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Comparative assessment of woody species diversity, structure and carbon stock of PFM and Non-PFM forests and its implication for REDD+ in Ethiopia

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ABSTRACT

Maintaining forest biodiversity and carbon sequestration potential of forest resources enhances the provision capacity of forest ecosystem services. Experience from around the world and in Ethiopia has shown that shifting forest management from state-centred to community-centred arrangement can result in a better forest stock. Therefore, this study examined the status of woody species diversity, regeneration and total living biomass carbon stock of forests under participatory forest management (PFM) and the adjacent state managed non-participatory forest management (Non-PFM) in South eastern Ethiopia and implications to REDD+. Data were collected from 89 (44 PFM and 45 Non-PFM) nested circular plots from four PFM and three Non-PFM selected forest sites with transects laid systematically. Tree DBH and height were measured, the number of saplings, seedlings, mature trees were counted and species names were recorded. Woody species diversity was estimated using shannon, simpson, and evenness diversity indices. A total of 29 and 23 woody species were recorded in PFM and Non-PFM forests, respectively. Woody species diversity did not show significant difference between PFM and Non-PFM forests but it was relatively higher in PFM forest. The density per hectare of seedlings, sapling and mature trees were significantly greater in PFM forest than in Non-PFM forest. The mean aboveground biomass carbon stock of PFM forest (225.50±26.54) was significantly greater than that of the Non-PFM (156.24 ±15.72) forest. Hence, managing forests through participatory approaches contributes to the enhancement of sustainable management and climate change mitigation potentials through reducing emission from deforestation and forest degradation.

1. Introduction

Forest has vital roles in global carbon cycle as a source and a sink of greenhouse gases (GHG) emissions (FAO, 2022). Forest ecosystems store an estimated 662 gigatons of carbon (FAO, 2020a), an amount more than the carbon content in the whole atmosphere (Balesdent et al., 2018). Out of the total loss of carbon through man-made and natural factors forest conversion and land use change make up 12 - 20 % of the annual GHG emission (Saatchi et al., 2011). Tropical forests get more attention in research due to its highest carbon pool as compared to other biomes (Ngo et al., 2013; Riutta et al., 2018). According to FAO (2020a), tropical forest ecosystems store high amounts of carbon which are estimated to be 45 % of the global carbon pool in forest ecosystems. However, deforestation in the tropics is currently the hotspot of global forest carbon and biodiversity loss. Feng et al. (2022) indicated that the mean annual tropical forest carbon loss during 2015–2019 which was 1.99 pentagram C/yr is more than doubled from that of 2001–2005, which was 0.97 pentagram C/yr. This is why there is currently a considerable attention on researching the storage and emission potential of CO_2 in tropical forest ecosystems.

About 21 % of the global forests carbon stock is in Africa (Abere et al., 2017). However, annual forest loss has significantly increased across tropical Africa by 38 % since 2001 (Feng et al., 2022). Africa lost 3.9 million ha/year of forest area between 2010 and 2020, which was

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higher than the rate during 2000–2010, which was 3.4 million ha/year (FAO, 2020a).

In Ethiopia, deforestation was estimated to be 92,000 ha/year during 2015–2020 (FAO, 2020b). Due to a large-scale deforestation and forest degradation, the forestry sector alone accounts for the total emission of about 37 % CO_2 in Ethiopia (CRGE, 2011). The most commonly mentioned factors for deforestation in Ethiopia are rapid population growth with an increasing need for arable land and wood for construction and fuel, political unrest, forest fires, the insecure land ownership system, inadequate conservation approaches and a lack of awareness (Kuma et al., 2022; Hussein, 2023; Wola, 2023).

It is argued that PFM is an approach that has the potential of ensuring sustainable forest management and better and equitable socio-economic benefits from forest resources (Islam et al., 2015; Gilmour, 2016; Wood et al., 2019; Sungusia et al., 2020; Girma et al., 2023). In Ethiopia, PFM is considered as an opportunity for the implementation of REDD+ activities as most PFM forest areas have by-laws, where the rural community already co-owned, managed, and benefited from forest and woodland resources within their forest area.

REDD+ is an initiative under the UNFCCC to reduce emission from deforestation and forest degradation and increases forest stock due to sustainable management and forest enhancement and conservation (Wood et al., 2019; Skutsch and Turnhout, 2020). The REDD+ policy process in Ethiopia is thus evolving as firmly embedded in the country's development strategy. Ethiopia became an official member of the UN-REDD Programme in June 2011 and instituted the national REDD+ Secretariat in 2013. In effect, the national REDD+ Secretariat is undertaking various activities to pave the way for the development and implementation of REDD+ policies and programmes in Ethiopia. In 2012, a Readiness Preparation Grant was approved by the World Bank's Forest Carbon Partnership Facility (FCPF) for Ethiopia to formulate the national REDD+ strategy and advance her readiness for REDD+ (Bekele et al., 2015). The national REDD+ strategy adopted PFM as a vehicle for implementing REDD+ projects (MEFCC, 2018), with a view that PFM would give REDD+ *a* strong grassroots institution to effectively address deforestation and forest degradation, and facilitate a socially acceptable, cost-effective way of using carbon revenue (UNEP, 2015).

However, the impact of PFM on forest conditions and its linkage to carbon sequestration potential and REDD+ implementation in Ethiopia has received little research attention (Beyene et al., 2013). Besides that, literature contradicts about effectiveness of PFM on enhancing forest conditions. For example, Takahashi and Todo (2012), Ameha et al. (2014a), Zerga et al. (2019), and Sungusia et al. (2020) demonstrated PFM to have improved forest conditions and reduced forest disturbances. On the other hand, Persha and Meshack (2016) reported no significant difference between forests under PFM and those under Non-PFM in terms of deforestation rates between 2000 and 2012. Therefore, empirical research to compare PFM and adjacent non-PFM forests on forest carbon stock, vegetation structure and composition and changes are inevitable especially in Ethiopia as the country prepare for large REDD+ implementation. Research results on this study provide additional knowledge of contribution of community participation in sustainable management of forests and maintaining climate change mitigation potential of forests.

2. Materials and methods

2.1. Description of the study area

Ethiopia is located in the horn of Africa between 3°−15° north and 33°- 48° east, and covers about 1.1 million km^2 area. The forest cover of Ethiopia is currently estimated at 17.1 million ha (15.7 % land cover) (FAO, 2020b). Its vegetation is broadly categorized into four biomes with expected homogeneous carbon contents for the purpose of carbon estimation (Acacia-Commiphora, Combretum-Terminalia, Dry Afromontane Forest and Moist Afromontane Forest) (EFRL, 2017).

The study was conducted in Adaba-Dodola forest, which is located in Adaba and Dodola Districts, south eastern Ethiopia. It is bordered by vast agricultural plains located at elevation of about 2400 m and surrounded by mountain ranges. Adaba-Dodola forest is located between 6°00′−7°50′N and 39°00′−39°50′E. It is the part of the northern slope of Bale mountains eco-region within the elevation range of 2400 m to 3500 m above sea level (Bekele et al., 2004) (Fig. 1). The forest size has progressively reduced from 140,000 ha in the early 1980s to 53,000 ha in 1997 due to agricultural expansion, extraction of wood and forest fire (Ameha et al., 2014b, 2016).

Since 2000, a restricted use right was granted and whose bylaws recognizes members of the communities living in and around the forest on some parts of the study forest area. The PFM was launched as a pilot project by organizing the community into forest dwellers associations and giving forest block contracts as forest user groups for forest conservation and sustainable utilization of forest products and services. Forest user groups developed their by-laws that govern forest management. The remaining parts of the natural forest and plantation forests are still managed by the state enterprise (Tesfaye, 2011; Ameha et al., 2016). Oromia Forest and Wildlife Enterprise (OFWE) is a state based forest enterprise mandated to administer and manage forest and wildlife in Oromia regional state. The study site was purposively selected because it is a pioneer PFM area that has a success implementation story in Ethiopia (Bekele et al., 2004). The sites have been used by development partners and the government of Ethiopia to pilot REDD+ project. In addition, the availability of forest areas still owned and managed by the state is another opportunity to measure the effect of community involvement in forest conservation.

The livelihoods in the area mainly depend on agriculture, forestry, and livestock production (Bekele et al., 2004; Tesfaye, 2011; Ameha et al., 2016). The main forest products harvested are fuelwood and charcoal, grass and tree fodder, and timber for construction (Ameha et al., 2016). However, the forest is undergoing rapid changes due to large-scale anthropogenic disturbances in the form of livestock browsing, grazing and trampling, agricultural land expansion, and illegal human settlement (Bazezew et al., 2015). Illegal harvesting of firewood, construction wood, and sawing timber are also commonly reported (Tesfaye, 2011).

2.2. Sampling and data collection

A detailed reconnaissance survey was conducted to identify the vegetation patterns and local conditions. Then, the study sites were selected purposively based on the representativeness of the forest area for PFM and Non-PFM forest which are close to each other and are found along the similar slope gradient and aspect. From both management approaches, seven (4 PFM and 3 Non-PFM) forest sites have been selected based on the area covered by forest and suitability for comparison. Accordingly, four forest sites covering about 8831 ha were sampled from PFM forest while three forest sites covering 16,696 ha of forest were sampled from Non-PFM forest for vegetation survey (Fig. 1).

An inventory was carried out using systematic sampling method in both PFM and Non-PFM sites. The distance between transect lines and plots were estimated to be 500 m (e.g. Worku et al., 2012; Meragiaw et al., 2018). The number of sample plots/quadrats for vegetation survey were calculated by Pearson formula (Pearson et al., 2005) (Eq. (1) and 2).

$$n = \frac{(N*S)^2}{\frac{N^2*E^2}{t^2} + N*S^2} \quad (1)$$

Where,

E = allowable error or the desired half width of the confidence interval. Calculated by multiplying the mean carbon stock derived from previous study

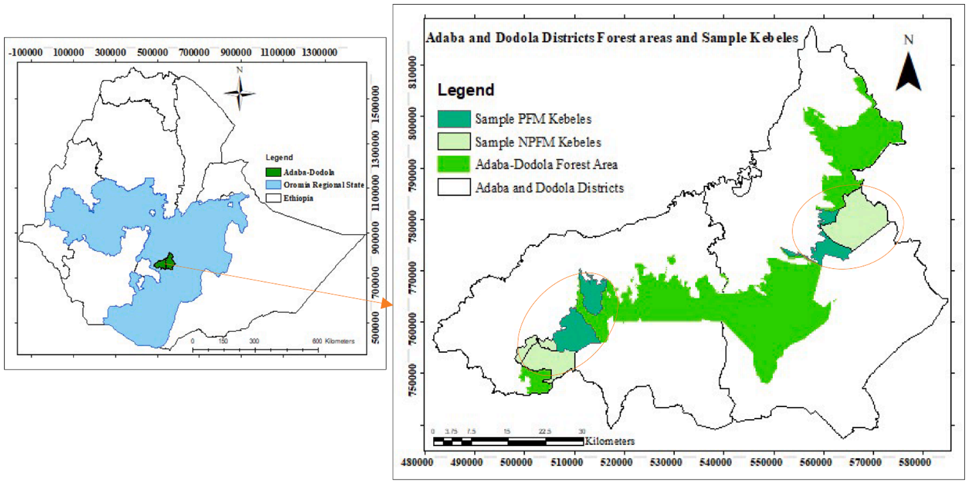

Fig. 1. Map of the study area with the sampled forest sites.

by Gebeyehu et al. *(2019) conducted in Awi dry afromontane forest the desired precision,* i.e., *mean carbon stock (191.6) * 0.03 (for 3 % precision),*

t = the sample statistic from the t-distribution for the 95 % confidence level; t usually is set at 2 as sample size is unknown at this stage,

S = standard deviation derived from previous study by Gebeyehu et al. (2019) *in Gera forest (19.7)*

N = Maximum possible number of sampling units in the population which were calculated as follow (Subedi et al., 2010) *(Eq. (2)).*

$$N = \frac{A}{AP} \tag{2}$$

Where,

*A= the total research area in ha (*8831 ha *PFM forest and 16,696 ha Non-PFM forest); AP = sample plot size in ha which will be 0.*1256 ha

Accordingly, vegetation data were collected from a total of 89 plots (44 plots in PFM and 45 plots in non-PFM forests). Nested circular plots of a 20 m radius were utilized since a circular plot is recommended for irregularly distributed trees in a natural forest (FSC, 2018; Kleinn et al., 2020) (Fig. 2). Vegetation data for the above ground biomass estimation were collected through three concentric circular quadrants with radii of 20, 14, and 4 m (Pearson et al., 2005; Van et al., 2016). Additionally, one circular plot with 2 m radius was established in the centre of the main plot for counting seedlings (< 1 m height), and saplings (1- 5 cm DBH and >1 m height) were counted within 4 m radius to estimate the regeneration status of the forests (Mukama et al., 2012; Abunie and Dalle, 2018).

In each plot, tree/shrub species name were recorded, tree/shrub height and DBH were measured by hypsometer and DBH meter or calliper, respectively from the three concentric circular quadrants with radii of 20, 14, and 4 m. Wood density was identified from MEFCC (2017) document and also from website of World Agroforestry Centre (http://db.worldagroforestry.org//wd, *accessed May 15, 2023*), for species not found in either databases, 0.58 g/cm^3 which is an average wood density for tropical forest in Africa was used (FAO, 1997). The vegetation data collection were conducted from April –November 2022.

2.3. Data analysis

2.3.1. Analysis of woody plants diversity, structure and regeneration status of the forest

Shannon-Weiner species diversity (H) was used to measure the proportion of each species in the forest, Simpson Diversity index (D) was used to measure level of biodiversity in the forest while evenness (E) was to measure commonness of species (Zerihun, 2012; Magurran, 2004). Woody species density was calculated by dividing the number of all individual woody species over the area in hectares (Worku et al., 2022).

The woody species structure of all species encountered in the samples were grouped into eight (8) diameter and seven (7) height equal classes. These are *Class I* =< 5 cm, *Class II* = *5*–25 cm, *Class III* = *26*–45 cm, *Class IV* = *46*–65 cm, *Class V* = *66*–85 cm, *Class VI* = *86*–105 cm, *Class VII* = *106*–125 cm, *Class VIII* = >126 cm DBH classes and *Class I* =< 4 m, *Class II* = *4*–10 m, *Class III* = *11*–15 m, *Class IV* = *16*–20 m, *Class V* = *21*–25 m, *Class VI* = *26*–30 m, *Class VII* = >30 m height classes.

The regeneration status were also derived from the total count of seedlings, saplings and adult trees from both PFM forests and Non-PFM forests.

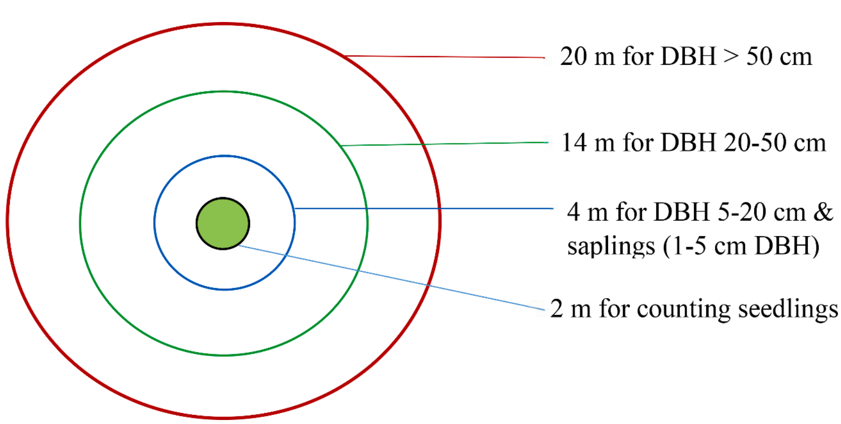

Fig. 2. Sample Plot size used for collecting vegetation data.

2.3.2. Estimation of above and below ground biomass carbon stock

The aboveground biomass (AGB) was estimated using Chave et al. (2014) which is commonly used for tropical Afromantane forests (Abere et al., 2017; Mamo, 2019; Sebrala et al., 2022) (Eq. (3)).

$$AGBest = 0.0673\ x\ (\rho D2H)\ 0.976 \quad (3)$$

Where,

ρ = wood specific density (g/cm^3), D =DBH (cm), H = tree height (m), AGB_{est} = Estimated above ground biomass (Kg). The calculated AGB of all trees in a plot were then summed and converted to Mg per hectare (Mg/ha).

Since the plot areas are part of the tropical and sub-tropical region, the biomass stock density of a sampling plot was converted to carbon stock densities after multiplication with the IPCC (2006) default carbon fraction of 0.47. The belowground biomass carbon of woody species (BGBC) was estimated following Picard et al. (2012) and FAO (2020a) where the belowground biomass carbon is 27 % of the aboveground biomass carbon in tropical dry forest. The total living biomass carbon stock was calculated following Pearson et al. (2005) formula. The total CO_2 equivalent captured in the above ground biomass and the below ground biomass was multiplied by 3.67 (Pearson et al., 2007; Mamo, 2019).

Finally, one-way ANOVA was performed to compare the mean differences in vegetation variables of PFM forest and Non-PFM forest. The mean difference was considered significant at ($p \leq 0.05$). The data were analysed by using R-software.

3. Results

3.1. Woody species diversity

A total of 31 woody species 29 in PFM and 23 in Non-PFM forests were identified in the study area (Appendix 1). Six species which occurred in only PFM forest indicated greater species richness in PFM than in Non-PFM forest. Two species were recorded in Non-PFM only of which one species called *Brucea antidysenterica* is mostly considered as an indicator of forest degradation.

There is no significant variation in species diversity and evenness between PFM and Non-PFM forests (Table 1). However, both Shannon and Simpson diversity indices show an incremental trend in PFM than in Non-PFM forests. Evenness was also relatively higher in PFM (0.51 ±0.06) than in Non-PFM (0.39±0.03) forests. This indicates that there is a better species diversity and evenness in PFM. This finding could be attributed to the repeated disturbances in Non-PFM forest by human activities such as illegal extraction of wood products for construction, charcoal production, firewood and farm utensils and livestock grazing. This leads to a loss of seedling of some species because of animal browsing and trampling and selective and illegal extraction of forest resources by the local people. This could lead to the dominance of certain species in Non-PFM forest than is the case in PFM forest.

3.2. Woody species structure

3.2.1. Stem density and species abundance

The average woody species stem density of the PFM forest were 5115 stems/ha and the average woody species density of Non-PFM forest were 2114 stems/ha. This result indicates that PFM forest site has more than double the number of individual stems than is the case with Non-PFM. Among the identified 29 woody species in PFM forest *Juniperus procera* (1552 stem/ha), *Olea europaea* (578 stem/ha) and *Podocarpus falcatus* (401 stem/ha) are the three highly abundant species, whereas *Myrsine melanophloeos* (567 stem/ha), *Maytenus undatus* (282 stem/ha) and *Juniperus procera* (266 stem/ha) are the top three abundant species in Non-PFM forest (Table 2). The difference in species abundances could be attributed to high human pressure on economically important trees such as *Juniperus procera, Olea europaea* and *Podocarpus falcatus* in Non-PFM forest.

Table 1
Woody species diversity of PFM and Non-PFM forests in Adaba-Dodola ($n = 89$).

Forest type	Shannon index	Simpson index	Evenness
PFM	1.96 ± 0.22	0.77 ± 0.08	0.51 ± 0.06
Non-PFM	1.52 ± 0.11	0.73 ± 0.03	0.39 ± 0.03
P-Value	0.119	0.610	0.116

3.2.2. Diameter class distribution

The forest structure in both PFM and Non-PFM forests showed an inverted J-shape for woody species diameter distribution (Fig. 3). That means, small sized stems are present in a large amounts while large size stems are present in small amounts.

The result from statistical separation shows that stems in DBH classes <5 cm and 5–25 cm are significantly greater ($P = 0.02$ and $P = 0.00$, respectively) under PFM forests as compared to diameter classes <5 cm and 5–25 cm of Non-PFM forest (Table 3). In DBH class 106–125 cm, there are significantly greater ($p = 0.012$) individuals in PFM forest than is the case in Non-PFM forest. However, in DBH Classes 46–65 cm and 66–85 cm, there is comparatively lower number of individuals in PFM than is the case in Non-PFM forest. The overall study indicated that forest structure in PFM is comparatively more stable than is in Non-PFM forest.

3.2.3. Height class distribution

Height can be used as an indicator of health, productivity and the age of forest stands. The height class distribution of both PFM and Non-PFM forests have the same inverted J-shape trend as the DBH class distribution but the density of stems within the same class is higher in PFM forest than in the Non-PFM forest (Fig. 4). An inverted J-shape distribution of height classes indicated an uninterrupted and good regeneration of woody species. More than 96 % of individual woody species in PFM forest were in the height Classes of <4 m and 4–10 cm while more than 94 % of individual species in the Non-PFM forest were within the same height Classes. A decrease in the number of individual trees/shrubs as height class increase towards the highest class shows that the small-sized stems are abundant in the forest, which is a characteristic of high rate of regeneration.

3.2.4. Regeneration status

The average density of seedlings, saplings, and mature woody plants in the studied PFM forest were 3619, 710 and 786 stems/ha, respectively. However, the density of adults was higher than the density of saplings in the PFM forest. The average density of seedlings, saplings, and adult woody species of the Non-PFM forest were 1610, 310 and 194 stems/ha, respectively. The result indicates that there are highly significant differences between PFM and Non-PFM forests in terms of the three variables called seedling ($P = 0.022$), sapling ($p = 0.01$) and adult ($p = 0.00$) trees and shrubs (Table 4). These results indicated that there is greater seedling recruitment for the future sustainability of the PFM

Table 2
Abundant woody species in both PFM and Non-PFM forests.

No.	Species Name	Density/ha	
		PFM	Non-PFM
1	*Juniperus procera* Hochst. ex Endl.	1552	266
2	*Olea europaea* subsp. *cuspidata* (Wall. ex G. Don) Cif.	578	8
3	*Podocarpus falcatus* (Thunb.) R.Br.ex Mirb.	401	100
4	*Maytenus senegalensis* (Lam.) Exell	371	163
5	*Myrsine africana* L.	343	54
6	*Maytenus undata* (Thunb.) Blakelock	269	282
7	*Dovyalis abyssinica* (A. Rich.) Warb.	235	208
8	*Osyris quadripartita* Salzm. Ex Decne	129	17
9	*Myrsine melanophloeos* (L.) R.Br.ex Sweet	74	567
10	*Olinia rochetiana* A.Juss.	34	1

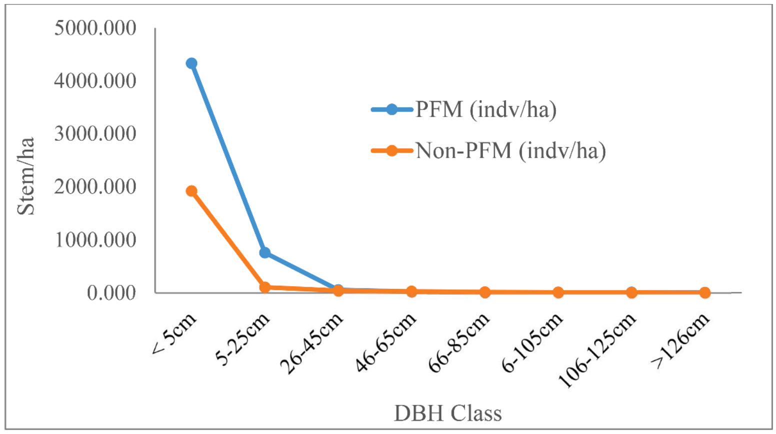

Fig. 3. DBH class distribution of PFM and Non-PFM forests from south eastern Ethiopia.

Table 3
Statistical variations among DBH classes in PFM and Non-PFM forests (Stems/ha).

Forest type	*DBH Classes*							
	< 5cm	5–25cm	26–45cm	46–65cm	66–85cm	86–105cm	106–125cm	>126cm
PFM	4329 ± 845.25	753 ± 130.4	52 ± 7.16	23 ± 2.91	10 ± 1.73	10±1.68	9 ± 1.68	4 ± 1.18
Non-PFM	1920 ± 413.72	103 ± 34.11	39 ± 5.81	25 ± 3.05	12 ± 2.46	7 ± 1.44	4 ± 1.00	4 ± 1.00
P-value	0.012**	0.000**	0.146	0.645	0.394	0.145	0.012*	0.859

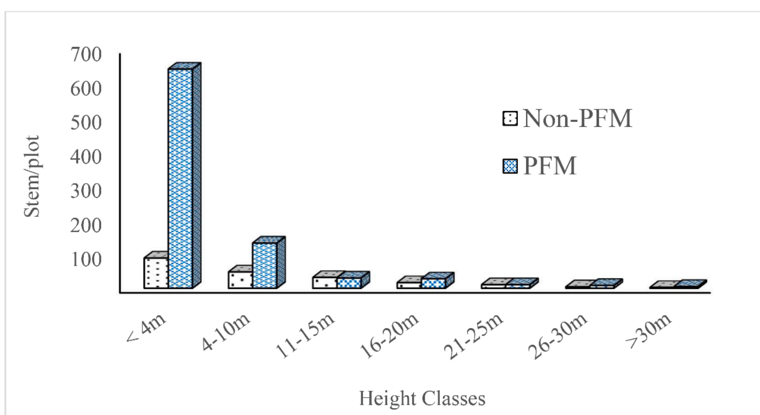

Fig. 4. Height class distribution of PFM and Non-PFM forests from south eastern Ethiopia.

Table 4
Distribution and density of seedlings, saplings and mature trees in PFM and Non-PFM forests ($n = 89$).

Forest type	Seedlings (stems/ha)	Saplings (stems/ha)	Mature trees (stems/ha)
PFM	3619 ± 789	710 ± 117	786 ± 99
Non-PFM	1610 ± 358	310 ± 97	194 ± 35
P-Value	0.022*	0.010**	0.000**

forest. Therefore, the forest area which is under community management has significantly better potential for sustainability.

3.3. Aboveground and belowground biomass and carbon stock

The mean total living biomass carbon stock and its CO_2 equivalent in PFM were 225.5 t/ha and 827.6 t/ha respectively, while the mean total living biomass carbon stock and its CO_2 equivalent in Non-PFM forests were 156.2 t/ha and 573.4 t/ha respectively. The difference of 69.3 t/ha carbon density and 254.2 t/ha CO_2 equivalent was the one to be considered as the difference made due to the better management practices of PFM forest by the local community. There is a statistically significant difference ($p = 0.026$) between PFM and Non-PFM forests in terms of the mean aboveground carbon stock (AGCS), the belowground carbon stock (BGCS), total living biomass carbon stock (TLBCS), and CO_2 equivalent of TLBCS (Table 5). This indicated that community-based management of stand structure would enhance biomass carbon stock.

The result of the study indicated that PFM forest have sequestered significant higher amount of carbon ($P = 0.026$) compared to Non-PFM forest (Table 5). The total biomass carbon stock CO_2 equivalent in PFM forest was 827.6 tCO_2 eq/ha whereas in the adjacent Non-PFM, it was 573.4 tCO_2 eq/ha. The differences in CO_2 equivalent of 254.2 tCO_2 eq/ha (44.3 % of Non-PFM) was the contribution of PFM in reducing CO_2 emission and enhancing carbon storage over Non-PFM. This result indicated that community forests have significant effect in avoiding carbon emission than is case with the state managed forests.

Table 5
Aboveground and belowground biomass and carbon stock of PFM and Non-PFM forests (ton/ha).

Forest type	AGB	AGCS	BGB	BGCS	Total LBCS	TLBCS CO_2 equiv.
PFM	377.8 ± 44.48	177.6 ± 20.90	102 ± 12	47.9 ± 5.64	225.5 ± 26.54	827.6 ± 97.4
Non-PFM	261.7 ± 26.34	123.02 ± 12.38	70.7 ± 7.1	33.2 ± 3.34	156.2 ± 15.72	573.4 ± 57.69
P-Value	0.026*	0.026*	0.026*	0.026*	0.026*	0.026*

Note: AGB = above ground biomass, AGCS = above ground carbon stock, BGB = below ground biomass, BGCS = below ground carbon stock, LBCS = Living biomass carbon stock, TLBCS = Total living biomass carbon stock.

3.4. Distribution of total living biomass carbon stock with species DBH class

For the purpose of this study, the plant species greater than or equal to 5 cm were categorized into seven DBH classes. Non-PFM forest shows greater carbon density than PFM forest at DBH classes of 46–65 cm and 66–85 cm (Fig. 5). This could be due to intensive forest logging in PFM blocks before the establishment of PFM of cooperatives and transfer of forest ownership to the local community.

4. Discussion

4.1. Woody species diversity

The overall result of the study indicated that PFM has better performance as compared to Non-PFM in terms of species diversity, stem density, species structural distribution, species regeneration and biomass carbon density. This could be due to over exploitation of forest resources from Non-PFM forest due to weak management practices observed during forest survey work. Similar studies observed that PFM has better species composition, species richness and distribution, regeneration, and carbon stock of forests (Baral and Katzensteiner, 2009; Newton et al., 2015; Basnet et al., 2018; Poudyal et al., 2019; Wood et al., 2019). A similar study conducted in south west Ethiopia also indicated that PFM results in positive impacts on forest condition as compared to Non-PFM forests (Takahashi and Todo, 2012)

Even though the difference is not statistically significant, the finding of this study on species diversity and richness is similar to the findings of previous studies conducted in Ethiopia and other countries which reported that woody species diversity and richness is higher in PFM forests than in Non-PFM forests (Blomley and Iddi, 2009; Gobeze et al., 2009; Ameha et al., 2014b; Tadesse et al., 2016; Basnet et al., 2018; Girma et al., 2023). The result of studies by Alemayhu and Tesfaye (2019) and Tadesse et al. (2016) also demonstrated that PFM forests had higher species diversity and more distribution of plant species than was the case with Non-PFM forest. A study by Poudyal et al. (2019) on the effect of forest management regimes in Nepal found that a greater number of tree species and species diversity occurred in PFM forests compared to forests in protected area and natural forests, which are Non-PFM. Astbah et al. (2019), also reported that the loss of seedling for some species could happen due to browsing and trampling by grazing herbivores and selective extraction of woods by the local people. In contrast, Anup (2017) observed that PFM forests were significantly poorer as compared to the Non-PFM forests in species richness and diversity. This could be because of special conservation attention given to certain economically and socially important trees by forest user groups and free intensive grazing practices in some PFM forests.

4.2. Stem density and species abundance

The mean stem density in PFM and Non-PFM forest was 5115 stems/ha and 2114 stems/ha, respectively. The difference is more than double; this could be because of repeated habitat disturbances in Non-PFM forest due to frequent and intensive interference of humans and livestock for grazing and other communal uses. A similar study conducted in Ethiopia indicated that forest under PFM has high number of average stem density than was the case with Non-PFM forest (Alemayhu and Tesfaye, 2019). However, the result of this study is in contrast with the finding in a study by Paudel and Sah (2015) who reported lower stem density in PFM forest than was the case in the neighbouring Non-PFM forest. This could be because of the differences in the management practices implemented in the PFM forests in different location and community commitment to manage the forests. Ecological disturbance by human and livestock also affect the abundance of certain species in a forest and leads to the dominance of certain species in the Non-PFM than in PFM forest. Similarly, Shrestha and McManus (2006) observed that community managed forests are dominated by few species promoted by the forest user groups for their social, economic, and political values. Baral and Katzensteiner (2009) also observed that PFM activities have affected plant community composition and distribution. Additionally, Wolde and Tadesse (2019) revealed the occurrence of illegal tree cuttings in Non-PFM forest at night which target certain tree species.

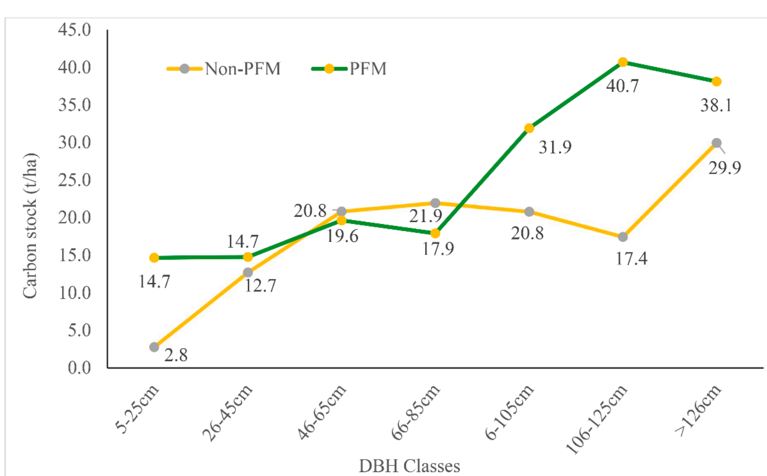

Fig. 5. Trends of Carbon stock (t/ha) in relation to DBH Class in PFM and Non-PFM Forest.

4.3. Regeneration status

The result from statistical separation shows that stems in DBH classes <5 cm and 5–25 cm are significantly greater under PFM forests (Table 3). This result could be because of higher human and livestock interference in Non-PFM forest which subdues the growth and survival of young tree/shrubs. The result of this study is also similar with the result of a study by Alemayhu and Tesfaye (2019) that reported PFM forest has a greater number of individuals across different DBH classes than the case with Non-PFM forest. However, in DBH classes 66–85 cm and 86–105 cm of this study there is comparatively lower number of individuals in PFM than is the case with Non-PFM forest. This could be due to selective logging of trees when they reach a certain DBH range mostly for round woods or poles for construction and timbers. Two of the dominant tree species in the study area *Juniperus procera* and *Podocarpus falcatus* processed for durable round wood and timber when they reach larger DBH of greater than 60 cm. Similar reports indicated that local people have their own criteria of cutting down trees for different purposes (Getaneh, 2007; Tadesse et al., 2016; Atsbha et al., 2019). A decrease in the number of individual trees/shrubs as height class increase towards the highest class shows that the small sized individuals are dominant in the forest, which is a characteristic of high rate of regeneration (Boz and Maryo, 2020). An inverted J-shape distribution of height classes indicated an uninterrupted and good regeneration of woody species in both PFM and Non-PFM forests (Atsbah et al., 2019; Worku et al., 2022). However, the number of individuals in each height classes are comparatively higher in PFM forest than in Non-PFM forest.

PFM forest harbour significantly higher number of seedlings, saplings and adult individuals than is the case with Non-PFM forest. This could be due to regulated access for forest products, controlled grazing and enclosure of forest areas by forest user groups in PFM forests. However, there is no enrichment planting in either PFM or Non-PFM forests. This result is similar to the result in study by Paudel and Sah (2015) that indicated higher number of seedlings in PFM forest than in Non-PFM forest. Baral and Katzensteiner (2009) also observed that PFM activities have positively affected age class distribution of the trees as compared to Non-PFM forest. Moreover, an open floor in PFM forest create a good condition for seedling natural regeneration (Paudel and Sah, 2015). Similarly, Alemayehu and Tesfaye (2019) indicated that regeneration of the forest under PFM management has exhibited higher number of seedlings and saplings as compared to the forest under Non-PFM. Also, forests under PFM management has a high number of average matured tree density than is the case with Non-PFM forests. However, based on a recommended determination of regeneration status used by Mengistu et al. (2023), which determine regeneration as "good" if there is the presence of seedling > sapling > adult trees and "fair" if there is the presence of seedling > sapling < adult trees, the regeneration status of PFM forest is fair while that of Non-PFM forest is good.

4.4. Implication for REDD+

Tropical forests are the major category of global forest loss and their destruction accelerates climate change due to the release of CO_2 to the atmosphere. Therefore, REDD+ is an important international mechanism of tackling deforestation and reducing the amounts of GHG emissions to mitigate the effects of climate change (UN-REDD, 2015). The climate debate is about reducing the concentration of GHG in the atmosphere. This includes improving all sinks and reducing all sources of GHG. The forest resources could be a sink in the form of total forest carbon stock through improving the total forest area and the carbon per hectare of forest or could be a source for CO_2 emission in the form of deforestation and forest degradation due to human and natural factors. However, PFM contributes to the emission reduction through supporting the reduction of causes of deforestation and degradation. Key elements for successful community forestry include effective decentralized forest management, improved technical and administrative capacity, clear tenure over land and forests and clarification of benefit sharing mechanisms. Therefore, PFM is a key strategy to strengthen REDD+ implementation (Bekele et al., 2015).

The significant differences in total biomass carbon stock in the PFM and Non-PFM forests of Adaba-dodola area (Table 5) could be because of the activities that reduce the negative change on a forest and/or the activities that enhance the negative changes on forest areas. The result of the study indicates that transferring forest resources to local community could lead to improve forest management resulting in regulated forest access, great sense of ownership, improved forest protection, and improved income from forest and to the betterment of forest condition and carbon storage potential. This could be considered as an opportunity for better implementation of REDD+. PFM forests in this study provided a greater sink of CO_2 by 44.3 % over Non-PFM forest in total living biomass.

Carbon stock assessment results revealed that there is a significantly higher biomass carbon density in the PFM forest than is the case in the Non-PFM forest with a difference of 69.3t/ha of carbon density which is 254.2t/ha CO_2 equivalent. Similar studies indicated the mean biomass and carbon stock is higher in PFM forest (Wood et al., 2019; Subedi et al., 2022). A comparative analysis from forests in Myanmar indicated that there is significantly higher above ground biomass in PFM forests (Basnet et al., 2018). Newton et al. (2015) also revealed that PFM in many countries demonstrated greater carbon sequestration. Another comparative study by Gurung et al. (2015) indicated that PFM forest had higher above and below ground carbon density than was the case with Non-PFM forest, which is managed by the government. Gebeyehu et al. (2019) in northern Ethiopia also reported that proper management of stand structure would enhance biomass carbon stock. Higher carbon density in PFM forest than in the Non-PFM forest could be due to effective management interventions (Gurung et al., 2015). Therefore, this finding suggests that reducing emission from deforestation and forest degradation through REDD+ programme is promising through a community-based forest management approach.

5. Conclusion and recommendation

Understanding the effect of different forest management approaches on woody species diversity, structure and biomass carbon density is crucial in order to make inferences about options for sustainable forest management. In this study, significantly greater amounts of carbon stock were recorded in the aboveground and the belowground biomass of woody species in the PFM forest than was the case in the adjacent Non-PFM. Significantly, greater density of seedling and saplings in PFM forest is an indicator for future potential of PFM forest in sustaining the regenerative capacity and to improve carbon storage capacity of the forest than in Non-PFM forest. Stem density was also significantly higher in PFM forest than Non-PFM forest. The abundance of economically important tree species in PFM indicated that Non-PFM forest are highly susceptible to selective logging of some species. PFM forest has the potential of reducing emission or sink of CO_2 by 44.3 % over Non-PFM forest. Generally, the forest which is managed by the local community through PFM have an important contribution for woody species conservation and carbon sequestration to contribute for REDD+ implementation pillars than the forest area managed by the state.

Based on the results from this study: (1) transferring forest areas managed by the government to community-based cooperatives could be the best option for effective implementation of REDD+. (2) Investigating the reason behind selective decline in selected species abundance at certain age should be a focus of future studies. Finally, (3) additional investigations are important on the forest governance and livelihood aspect of participatory management in the study area.

CRediT authorship contribution statement

Lemma Tiki: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Motuma Tolera:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Jumanneh M. Abdallah:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kristina Marquardt:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix 1. Woody plant species recorded in PFM and Non-PFM forests

No.	Species Name	Local Name	PFM	Non-PFM
1	*Allophylus abyssinicus* (Hochst.) Radlk.	Hirkamu	+	–
2	*Bersama abyssinica* Fresen.	Horoka	+	+
3	*Brucea antidysenterica J.F.Mill.*	Chirofta	–	+
4	*Buddleja polystachya* Fresen.	Bulchana	+	+
5	*Carissa spinarum* L.	Agamsa	+	–
6	*Discopodium penninervum* Hochst.	Mararo	+	+
7	*Dombeya torrida* (J.F.Gmel.) Bamps	Danisa	+	–
8	*Dovyalis abyssinica* (A. Rich.) Warb.	Koshimo	+	+
9	*Ekebergia capensis* Sparrm.	Anonu	+	–
10	*Galiniera saxifraga (*Hochst.) Bridson	Korala	+	+
11	*Hagenia abyssinica* (Bruce) J.F.Gmel	Heto	+	+
12	*Hypericum revolutum* Vahl.	Garamba	+	+
13	*Ilex mitis (L.) Radlk.*	Amshika	–	+
14	*Juniperus procera* Hochst. ex Endl.	Hindhesa Biya	+	+
15	*maytenus senegalensis* (Lam.) Exell	Hacaacii	+	+
16	*Maytenus undata* (Thunb.) Blakelock	Kombolcha	+	+
17	*Myrica salicifolia* Hochst. Ex. A.Rich.	Tona/Barodo	+	–
18	*Myrsine africana* L.	Kechema	+	+
19	*Myrsine melanophloeos (L.)* R.Br.ex Sweet	Tula	+	+
20	*Nuxia congesta* R. Br. ex Fresen.	Bitana	+	+
21	*Olea europaea* subsp. *cuspidata* (Wall. ex G. Don) Cif.	Ejersa	+	+
22	*Olinia rochetiana* A.Juss.	Guna/Dalacho	+	+
23	*Oncoba spinosa* Forssk.	Kokolfa	+	–
24	*Osyris quadripartita* Salzm. Ex Decne	Wato	+	+
25	*Pittosporum abyssinicum* Delile	Ara	+	+
26	*Podocarpus falcatus* (Thunb.) R.Br.ex Mirb.	Birbirsa	+	+
27	*Rhamnus staddo* A. Rich.	Kadida	+	+
28	*Rhus glutinosa* Hochst. ex A. Rich.	Tatessa	+	–
29	*Schefflera abyssinica (*Hochst. ex A. Rich.) Harms	Gatame	+	–
30	*Schefflera volkensii* (Engl.) Harms	Ansha	+	+
31	*Vernonia myriantha Hook.f.*	Reji	+	+

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