ASSESSING THE IMPACT OF FRUIT TREE-BASED AGROFORESTRY, PARKLAND AGROFORESTRY, AND BOUNDARY PLANTING ON SOIL FERTILITY AND CARBON STOCK IN ERER DISTRICT, ETHIOPIA

DABA BOGALE SIMA AND ABEBAW SHEMELIS

[1]*Forest Development, P.O.Box 708, Dire Dawa, Ethiopia*
[2]*Alemayehu Ethiopia, Forest Development, Ethiopia; email: shabebaw2070@gmail.com*
**Corresponding author email: dababogale@gmail.com*

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ABSTRACT

Soil degradation driven by deforestation and intensive agriculture has significantly reduced agricultural productivity and ecosystem services in Ethiopia's dryland regions, particularly in the Erer District. This study evaluated the effectiveness of three agroforestry systems fruit tree-based agroforestry, parkland agroforestry, and boundary planting compared to conventional agriculture in enhancing soil fertility and soil organic carbon (SOC) stocks. A systematic plot design was implemented using 16 plots, each measuring 20 × 20 meters, with treatments randomly assigned to ensure representative sampling across the district. Within each plot, composite soil samples were collected at three depths (0–20 cm, 20–40 cm, and 40–60 cm) to capture vertical variations in soil properties. Key soil properties, including total nitrogen, available phosphorus, and potassium, were analyzed using standard laboratory methods, while SOC was estimated following established protocols. Additionally, above- and below-ground biomass were quantified using generalized allometric equations adapted to the local context. Results indicated that fruit tree-based agroforestry significantly increased nutrient availability and SOC, especially in the topsoil, and registered the highest above-ground biomass, suggesting a superior capacity for carbon sequestration and soil health improvement. Parkland agroforestry also enhanced soil fertility and SOC, albeit to a moderate degree, with its diverse species composition contributing to more stable nutrient cycling and moisture retention. In contrast, boundary planting, while showing the smallest gains in nutrient and SOC levels, was particularly effective in reducing soil erosion and improving localized water conservation, thus supporting overall soil quality. Collectively, these findings suggest that tailored agroforestry practices, especially fruit tree-based systems, can be sustainable strategies for restoring degraded soils, mitigating climate change, and boosting agricultural productivity in dryland areas. This study provides critical insights for policymakers and land managers seeking to implement agroforestry interventions for long-term environmental conservation and sustainable land use in the Erer District.

Keywords: Agroforestry, climate change adaptation and mitigation, soil fertility and Health, conventional agriculture.

INTRODUCTION

Soil is essential for plant growth, biodiversity, water quality regulation, and carbon sequestration, all of which help mitigate climate change (Dignac *et al*., 2017; Yatoo *et al*., 2020). Globally, however, soil degradation is accelerating due to human activities such as deforestation and intensive agriculture, leading to reduced productivity, loss of biodiversity, and diminished ecosystem services (Bunning *et al*., 2010; Mekuria *et al*., 2007). Processes such as erosion, compaction, and nutrient depletion undermine soil fertility and the overall functionality of ecosystems (UNEP, 2015). In particular, the conversion of forests to agricultural land has been shown to significantly reduce Soil Organic Carbon (SOC), which is critical for maintaining soil health (Guo & Gifford, 2002).

In response to these challenges, agroforestry has emerged as a promising soil management strategy that integrates trees with crops to improve soil health, enhance organic matter, reduce erosion, and boost biodiversity (Torquebiau, 1990; Nair, 2011). Globally, agroforestry practices span over one billion hectares, underscoring their importance for sustainable land management (Zomer *et al*., 2009). The Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019) emphasizes agroforestry's role in mitigating biodiversity loss and enhancing ecosystem services, particularly in areas vulnerable to climate change. Agroforestry systems not only add organic matter to the soil, fostering nutrient cycling (Barrios *et al*., 2023; Fahad *et al*., 2022), but also improve water retention, thereby increasing soil resilience in drought-prone regions (Visscher *et al*., 2024).

Fruit tree-based agroforestry systems, for instance, excel in carbon sequestration by storing carbon in their biomass, thereby contributing to global climate change mitigation efforts (Jose & Bardhan, 2012; Luedeling *et al*., 2011). Moreover, these systems offer local benefits by reducing deforestation pressures through alternative sources of timber and non-timber forest products (Zomer *et al*., 2016).

In Ethiopia, agroforestry is not a new concept but a time-tested traditional practice that addresses several local challenges. In regions such as the highlands, Somali, and Oromia Zones, where high population pressure, recurrent droughts, and soil degradation have led to declining agricultural productivity, agroforestry has been successfully applied to restore soil fertility and support food security (Alemu, 2016; Jemal *et al*., 2018). For example, in the highlands, fruit tree-based systems have been implemented to reduce soil erosion and improve water retention, thereby creating micro environments conducive to sustainable crop production. Similarly, parkland agroforestry—where trees are interspersed within croplands—and boundary planting along field edges have been adopted in various Ethiopian districts to mitigate soil degradation, enhance water retention, and reduce erosion (Nair, 2011; Kuyah *et al*., 2012).

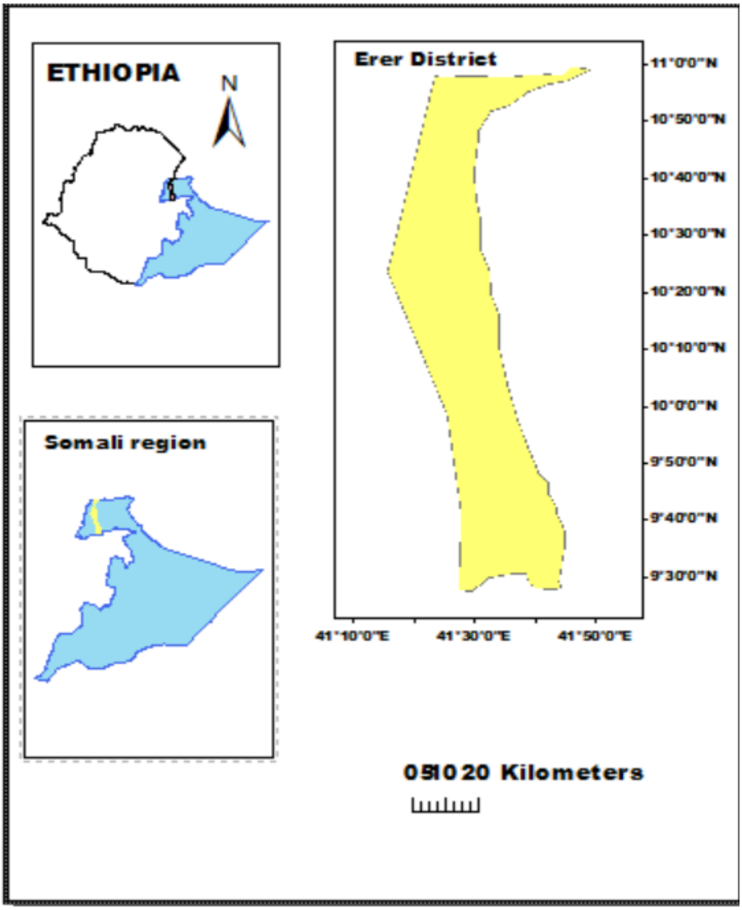
Despite these successes, challenges such as limited technical support, restricted market access, and insufficient policy integration remain, impeding the full potential of agroforestry in Ethiopia. This study aims to assess the impact of fruit tree-based agroforestry, parkland agroforestry, and boundary planting on soil fertility by measuring changes in soil nutrients and overall soil health; evaluate the effectiveness of these practices in increasing Soil Organic Carbon (SOC) to contribute to carbon sequestration and climate change mitigation; and quantify improvements in biomass production that link enhanced soil health to increased agricultural productivity. By addressing these objectives in the Erer district of Eastern Ethiopia, this research provides a clear roadmap for evaluating and optimizing agroforestry practices, offering valuable insights for policymakers and land managers seeking sustainable solutions to soil degradation, climate change, and agricultural sustainability in regions facing similar challenges.

METHODOLOGY

Description of the Study Area

The study was conducted in Erer district, located in the Shinile Zone of the Somali Region, Ethiopia (9°30'0"–11°0'0"N, 41°10'0"–41°50'0"E) (Fig. 1). The district had a total population of 100,556, with 17,039 urban inhabitants and 83,517 farmers, as reported in the 2007 Census (CSA, 2007). Erer district was selected for this study due to its ecological significance as a dryland agro-ecological zone where different land-use systems (fruit tree-based agroforestry, parkland plantations, and boundary planting) are employed to enhance soil fertility and carbon sequestration (Hailu *et al*., 2020). The district is a hotspot for land degradation, making sustainable land management practices such as agroforestry essential for restoring soil productivity and mitigating climate change impacts (Amede *et al.*, 2017).

Fig. 1: Study area map



Ecological and Climatic Conditions

The study area exhibits diverse ecological and climatic conditions that influence land-use practices. The altitude ranges between 450 and 1200 meters above sea level, affecting micro-climatic conditions, soil moisture retention, and vegetation composition (Takele & Mektel, 2019). Lower elevations experience more arid conditions, while higher elevations support more diverse land-use systems. The region follows a bimodal rainfall pattern with two rainy seasons: March to May (long rains) and July to September (short rains). Annual rainfall varies between 300 mm and 600 mm, directly influencing soil moisture availability and agricultural productivity (Israel, 2019). The temperature ranges between 35°C and 40°C, accelerating organic matter decomposition and affecting soil nutrient cycling (FAO, 2021).

Soil Characteristics

The predominant soil types in the study area are Arenosols and Cambisols. Arenosols are sandy, highly permeable soils with low fertility, limiting their capacity to retain moisture and nutrients (IUSS Working Group WRB, 2015). These soils dominate lower-altitude areas, where dryland farming is particularly challenging. Cambisols, found in relatively higher elevations, have weakly developed soil profiles but moderate fertility, supporting a wider range of vegetation (FAO, 2021). Soil degradation is a significant concern in the region, driven by deforestation, overgrazing, and improper land management (Hurni *et al*., 2016), necessitating soil conservation efforts such as agroforestry and organic amendments (Teklu & Gezahegn, 2018).

Livelihoods and Land Use

Agriculture and livestock production form the backbone of livelihoods in the Erer district, with most households practicing mixed farming (Israel, 2019). Land use is characterized by a dominance of cereal production, covering 57.13 % of cultivated land, while root crops and vegetables account for 1.66 % and 1.14 %, respectively. Permanent crop cultivation includes 8,000 hectares of khat, 12,000 hectares of coffee, and 198.52 hectares of fruit trees (Takele & Mektel, 2019). Livelihood strategies are diverse, with 64.63 % of farmers engaging in both crop cultivation and livestock rearing, 9.02 % focusing solely on crops, and 26.34 % specializing in livestock (CSA, 2007). The Sitti Zone, encompassing the study area, is predominantly an arid and semi-arid lowland, where pastoralism and agro-pastoralism are key economic activities (Amede *et al*., 2017).

Major Land Use Types

The study focused on four major land-use types, each characterized by distinct vegetation and management practices: Fruit Tree-Based Agroforestry, This system integrates fruit trees such as ***Mangifera indica*** (Mango), ***Citrus sinensis*** (Orange), ***Persea americana*** (Avocado), and ***Carica papaya*** (Papaya) with leguminous crops and seasonal vegetables. Organic inputs from leaf litter contribute to soil organic matter enrichment, improving soil health and productivity (Negash & Starr, 2015). Parkland Agroforestry, Scattered trees are retained within cropland to provide shade, soil improvement, and fodder. Dominant species include ***Acacia senegal***, ***Acacia tortilis***, and ***Faidherbia albida***, which are traditionally managed by smallholder farmers for their ecological and economic benefits (Luedeling *et al*., 2016). Boundary Planting, Perennial trees such as ***Moringa oleifera***, ***Acacia abyssinica***, and ***Grevillea robusta*** are planted as hedgerows along field borders. These serve as windbreaks, soil stabilizers, and sources of fodder, playing a crucial role in erosion control and microclimate regulation (Teklu & Gezahegn, 2018). Conventional Agriculture. This land use type primarily involves annual crop cultivation, such as ***Sorghum*** and ***Maize***, without tree integration. It is characterized by frequent tillage, low organic inputs, and high vulnerability to erosion, making it less sustainable compared to agroforestry-based systems (Hurni *et al.*, 2016).

Soil Sampling and Analysis

A total of 16 plots were randomly assigned across four land use types: fruit tree-based agroforestry, parkland agroforestry, boundary planting, and conventional agriculture (control), resulting in 64 composite soil organic carbon (SOC) samples. Fieldwork was conducted from November 5 to December 16, 2022, with two rounds of data collection, including a reconnaissance survey. Soil samples were collected from 20 x 20 meter plots at three depths: 0-20 cm (topsoil, where microbial activity, organic matter decomposition, and root interactions occur), 20-40 cm (subsoil, important for nutrient leaching, root development, and water infiltration), and 40-60 cm (deep soil, assessing long-term impacts of land use on carbon storage and nutrient accumulation).

The study sites were selected based on proximity (within a 5–10 km radius) to minimize climatic variation, and similar topographical characteristics, including slope and aspect, were considered to control for erosion effects. Standardized sampling times were followed to ensure consistency in season, reducing temporal variations in soil moisture and fertility. The 20 m × 20 m plot size was used for soil sampling. At each depth, five soil cores were taken per quadrat and pooled into a composite sample for analysis. Samples were air-dried, sieved (2 mm), and stored for laboratory testing.

Soil Bulk Density (BD, g/cm³) was measured using the core method, followed by oven-drying at 105°C for 48 hours. Soil Organic Carbon (SOC, %) was determined using the Walkley-Black wet oxidation method. Total Nitrogen (N, %) was analyzed using the Kjeldahl digestion method. Available Phosphorus (P, mg/kg) was extracted using the Olsen method, and Exchangeable Potassium (K, cmol/kg) was measured using flame photometry following ammonium acetate extraction. This methodology ensured accurate data collection, enabling a comprehensive assessment of soil fertility and carbon sequestration across different land use systems in the Erer district.

The calculation of carbon stock for each layer was performed following the methodology outlinedby (Pearson *et al.*, 2013) Eq.1

$$= \text{Bulk density} = \frac{mass\ of\ oven\ dry\ soil(g)}{volume\ of\ clinder\ in\ (cm-3)} \qquad Eq.\ 1$$

$$C_i = BD_i\ (1 - CF_i\ ) \times d_i \times OC_i \qquad \text{Eq. 2}$$

Where C *i* is carbon stock of the ith layer, BD *i* is bulk density of the ith layer (kg/m^3), CF *i* is coarse fragment content of the ith layer, OC is the soil's organic carbon content (%) and d *i* is the thickness of the ith layer (m). Finally, the carbon stock was expressed in tone (t) ha^{-1}.

Above and Below-ground biomass estimation

All woody species with a diameter at breast height (DBH) greater than 2.5 cm and a height exceeding 1.3 m were measured and recorded, including fruit trees, non-fruit trees, and shrubs taller than 40 cm (Negash *et al.*, 2013). For estimating the aboveground biomass (AGB), we used generalized allometric equations suited for a comparable biophysical context (Chave *et al.*, 2014), as species-specific equations for the land-use systems in our study area were unavailable. The equation developed by Kuyah *et al.* (2012) for estimating carbon stocks in woody species, including fruit trees in agroforestry systems, was applied, with a 49 percent conversion factor for carbon stock. Belowground biomass (BGB) estimation was based on its relationship with AGB, as disturbances to the topsoil can reduce

BGB. Since BGB can account for 20 to 26 percent of total biomass, we used a global average value of 26 percent of AGB, following Cairns et al. (1997), along with the 49 percent carbon conversion factor as suggested by Negash & Starr (2015). However, this method has limitations: the equations were developed for different ecological zones and may not fully reflect local species growth, and variations in root-to-shoot ratios across soil types and species may affect the estimates. Additionally, the absence of destructive sampling could lead to errors in estimating BGB. To mitigate these limitations, our estimates were compared with findings from similar studies in semi-arid landscapes for validation.

Table 1: Biomass stock assessment

Biomass Component	Equation	R^2	n	Source
AGB (Aboveground Biomass)	$0.091 * d^{2.472}$	0.95	72	Kuyah *et al*. (2012), Chave *et al*. (2013)
BGB (Belowground Biomass)	0.26AGB	-	-	Mesele Negash *et al*. (2013)
AGB (Shrubs)	$0.147*d_2$	0.80	31	Kuyah et al. (2012a)
BGB (Shrubs)	$0.490AGB_{0.923}$	0.95	72	Kuyah *et al*. (2012b)

Notes: AGB: Aboveground biomass (kg dry matter/plant), BGB: Belowground biomass (kg dry matter/plant), d: Diameter at breast height (cm), AGBshrubs: Aboveground biomass for shrubs and d40: Stem diameter (cm) of shrubs measured at 40 cm height

Statistical Analysis

Soil parameters were analyzed using one-way ANOVA to assess differences among land uses. Tukey's HSD test identified significant pairwise differences at a 5 % significance level. Linear regression models examined the relationship between SOC and biomass accumulation, as well as the effect of soil properties on crop yield and tree growth. To control variability, plots were selected within uniform topographical conditions, and sampling was conducted in the same season. Data normality was tested using the Shapiro-Wilk test before applying parametric analyses. All statistical analyses were conducted using SPSS and R 4.0.3 software.

RESULTS

The Impact of Land Use on Selected Nutrients

Total Nitrogen Percentage

The study found that fruit tree-based agroforestry (FTBA) exhibited the highest mean accumulation of total nitrogen (TN) across both the topsoil (0-20 cm) and middle soil depths (20-40 cm), with concentrations of 2.83 % and 2.84 %, respectively. This was followed by parkland agroforestry (PA), which showed slightly lower TN levels at these depths (2.10 % and 2.36 %). Boundary planting (BP) and conventional agriculture (CA) exhibited the lowest nitrogen levels, particularly in the middle soil layer, with concentrations of 1.34 % and 1.48 %, respectively. Statistical analysis revealed significant differences in nitrogen percentages, particularly in the topsoil depth, where FTBA consistently demonstrated higher TN levels compared to other land uses. Pairwise comparisons using Tukey HSD tests confirmed significant differences ($p < 0.05$) between FTBA and the other land uses at both the topsoil and middle soil depths. In the lower soil layer (40-60 cm), no significant differences in nitrogen levels were observed among the four land uses ($p > 0.05$), indicating a uniform distribution of nitrogen at this depth. This uniformity could be attributed to factors such as limited plant root penetration and similar nitrogen uptake across different land uses at deeper

Phosphorus Availability

Phosphorus availability in the soil was highest in FTBA, where the peak concentration was observed in the topsoil (4.27 mg kg^{-1}), with levels decreasing with depth. Boundary planting (BP) and CA followed a similar trend, with higher phosphorus accumulation in the middle and lower depths. Conventional agriculture exhibited the lowest phosphorus concentration at the surface (Fig. 2). Statistical analysis revealed significant variation in phosphorus availability at the topsoil depth (0-20 cm) ($F(3, 12) = 21.167$, $p = 0.00$). Tukey HSD analysis showed that FTBA had significantly higher phosphorus availability compared to PA, BP, and CA at this depth ($p < 0.05$). However, no significant differences in phosphorus availability were found at the middle (20-40 cm) and lower (40-60 cm) depths ($p > 0.05$) (Table 2). The limited mobility of phosphorus in the soil could explain the observed pattern of higher concentrations in the topsoil. Phosphorus is known to have low mobility due to its tendency to bind with soil particles and organic matter, restricting its downward movement to deeper soil layers.

Potassium Accumulation

FTBA demonstrated the highest accumulation of available potassium (149.5 mg kg^{-1}), followed by PA (128.25 mg kg^{-1}), BP (127.25 mg kg^{-1}), and CA (86.75 mg kg^{-1}) (Table 2). Statistical analysis ($F(3, 12) = 11.546$, $p = 0.001$) confirmed significant differences, with Tukey HSD tests revealing that FTBA had significantly higher potassium levels compared to the other land uses ($p < 0.05$). A graphical better illustrated the differences in potassium accumulation across the land uses and depths for clarity (Fig. 3).

Fig. 2: Nitrogen and phosphorus availability across land-uses

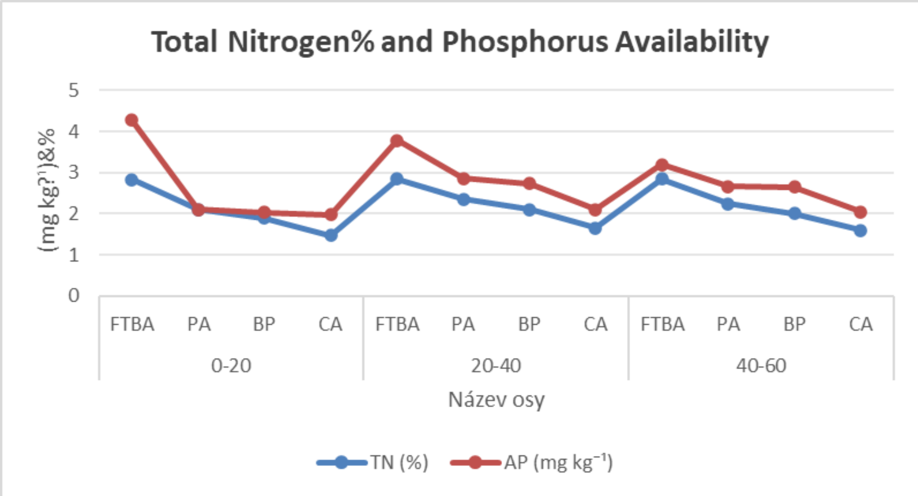


Fig. 3: Potassium Accumulation across the land uses

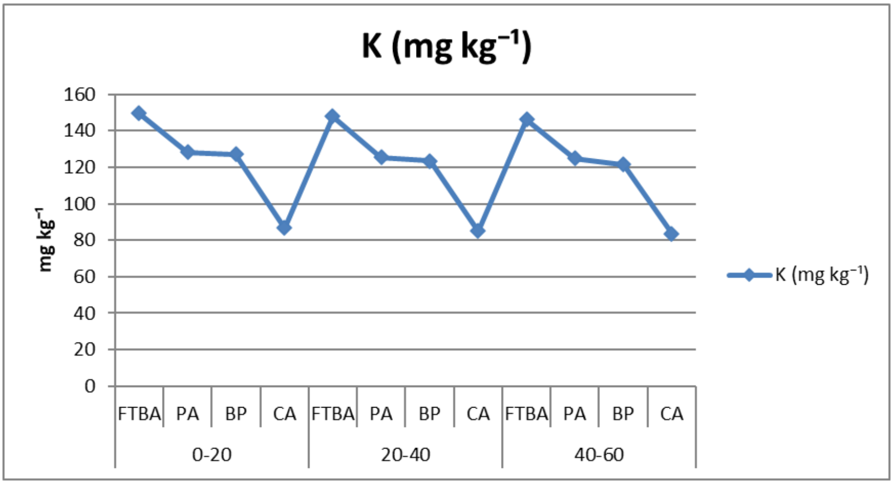


Table 2: Soil selected nutrient

		Mean±SD				TN%		AP (mg kg-1)		K(mg kg-1)	
Soil depth	**Land uses**	**TN%**	**AP (mg kg^{-1})**	**K(mg kg^{-1})**	**Df**	**F**	**Sig.**	**F**	**Sig.**	**F**	**Sig.**
0- 20cm	FTBA	2.83±0.20	4.27±0.34	149.5±28.60	3	40.149	0	21.167	0	11.546	0.001
	PA	2.10±0.11	2.11±0.54	128.25±6.24	12						
	BP	1.89±0.20	2.04±0.52	127.25±4.86	15						
	CA	1.48±0.20	1.98±0.48	86.75±8.50							
20 -40cm	FTBA	2.84±0.08	3.10±0.50	81.25±9.43	3	64.522	0	5.126	0.016	0.174	0.912
	PA	2.36±0.18	2.02±0.23	78.25±8.92	12						
	BP	1.34±0.19	3.13±0.79	78.75±21.78	15						
	CA	2.28±0.13	2.16±0.38	74.00±13.78							
40 -60 cm	FTBA	1.96±0.20	2.99±0.17	93.5±19.28	3	1.421	0.285	3.001	0.073	0.34	0.797
	PA	2.00±0.16	2.03±0.84	85.25±25.58	12						
	BP	2.03±0.31	2.75±0.53	86.00±23.68	15						
	CA	1.73±0.23	2.21±0.23	77.75±18.99							

Where FTBA= fruit tree based Agroforestry, PA= parkland Agroforestry, BP = boundary planting, CA= conventional agriculture

Table 3: Soil Properties by Depth & Management

Depth		***Bulk density g/cm³***	***OM%***	***SOC***	***df***	***F***	***Sig.***
0- 20cm	FTBA	1.42±0.35	2.9±0.60	3.93±0.54	3	12.182	0.001
	PA	1.3±0.18	2.9±0.62	2.95±0.49	12		
	BP	1.4±0.32	2.98±0.25	3.03±0.72	15		
	CA	1.43±0.36	2.95±0.65	1.65±0.31			
20 -40cm	FTBA	1.25±0.14	3.05±0.52	3.78±0.64	3	2.099	0.154
	PA	1.35±0.13	3±0.34	2.68±0.66	12		
	BP	1.28±0.17	2.9±0.55	3.25±1.06	15		
	CA	1.33±0.17	3±.083	2.40±0.94			
40 -60 cm	FTBA	1.45±0.20	2.9±0.60	3.30±0.80	3	2.982	0.074
	PA	1.45±0.31	2.9±0.22	3.33±0.55	12		
	BP	1.43±0.40	2.95±0.70	3.18±0.96	15		
	CA	1.48±0.17	3.18±0.68	1.98±0.61			

Where FTBA= fruit tree based Agroforestry, PA= parkland Agroforestry, BP = boundary planting, CA= conventional agriculture

Soil Organic Carbon (SOC) Estimation under Different Land Uses

Among all land uses, FTBA exhibited the highest soil organic carbon accumulation across all depths, with the greatest concentration in the topsoil (3.93 t C ha^{-1}), followed by the sub-surface (3.78 t C ha^{-1}). Parkland agroforestry (PA) demonstrated a slightly lower SOC accumulation at the sub-surface (3.33 t C ha^{-1}), while CA exhibited the lowest levels at all soil depths. Statistical analysis confirmed significant variation in SOC accumulation at the topsoil depth ($F(3, 12) = 12.182$, $p = 0.001$), with Tukey HSD analysis indicating a significant difference ($p < 0.05$) between FTBA and CA, which had the lowest SOC concentration (1.65 t C ha^{-1}).

At the deeper layers (20-40 cm and 40-60 cm), no significant differences in SOC accumulation were found across the land uses ($p > 0.05$). However, FTBA continued to demonstrate higher SOC accumulation than other land uses, likely due to enhanced organic matter inputs from leaf litter, root biomass, and the higher above ground biomass of trees. Further analysis of biomass data revealed that FTBA had the highest above ground biomass (AGB) at 108.2 tons ha^{-1} and the greatest total biomass at 137.45 tons ha^{-1}, further contributing to the higher SOC levels. These findings suggest that FTBA may be a more effective land use practice for enhancing soil organic carbon sequestration compared to other systems (Table 4 and Fig. 4 and 5).

Table 4: The DBH and height of tree species to measure carbon biomass

	Species names		**No individual species**	**DBH (cm)**	**Av. Height(m)**
FTBA$_{tree}$	Mango	*Mangifera indica*	22	124.9	4.5
	Avocado	*Persea Americana*	28	109	4.2
	Moringa	*Moringa oleifera*	15	76.1	5.6
	Albizia	*Albizia* spp.	9	145	7.4
	Gravellia	*Grevillea robusta*	15	88.3	6.3
	Acacia	*Acacia* spp.	9	128.7	5.8
	Neem	*Azadirachta indica*	14	119	4.7
FTBA$_{shrubs}$				**Av.= 113.0**	**Av.= 5.5**
	Pineapple	*Ananas comosus*	6	15.2	3.1
	Lemon	*Citrus limon*	7	18.5	3.4
	Plum	*Prunus domestica*	5	19.6	2.8
	Apple	*Malus domestica*	5	16.2	4.2
	Orange	*Citrus sinensis*	18	12.1	3.6
				Av.= 16.3	**Av.** = 3.42
PA$_{tree}$	Mango	*Mangifera indica*	8	114	5.9
	Albizia	*Albizia* spp.	4	85	6.4
	Gravellia	*Grevillea robusta*	6	48.2	4.3
	Acacia	*Acacia* spp.	4	57.8	6.8
			Shrubs		
	Apple	*Malus domestica*	5	4.8	3.37
	Orange	*Citrus sinensis*	18	5.8	3.32
				Av.= 5.4	**Av. = 3.35**
boundary planting	Albizia	*Albizia* spp.	6	55.6	6.4
	Neem	*Azadirachta indica*	4	39	4.7
	Moringa	*Moringa oleifera*	9	46.5	5.6
	Gravellia	*Grevillea robusta*	8	14.5	6.3
	Casimiroa	*Casimiroa edulis L.*	25		
		Shrubs		8	5.1
	Gliricidia	*Gliricidia sepium*	70	5.4	4.8
	Casuarina	*Casuarina* spp.	45	11	4.3
				Av**. =8.1**	**Av.= 4.73**

Fig. 4: Estimated biomass of agroforestry land use practices

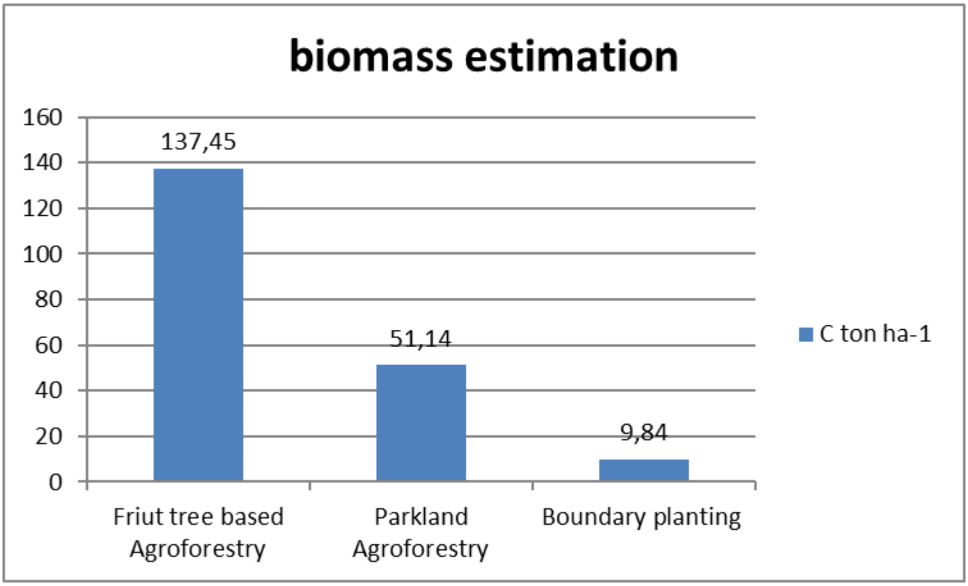
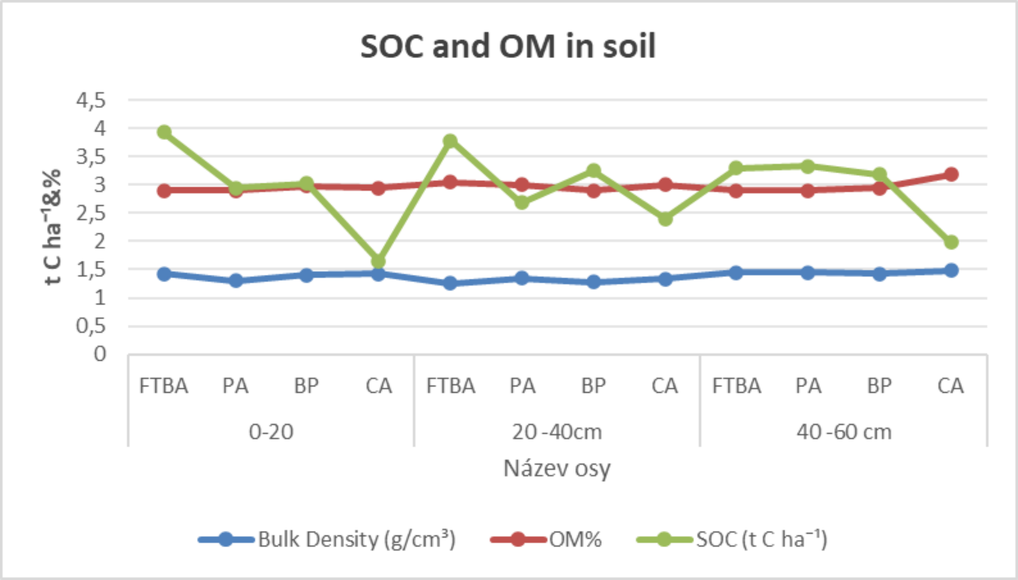


Fig. 5: Soil organic carbon and organic matter across the land uses



DISCUSSION

The findings of this study underscore the significant potential of fruit tree-based agroforestry systems in enhancing soil nutrient management and organic carbon accumulation. These systems show promise in improving soil health, particularly in nutrient-depleted soils, by enhancing nitrogen fixation, phosphorus availability, potassium accumulation, and Soil Organic Carbon (SOC) levels. However, a critical evaluation reveals some important limitations and areas that require further exploration, particularly with regard to species-specific variability, generalization of the results, and socioeconomic barriers to adoption.

Our study found significantly higher nitrogen levels in fruit tree-based agroforestry systems, which reflects their role in sustainable nitrogen management. The enhanced nitrogen availability can be attributed to symbiotic relationships between tree roots and nitrogen-fixing microorganisms, especially in species like *Albizia spp.* and *Acacia spp.*, known for their nitrogen-fixing properties (Zebene & Solomon, 2018; Buresh & Giller, 1998; Mafongoya *et al.*, 2006). However, the extent of nitrogen fixation varies considerably depending on the tree species, suggesting that future research should focus on how specific species contribute to nitrogen cycling and whether species combinations could optimize nitrogen fixation in these systems. Moreover, the lack of significant differences in nitrogen percentages at deeper soil depths (40–60 cm) raises questions about the movement and availability of nitrogen beyond the root zone. This aligns with previous studies (Cardinael *et al*., 2020; Kuyah *et al*., 2019), but further investigation into mechanisms such as root activity, microbial processes, and leaching is needed to better understand long-term nitrogen sustainability in deeper soil layers.

Fruit tree-based agroforestry systems also significantly improved phosphorus availability at the topsoil level (0–20 cm), primarily due to enhanced organic matter decomposition and root-mediated nutrient release. This aligns with findings from previous studies (Hinsinger, 2001; Lehmann *et al*., 2014). However, phosphorus mobility remains limited at deeper soil depths, which is consistent with its generally low mobility in soils (Wang *et al*., 2021). This suggests that enhancing phosphorus availability in deeper layers may require specific management practices, such as introducing phosphorus-soliloquizing microorganisms or organic amendments. Despite the potential for improving phosphorus retention and reducing loss through erosion and runoff, scalability in resource-limited regions is a key challenge. Smallholder farmers may struggle with the financial and logistical requirements to establish and maintain fruit tree-based agroforestry systems. Addressing these barriers, including access to resources and technical support, will be critical for scaling up agroforestry practices. The substantial potassium accumulation observed in fruit tree-based agroforestry systems reflects their potential for enhancing soil nutrient status, driven by nutrient cycling and root exudation processes. However, the results are specific to the context of Erer district, and generalizing these findings to other regions with different soil types or climatic conditions is uncertain. Future research should focus on potassium dynamics in diverse agro ecological settings to validate the findings and determine how potassium cycling differs across regions.

One of the most promising aspects of fruit tree-based agroforestry systems is their potential for enhancing Soil Organic Carbon (SOC) levels, which is crucial for soil health and carbon sequestration. This study found that these systems contribute to SOC stabilization through organic matter inputs, such as leaf litter and root biomass revealed by (Smith *et al*., 2020; Asfaw *et al*., 2019; Nair *et al*., 2011). However, while above ground biomass production was highlighted, the contribution of below ground biomass to carbon storage should not be overlooked. Future research should include a more comprehensive assessment of below ground carbon dynamics to provide a fuller understanding of agroforestry role in climate change mitigation. The higher biomass production observed in fruit tree-based systems further supports their potential as a strategy for carbon sequestration. However, establishing such systems involves significant initial investment and long-term maintenance, which may be difficult for smallholder farmers without adequate support. The scalability of these systems, particularly in resource-poor regions, remains a critical limitation.

Agroforestry offers diversified income (Ajayi *et al.*, 2007), yet land tenure conflicts, market access, and long tree maturity periods impede uptake (Garrity, 2012; van Noordwijk *et al.*, 2021). Case studies demonstrate that farmer training and subsidies enhance adoption (Santoso *et al.*, 2020), emphasizing the need for policy support. Geographic specificity also limits extrapolation; multi-regional trials (Sinclair *et al.*, 2022) could identify context-specific solutions.

Long-term studies are critical to assess agroforestry sustainability under climate variability (Jose, 2016). Additionally, interdisciplinary research integrating biophysical and socioeconomic factors (Pretty *et al.*, 2018) will optimize system design and scalability. Fruit tree-based agroforestry systems in Eastern Ethiopia enhance soil health and carbon storage, yet their success hinges on addressing species-specific nutrient dynamics, socioeconomic barriers, and regional adaptability. Prioritizing farmer-centered policies and interdisciplinary research will unlock their full potential for sustainable land management.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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