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RESEARCH PAPER

Carbon Stock Potentials in Woody Plants of Tullu Qondala Exclosure in Ethiopia: its Implications to Climate Change Mitigation

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Abstract

Rehabilitation of degraded land plays a vital role in enhancing carbon stock storage, which is one of the important ecosystem services. The objective of this investigation was to determine the extent to which exclosures contribute to carbon storage by analyzing the carbon stocks of woody plants both above and below ground, utilizing a non-destructive allometric model within the Tullu Qondala Exclosure. A systematic sampling method was used to conduct the vegetation sampling. Vegetation data were collected from a total of 30 main plots each with the size of 20 m x 20 m. Woody plants were measured for diameter at breast height (DBH) of ≥ 5 cm and height of ≥ 1.5 m. The mean above-ground biomass (AGB) and below-ground biomass (BGB) were 56.9 ± 4.38 t/ha and 11.38 ± 0.88 t/ha, respectively. The total mean carbon stock density of woody plant species at the study site was 34.142 ± 13.86 t/ha, with 28.45 ± 2.19 t/ha stored in AGB and 5.69 ± 0.44 t/ha in BGB. The total aboveground and below-ground carbon contents were 853.56 t/ha and 170.71 t/ha, respectively. The carbon stocks density in the above and below ground biomasses were high as compared to some previous studies. These differences among the compared exclosure could be attributed to variations in the presence of bigger sized trees with a higher basal area and, a higher density of woody species. Additionally, the length of time an area has been under exclosure can significantly impact the density of carbon stocks, given that these stocks are influenced by biomass, which tends to increase with prolonged exclosure. This study demonstrated that establishing area exclosures in the region is an effective strategy for sequestering carbon. The carbon stock found in this area highlights its important role in addressing climate change. Therefore, it's crucial for all sectors involved, both local and national, to come together and implement strong conservation strategies to fully utilize these benefits.

Keywords: Biomass, carbon, exclosure, woody plants, climate change mitigation

Introduction

Climate change, along with its environmental challenges, has emerged as one of the most pressing issues we encounter on a global scale. Developing countries particularly in African countries are bearing the burden of it. Ethiopia, for example, has been experiencing extended droughts, erratic rainfall (Belay *et al*., 2025). which affected agricultural production and food security indicating the need for adaptation and mitigation strategies (Chapman *et al*., 2020).

Mitigating climate change entails storing C in vegetation and understanding the connections between carbon storage and ecosystem health (Don *et al*., 2024). Through carbon storage in above-and belowground structures, woody vegetation significantly contributes to the reduction of greenhouse gas emissions (Kafy *et al*., 2023; Shiferaw *et al*., 2022) . In this regard, tropical forest has a great role in storing substantial quantity of carbon which accounts 50% of the world vegetation biomass (Brown, 2002; Iticha, 2017). However, the provision of ecosystem services has been dramatically reduced due to high deforestation and extensive biodiversity lose (Guariguata and Balvanera, 2009) which in turn limited the carbon storage pools in forests in different part of the world and increased carbon emissions in the atmosphere (Tsegay and Meng, 2021). The CO_2 emission due to deforestation is reported to be about 70% and 13% for Africa and world respectively (FAO, 2020; Pan *et a*l., 2011).

Implementing conservation and management measures, restoring ecosystems and watersheds, and reducing deforestation could all help in reducing the buildup of C in the atmosphere (Brown, 2002; Houghton *et al*., 2001). Thus, forests have the ability to form a major component in the mitigation of global warming and adaptation to climate change. According to (Pan *et al*., 2011), forest stores about 80% of all aboveground and 40% of all below ground terrestrial organic carbon. Protected areas play an important role in capturing and storing carbon from the atmosphere through improved vegetation. They also act as a good strategy for adapting to climate change (Abeje *et al*., 2016; Griscom *et al*., 2017). It's widely recognized that area closure can enhance the vegetation's cover, composition, density, richness, and diversity. Besides, it can have a positive impact on the economies and ecosystems of the nearby communities(Birhane *et al*., 2006; Gebeyehu *et al*., 2019; Tefera and Soromessa, 2015).

In Ethiopia, there is land degradation because of deforestation, agricultural land expansion, and overgrazing which resulted in environmental degradation and ecosystem services (Mengistu *et al*., 2005; Mulugeta *et al*., 2005). The level of Ethiopia's forest land and C stock showed a decreasing trend during 1990 - 2015 due to deforestation (FAO, 2020). Ethiopia's total CO_2 emission is reported to be 400 Mt in 2030 (FDRE, 2015)

To deal with these issues, applying different sustainable land management practices such as enclosures is necessary. In reply to this, Ethiopia has followed different conservation strategies such as, watershed management, afforestation, reforestation, and restoration programs, to decrease these environmental risks (Mengistu *et al*., 2005). Before three decades, area closure was suggested as one of restoration strategy to encourage re-vegetation, prevent further ecosystem decline, and improve ecological conditions (Tesfay *et al*., 2020). As a result, there has been an increase in the area of degraded lands dedicated for its rehabilitation (Emiru *et al*., 2006). The Tullu Qondala Exclosure, a previously degraded natural forest, is one of the areas excluded from human and animal interference through a cooperation between the district agricultural office and local communities.

Although a number of studies have investigated the impact of area enclosures on restoring the diversity and structure of woody species in Ethiopia, we still have a lot to learn about their carbon sequestration capabilities especially in the central regions where these enclosures are used for land rehabilitation. Most research has focused on the northern and southern parts of the country, making it essential to explore biomass accumulation and carbon storage in central exclosures. This study sets out to measure the above and belowground carbon stock density of woody plants in the Tullu Qondala Exclosure to help fill this gap.

Materials and Methods

Description of Study Areas

Tullu Qondala Exclosure is found in Nono District, West Showa Zone, Oromia National Regional State, Ethiopia about 216 km west of the capital city, Addis Ababa. It covers a total area of 693.7 km2. The district is geographically situated between 370 20` to 370 30` Longitude and 80 30` to 80 40` Latitude. The elevation of the Tullu Qondala exclosure varies from 1126 and 2192 m.a.s.l (Nono District Administrative Office, 2021).

Climatically, most of Nono District falls within the Woinadega (90.83%) and Qolla (9.16%) agroclimatic zones (Messay, 2011). The mean annual temperature ranges between 16°C and 26°C. The Tullu Qondala Exclosure, established in 2004, was once a degraded natural forest before its closure for restoration.

The District Office of Agriculture partnered with local communities to enforce area closure, preventing human and livestock interference to promote ecological recovery.

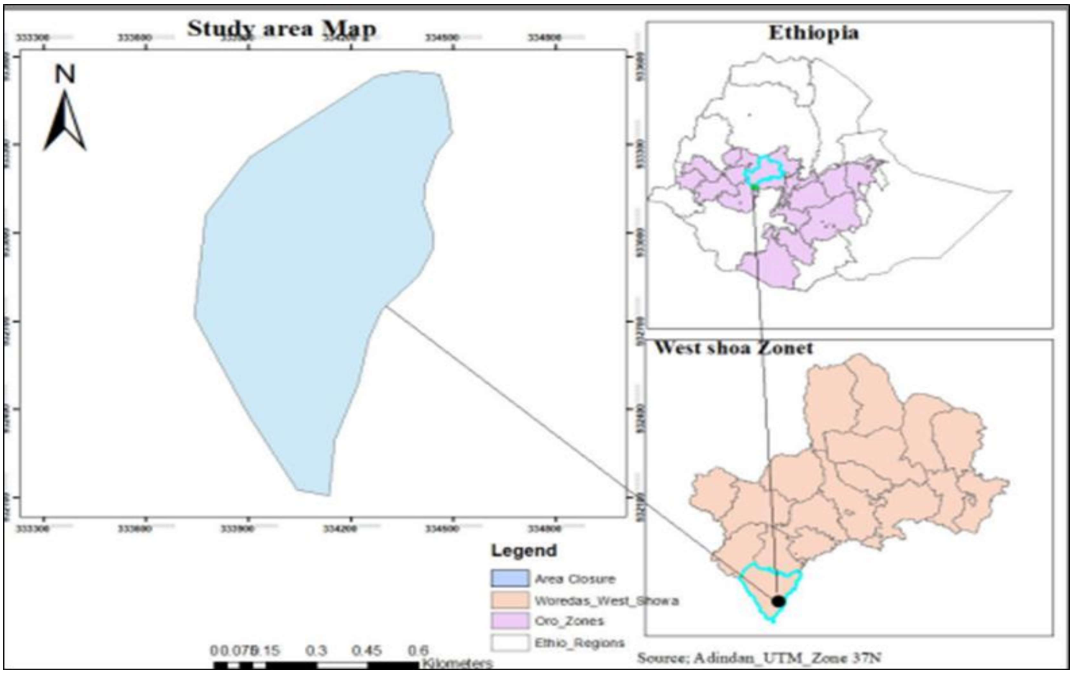

Figure 1: Location map of study area

Sampling design and measurements

Reconnaissance survey was made to obtain an overview of the study site, before the actual survey operation, followed by detailed preliminary survey on biophysical components. This site was chosen because it is relatively better protected and the extent of human disturbance is relatively less than in the other around areas. Systematic sampling design was employed to collect vegetation data from the study site.

The enclosure area covered 31 hectares, sampling was done based on systematic transect sampling technique following Mueller-Dombois, 1994. Three transect lines were established at a distance of 100m apart. Sampling quadrant of 20m x 20m was used to assess woody species. All the sampling plots were distributed along the transect line at a distance of 50m between the quadrants. To estimate the tree biomass, all live trees with a diameter ≥ 5 cm were recorded as indicated by (Pearson *et al*., 2005)

In this research, individual trees measuring ≥ 5cm diameter at breast height (DBH) and shrubs diameter at stump height (DST), about 30 cm above the ground, were measured from each quadrant. The DBH of the woody plants were derived from circumference ($D = C/\pi$, where D = DBH, C = Circumference, π = constant with value 3.14) measured by a measuring tape.

The quadrats were marked using plastic ribbon, four wooden pegs and compass. In each quadrat, the types and number of all individuals of the woody species were identified, counted and recorded by their local and/or scientific names (Azene, 2007; Emiru *et al*., 2006). The height and diameter of trees, shrubs, saplings and seedlings of the woody species were measured using a marked measuring stick and diameter tape, respectively were recorded following a standard method.

Tree diameters were measured at breast height (DBH), while shrubs and saplings were measured at stump height (DSH). Plants reaching 3 meters in height with a DBH exceeding 2.5 cm were classified as trees or shrubs. Those under 2 meters tall with a DBH below 2.5 cm were recorded as saplings, and plants shorter than 1 meter were considered seedlings only their total counts were counted (Birhane *et al*., 2007; Lai *et al*., 2009).

Carbon stock Data Analysis

Aboveground Biomass (AGB) and Carbon Stock

Various allometric models exist for estimating aboveground biomass, but the (Chave *et al*., 2014) model is recommended here due to its suitability for the study site, particularly for tropical forests with similar life zone characteristics. The AGB of trees with diameter at breast height ≥ 5cm was calculated using the model developed by (Chave *et al*., 2014). The model is as follows:

$$AGB = 0.0673 \times (\rho(DBH)^2H)^{0.976}$$

Where: AGB = aboveground biomass (in kg dry matter)

ρ = wood density (g/cm3)

DBH = diameter at breast height (in cm)

H = tree height (in m)

The place where this study was conducted is part of tropical region, 50% of the woody species biomass was assumed to be the carbon sink. Hence, the aboveground biomass carbon was estimated by biomass-carbon conversion factor of 0.5 (Brown, 2002; Pearson *et al*., 2005).

AGCS= AGB x 0.5

Where, AGCS = Above Ground Carbon Stock

AGB = Above Ground Biomass

To calculate the amount of carbon dioxide equivalence (CO_2e) that have been captured in the aboveground body, AGB is multiplied by 3.67 assuming that each ton of stored carbon is equivalent to3.67 (i.e. the ratio of the molecular weight of carbon dioxide (CO_2) to the atomic weight of carbon (44/12) =3.67 (Brown, 2002; Pearson *et al*., 2005).

Below-Ground Biomass (BGB) and carbon

Belowground biomass was estimated using the equation from Macdieken (1997). Similarly, Brown and (2002) and Pearson *et al*. (2005) described this approach as more efficient and effective, as it applies a regression model to determine belowground biomass based on aboveground biomass data. Therefore, the equation developed by Macdicken, 1997 was adopted for estimating belowground biomass. The equation is provided below

BGB = AGB x 0.2

Where BGB is belowground biomass, AGB is aboveground biomass, 0.2 is the conversion factor (or 20% of AGB).

To calculate the amount of carbon and CO2 in below ground biomass, the same procedure was applied like that of aboveground biomass. Finally, biomass carbon stocks are calculated by summing the carbon stock densities of different carbon pools in the stratum using the formula by Pearson *et al*. (2005).

Results

Biomass and Carbon Stock of woody species in Tullu Qondala Exclosure

Tullu Qondala exclosure had the density of 1349 individuals/ha of woody species with DBH ≥5cm (Table 1).

Table 1. Mean DBH and Height, frequency, relative frequency, density/ha and relative density of woody plant species in Tullu Qondala exclosure

Species Name	No of stems	Average DBH (cm)	Average height (m)	Frequency %	Relative Frequency	Density/ ha	Relative Density
Acacia abyssinica Hochst. ex Benth.	225	16.77	6.2	93.3	7.6	187.5	13.9
Acacia polyacanths (Willd)	57	18.19	7.64	80	6.5	47.5	3.52
Acacia seyal Del.	22	16.55	6.87	36.7	3	18.33	1.36
Albizia schimperiana Oliv.	24	14.18	6.06	33.3	2.7	20	1.48
Calpurnia aurea (Ait.)Benth.	14	5.71	4.04	26.7	2.2	11.67	0.86
Carissa spinarum (C. edulis)	53	6.51	4.3	60	4.9	44.17	3.27
Clausena anisata (Wild.) Benth.	8	6.11	4.23	20	1.6	6.67	0.49
Combretum molle R. Br. ex G.Don	454	12.69	5.62	100	8.2	378.33	28.04
Cordia africana Lam.	28	21.01	7.2	43.3	3.5	23.33	1.73
Croton macrostachyus Hochst. ex Del.	63	14.54	5.97	63.3	5.2	52.5	3.89
Dodonea angustifolia L.F	17	6.24	4.03	33.3	2.7	14.17	1.05
Ehertia cymosa Thonn.	75	11.51	5.06	66.7	5.4	62.5	4.63
Entada abyssinica steud.ex A.Rich.	40	15.37	6.14	43.3	3.5	33.33	2.47
Euclea divinorum Hiern	18	5.84	3.57	26.7	2.2	15	1.11
Ficus sur Forssk.	5	30.34	7.23	13.3	1.1	4.17	0.31
Ficus sycomorus.L	4	27.95	6.18	13.3	1.1	3.33	0.25
Ficus vasta Forssk.	8	35.42	8.23	20	1.6	6.67	0.49
Gardenia ternifolia Schumach. & Thonn.	63	17.09	5.67	66.7	5.4	52.5	3.89
Grewia bicolor Juss	88	8.22	4.16	63.3	5.2	73.33	5.44
Maytenus arbutifolia (A.Rich.) Wilczek	4	8.75	5.23	10	0.8	3.33	0.25
Olea europapea L.subsp. cuspidata (Wall.ex G. Don.) Cif.	8	7.45	5.25	16.7	1.4	6.67	0.49
Rhus natalensis Benth. ex Krauss.	63	6.25	4.57	53.3	4.3	52.5	3.89
Rhus vulgaris Meikle	119	5.68	4.26	86.7	7.1	99.17	7.35
Terminalia macroptera Guill & Perr.	101	16.58	6.18	76.7	6.3	84.17	6.24
Vernonia amygdalina Del.	9	6.05	4.39	23.3	1.9	7.5	0.56
Ximenia americana L.	49	5.63	4.04	56.7	4.6	40.83	3.03
Total	1619					1349.2	

The total mean tree biomass was 68.28±5.25 ranging from 19.77-136.12 t/ha. Due to a wide range in tree biomass of the study site, the quantity of carbon sequestered showed difference between plots ranging from 9.89-68.07 t/ha. The overall C stock of Tulu Qondala exclosure was 1024.3 t/ha with the mean value of 34.14±2.63 t/ha. For all the plots, the total aboveground carbon and belowground carbon was 853.56 t/ha and 170.71 t/ha respectively (table 2).

Table 2. Overall and mean values of biomass and C stock (t ha−1) in in Tullu Qondala exclosure

	AGB	BGB	AGB+BGB	AGC	BGC	AGC+BGC
Mean	56.9±4.38	11.38±0.88	68.28±5.25	28.45±2.19	5.69±0.44	34.14±2.63
Total	1707.1	341.42	2048.5	853.56	170.71	1024.3

AGB = Aboveground biomass, BGB = Belowground biomass, AGC = Aboveground carbon, BGC = Belowground carbon, TB = Total biomass, and TC = Total carbon

Woody Species Contribution for Biomass and C Stock in Tullu Qondala Exclosure

The highest aboveground carbon stock per woody species was recorded from *Acacia abyssinica (*7.63) followed by *Combretum molle(*4.8)*, Terminalia macroptera(*3.31)*, Acacia polyacanths(*2.6)*,Gardenia ternifolia (*1.66) *and Croton macrostachyus(*1.07) tons of Carbon/species ha $^{-1.}$ About 78.195 % of the AGC stock was contributed by these six woody plant of the study area while the rest of the woody plant species contributed only 21.805 % of the AGC. The minimum aboveground C stock of woody plant species was scored from *Vernonia amygdalina* 0.0151 tons/ha (Table 3). High C stock was recorded in *Ficus vasta* (0.125 ton per single tree). *Ficus sur, Ficus sycomorus, Acacia polyacanths,* and *Acacia abyssinica* also contributed high carbon in Tullu Qondala exclosure. The minimum and maximum carbon stock per single tree/shrubs was 0.002 and 0.125 tones recorded for *Vernonia amygdalina* and *Ficus vasta*, respectively (S2).

Table 3. Means (±SD) AGB and C stock of each species from Tullu Qondala area exclosure

Species	AGB	AGC	CO_2 in AGB	GB	BGC	CO_2 in BGB	TB	TC Stock
Acacia abyssinica Hochst. ex Benth.	18.32	9.16	33.61	3.66	1.83	6.72	22	10.99
Combretum molle R. Br. ex G.Don	11.52	5.76	21.14	2.3	1.15	4.23	13.8	6.91
Terminalia macroptera Guill & Perr	7.95	3.97	14.59	1.59	0.79	2.92	9.54	4.77
Acacia polyacanths (Willd)	6.22	3.11	11.41	1.24	0.62	2.28	7.46	3.73
Gardenia ternifolia Schumach. & Thonn.	3.99	1.99	7.32	0.8	0.4	1.46	4.78	2.39
Croton macrostachyus Hochst. ex Del.	2.56	1.28	4.7	0.51	0.26	0.94	3.07	1.54
Cordia africana Lam.	2.07	1.03	3.79	0.41	0.21	0.76	2.48	1.24
Entada abyssinica steud.ex A.Rich	2.03	1.02	3.73	0.41	0.2	0.75	2.44	1.22
Ficus vasta Forssk.	2	1	3.68	0.4	0.2	0.74	2.4	1.2
Ehertia cymosa Thonn.	1.64	0.82	3.02	0.33	0.16	0.6	1.97	0.99
Acacia seyal Del.	1.18	0.59	2.16	0.24	0.12	0.43	1.41	0.71
Albizia schimperiana Oliv.	0.89	0.45	1.64	0.18	0.09	0.33	1.07	0.54
Ficus sur Forssk.	0.82	0.41	1.5	0.16	0.08	0.3	0.98	0.49
Grewia bicolor Juss	0.68	0.34	1.24	0.14	0.07	0.25	0.81	0.41
Rhus vulgaris	0.61	0.31	1.12	0.12	0.06	0.22	0.74	0.37
Ficus sycomorus	0.52	0.26	0.95	0.1	0.05	0.19	0.62	0.31
Rhus natalensis Benth. ex Krauss.	0.42	0.21	0.77	0.08	0.04	0.15	0.5	0.25
Carissa spinarum (C. edulis)	0.38	0.19	0.69	0.08	0.04	0.14	0.45	0.23
Ximenia americana L.	0.33	0.16	0.6	0.07	0.03	0.12	0.39	0.2
Dodonea angustifolia L.F	0.17	0.08	0.3	0.03	0.02	0.06	0.2	0.1
Olea europaea L.subsp. cuspidata (Wall.ex G. Don.) Cif.	0.08	0.04	0.15	0.02	0.01	0.03	0.1	0.05
Euclea divinorum Hiern	0.08	0.04	0.15	0.02	0.01	0.03	0.1	0.05
Calpurnia aurea (Ait.)Benth.	0.07	0.03	0.12	0.01	0.01	0.02	0.08	0.04
Maytenus arbutifolia (A.Rich.) Wilczek	0.07	0.03	0.12	0.01	0.01	0.02	0.08	0.04
Clausena anisata (Wild.) Benth	0.04	0.02	0.07	0.01	0	0.01	0.04	0.02
Vernonia amygdalina Del.	0.04	0.02	0.07	0.01	0	0.01	0.04	0.02
Mean	2.49± 0.82	1.24± 0.41	4.56±1.5	0.5±0 .16	0.25± 0.08	0.91±0. 3	2.98± 0.98	1.49± 0.49
Total	64.61	32.3	118.56	12.92	6.46	23.71	77.5	38.76

AGB = Aboveground biomass, AGC = Aboveground carbon, BGB = Belowground biomass, BGC = Belowground carbon, TB = Total biomass, and TC = Total carbon

Carbon Stock Density of Tullu Qondala Exclosure

In the Tullu Qondala exclosure, the total carbon (C) stock was determined by adding up the aboveground biomass carbon (AGB) and belowground biomass carbon (BGB) from all the sampled plots. This thorough evaluation showed quite a bit of variation in how much carbon each plot could store, which is influenced by factors like vegetation density, the types of species present, and the characteristics of the soil. Plot 27 had the lowest carbon stock at just 9.9 tons/ha, likely due to its sparse vegetation or some recent disturbances. On the other side, plot 7 boasted the highest stock at 68.1 tons/ha, probably due to its mature woody species (Fig. 2).

Overall, the average carbon stock for the entire study area was 34.14 ± 2.63 tons/ha, suggesting a moderate potential for carbon sequestration when compared to other similar exclosure systems in semi-arid regions.

Furthermore, the carbon sequestration potential representing the capacity of the ecosystem to absorb and store atmospheric CO_2 was estimated to be 118.56 tons/ha in AGB and 23.71 tons/ha in BGB (Table 3).

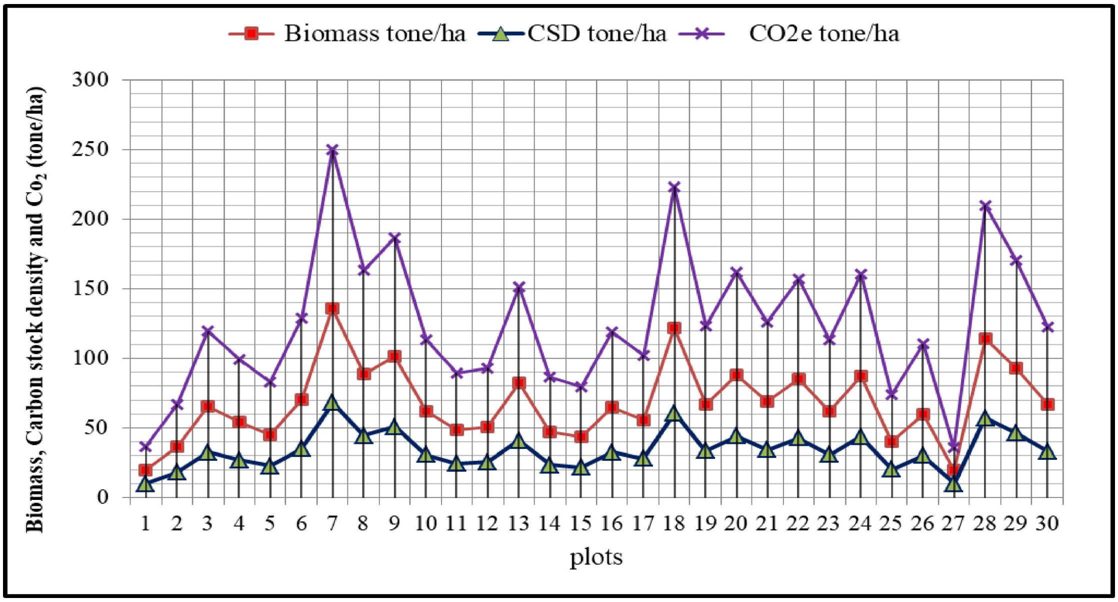

Figure: 2 Biomass, C stock density (CSD) and Co2 tone/ha per plots

In the study area, the ten key tree species showed quite a bit of variation in how much they contributed to total carbon storage. At the top of the list was *Acacia abyssinica*, which was the standout species, capturing the most carbon. Following closely in second place was *Combretum molle*. *Terminalia macroptera* took the third spot, while *Acacia polyacantha and Gardenia ternifolia* came in fourth and fifth, respectively. *Croton macrostachyus, Cordia africana, Entada abyssinica, Ficus vasta, and Ehretia cymosa* showed progressively decreasing carbon storage capacities, listed here in descending order of their contributions

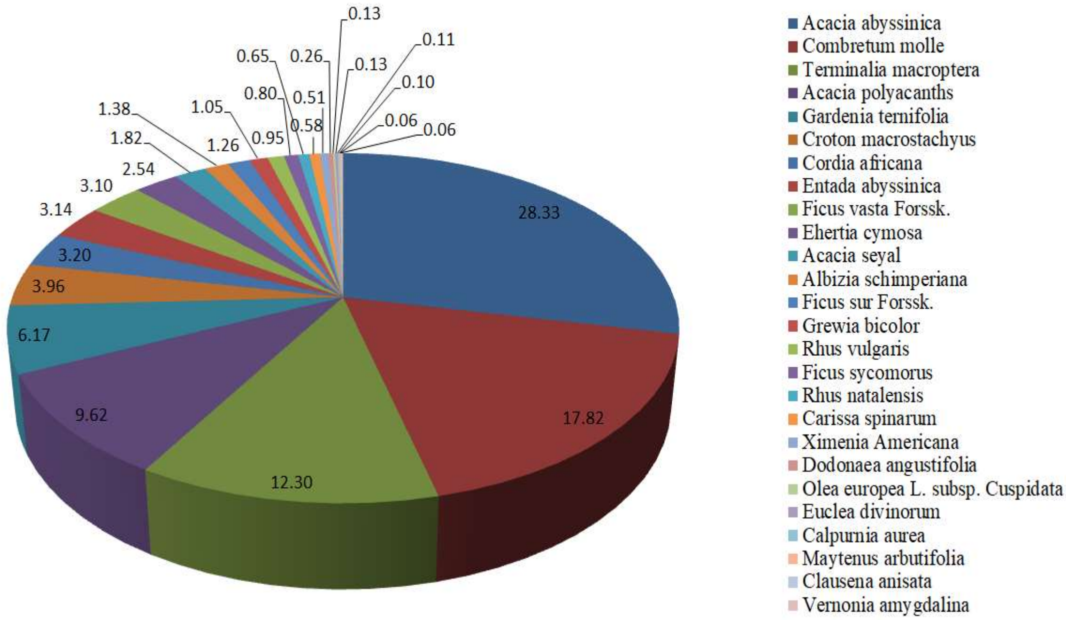

Figure 3. Contribution of woody species for the total carbon of Tullu Qondala exclosure (in percent)

The top 10 most important species accounted for 90.18% of the total aboveground biomass (AGB) and aboveground carbon (AGC) stocks in Tullu Qondala Exclosure, while the remaining species contributed only a minor fraction (Figure 4). Among these dominant species, three, *Acacia abyssinica, Combretum molle,* and *Terminalia macroptera* were particularly significant, collectively representing 58.48% of the entire carbon stock. This highlights their crucial role in carbon sequestration within the exclosure, underscoring their ecological importance in the ecosystem.

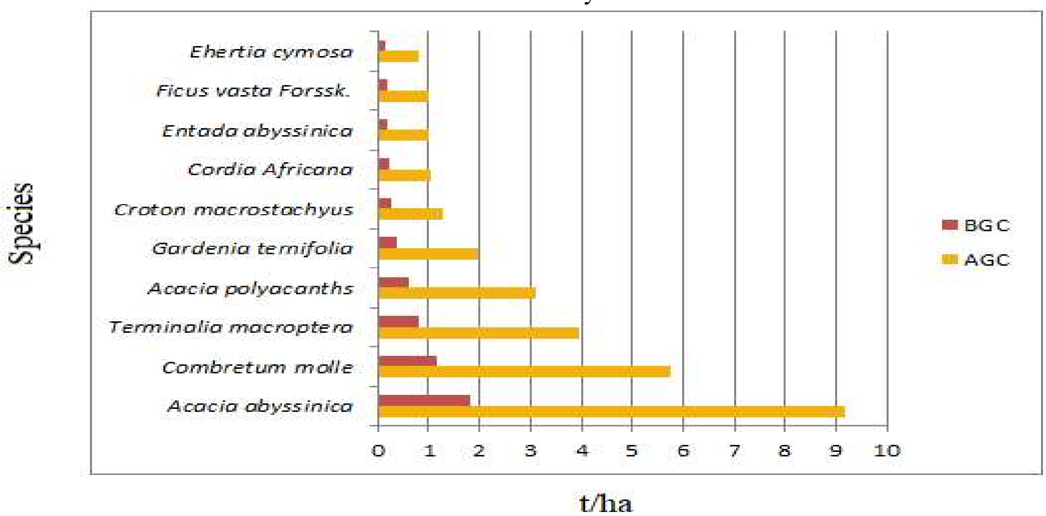

Figure 4. The share of ten most important tree species to the BGC and AGC in Tullu Qondala exclosure

Discussion

Biomass and Carbon Stock of Tullu Qondala Area Exclosure

The study evaluated tree carbon stocks using the IPCC-recommended global carbon fraction of 0.5 (50% of biomass), based on the assumption that half of a tree's dry biomass is carbon. This widely accepted default value is commonly used in forest carbon accounting, especially when direct measurements are not available, as supported by various studies and the IPCC Guidelines (IPCC, 2006). Exclosures, restricted areas for livestock and humans, effectively restore degraded lands (Mekuria *et al*., 2018). Combined with enrichment planting, introducing native or high-biomass species, they boost biomass carbon stocks (Ashenafi *et al*., 2019). However, the Tullu Qondala Area Exclosure showed uneven distribution of carbon stock input between AGB and BGB. This disparity could be attributed to issues like species composition, age structure of vegetation, and soil organic carbon dynamics (Lemenih and Itanna, 2004). Such variations underline the need for site-specific evaluation when carrying out restoration strategies, as carbon sequestration potential can vary based on ecological and management conditions (Chave *et al*., 2014).

This study indicated notable disparities in biomass accumulation across different tree species, with *Acacia abyssinica* demonstrating the highest biomass, succeeded by *Combretum molle, Terminalia macroptera, Acacia polyacantha, Gardenia ternifolia,* and *Croton macrostachyus.* On the other hand, species such as Calpurnia aurea, Maytenus arbutifolia, Clausena anisata, and Vernonia amygdalina contributed relatively less to the total biomass (Table 3). These differences can be attributed to different factors such as wood density, species size (height and DBH), species abundance, and the level of anthropogenic pressure in the area.(Agerie *et al*., 2019; Chave *et al*., 2014).

In the Tullu Qondala Exclosure, we noticed a remarkable dominance of just a handful of key species when it comes to aboveground biomass (AGB) and aboveground carbon (AGC) stocks. The top 10 species alone made up a whopping 90.18% of the total AGB and AGC, leaving the rest of the species with only a tiny contribution . This trend is consistent with what we've seen in other tropical and subtropical dry forests, where a small number of species tend to take the lead in storing carbon in the ecosystem, due to their larger size, denser wood (like Chave *et al*., 2014; Poorter *et al*., 2015).

There is a strong association between stand basal area and aboveground biomass in which they are directly influenced by the diameter of tree. The basal area increases with tree size, which in turn increase the aboveground biomass (AGB) and carbon (C) storage capacity (Agerie Nega *et al*., 2019; Brown, 2002). Larger and denser trees, such as *Ficus vasta*, accumulate more carbon in both aboveground (AG) and belowground (BG) forms relative to smaller species like *Vernonia amygdalina*, which showed the lowest carbon stock in the Tullu Qondala Exclosure (S2). This result is in agreement with similar studies that indicate tree size and wood density as important determinants of carbon sequestration potential (Gibbs *et al*., 2007).

Concerning the ecological and management effect, the presence of high-biomass species such as *Acacia abyssinica* and *Ficus vasta* highlights their ecological significance in carbon storage and ecosystem productivity. On the other hand, the lower contribution of species like *Vernonia amygdalina* could be attributed to their smaller size or lower wood density. Sustainable forest management strategies should focus the conservation of large, high-biomass species to enhance carbon sequestration, particularly in Exclosure systems that enable natural regeneration (Lemenih and Kassa, 2014). Moreover, reducing anthropogenic pressures like selective logging and grazing can increase biomass retention and carbon storage potential in these ecosystems (Aerts *et al*., 2007).

The AGB and C density of woody plant species in Plot 27 were significantly lower than those in the other sampled plots, while Plot 7 showed the highest amount (Figure 2). This difference could be attributed to the presence of several large-diameter trees in Plot 7, which may have a key role in its increased mean AGB and carbon stocks (Chave *et al*., 2014). Additionally, variation in woody species density and diameter distribution among the plots were observed as critical factors affecting carbon storage capacity (Basuki *et al*., 2009). The higher presence of mature, large-sized trees in Plot 7 likely increased its carbon sequestration potential, whereas the relatively lower tree density and smaller diameter classes in Plot 27 may be the reason for its lower biomass accumulation.

This study showed that the biomass density in Tullu Qondala Exclosure ranged from of 9.88 t/ha to 68.07 t/ha, with mean biomass carbon stock density of 34.142 ± 13.86 t/ha. The corresponding mean carbon dioxide equivalent was 125.3 ± 50.86 t/ha (Table 2). These results were higher than those reported in similar studies, such as (Haftom *et al*., 2019) in Southern Tigray, Northern Ethiopia (4.58 ± 3.75 t/ha), and (Abebe and Mekuria, 2021) in two exclosure sites in SNNPRS, Southern Ethiopia (4.37 ± 0.671 and 11 ± 2 t/ha). The variation in carbon stock density could be attributed to issues such as the occurrence of larger trees with greater basal area, higher woody species density, and the allometric model applied (Lasco and Pulhin, 2009).

The length of exclosure time significantly affects carbon stock density, as carbon stocks are directly related to biomass accumulation, and longer exclosure periods increase total biomass (Abebe and Mekuria, 2021). Activities such as afforestation and the restoration of degraded forest lands, together with effective management approaches, could enhance carbon stocks across major pools through sequestration (Lal, 2005). These activities could also play an important role in mitigating climate change by improving CO_2 sequestration.

In its Intended Nationally Determined Contribution (INDC), Ethiopia has promised to reduce greenhouse gas (GHG) emissions by 64% by 2030, relative to a situation where things just keep going as they are, which would lead to an impressive 255 $MTCO_2eq$. Particularly, the forestry sector is expected to contribute about 50.9% (or 130 $MTCO_2eq$) of the country's emissions (FDRE, 2015). This underlines how important it is to precisely assess the carbon storage potentials of Ethiopia's forest ecosystems.

Conclusion

This research assessed the biomass and total carbon stock of the Tullu Qondala Exclosure, found in West Shewa, Oromia, Ethiopia. The study site has faced degradation problem and been excluded from human and animal interference for more than 15 years. The findings showed that the exclosure has improved both biomass growth and soil carbon storage, indicating its importance as an effective restoration strategy for degraded landscapes. The results also showed that long-term exclosure practices enhance carbon sequestration in both aboveground and belowground biomass. The increase in carbon stock within the Tullu Qondala exclosure indicates its potential in addressing climate change. By changing degraded lands into exclosures, Ethiopia can enhance ecological recovery while increasing carbon stocks, coinciding with the national REDD+ goals..

Conflict of interest statement

The authors declare no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Supplementary information (S1)

List of woody plant species collected from study area

No	Scientific name	Family	Local name	Habit
1	*Acacia abyssinica*	Fabaceae	Laaftoo	Tree
2	*Acacia polyacanths*	Fabaceae	Harmukkoo	Tree
3	*Acacia seyal*	Fabaceae	Waaccuu	Tree
4	*Albizia schimperiana*	Fabaceae	Muka-arbaa	Tree
5	*Calpurnia aurea*	Fabaceae	Ceekaa	Shrub
6	*Carissa spinarum*	Apocynaceae	Agamsa	Shrub
7	*Clausena anisata*	Rutaceae	Ulmaayii	Shrub
8	*Combretum molle*	Combertaceae	Rukeessa	Tree
9	*Cordia africana Lam.*	Boraginaceae	Waddeessa	Tree
10	*Croton macrostachyus.*	Euphorbiaceae	Makkanniisa	Tree
11	*Dodonea angustifolia*	Sapindaceae	Ittacha	Shrub
12	*Ehertia cymosa Thonn.*	Boraginaceae	Ulaagaa	Tree
13	*Entada abyssinica*	Fabaceae	Ambaltaa	Tree
14	*Euclea divinorum Hiern*	Ebenaceae	Mi'eessaa	Shrub
15	*Ficus sur Forssk.*	Moraceae	Harbuu	Tree
16	*Ficus sycomorus L.*	Moraceae	Odaa	Tree
17	*Ficus vasta Forssk.*	Moraceae	Qilxuu	Tree
18	*Gardenia ternifolia*	Rubiaceae	Gambeela	Tree
19	*Grewia bicolorJuss*	Tiliaceae	Harooressa	Shrub
20	*Maytenus arbutifolia*	Celastraceae	Kombolcha	Tree
21	*Olea europea sub sp. Cuspidata*	Oleaceae	Ejersa	Tree
22	*Rhus natalensis*	Anacardiaceae	Xaaxessaa	Shrub
23	*Rhus vulgaris Meikle*	Anacardiaceae	Daboobessa	shrub
24	*Terminalia macroptera*	Combretaceae	Dabaqqaa	Tree
25	*Vernonia amygdalina Del.*	Asteraceae	Eebicha	Shrub
26	*Ximenia americana L.*	Olacaceae	Hudhaa	Shrub

Supplementary information (S2)

Mean AGB (Aboveground Biomass) and carbon stock per total and single tree species recorded from study site

No	Scientific name	Number of stems	Average DBH (cm)	Average height (m)	AGB/ Species (kg)	AGB/ Species (ton)	Carbon/ Species (ton)	Carbon/ Species (ton/ha)	Carbon/ single tree (ton)	CO2/ species (ton)	CO2/ species (ton/ha)	CO2/ single tree (ton)
1	*Acacia abyssinica*	225	16.77	6.2	18316.1	18.316	9.158	7.632	0.041	33.61	28.008	0.149
2	*Combretum molle*	454	12.69	5.62	11519.26	11.519	5.76	4.8	0.013	21.138	17.615	0.047
3	*Terminalia macroptera*	101	16.58	6.18	7949.417	7.949	3.975	3.312	0.039	14.587	12.156	0.144
4	*Acacia polyacanths*	57	18.2	7.64	6217.941	6.218	3.109	2.591	0.055	11.41	9.508	0.2
5	*Gardenia ternifolia*	63	17.09	5.67	3987.288	3.987	1.994	1.661	0.032	7.317	6.097	0.116
6	*Croton macrostachyus*	63	14.54	5.97	2560.14	2.56	1.28	1.067	0.02	4.698	3.915	0.075
7	*Cordia africana*	28	21.01	7.2	2067.199	2.067	1.034	0.861	0.037	3.793	3.161	0.135
8	*Entada abyssinica*	40	15.37	6.14	2030.412	2.03	1.015	0.846	0.025	3.726	3.105	0.093
9	*Ficus vasta Forssk.*	8	35.42	8.23	2002.814	2.003	1.001	0.835	0.125	3.675	3.063	0.459
10	*Ehertia cymosa*	75	11.51	5.06	1643.531	1.644	0.822	0.685	0.011	3.016	2.513	0.04
11	*Acacia seyal*	22	16.6	6.87	1175.019	1.175	0.588	0.49	0.027	2.156	1.797	0.098
12	*Albizia schimperiana*	24	14.2	6.06	893.069	0.893	0.447	0.372	0.019	1.639	1.366	0.068
13	*Ficus sur Forssk.*	5	30.34	7.23	815.4	0.815	0.408	0.34	0.082	1.496	1.247	0.299
14	*Grewia bicolor*	88	8.22	4.16	675.635	0.676	0.338	0.282	0.004	1.24	1.033	0.014

15	*Rhus vulgaris*	119	5.68	4.26	613.378	0.613	0.307	0.256	0.003	1.126	0.938	0.009
16	*Ficus sycomorus*	4	27.95	6.18	520.081	0.52	0.26	0.217	0.065	0.954	0.795	0.239
17	*Rhus natalensis*	63	6.25	4.57	419.147	0.419	0.21	0.175	0.003	0.769	0.641	0.012
18	*Carissa spinarum*	53	6.51	4.3	376.764	0.377	0.188	0.157	0.004	0.691	0.576	0.013
19	*Ximenia americana*	49	5.63	4.04	326.993	0.327	0.163	0.136	0.003	0.6	0.5	0.012
20	*Dodonaea angustifolia*	17	6.24	4.03	165.222	0.165	0.083	0.069	0.005	0.303	0.253	0.018
21	*Olea europea sub sp. Cuspidata*	8	7.45	5.25	81.805	0.082	0.041	0.034	0.005	0.15	0.125	0.019
22	*Euclea divinorum*	18	5.84	3.57	81.395	0.081	0.041	0.034	0.002	0.149	0.124	0.008
23	*Calpurnia aurea*	14	5.71	4.04	68.359	0.068	0.034	0.028	0.002	0.125	0.105	0.009
24	*Maytenus arbutifolia*	4	8.75	5.23	67.104	0.067	0.034	0.028	0.008	0.123	0.103	0.031
25	*Clausena anisata*	8	6.11	4.23	36.933	0.037	0.018	0.0154	0.002	0.068	0.0565	0.008
26	*Vernonia amygdalina*	9	6.05	4.39	36.346	0.036	0.018	0.0151	0.002	0.067	0.0556	0.007
	Mean				2486.41	2.49	1.24	1.04	0.02	4.56	3.8	0.09

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