amount of remaining unreacted potassium dichromate is proportional to the amount of organic carbon oxidized.

The Walkley–Black method is known to underestimate the actual organic carbon content in the soil due to incomplete oxidation. The correction factor of 1.33 compensates for the incomplete oxidation of organic carbon, providing a more accurate estimation of the true carbon content in the soil. It accounts for the carbon that would have been oxidized if the Walkley–Black method had achieved complete conversion. The value of 1.33 is derived from previous studies, such as the work of Rosell et al. (2001), which determined the appropriate correction factor to improve the accuracy of carbon content measurements. By applying the correction factor, the Walkley–Black method can provide a more reliable estimation of the carbon content in soil samples, accounting for the incomplete oxidation that may occur during the analysis. For bulk density analysis the soil samples were oven-dried at 105°C for 48 hours and then weighed.

Estimation of biomass carbon stocks

Biomass carbon stocks were estimated on the basis of dry matter biomass and carbon content. The estimation of aboveground biomass was calculated using allometric equation developed by (Chave et al. 2014).

$$AGB = 0.0673\,(pD^2H)^{0.976} \qquad (2)\ \text{Eq. 2}$$

where, *AGB* = aboveground biomass (kg/tree), ρ = wood density, g cm^{-3}, *DBH* = diameter at breast (cm), *H* = height (m).

The Chave et al.'s (2005, 2014) equation was selected because it covers a wide range of climatic conditions and vegetation types including tropical forests, subtropical forests, and woodland savannas. The Chave et al.'s (2005, 2014) equations represented a major step forward in tropical forest carbon accounting. They are also currently being proposed for inclusion in the Intergovernmental Panel on Climate Change (IPCC) emission factor database and REDD protocols (IPCC 2007). Wood density values (oven-dry mass per unit of green volume) for each species were adapted from global wood density database (Zanne et al. 2009). Biomass contains carbon from 45% to 50% of dry matter (Kishwan et al. 2012; Pandey et al. 2014). In other study conducted in temperate Cedrus deodara forests in Central Himalaya (India), the total amount of carbon stocked was 0.45 times of dry biomass as suggested by Woomer (1993). In this study, default value of 50% carbon content was used to convert the biomass to carbon stocks. On the other hand, the estimation of aboveground biomass did not take into account the vegetation that grows beneath the main forest canopy. In order to benefit the nearby communities participating in this project, farmers were allowed to gather dead trees for firewood and harvest grass to feed their livestock using a "cut-carry" system.

The belowground biomass (stump plus coarse roots, >2 cm diameter) was calculated based on the proportion of 26% of the above ground biomass (Cairns et al. 1997). While the multiplication factor 3.67 was used to estimate CO_2 equivalent (Pearson et al. 2007).

Estimation of soil organic carbon

The *SOC* stock was calculated following (Pearson et al. 2005).

$$SOC = BD\ x\ D\ x\ \%C \qquad (3)\ \text{Eq. 3}$$

where, *SOC* = soil organic carbon stock per unit area (Mg ha^{-1}), *BD* = soil bulk density (g cm^{-3} < 2 mm), *D* = soil depths or layer (cm) the sample was taken, *C* = carbon concentration (%). Then, course fraction content (> 2 mm) was corrected by multiplying by 100% – volumetric content of coarse fraction, %/100%. The volumetric content of the coarse fraction was calculated from the gravimetric contents of >2 mm material in the soil samples and an assumed density of solids value of 2.65 g cm^{-3}. The *SOC* stock of 0–20 cm was calculated based on summing up the carbon stock in 0–10 cm and 10–20 cm soil layers. The total carbon stock for the studied ecosystem was estimated by summing up the carbon stocks in the biomass and *SOC* stocks (equation 4).

$$TC = AGB + BGB + SOC \qquad (4)\ \text{Eq. 4}$$

where, *TC* = total carbon, *AGB* = aboveground biomass carbon, *BGB* = belowground biomass carbon, *SOC* = soil organic carbon in Mg/ha.

Statistical analysis

The C stocks (Mg ha^{-1}) of the biomass and soil were calculated for each of the 54 plots. The size and variation in the C stocks for each elevation were described by the mean and its standard error. To test for differences in C stocks between the three-elevation range, two-way ANOVA (analysis of variance) were performed (α = 0.05). Two-way ANOVA is utilized to assess the effects of altitudinal gradient and soil depth on carbon stocks, as well as to determine if there is an interaction effect between these variables on forest carbon stocks. Additionally, the normality of the data was evaluated using the Shapiro–Wilk and Kolmogorov–Smirnov tests prior to conducting ANOVA, and the data were confirmed to be normally distributed. Levene's test was used to check for the homogeneity of variance that indicated homogenous in all cases. SAS system (SAS version 9.0; SAS Institute, Cary, NC, USA) was used for the statistical analysis.

Results

Species composition along altitudinal gradients

Sixty-eight tree species belonging to 38 genera and 25 families were recorded in Humbo FMNR forest ecosystem in the study area. Among the dominant woody species in the forest ecosystem, *Terminalia brownii* (Fresen) recorded 28.8% and 23.7% of the aboveground biomass carbon stocks in lower and middle elevation, respectively. *Acacia hockii* (Del Willd.) and *Psydrax schimperiana* (Bridson) accounted for 24.9% and 22.8% in the higher elevations, respectively. *Acacia hockii* (Del Willd.) recorded 17.1% of the total aboveground biomass carbon across the three studied elevation ranges (Table 1).

The results showed that *T. brownii* (Fresen), *A. hockii* (Del) Willd. and *Dodonaea viscosa* (L.) Jacq. dominant in a forest ecosystem and have been found to be effective at sequestering carbon, which is a process of capturing carbon dioxide from the atmosphere and storing it in the form of carbon in plants, soil, and other organic matter. The CSP of these three species has been quantified, and the results indicate that *A. hockii* (Del) Willd. is the most efficient species in terms of carbon sequestration, followed by *T. brownii* (Fresen) and *D. viscosa* (L.) Jacq. The total amount of carbon sequestered by these three species in the forest ecosystem was found to be equivalent to 4,945.3, 15,744.0, and 1,793.7 in terms of CO_2 equivalent, respectively.

Table 1 Characteristics of dominant tree species recorded along altitudinal gradients in Humbo FMNR forest in southern Ethiopia

No.	Species	Mean height (m)	Mean DBH (cm)	Stand density (tree/ha)	Density (%)	Dominance (%)	IVI
Lower elevation (1,470–1,610 m a.s.l.)							
1	*Terminalia brownii* Fresen.	3.12	4.64	571	16.27	28.78	48.28
2	*Combretum collinum* Fresen.	2.95	4.42	367	10.45	16.97	30.65
3	*Schrebera alata* (Hochst.) Welw	2.76	3.34	338	9.62	9.52	22.37
4	*Flacourita indica* (Burm. f.) Merr.	2.56	2.91	367	10.45	6.99	20.67
5	*Rhus natalensis Bernh.* ex Krauss	2.79	3.31	254	7.24	6.24	16.71
6	*Euclea schimperi*	2.89	3.64	179	5.11	5.21	13.54
7	*Dodonaea viscosa* (L.) Jacq.	1.88	1.57	283	8.08	1.56	12.86
8	*Pappea capensis* Eckl. & Zeyh.	3.63	5.37	188	5.34	2.74	11.31
9	*Capparis fascicularis* DC.	2.37	2.98	117	3.33	2.34	8.89
10	*Dichrostachys cinerea* (L)	2.25	3.42	83	2.38	2.15	7.75
Middle elevation (1,610–1,750 m a.s.l.)							
1	*Terminalia brownii* Fresen.	3.90	4.81	463	13.11	23.72	39.88
2	*Dodonaea viscosa* (L.) Jacq.	3.19	2.57	696	19.72	11.78	34.55
3	*Schrebera alata* (Hochst.) Welw	4.39	4.02	242	6.85	9.19	19.10
4	*Combretum collinum* Fresen.	4.11	4.45	200	4.96	7.35	15.37
5	*Euclea divinorum*	4.95	3.93	108	3.07	3.89	10.02
6	*Mytenus arbutifolia* R. wilczek	3.14	2.41	167	4.72	2.20	9.98
7	*Rytigynia neglecta* (Hiern) Robyns	4.07	3.36	129	3.66	3.99	9.69
8	*Olea europea* (sub spec. cuspidata) L.	3.13	3.92	104	2.95	3.58	9.60
9	*Protea gaguedi* J. F. Gmel.	3.66	5.15	67	1.89	4.23	9.18
10	*Maerua triphylla* A. Rich.	4.47	2.91	96	2.72	2.00	7.77
Higher elevation (1,750–1,890 m a.s.l.)							
1	*Euclea schimperi*	3.25	2.91	692	24.16	3.16	30.77
2	*Acacia hockii* Del Willd.	3.28	11.58	67	2.33	24.88	30.65
3	*Psydrax schimperiana* Bridson	5.25	56.9	8	0.29	22.79	25.38
4	*Olea europea* (sub spec. cuspidata) L.	5.1	46.05	8	0.29	15.25	17.84
5	*Syzygium guineense* (L.) Skeels	4.89	6.6	188	6.55	7.25	17.25
6	*Carissa edulis* Vahl	3.49	2.29	346	12.08	0.93	16.46
7	*Samium ellipticum* (Krauss) Pax	10.05	39.75	17	0.58	13.12	16.01
8	*Myrsine africana* L.	2.23	1.39	329	11.50	0.32	15.26
9	*Mytenus arbutifolia* R.wilczek	2.48	1.93	221	7.71	0.44	11.60
10	*Albizia grandibracteata* Taub.	7.94	12.23	58	2.04	4.42	9.90

FMNR: Farmer Managed Natural Regeneration; DBH: diameter at breast height; IVI: importance value index; a.s.l.: above sea level.

Estimation of biomass carbon stocks

The aboveground biomass carbon stocks for woody species did not significantly differ between middle and lower elevations but both of them significantly ($p < 0.05$) varied from higher elevation (Table 2). The aboveground biomass carbon stock for higher elevation was by 9.5 and 14% higher than lower and middle elevations, respectively.

Like the aboveground biomass carbon stocks, belowground biomass carbon stock showed increasing trend with increasing elevation. The belowground biomass carbon stock in the higher elevation was significantly ($p < 0.05$) different from the remainder two elevation ranges. The mean aboveground and belowground biomass carbon stocks ranged from 1.0 to 4.0 Mg ha^{-1} in the three studied elevation ranges (Table 2).

SOC stocks along elevation ranges

The SOC inventories across elevation ranges and soil depths are presented in Table 3. SOC stocks showed an increasing trend, although C stocks (0–20 cm) did not decrease significantly ($p < 0.05$) along the elevation ranges. However, SOC stocks in the layer (0–10 cm) showed a decreasing trend compared to soil depth (10–20 cm) and decreased significantly with soil depth ($p < 0.05$). Total SOC (0–20 cm) stocks ranged from 17.7 to 27.1 Mg ha^{-1} (Table 3). Accordingly, the SOC in the upper soil layer and the lower soil layer recorded 24.6 and 18.7 Mg ha^{-1}, respectively, indicating that the upper layer has accumulated 24% more carbon than the lower soil layer.

The impact of altitude, soil depth and interaction on SOC stocks is presented in the ANOVA Table 4. SOC is significantly affected by soil depth ($p < 0.05$). However, elevation and the interaction between elevation and soil depth had no significant effect on SOC ($p > 0.05$).

Total carbon stocks along elevation

Total carbon stocks increased significantly ($p < 0.05$) with elevation ranges. As the results showed, the SOC contributed higher carbon accumulation (81%), followed by aboveground biomass (15%) and belowground biomass (4%) to the total carbon stock (Fig. 2). The results also showed that the highest carbon stocks were recorded for higher elevations (14.74 ± 2.73 Mg ha^{-1}) and the lowest for lower elevations (1.99 ± 2.47 Mg ha^{-1}). Similarly, the biomass stock for the higher elevation was highest (13.84 ± 2.79 Mg ha^{-1}), followed by the contribution of the middle and lower elevation, indicating a consistent trend of the total carbon contribution of the biomass along the altitude ranges.

Discussion

Estimation of biomass carbon stocks

The carbon stocks of aboveground biomass for woody species exhibited no significant differences between the middle and lower elevation zones; however, both differed significantly from the higher elevation. Similarly, the carbon stocks of belowground biomass demonstrated an upward trend with increasing elevation. Furthermore, the belowground biomass carbon stock at higher elevations was

Table 4 Mixed model effects of elevation and depth on soil organic carbon of the study area

Response variable	Degree of freedom	F-value	*p*-value
Elevation	2	1.29	0.280
Depth	1	10.77	< 0.001
Elevation × depth	2	0.29	0.752

Table 2 Biomass carbon stocks along altitudinal gradients of the Humbo FMNR forest in Southern Ethiopia ($n = 54$ plots)

Carbon stock	Altitudinal gradients (m above sea level)			F-value	*p*-value
	1,470–1,610	1,610–1,750	1,750–1,890		
AGBC (Mg ha^{-1})	1.05 ± 2.00^{b}	1.53 ± 2.00^{b}	10.98 ± 2.20^{a}	6.77	< 0.001
BGBC (Mg ha^{-1})	0.27 ± 0.52^{b}	0.39 ± 0.52^{b}	2.85 ± 0.57^{a}	6.77	< 0.001
TBC (Mg ha^{-1})	1.32 ± 2.53^{b}	1.93 ± 2.52^{b}	13.84 ± 2.79^{a}	6.77	< 0.001

Values are presented as mean ± standard error of the mean.
FMNR: Farmer Managed Natural Regeneration; AGBC: above ground biomass carbon; BGBC: below ground biomass carbon; TBC: total biomass carbon.
Similar letters indicate no significant differences and different letters indicate significant differences between groups at $p < 0.05$.

Table 3 Soil organic carbon stocks along elevation ranges of Humbo FMNR forest in Southern Ethiopia ($n = 54$ plots)

Soil depth	Elevation			F-value	*p*-value
	1,470–1,610	1,610–1,750	1,750–1,890		
0–10 cm (Mg ha^{-1})	27.12 ± 2.42^{a}	24.14 ± 2.14^{a}	27.12 ± 2.20^{a}	1.23	0.300
10–20 cm (Mg ha^{-1})	17.70 ± 2.11^{a}	18.76 ± 1.99^{a}	19.59 ± 1.99^{a}	0.21	0.810
0–20 cm (Mg ha^{-1})	19.72 ± 1.60^{a}	21.40 ± 1.45^{a}	23.2 ± 1.48^{a}	1.29	0.281

Values are presented as mean ± standard error of the mean.
FMNR: Farmer Managed Natural Regeneration.
Similar letters show no significant differences, and different letters indicate significance differences between groups at $p < 0.05$.

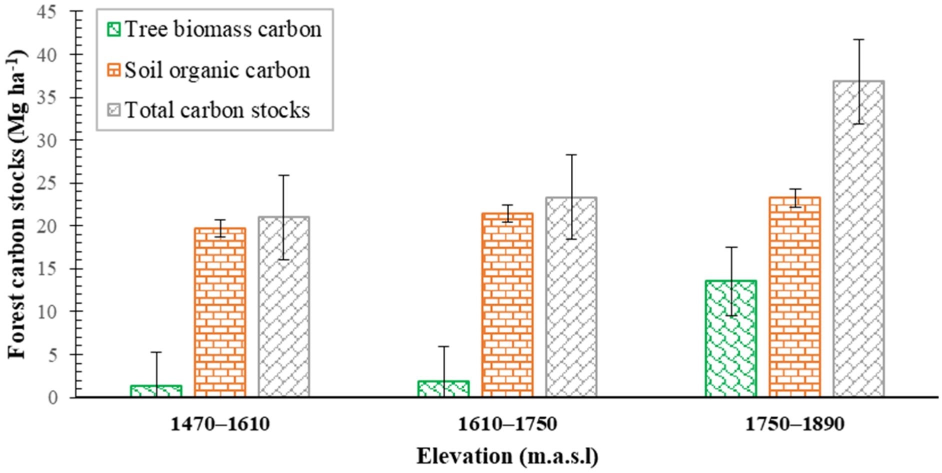

Fig. 2 Mean carbon stock of Humbo Farmer Managed Natural Regeneration forest ecosystem under the three elevation gradients.

significantly different from those at the middle and lower elevations. Similar study has been conducted in nearby forest showed that there was no significant change in above ground biomass carbon and below ground biomass carbon along altitudinal gradients (Chinasho et al. 2015). In contrast, according to Sheikh et al (2009), the stocks of SOC were found to be decreasing with increasing altitude from 185.6 to 160.8 t C/ha and from 141.6 to 124.8 t C/ha in temperature and subtropical forests, respectively. Studies elsewhere on the mean aboveground biomass carbon stock along high elevations ranges from 14 to 123 Mg ha^{-1} in tropical dry forests (Murphy and Lugo 1986), in tropical dry forests in sub-Saharan Africa from 17 to 72 Mg ha^{-1} (Gibbs et al. 2007) and in tropical dry deciduous forests of ranges recorded in other parts of the tropics 14.7 to 43.2 Mg ha^{-1} (Chaiyo et al. 2011). Also, similar results were reported for the African tropical dry forest with 10 to 34 Mg ha^{-1} (Henry 2010). Similarly, the belowground biomass carbon stocks in the present study were lower than the global average of tropical dry forests, which is 10 to 45 Mg ha^{-1} (Murphy and Lugo 1986). However, the current find was much smaller than in the other tropical dry forests. On the other hand, the belowground biomass carbon stocks in the present study in dry forests of southern Ethiopia range from 2.9 to 5.2 Mg ha^{-1} (Tesfaye and Negash 2018). Therefore, the discrepancy from other studies could be due to discrepancies in stand structure and composition, topography, elevation and disturbance factors (Chave et al. 2004).

SOC stocks along elevation ranges

SOC stocks displayed an increasing trend, though carbon stocks within the 0–20 cm layer did not show significant decreases across different elevational ranges. In contrast, SOC stocks in the 0–10 cm layer exhibited a decreasing trend relative to the deeper soil layer (10–20 cm) and decreased significantly with increasing soil depth. It may be due to the higher microbial activities in the upper soil layers (0–20 cm). Higher microbial activities at upper soil layers leading to accelerating decomposition are reported by Singh et al. (1990), Upadhyay and Singh (1989). Moreover, the upper soil layer contains most of the root tips and has porous and nutritious soil (Usman et al. 1999).

SOC is significantly affected by soil depth. This may be due to the accumulation of SOM in the topsoil. The higher concentration of SOC in top layer has also been reported by various authors (Dinakaran and Krishnayya 2008; Alamgir and Amin 2008). According to Nagy (2009), there could be a noticeable change in organic matter in the surface horizon and rooting zone of finely textured soils due to the tendency of fine particles to bind tightly to organic matter, therefore finely textured soils are more likely to accumulate dissolved organic matter (Sanchez et al. 2006).

The mean SOC stock recorded in the Sahelian woodlands was 21.5 Mg ha^{-1} (20–120 Mg ha^{-1}) (Saiz et al. 2012). In contrast, the SOC content recorded in our study was lower than in African savannas and woodlands (30–140 Mg C ha^{-1}) (Ciais et al. 2011). The present results were also less comparable to those found in arid land ecosystems in southern Ethiopia (Tesfaye and Negash 2018; Wolde et al. 2014) and semi-arid pastoral ecosystems in northern Kenya (Dabasso et al. 2014). The difference from other studies could be due to soil physical structure, species composition and the rate of litter decomposition (Muñoz-Rojas et al. 2012).

Total carbon stocks along elevation

Total carbon stocks increased significantly with elevation ranges. This is likely related to vegetation distribution, tree density, basal area, wood density, and often larger diameters associated with elevation ranges (Pan et al. 2013).

The analysis confirmed that there was a higher soil carbon stock than biomass in our study area. This could be due to the accumulation of new roots and a high litter input. Similar results were found in other studies (Girmay et al. 2008; Ryan et al. 2011). The higher carbon stocks in the soil would be a good way to conserve carbon long-term. Soil carbon sequestration might also be more preferable than biomass carbon, which ultimately decomposes. Also, soil carbon sequestration improves food productivity, food security, maintaining water flow and water quality, enhancing biodiversity, and strengthening elemental recycling (Lal et al. 2015).

The higher proportion of ecosystem C stocks at the higher elevations may be due to the dominance of some species such as *A. hockii* (Del Wild.), *P. schimperiana* (Bridson), and *Olea europea* (Cuspidata), as well as dense tree canopies that have a higher litter input deliver to the soil and could thus increase SOC stocks (Giliba et al. 2011; Grand and Lavkulich 2011; Yao et al. 2010). A slightly lower mean SOC content at lower elevations could be associated with species composition, the rate of litter decomposition, and hence impacts on SOC stocks (Muñoz-Rojas et al. 2012). This requires efforts to conserve this dry forest ecosystem to manage the impacts of climate change and improve other ecosystem services (Tesfaye and Negash 2018). This would also create an opportunity to benefit from future ecosystem services payment and carbon financing and improve the livelihoods of the forest-dependent community nearby.

Conclusions

The study holds immense importance, particularly from a management perspective, as it provides valuable insights into the role of the Humbo FMNR forest Project in mitigating climate change and reducing GHG emissions. The project's primary objective is to restore degraded natural forests and actively involve the local community in their management, with the aim of sequestering carbon and contributing to climate change mitigation efforts. The findings of the study reveal that while SOC contributes significantly to the overall carbon stock, biomass has a stronger impact on carbon stock variation across different altitudinal gradients in the study area. Thus, altitudinal gradients can significantly affect vegetation types, species diversity, and ecological processes such as photosynthesis and nutrient cycling. Higher altitudes may favour certain plant species or growth forms that are efficient in sequestering carbon, leading to higher biomass carbon stocks. In contrast, SOC stocks may vary less across altitudinal gradients due to slower decomposition rates or limitations in nutrient availability at higher elevations. This implies that the amount of carbon stored in the living vegetation, such as trees and other plant biomass, has a greater influence on the variation of carbon stocks with changes in altitude compared to the carbon stored in the soil.

The study further demonstrates the success of the Humbo FMNR forest Project, as it has resulted in the accumulation of more biomass and carbon stocks at higher elevations compared to lower elevations. This suggests that the project has effectively restored and regenerated the forest ecosystem, leading to increased carbon sequestration and storage. The findings highlight the significance of altitude variations in influencing ecosystem carbon stocks, with the soil playing a crucial role in storing a substantial proportion of carbon, particularly at higher elevations. Additionally, the study identifies three dominant woody species, namely *A. hockii*, *P. schimperiana*, and *T. brownii*, which play a critical role in mitigating the impacts of climate change and enhancing other ecosystem services. These species have the potential to sequester significant amounts of carbon through their growth and development, contributing to the overall carbon stock in the forest. Their presence and abundance in the Humbo FMNR forest indicate the success of the reforestation efforts and highlight their importance in the sustainable management of dry forest ecosystems.

Furthermore, the study emphasizes that the Humbo forest ecosystem has the potential to reduce emissions and can benefit from carbon finance schemes. This implies that the project could potentially generate carbon credits or participate in carbon offset programs, which would provide financial incentives for the sustainable management of the forest. These financial resources can be utilized to support the development and implementation of sustainable management strategies for dry forest ecosystems, benefiting both the environment and the local community. Overall, the results of this study underscore the importance of reforestation initiatives, such as the Humbo FMNR forest Project, and sustainable forest management practices in combating climate change and promoting ecosystem services. The project's success in sequestering carbon, accumulating biomass and carbon stocks, and identifying key woody species highlights its potential as a model for sustainable forest management and climate change mitigation efforts.

The study has limitations in terms of its scope, sample size, soil sampling depth, and species-specific information. On the other hands, the assessment of carbon stock overlooked the presence of vegetation beneath the primary forest canopy. To support the neighbouring communities involved in the project, farmers were granted permission to collect fallen trees for firewood and harvest grass to feed their livestock using a "cut-carry" method. Consequently, incorporating the significant role played by this understory vegetation in measuring carbon stock posed a considerable challenge. This limitation hindered the comprehensive evaluation of carbon storage in the ecosystem. Future research directions include long-term monitoring, comparative studies, ecosystem services assessment, socio-economic analysis, and exploring the scalability of the FMNR approach. These avenues of research will contribute to a more comprehensive understanding of carbon sequestration and sustainable forest management.

The study's findings contribute significantly to future carbon policy by validating the effectiveness of the Humbo FMNR forest project in carbon sequestration and biomass accumulation, particularly at higher elevations. The emphasis on biomass's role in carbon stock variation suggests that policies should focus on protecting and enhancing forest biomass, especially in high-altitude areas. Identifying key species such as *A. hockii*, *P. schimperiana*, and *T. brownii* informs species selection for reforestation projects, enhancing carbon stock. Policymakers can use this evidence to promote and fund similar projects, recognizing their role in climate change mitigation.

Abbreviations

GHG: Greenhouse gas
CDM: Clean Development Mechanism
FMNR: Farmer Managed Natural Regeneration
CSP: Carbon sequestration potential
DBH: Diameter at breast height
IPCC: Intergovernmental Panel on Climate Change
REDD$^+$: Reducing emissions from deforestation and degradation plus
SOC: Soil organic carbon
SOM: Soil organic matter
UNFCCC: United Nations Framework Convention on Climate Change

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Authors' contributions

WA wrote the manuscript, conceived the idea and designed of the study, collected data and performed statistical analysis. MM and CT participated on data collection. MT and ZM conceived the idea and design of the study. FY examined the manuscript. All authors read and approved the final manuscript.

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