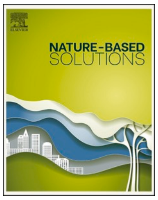
Nature-Based Solutions 4 (2023) 100079

Contents lists available at ScienceDirect

Nature-Based Solutions

journal homepage: www.elsevier.com/locate/nbsj



The potential of traditional agroforestry practices as nature-based carbon sinks in Ethiopia

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A R T I C L E I N F O

Keywords:
Biomass carbon
Climate change
Greenhouse gasses
Land management, soil carbon

A B S T R A C T

Traditional agroforestry practices have economic, social, and environmental benefits to sustain human and ecological systems. The demand for short-term economic benefit has derived from the traditional agroforestry practices towards monoculture cash crop production in the tropics. This study aimed to assess the greenhouse gas emission reduction capacity of traditional agroforestry systems concerning biomass and soil carbon stocks in the districts of Amhara Region, Ethiopia. From three agroforestry practices, namely, multistory, woodlots, and parkland, 300 smallholder farmers' farms were randomly selected to carry out vegetation inventory and 180 farms for litter and soil sampling. The soil samples were taken the depths 0–20 cm, 20–40 cm, and 40–60 cm. The biomass of all woody plants was estimated using already developed allometric equations. The mean total biomass carbon sink of multistory is 40.7 ton ha^{-1} which was significantly ($p < 0.001$) higher than woodlot, 20.8 ton ha^{-1}, and parkland 5.4 ton ha^{-1}. The mean total ecosystem (biomass plus soil) carbon of the multistory, 199.5 ton ha^{-1} was significantly ($p < 0.001$) higher than woodlot, 134.4 ton ha^{-1}, and parkland, 108.0 ton ha^{-1}. Soil organic carbon stocks accounted for 72–88, 83–88, and 92–98% of the total ecosystem carbon is stored in multistory, woodlot, and parkland, respectively. The study revealed that agroforestry practices could contribute to carbon sinks in the biomass and soils making it one of the nature-based solutions to climate change mitigation. This reduces greenhouse gas emissions and hence enhances the climate change mitigation and adaptation roles of the existing land uses.

Introduction

Anthropogenic activities are contributing to climate change through increasing greenhouse gas (GHG) emissions to the atmosphere. Agriculture is a source of GHG emissions, but agroforestry has the potential to sequester carbon and mitigate agricultural GHG emissions [1] . Agroforestry practices could reduce the emission of Methane (CH_4), Nitrous Oxide (N_2O), and Carbon Dioxide (CO_2) respiration from the soil, but few studies have examined these realities. Agroforestry systems are common features in different agricultural landscapes. Tree-based landscapes have an important role in climate change mitigation programs and policies such as Reducing Emissions from Deforestation and Forest Degradation (REDD+).

The inclusion of trees in croplands and pasturelands through agroforestry practices could lead to reduced GHG emissions into the atmosphere in three ways. First, trees provide greater above- and belowground biomass compared to herbaceous vegetation and almost 50% of the dry mass is carbon [2]. Second, trees increase the total fine root production, rhizoid position, and litter fall, which could promote organic carbon sequestration in soil [3,4]. Third, the system may not only increase total ecosystem carbon storage but also reduce emissions of GHGs such as CH_4 and N_2O from soils [1,5-8]. The focus of this study was on the third approach which is hardly researched in the Ethiopian context.

Forest and grassland cover types reduce net GHG emissions from agricultural soils. Insights of evidence are now emerging that agroforestry systems are found to increase aboveground and soil carbon stock and play both adaptation and mitigation roles. The Intergovernmental Panel on Climate Change (IPCC) has reported that agroforestry can perform a key role in the era of global climate change due to its carbon sequestration ability. However, the potential of trees on farmlands to sequester carbon depends upon the woody species composition, ages of trees, geographic location, agro-ecological conditions (climate, altitude, and wind), management regimes, and soil characteristics [9–12].

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https://doi.org/10.1016/j.nbsj.2023.100079
Received 17 April 2023; Received in revised form 4 July 2023; Accepted 14 July 2023

Besides, there is limited empirical data to support the implementation of agroforestry practices for carbon sequestration as a means of nature-based solution in climate change mitigation and building the wellbeing of the communities. This data gap may contribute to the lack of evidence-based policymaking that supports the use of agroforestry for carbon sinks in the Ethiopian landscape. Traditional agroforestry (TAF) could contribute to GHG emissions reduction. Therefore, the objective of this research was to quantify the potential of traditional agroforestry (TAF) practices for carbon sequestration in Ethiopia specific to three selected districts in the Amhara region.

Material and methods

Sit description

The study was conducted in three districts, namely, Gozamen, Gubalafto, and Jabitehnan, of the Amhara region, which are characterized by widely practiced traditional agroforestry (TAF) which is used as the basis for selection of the districts. The most common agroforestry practices in these districts are multistory agroforestry (MAF), woodlot (WAF) and parkland agroforestry (PAF). The districts are located at 10°1′ 46″ to10° 35′ 12″ N and 37° 23′ 45″ to 37° 55′ 52″ E, 10°40′N and 37°11′E and 11°34′54’’and 11° 58′59’’N and 39°6′9″ and 39°45′58’’ E, respectively. Jabitehnan and Gozamen distract are found in the southwest Amhara region with an altitudinal range of 1200 to 3510 m.a.s.l. having three agro-climatic zones, namely, Dega, Woina-Dega, and Kola [13]. While the Gubalafto district is found in the eastern Amhara Region. It has a mountainous landscape, hills and valleys, and varied altitudes ranging from 1300 to 3900 m.a.s.l. (Fig. 1).

In the period 1988 to 2018, the mean temperatures of the study sites were17.7 °C for Gozamen, 20 °C for Gubalafto, and 21.5 °C for Jabitehnan. All study sites have bimodal rainfall, with a mean annual rainfall of 1017.3 mm for Gubalafto, 1139.6 mm for Jabitehnan, and 1338.4 mm for Gozamen.

Sampling design and techniques

The smallholders’ cultural practices in multistory agroforestry (MAF) include growing of trees for timber and fruits in upper story, perennial cash crops at middle story and different herbs at the under story. The cash crop plants are mostly coffee, gesho and khat having an irregular spacing. Farmers apply cow dung to the cash crops followed by weed slashing. They convert agricultural and communal lands to MAF due to the high economic return from the latter. In the woodlot agroforestry practice, farmers establish small sized plantation, especially Eucalyptus spp., using close spacing of nearly two meter. The spacing of trees in MAF and parkland agroforestry (PAF) varies with the component species to allow space for understory crops.

Reconnaissance survey was conducted with woreda experts and local communities for identifying potential sites, then randomization was applied to select the three districts from the list of potential traditional agroforestry practicing districts followed by identification of inventory sites. There were 2024, 1645 and 1812 smallholder farmers practicing TAF in Gozamen, Jabitehnan and Gobalafto districts, respectively. Then after, representative samples of 300 farms (50 farms x 6 sites) were randomly selected for woody species inventory and 180 farms (30 farms x 6 sites) were used for soil, herb, and liter data collection. Plot sizes were determined based on the characteristics of TAF type and land size allocated to it by farmers. For woody species inventory two 50 samples plots were randomly laid in systematically selected 50 smallholder farms in each district on which TAF practices were implemented. The plot sizes were 20 m x 20 m for multistory agroforestry (MAF) practices (including coffee, khat, gesho, and fruit-based systems), 50 m x 100 m for parkland agroforestry (PAF) practices, and 10 m x10 m for woodlot agroforestry (WAF) practices.

The soil samples were collected from five 1 m x 1 m sub-plots (four at the corner and one at the center) in the main plots. Three soil depths of 0–20 cm, 20–40 cm, and 40–60 cm were taken for soil sample. Total soil organic carbon (SOC) in Mg ha^{-1} for each depth was calculated based on SOC concentration (SOC%), soil layer thickness (z meters), and bulk density (ρ Mg m^{-3}) of the samples [14].

The location of plots was determined based on Negash’s approach to the selected farm[15]. The selected plot was then pined in the field by using a global positioning system (GPS). Altitude, slope, aspect, and site history, such as the previous land use systems on the site, were also obtained by interviewing farmers and by measurement, and then

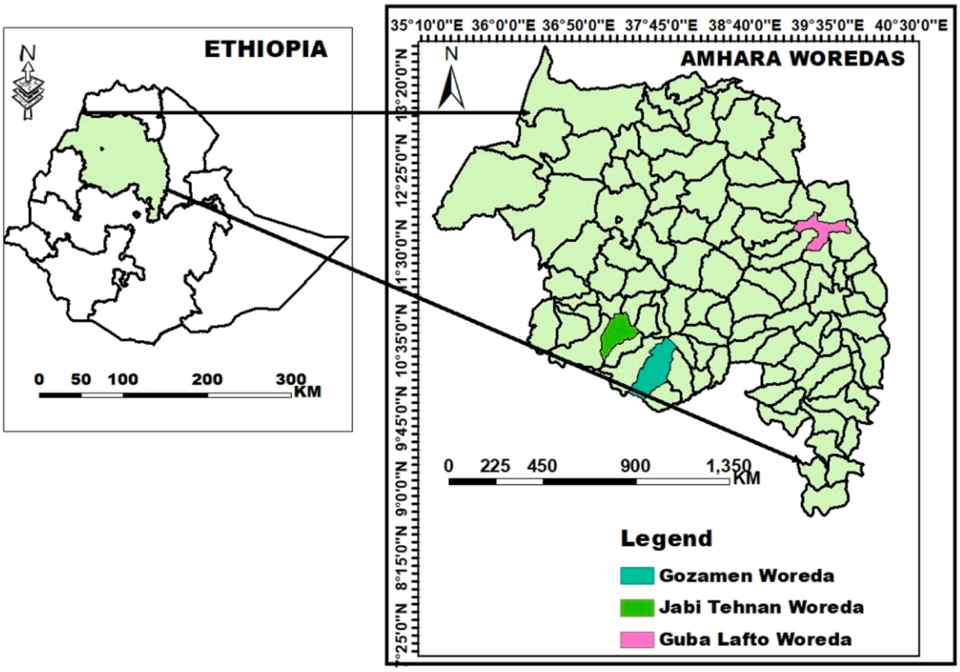

Fig. 1. Map of the study site.

recorded in data sheet. The replicates were randomly distributed independently across the districts. The average farm size of MAF was 0.45, 0.36, and 0.20 ha in Jabitehenan, Gozamen, and Gubalafto districts, respectively.

Data collection

According to IPCC [16], samples were selected from each type of agroforestry practice. From the samples, emissions/removals data was collected from biomass, dead organic matter, soil carbon, and non-CO_2 GHGs emissions from livestock population, application of inorganic fertilizer, and biomass burning.

Woody species inventory

All woody species $\geq$ 2.5 cm diameter at breast height (dbh) and total height (h) $\geq$ 1.5 m within the sample plots were measured and recorded. For coffee, stump diameter at 40 cm height aboveground (d_{40}), and for *enset, gesho* and *khat* plant basal diameter at 10 cm height (d_{10}) were measured and recorded. A shrub was defined as a woody perennial with multiple stems $\geq$2.5 cm dbh and height $\geq$1.5 m, without a dominant stem [17]. Name of species, dbh, total height, life forms (tree or shrub), establishment method (retained or planted), and native/non-native species were recorded in data sheet. All stem diameters (dbh, d_{40}, and d_{10}) were measured in two perpendicular directions and averaged. The diameter equivalent equation was used for multi-stemmed individual woody plants having more than one stem [18].

$$de = \sqrt{\sum_{i=1}^{n} di^2} \tag{1}$$

where: de is the diameter equivalent (at breast or stump height) in centimeters; d_i is the diameter of the i^{th} stump or breast height in centimeters. Plant species identification using their vernacular names was conducted with the help of the key informants and checked using the floras of Ethiopia and Eritrea [19,20].

Litter, herb, and grass sampling

Litter, herb, and grass samples were collected from 1 m x 1 m subplot within the larger plot. A total of five sub-plots (four at the corners and one in the center) were used. In each plot, five samples of litter, herb, and grass were collected and placed in a plastic bag to measure the fresh weight. A composite subsample of 200 g was taken for each sample to the laboratory [21].

Soil sampling

The soil sampling was carried out both for bulk density and soil carbon stock analysis. A total of 90 soil samples were collected from the 30 plots used for woody species inventory in each district. Soils samples were collected using soil auger and core sampler after all herb and litter materials were collected by digging 60 cm pit and were mixed to obtain composite sample for each plot, for soil carbon and soil bulk density, respectively [22,4].

Non-CO_2 emissions

Non-CO_2 GHGs usually involve an emission rate from a source directly to the atmosphere. The rate is generally determined by an emission factor for a specific gas (e.g., CH_4, NO_2) and source category and an area (e.g., soil or area burnt), population (e.g., livestock), or mass (e.g., biomass or manure) that defines the emission source. To calculate the total emission of non-CO_2 gasses, subcategories in the agriculture sector, such as manure management, rice cultivation, synthetic fertilizers, manure applied to soils, crop residues, cultivation of organic soils, burning crop residues, and energy use in agriculture [23] and cropland land use types were assessed [16]. Therefore, data for the number and type of animals within the system of particular farmland, type of crop, area burnt in cropland, cultivated area of rice, amount of nitrogen fertilizer applied in farmland (within the system), and emission factors were considered. The fertilizer application rate varies from district to district based on soil and climate characteristics as well as the type of crop. The rate, on average, ranges from 103 to 362 kg/ha in Gozamen, 150–165 kg/ha in Gubalafto and 138–352 kg/ha in Jabitehnan versus a single recommendation for all crops of 200 kg/ha at national level, 100 kg/ha each of DAP and urea [24].

Non-CO_2 emission (emission from livestock, burning of crop residue and inorganic fertilizer) data were analyzed based on methods of Tier 1 inventories and the default emission factors using the equation Em = A*EF. Where; Em is non-CO2 emissions, tonnes of the Non-CO_2 gas; A is activity data relating to the emission source (can be area, animal numbers or mass unit, depending on the source type); and EF is emission factor for a specific gas and source category, tonnes per unit of A.

Data analysis

The IPCC [16] approach was used to estimate non-CO_2 emissions to the atmosphere by applying the EX-ACT (V8.5.4b) tools for the estimation and analysis of emissions from crop residues, livestock, and manure management and use of inorganic fertilizer. After emission was determined, statistical techniques like ANOVA, frequency, and chi-square were used to describe, compare and test results from different categories. One-way ANOVA was used to test differences in stand structure, biomass carbon, and soil carbon stock between the TAF practices.

Determination of biomass carbon stocks

Appropriate allometric models were chosen on their suitability to the farming sites where the equations were developed are similar to our study sites (Table 1). Wood density values (oven-dry mass per unit of green volume) for each species were taken from a global database [25] and varied between 0.32 g cm^{-3} (*Carica papaya*) and0.70 g cm^{-3} (*Olea europaea)* under the range that used in the development of the equation [26]. The model also had a high coefficient of determination and a lower Akaike information criterion (AIC) value.

The expansion factor was calculated in hectare (ha) divided by the area of the sample in square meters. Hence, the biomass density was calculated by multiplying the dry mass by an expansion factor calculated

Table 1
Different equations used for the determination of biomass for the different species.

Species	Equation	R^2	d (cm)	% C	Sources
All woody species.	$AGB=0.225d^{2.341} x\ \rho^{0.73}$	0.98	>2.5	48	[26]
	$BGB=0.490AGB^{0.923}$	0.95	>10	48	[27]
	BGB=0.28xAGB		<10	48	[27]
Coffee(*coffee arebica*)	$AGB=0.147d_{40}^2$	0.8	>3.8	49	[28]
	BGB=0.28xAGB		<10	48	[27]
Khat (*Catha edulis* & Gesho (*Rhamnus prinoides*)	$AGB=0.4796d_{10}^{1.5818}\ dh^{0.1089}$	0.97	>2.5	48	[29]
	BGB=0.28xAGB		<10		[27]
Enset(*Enset vetricosum*)	$lnAGB=6.57+2.316ln(d_{10})+0.124ln(dh)$	0.91	>20	47	[30]
	$BGB=7 \times 10^{-6}\ d_{10}^{4.082}$	0.68	>20	47	[30]
Banana (*Musa* spp.)	AGB=−6415+2.940lnd	0.8	>10	48	[31]
	BGB=0.24xAGB		>10	48	[31]
Eucalyptus camaldulnesis	$AGB=0.0155(d^2(2.5823))$ >5			50	[32]
	BGB= 0.26xAGB			50	[33]

Where: AGB is the aboveground biomass of plans (kg dry matter/plant), d is the diameter at breast height (cm); and ρ is species wood density (g cm^{-3}), BGB is the belowground biomass of plants, d_{40} and d_{10}= stem diameter at 40 and 10 cm height.

from the sample plot size [14]. For the estimation of litter biomass carbon stock, the sub-samples taken in the field were used to determine the oven-dry to fresh weight ratio [21]. Total aboveground biomass carbon stocks were calculated as the sum of all woody plants (tree, coffee, khat, gesho, and litter) and the total belowground biomass carbon stocks is the sum of the carbon stocks associated with all woody plant stumps and coarse roots. Total biomass carbon stocks are defined as the sum of the total aboveground and belowground biomass carbon stocks.

Total SOC t ha^{-1} for each depth was calculated based on SOC concentration (SOC%), soil layer thickness (z meters) and bulk density (ρ t m^{-3}) of the samples by Eq. (2) [34].

$$\text{TotalSOCtha}^{-1} = \text{SOC}(\%) \times \rho\left(\text{Mgm}^{-3}\right) \times \text{z(meters)} \times 10,000 \tag{2}$$

The soil organic carbon (SOC) stock values for the three layers (0–20 cm, 20–40 cm, and 40–60 cm) were summed to give the SOC stock for the entire 0–60 cm layer. Carbon stocks from agroforestry are defined as the sum of the total biomass carbon and SOC (0–60 cm) stocks.

Determination of litter and soil organic carbon contents

The carbon content (%) of the khat and litter biomass samples was determined from organic matter contents through loss-on-ignition (LOI) at 550 °C for 2 h, assuming that 50% of the organic matter was lost through burning is carbon content [35]. The litter biomass organic matter contents in MAF, WAF, and PAF (residues) were estimated at 71, 70, and 66%, respectively. Multiplying these values by 50% resulted in litter carbon valued at 32% for MAF, 29% for WAF, and 28% for PAF.

The soil samples for soil organic carbon analysis that was collected from the field were air-dried, mixed well, and passed through 2 mm sieve for chemical analysis [21]. Walkley-Black analysis for soil organic carbon [36] was conducted at Gonder Soil Laboratory. Bulk density was determined by dividing the core samples in an oven at 105 °C of soil weight and dividing it by the volume of the core sampler by volumetric method. The carbon stock density of soil organic carbon was calculated as Eqs. (3) and 4 [14].

$$\text{SOC}\left(\text{Mgha}^{-1}\right) = \left[\left(\text{soilbulkdensity}, \left(\text{g}/\text{m}^3\right) \times \text{soildepth(m)} \times \text{C\%}\right)\right] * 100 \tag{3}$$

The calculation of the bulk density of the mineral soil was calculated as in Eq. (4).

$$\text{Bulk density}\ \left(\text{g}/\text{m}^3\right) = \frac{\text{oven} - \text{dry mass}\ \left(\text{g/m}^3\right)}{\text{core volume}\ \left(m^3\right)\left[\frac{\text{Mass of coarse fragments (g/m3}}{\text{density of rock fragments}\ \left(\text{g/m}^3\right)}\right]} \tag{4}$$

where: The bulk density is for the ⟨ 2 mm fraction, and coarse fragments are ⟩ 2 mm. The density of rock fragments is often given as 2.65 g/cm^3.

Results

Stand characteristics of traditional agroforestry

The basal area and stem per hectare were significantly ($p < 0.01$) different between the three studied agroforestry practices in each district. They were the highest in MAF, followed by WAF, and least in PAF in the study sites, but DBH was inversely observed (Table 2). The stem density of native woody species accounted for 8–13% and 100% of the total in the MAF and PAF, respectively. The basal area of native woody species shared 34–51% of the total in MAF. This shows that the basal area is influenced by tree diameter rather than stem density.

Soil characteristics

The textural classes of soil were not only varied across the studied sites but also within agroforestry practices in each study site. Clay loam, sand clay loam, and clay are dominantly found in Gozamen, Gubalafto, and Jabitehnahn districts, respectively. The mean of soil bulk density was relatively lower in MAF, followed by WAF, and higher in PAF across each study site (Table 3).

Biomass carbon stock across agroforestry practices

The total biomass carbon stock significantly ($p < 0.05$) varies between the three traditional agroforestry practices in each district (Table 4). The mean biomass carbon storage capacity was the highest in multistory, which ranges from 24.7 to 60.6 Mg C ha^{-1}, followed by woodlot 14.6–23.9Mg C ha^{-1} and parkland 2.8- 8.1 Mg C ha^{-1} across the three districts. Aboveground biomass carbon accounted for, on average, 72%, 76%, and 76% with the ranges from 70 to 73%, 74–78%, and 70–80% of the total biomass carbon sinks for the three studied agroforestry practices in Gozamen, Gubalafto, and Jabitehnan districts, respectively.

There was conversion of PAF to MAF and WAF in the study areas. The conversion of PAF to MAF and WAF could improve the carbon captured from the atmosphere through total biomass growth by 1.9 to 20.5 and 1.8 to 4.2 times, respectively. The contribution of cash crops to mean total carbon stocks is 23% of total carbon biomass stocks in MAF. The litter plus herb biomass carbon contributions were 8.8%, 6.7%, and 4.2% in MAF in Gozamen, Gubalafto, and Jabitehnan districts, respectively. The woodlot litter plus herb biomass carbon, respectively, share 12%, 7%, and 8% in Jabitehnan, Gubalafto, and Gozamen districts.

Soil organic carbon in agroforestry

The soil organic carbon storage in MAF significantly ($p < 0.001$) varied from the WAF and PAF practices across the districts (Table 5).

Table 2
The stand characteristics of the three studied systems (mean ± SD).

		Stand Characteristic					
Districts	AFS(N=100)	DBH^2(cm)	DSH^1(cm)	BA(m^2ha^{-1})	H(m)	Stem No/ha	Age(year)
Gozamen	Multistory	16.3±3.4^b	7.2±2.4	23.1±14.3^b	3.25±0.9	5038.7±1502.9^b	11.1±4.3
	Parkland	32.4±11.8^c	–	5.97±6.7^a	9.04±4.6	56.9±37.7^a	–
	Woodlot	9.6±3.9^a	–	43.29±26.3^c	9.38±3.1	4914.4±595.9^b	9.6±4.3
	P	<0.001	–	<0.001	<0.00	<0.001	
Gubalafto	Multistory	15.76±8.6^b	7.7±1.7	27.49±18.6^b	3.69±0.6	4764±1546.6^c	12.1±3.9
	Parkland	15.11±6^b	–	2.86±2.4^a	7.25±2.6	86.21±43.9^a-	
	woodlot	11.95±4.6^a	–	32.86±17.9^c	11.30±4.9	3410±1143.8^b	11.4±6.1
	P	<0.05	–	<0.001		<0.001	
Jabitehnan	Multistory	19.26±5.3^b	7.5±0.95	26.58±13.2^c	4.4±1.1	4696.20±1223.8^b	13.3±4.5
	Parkland	21.77±11.2^b	–	2.79±1.9^a	6.59±3.7	52.27±35.0^a	–
	Woodlot	6.69±1.3^a	–	20.02±6.6^b	9.8±2.2	5091.11±335.1^c	11.2±5.4
	P	<0.001	–	<0.001		<0.001	

Note: DSH= diameter at stump height; BA = basal area; DBH =diameter at breast height; H= height.

Table 3
The soil physicochemical properties of the three studied TAFS in the districts.

			Physicochemical properties of soils							
Districts	AFS	Depth	PH	%OC	%TN	SBD	Sand%	Silt%	Clay%	Texture Class
Gozamen	MAF	0–20	5.8	3.7	0.29	0.93	30.5	30.3	39.2	Clay Loam
		20–40	5.9	3.0	0.24	0.96	29.6	33.2	37.2	Clay Loam
		40–60	5.8	1.7	0.14	0.99	25.6	42.2	35.2	Clay Loam
	PAF	0–20	5.4	2.2	0.14	1.02	33.6	33.6	32.8	Clay Loam
		20–40	5.5	1.6	0.10	1.01	36.3	30.9	32.9	Clay Loam
		40–60	5.8	1.2	0.08	1.01	35.2	26.6	38.2	Clay Loam
	WAF	0–20	5.5	2.2	0.18	0.92	34.0	36.0	30.0	Clay Loam
		20–40	6.1	2.0	0.16	0.94	38.0	37.0	25.0	Loam
		40–60	5.4	1.5	0.12	0.95	32.0	31.5	36.5	Clay Loam
Gubalafto	MAF	0–20	7.1	3.2	0.26	0.95	59.9	22.1	18.0	Sandy Loam
		20–40	7.7	2.3	0.18	0.99	47.9	28.1	24.0	Loam
		40–60	7.8	1.8	0.15	1.04	49.2	29.1	21.8	Loam
	PLAFS	0–20	7.8	1.6	0.10	1.20	65.0	28.0	7.0	Sandy Loam
		20–40	7.9	1.4	0.09	1.28	54.5	28.5	17.0	Sandy Loam
		40–60	7.9	1.3	0.08	1.31	69.5	26.0	4.5	Sandy Loam
	WAF	0–20	7.5	2.4	0.19	1.00	67.4	20.6	12.0	Sandy Loam
		20–40	7.5	1.8	0.14	1.04	56.3	25.0	18.7	Sandy Loam
		40–60	7.5	1.5	0.12	1.05	59.0	25.3	15.7	Sandy Loam
Jabitehnan	MAF	0–20	6.7	3.7	0.29	0.96	27.3	24.1	48.7	Clay
		20–40	6.8	2.4	0.20	0.99	27.8	25.3	46.9	Clay
		40–60	6.8	1.7	0.14	1.02	28.3	24.6	47.2	Clay
	PAF	0–20	5.2	2.5	0.16	1.08	30.8	28.4	40.8	Clay
		20–40	5.6	1.7	0.11	1.09	27.2	26.0	46.8	Clay
		40–60	6.0	1.3	0.09	1.10	32.4	25.2	42.4	Clay
	WAF	0–20	5.6	2.8	0.22	0.95	24.6	20.3	55.1	Clay
		20–40	5.5	2.1	0.17	0.98	20.8	25.6	53.6	Clay
		40–60	5.5	1.4	0.12	1.00	18.0	22.8	59.2	Clay

Note: *MAF = multistory agroforestry systems; PAF = parkland agroforestry systems; WAF = Woodlot agroforestry systems; SBD = soil bulk density.*

Table 4
The biomass carbon stored in TAFS in each district (Mean ± SD (t C ha^{-1}).

Districts	AFS	AGBC	BGBC	Herb	Liter	TBC
Gozamen	Multistory	17.9 ±12.6	4.6 ±3.3	0.79 ±0.2	1.4 ±0.9	24.7 ±16.8^{b}
	Parkland	5.7±1.8	2.4 ±0.6	–	–	8.1±2.4^{a}
	Woodlot	17.1 ±9.6	4.5 ±2.5	0.35 ±0.1	1.6 ±0.8	23.6 ±12.1^{b}
Gubalafto	Multistory	27.1 ±17.3	7.0 ±4.5	0.77 ±0.4	1.7 ±0.7	36.7 ±22.8^{c}
	Parkland	3.8±1.2	1.5 ±0.2	–	–	5.3±1.4^{a}
	Woodlot	17.6 ±12	4.6 ±3.1	0.68 ±0.5	1.1 ±0.4	23.9 ±16.1^{b}
Jabitehnan	Multistory	46.5 ±17.1	12.1 ±4.4	0.46 ±0.6	1.6±1	60.7 ±23.5^{c}
	Parkland	2.2±0.9	0.6 ±0.2	–	–	2.8±1.1^{a}
	Woodlot	10.2 ±6.7	2.7 ±1.7	0.27 ±0.1	1.5 ±0.8	14.6 ±8.4^{b}

Note: AGBC = aboveground biomass Carbon; BGBC = belowground biomass Carbon; TBC = total biomass Carbon.

The highest mean soil carbon was found in MAF (156.2 to 180.2 tC ha^{-1}) followed by WAF (109.4 to 115.1 t C ha^{-1}) and PAF (97.9 to 111.5 Mg C ha^{-1}). Of the total SOC (0–60 cm), the surface layer (0–20 cm), on average, contributed 48.9% in MAF, 52.5% in PAF, and 50% in WAF across the districts.

Total carbon stock in traditional agroforestry

Table 5
Soil carbon stock in the TAFS in each district (mean ± SD (ton C ha^{-1}).

Districts	Soil depths	Agroforestry systems			F	P value
		Multistory	Parkland	Woodlot		
Gozamen	0–20	79.1 ±12.0^{b}	51.8 ±12.9^{a}	50.6 ±14.5^{a}	30.8	0.001
	20–40	49.1 ±11.7^{b}	32.1 ±12.6^{a}	33.9 ±7.9^{a}	35.4	0.001
	40–60	28.9 ±11.7^{cb}	20.5 ±9.2^{a}	24.9 ±10.5^{ab}	6.6	0.03
	0–60	**157.1 ±30.0^{b}**	**104.4 ±30.6^{a}**	**109.4 ±20.7^{a}**	34.7	0.001
Gubalafto	0–20	76.4 ±19.8^{b}	45.4 ±12.1^{a}	57.2 ±14.2^{a}	16.9	0.001
	20–40	48.5±9.8^{b}	32.5 ±10.9^{a}	37.4 ±16.8^{a}	8.1	0.03
	40–60	31.3±11.7	20.0 ±11.5	20.5 ±14.9	4.9	0.01
	0–60	**156.2 ±30.9^{b}**	**97.9 ±33.3^{a}**	**115.1 ±45.3^{a}**	13.1	0.001
Jabitehnan	0–20	85.8 ±12.4^{b}	59.9 ±11.9^{a}	57.9 ±9.7^{a}	21.7	0.001
	20–40	58.9±8.5^{b}	34.3 ±8.8^{a}	36.9 ±8.2^{a}	15.2	0.001
	40–60	36.5±6.4^{b}	21.3 ±5.2^{a}	23.7 ±6.7^{a}	10.9	0.003
	0–60	**180.2 ±21.6^{b}**	**111.5 ±18.6^{a}**	**117.6 ±19.6^{a}**	32.7	0.001

The mean total carbon stocks significantly ($p < 0.01$) varied among the three agroforestry practices (Fig. 2). The total carbon stock in MAF > WAF > PAF in all the three districts. The highest total carbon stock was recorded in MAF (186.8 ± 52.7 to 240.9 ± 56.11 t C ha^{-1}), followed by WAF (118.5 ± 32.6 to 139±38.3t carbon ha^{-1}) and PAF (103.2 ± 33.4 to 116.8 ± 27.9t C ha^{-1}). The SOC accounted for 73–86%, 83–88%, and 92–98% of the mean total carbon stocks in MAF, WAF, and PAF across the districts, respectively.

Emission from synthetic fertilizer

On average, 1.5–2.4 tCO_2e ha^{-1} yr^{-1} and 0.57–2.2 tCO_2e ha^{-1} yr^{-1} were emitted during maize and wheat production through inorganic fertilizer, respectively (Fig. 3 and Table 6). Farmers used extra DAP and UREA from recommended rate and this has contributed up to 75% and

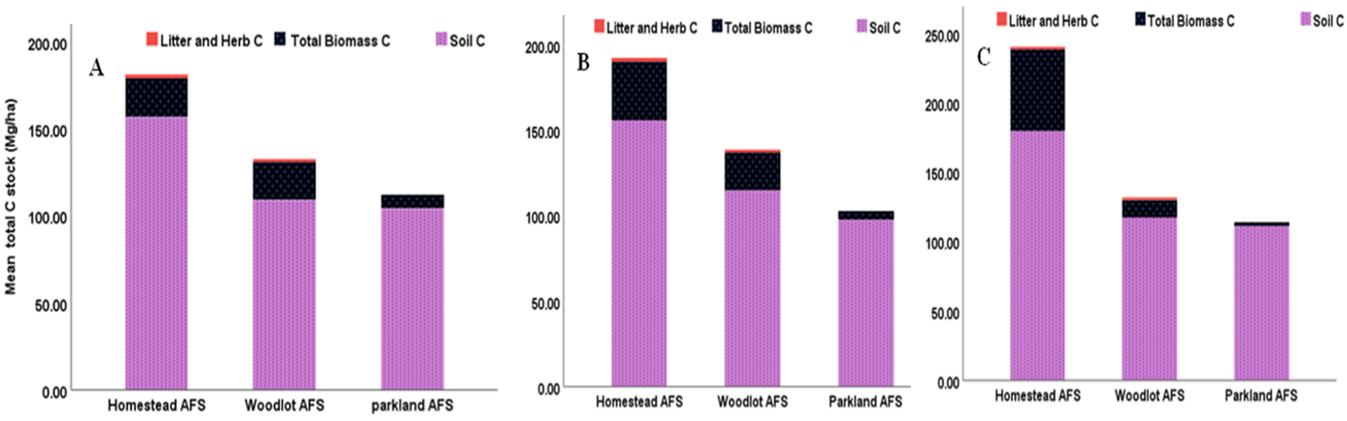

Fig. 2. The mean total C stocks of the three TAFS (A) Gozamen, (B) Gubalafto, (C) Jabitehnan).

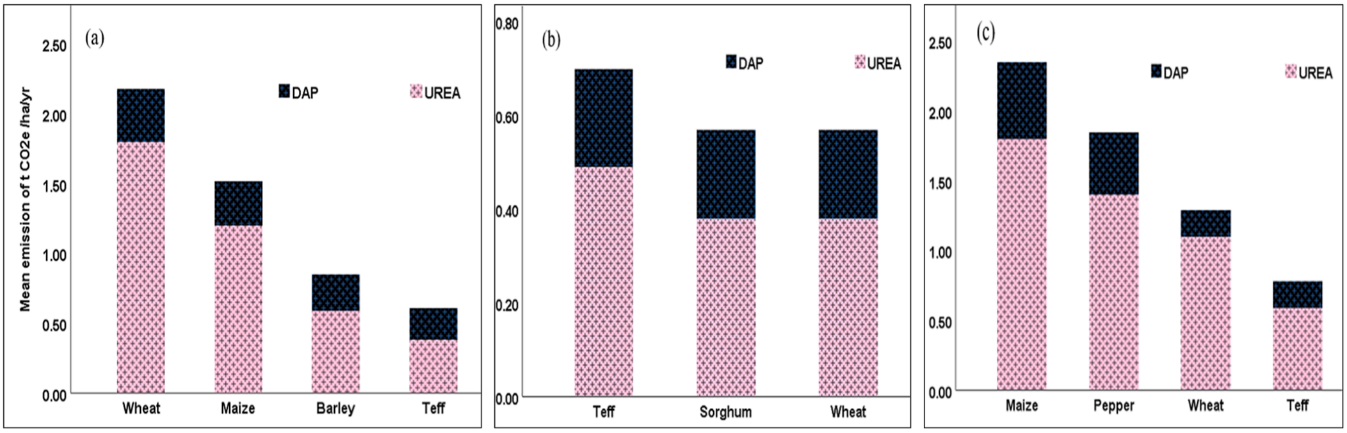

Fig. 3. The mean CO_2e source of emission from the use of synthetic fertilizer to PAFP in Gozamen (a), Gubalafto (b), and Jabitehnan (c) districts.

Table 6
Emission ($tCO_2e\ HH^{-1}yr^{-1}$) from livestock production and use of synthetic fertilizer application.

Districts	Statistics	Livestock production	Synthetic fertilizer
Gozamen	Minimum	4.5	0.39
	Maximum	35.6	2.8
	Mean±SD	11.3±5.3	1.82±0.45
Gubalafto	Minimum	2.4	0.26
	Maximum	7	1.1
	Mean±SD	6.4±3.3	0.37±0.12
Jabitehnan	Minimum	2.6	0.45
	Maximum	16	2.4
	Mean±SD	5.6±3.6	1.75±0.42

25% of GHG emissions, respectively. Sixty-three percent of the GHG emission from pepper cultivation, 44% from maize, and 22% from teff and wheat cultivation, urea accounted for 62–83%, 67–70% and 67–85% of total emissions from the use of synthetic fertilizer in the smallholder farmers in Gozamen, Gubalafto, and Jabitehnan, respectively (Fig. 3). The CO_2e emission from residues and firewood is also considerable (Fig. 4).

The results show that about 18% and 10% of dairy cattle crossbreed from the total dairy cattle in the Jabitehnan and Gubalafto districts, respectively. This has contributed to 9.4% and 4.2% emission reduction from the source. The main causes of variation were the number of livestock, feeding production system, and type of livestock.

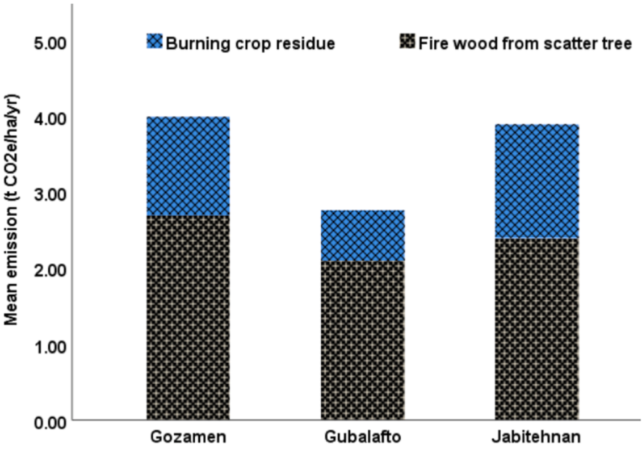

Fig. 4. The mean CO_2e emission from burning of crop residues and firewood.

Discussions

Biomass carbon stock in traditional agroforestry systems

In each district, the variation in biomass carbon was significantly different between TAF ($p < 0.05$). The variation may be due to climate parameters (temperature and precipitation), soil management, and application of input. The results show that biomass and carbon storage largely depends on the agroforestry system in place, the structure and function, which are, to a great extent, determined by environmental and socioeconomic factors. Other factors influencing carbon storage in agroforestry systems are mean annual increment, which varied with the size, age, density, and nature of tree species, agronomic management practices and plantation, as well as the quality of planting stock. Studies show that carbon storage varied from 12 to 228 Mg C ha^{-1} in humid tropical eco-regions and from 68 to 81 Mg C ha^{-1} in dry lowlands [37]. Similarly, in a semiarid region of India, biomass carbon storage varied from 7.12 to 57.03 Mg C ha^{-1} in different agroforestry practices [10].

In this study, trees in agroforestry have accounted for 61–79% of the carbon storage, which was on average 73% of the carbon in MAF. Likewise, Henry et al. [38] 55–81%, Negash and Starr [39]77%, and Betemariyam *et al.* [40] 67- 85% of carbon storage were reported form agroforestry practices. In the study area, the mean range of MAF was 24.7–60.7 Mg C ha^{-1} across the study districts while other studies in the tropical agroforestry [41–43] have come up with 21–63.5 Mg ha^{-1}. Furthermore, other studies conducted by Betemariyam *et al.* [40] and Mohammed and Bekele [44] found 63.1 Mg ha^{-1} and 58..3 Mg ha^{-1} of coffee-based AFS in southwest Ethiopia, respectively.

The biomass carbon storage potential of AFS in the southeastern rift valley of Ethiopia was estimated at the range of 46–78 Mg C ha^{-1} [39]. This result was higher than the total biomass carbon stock found in MAF in this study. The variation may be due to number of trees, age, the diameter size of trees, and management types. In the same token, 9.6 - 109.7 Mg C ha^{-1} TBC stocks were found among the smallholdings AFS. This result was in line with the global figure of 12–228 Mg ha^{-1} in the AFS [45–47] and 22–122 Mg C ha^{-1} of indigenous AFS in the southeastern rift valley of Ethiopia [39]. MTAFS have a mean of 90.3 to 220.2 t CO_2e ha^{-1} total biomass C stocks reduction capacity among the smallholdings. That was an estimated 0.56–8.6 Mg CO_2e ha^{-1}yr^{-1}C sequestration rate across the sites. Similar reports have shown 219.15 t CO_2e ha^{-1} in indigenous AFS in southeast Ethiopia [48].

The PAF has lower biomass carbon stock (2.8–8.7 Mg ha^{-1}) as compared to MAF and WAF practices across study sites. The study by Pellikka et al. [2] in Kenya has found 2.3 to 9.1 t C ha^{-1} for PAF practices.

Soil organic carbon stock in traditional agroforestry

The MAF soil organic carbon stock was significantly ($P< 0.001$) higher than PAF and WAF across the study sites (Table 5). The SOC stocks (0–60 cm depth) was found in the range of 104–225 Mg ha^{-1}in smallholder farmers' farms. Other studies have shown the range of 109–253 Mg ha^{-1}in indigenous agroforestry in the rift valley landscape of Ethiopia [39] and 14 to 253 Mg C ha^{-1}in dry afromontane forest ecosystems in the Amhara Region [49]. The overall mean of MAF (164.2 ± 21.6 Mg C ha^{-1}) is also comparable with 150.6 ± 6.9 7 Mg ha^{-1} of indigenous agroforestry systems in southeastern Ethiopia [48,50]. The study in homegarden agroforestry and coffee-based agroforestry systems in southwestern Ethiopia [40] showed the mean of 131.86±13.88 Mg C ha^{-1}. The variations may be due to tree composition, site characteristics, management practices, soil condition, climate, system age, and land-use history. The conversion from PAF to MAF practices shows a substantially accumulated mean of 18 to 41% carbon at 0–20 cm soil depth across the study sites (Table 5). The mean carbon difference significantly varied from 25 to 39% between MAF and PAF at 0–60 cm depth, where the highest and least carbon was recorded in the Gozamen and Jabitehnan, respectively. The variation may be due to the frequent application of cow dung and compost, and management practices (hoeing, mulching, and watering). Research findings indicated cropland converted to agroforestry has shown significant increase of 26% in soil carbon stock [51]. In other studies, incorporating trees on land leads to an increase in SOC stocks [52,4]. This is associated with the amount and characteristic of litter and annual herbs in the MAF practices. Nair et al. [4] ranked SOC stocks as follows: forests > agroforests > tree plantations > arable crops while in this study the pattern is agroforestry > woodlot > parkland. According to De Stefano and Jacobson [51], among agroforestry systems, positive significant increases of SOC stocks were observed in the change from agriculture to agrisilviculture (0–15, 0–30, 0–100 cm), agriculture to agrosilvopastoral systems (0–60, 0–100 cm), and agriculture to silvopasture (0–100 cm).

Total carbon storage

The accumulation of carbon in agroforestry practices varied from practice to practice as well as from site to site (Fig. 3). The variation may be due to climate, soil management, and application of organic and inorganic inputs. These factors affect the growth of plant roots and the decomposition of the litter in the soil. The highest range of total carbon stock was found in the MAF (121–302 Mg C ha^{-1}), followed by WAF (59–242 Mg C ha^{-1}), and the least in PAF (51–183 Mg C ha^{-1}). The kind of tree species grown and composition of systems, harvesting frequency of biomass yield from the system, and use of different agronomic practices could affect the carbon stock. The MAF has stored, on average, 683.3–784.6 t CO_2e ha^{-1}. That means, it has the potential to reduce 13.4 to 36.5 Mg CO_2e ha^{-1} yr^{-1} (27.7 ± 10.6 Mg CO_2e ha^{-1} yr^{-1}) from the atmosphere. Agroforestry in southeastern Ethiopia found to have a mitigation potential of 772.02 Mg CO_2e ha^{-1} [48], on average, 27.2 ± 13.5 Mg CO_2e ha^{-1} yr^{-1} [7] as compared to 6–22 Mg CO_2e ha^{-1} yr^{-1} in agroforestry systems in east and west Africa [53]. The greater total carbon stock densities were found in MAF, probably due to the presence of large trees, litter production, fast decomposition of litter, and recovery of SOC stocks after shifting to MAF.

Soil organic carbon has a substantial role in carbon sequestration potential in all agroforestry practices in the study sites. The results have shown that from the total carbon storage, MAF has contributed for 72–88%, WAF for 83–88%, and PAF for 92–98%. Indeed, in another study SOC has found to contribute 52–91% of the total carbon in MAF [39]. A coffee-based system has contributed 56–70% of the total carbon stock [41].

Conforming to the definition of the International Union for the Conservation of Nature and the United Nations Environment Assembly of the United Nations Environment Programme [54,55], agroforestry practices are actions to protect against soil erosion and loss of biodiversity in the agroecosystems to sustainably use these systems to attain food security. Agroforestry is also a farmers' managed natural/artificial tree regeneration strategy that helps to restore the farming landscape with trees that address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, and resilience and biodiversity benefits in the agroecosystems. The results conforms that traditional agroforests can make a significant contribution to biodiversity conservation and carbon sequestration having a great implication as a nature-based solution for climate change mitigation and adaptation as well as improving human wellbeing [56–58]. Agroforestry produces multiple benefits for agricultural yields, biodiversity, carbon storage, and ecosystem services for which nature-based solution are often cited about. The results of this study entail agroforestry is an important nature-based solution that fits well with African farming systems, skills, and livelihoods [59].

Conclusions

The three studied TAF practices have high potential to store carbon both in the biomass and in the soils thereby reduce GHG emission. In this study, the MAF practice has the highest GHG redaction capacity from the atmosphere than WAF and PAF as it relatively store more carbon. This suggests, as a nature-based solution, that MAF practice need to be promoted for climate change mitigation and adaptation in the face of climate change. That is, landscape restoration programs and REDD+ investment programs should consider AFS in watershed management for multiple roles such as climate change mitigation and built green economy strategy as being one of the nature-based solutions to climate change mitigation and adaptation as well as building the health of the environment and wellbeing of the communities. Further studies will be required: establishing commercial AFS for enhancement of climate change adaptation and mitigation potentials as this study highlights the role of TAF practices in carbon sequestration potential both in above ground and below ground showing a naturally negative emission balance. There is a need to device better agroforestry management options along with the development of emission factors at the country level for land-used systems, livestock husbandry, and manure management as we have used the IPCC default value for emission calculation. To this end, policy-makers, program managers, extension workers, and the local community, as well as other stakeholders, should give attention to the improvement of agroforestry practices for the sustainable reduction of GHG from land use emissions.

NBS impacts and implications

- We found that traditional agroforestry stored considerable carbon both in biomass and soil
- Carbon storage potential differed across traditional agroforestry systems
- Multistory agroforestry system has found to store the highest carbon of 40.7 ton ha-1
- Traditional agroforestry system plays adaptation and mitigation role in climate change
- Soil physicochemical characteristics found to vary across and within agroforestry systems

Traditional agroforests can make a significant contribution to biodiversity conservation and carbon sequestration having a great implication as a nature-based solution for climate change mitigation and adaptation as well as improving human wellbeing. Therefore, the management of traditional agroforestry systems is one of the alternative nature-based solutions for climate change mitigation and adaptation.

Declaration of Competing Interest

The authors declare that there is no potential conflicts of interest.

Data availability

Data will be made available on request.

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