Agroforest Syst (2025) 99:35
https://doi.org/10.1007/s10457-025-01138-3

Farmers' perceptions of *Terminalia brownii* management in agroforestry Parklands and its impact on soil physicochemical properties in the South Ari District, Southern Ethiopia

Mitiku Ayele Handiso · Bruk Lemma · Zebene Asfaw · Tobias Bromm · Beyene Teklu Mellisse · Bruno Glaser

Received: 28 May 2024 / Accepted: 13 January 2025 / Published online: 1 February 2025

Abstract Smallholder farmers in the South Ari District of southern Ethiopia retain natural forest remnants of *Terminalia brownii* trees in their crop fields. However, little is known about their perceptions of its management in crop fields and its impacts on soil properties. Therefore, we investigated farmers' perceptions and the impacts of scattered *Terminalia brownii* trees on soil physicochemical properties. For this purpose, we collected household survey data from 80 farmers and 54 composite soil samples from four directions at three radial distances and two soil depths. A randomized complete block design was used with three independent random field replications for the treatments within factorial arrangements, including the three radial distances and two soil depths. Based on the survey data, 90% of the respondents manage scattered *Terminalia brownii* trees in their crop fields. Among them, 63% use pollarding, while 49% use pruning techniques to enhance the impact on crops grown beneath trees. Our results revealed that soil organic carbon, total nitrogen, plant-available potassium and phosphorus, and bulk density were significantly higher ($P < 0.05$) under the tree canopy. However, soil texture, pH, electrical conductivity, cation exchange capacity, and exchangeable bases depicted no significant differences between the tree canopy and open fields. Hence, retaining *Terminalia brownii* trees on the crop field is crucial for farmers to improve the soil physicochemical properties. However, sustained long-term studies are essential to gain a comprehensive understanding of the diverse functions of *Terminalia brownii* and its impact on microclimate dynamics and crop productivity.

Keywords Canopy · Combretaceae · Crop fields · Organic matter · Pollarding · Pruning

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-025-01138-3.

M. A. Handiso
Jinka Agricultural Research Center, South Ethiopia Agricultural Research Institute, P.O. Box 96 Jinka, Ethiopia

M. A. Handiso · Z. Asfaw · B. T. Mellisse
Wondo Genet College of Forestry and Natural Resources, Hawassa University, Hawassa, Ethiopia

M. A. Handiso · B. Lemma (✉) · T. Bromm · B. Glaser
Institute of Agricultural and Nutritional Sciences, Soil Biogeochemistry, Martin Luther University Halle-Wittenberg, Von-Seckendorff-Platz 3, 06120 Halle (Saale), Germany
e-mail: bruklemma@gmail.com

B. Lemma
Forest and Rangeland Biodiversity Directorate, Ethiopian Biodiversity Institute, P.O. Box 30726, Addis Ababa, Ethiopia

Introduction

Ethiopia has the second-most inhabitants, with more than 125 million people, in Africa, and its economy is hardly based on agriculture, which generates up to 40% of its GDP, 80% of its export revenue, and employs 75% of its labor force (Gebre-Selassie 2004; Neglo et al. 2021). Hence, the socio-politico-economic stability of the country is tightly linked to agricultural production (Dawid & Mohammed 2021; Mekuria 2018; Yadessa et al. 2009). However, it is adversely affected by declining soil fertility due to high rates of soil erosion, land degradation, rapid population growth, deforestation, climate change, and continuous cultivation of the land without adequate management of organic matter inputs (Gebre-Selassie 2004; Demelash and Stahr 2010; Bekele 2018). To combat those and related problems in Ethiopian agriculture, traditionally practiced agroforestry parkland systems or integrating selected indigenous multipurpose trees in the agricultural field is one of the options as climate-smart agriculture (Kassa et al. 2010; Bekele 2018; Muchane, et al. 2020)

Traditionally, different tree species have been managed in the Ethiopian agroforestry parkland system, including *Acacia tortilis, Acacia seyal, Albizia gummifera, Vitex doniana, Balanites aegyptiaca, Cordia africana, Croton macrostachyus*, *Faidherbia albida,* and *Terminalia brownii* (Bekele 2018; Anbessa and Utaile 2024). Those multipurpose trees have grown on crop fields, which characterize a large portion of the Ethiopian agricultural landscape, and they are the most dominant agroforestry trees in the country's semi-arid and sub-humid zones (Tscharntke et al. 2011). Trees are an integral part of the system that improves the soil physicochemical properties and crop yield by providing favorable microclimates and shelter, reducing environmental degradation, and improving water infiltration under changed climatic conditions as a climate-smart agriculture practice (Ayres et al. 2009; Ogunkunle et al. 2013). Some studies of the Ethiopian agroforestry parkland system revealed a soil fertility gradient, i.e., fertility decreasing from a tree base to the edge of its crown or beyond (Asfaw 2007; Tolera et al. 2008; Anbessa and Utaile 2024). Thus, yield improvement and soil fertility enhancement are obtained under a scattered tree canopy. For instance, sorghum grain yields under the canopy of *Cordia africana* increased by 14% compared to those grown on crop fields without trees (Boffa 2000).

In the study area (South Omo zone, Fig. 1), some farmers maintain different shrubs and tree species on their crop fields for various purposes, especially for soil fertility improvement and crop yield enhancement. It was assumed that local people's perceptions about the effect of *Terminalia brownii* management were significantly influenced by the economic condition of the farmers. Among those trees, *Terminalia brownii* is the most dominant one. *Terminalia brownii* Fresen belongs to the family Combretaceae, a semi-deciduous tree that grows up to 13 m high with a rounded, flat-topped, and spreading crown. It is an important tree growing in semi-arid areas utilized for firewood, charcoal, timber, mulch, soil improvement, traditional medicine, and fodder (Tesemma Bekele et al. 1993). However, little is known on the perceptions of smallholder farmers about *Terminalia brownii* management techniques and their impacts on soil properties. Therefore, the present study was initiated to assess smallholder farmers' perceptions of scattered *Terminalia brownii* management and its impacts on soil physicochemical properties.

Material and methods

Description of the study area

The study was conducted in the South Ari District of the South Omo Zone, Southern Ethiopia (Fig. 1) geographically situated at 05°51'–05°88' N and 36°32'–36°58' E, with an elevation ranging between 500 m asl and 3500 m asl (Handiso et al. 2023). It is located 770 km southwest of Addis Ababa, the capital city of Ethiopia.

Topography and climate

Topographically, the South Ari District is divided into highland areas ranging from 2500 to 3500 m asl with cold weather (locally called Dega), midland areas with relatively warm conditions (locally called Weyna Dega) ranging from 1500 to 2500 m asl, and lowland terrain with semi-arid weather (locally called Kolla) ranging from 500 to 1500 m asl., which comprises 24%, 65%, and 11% of the land area, respectively. Like other eastern African

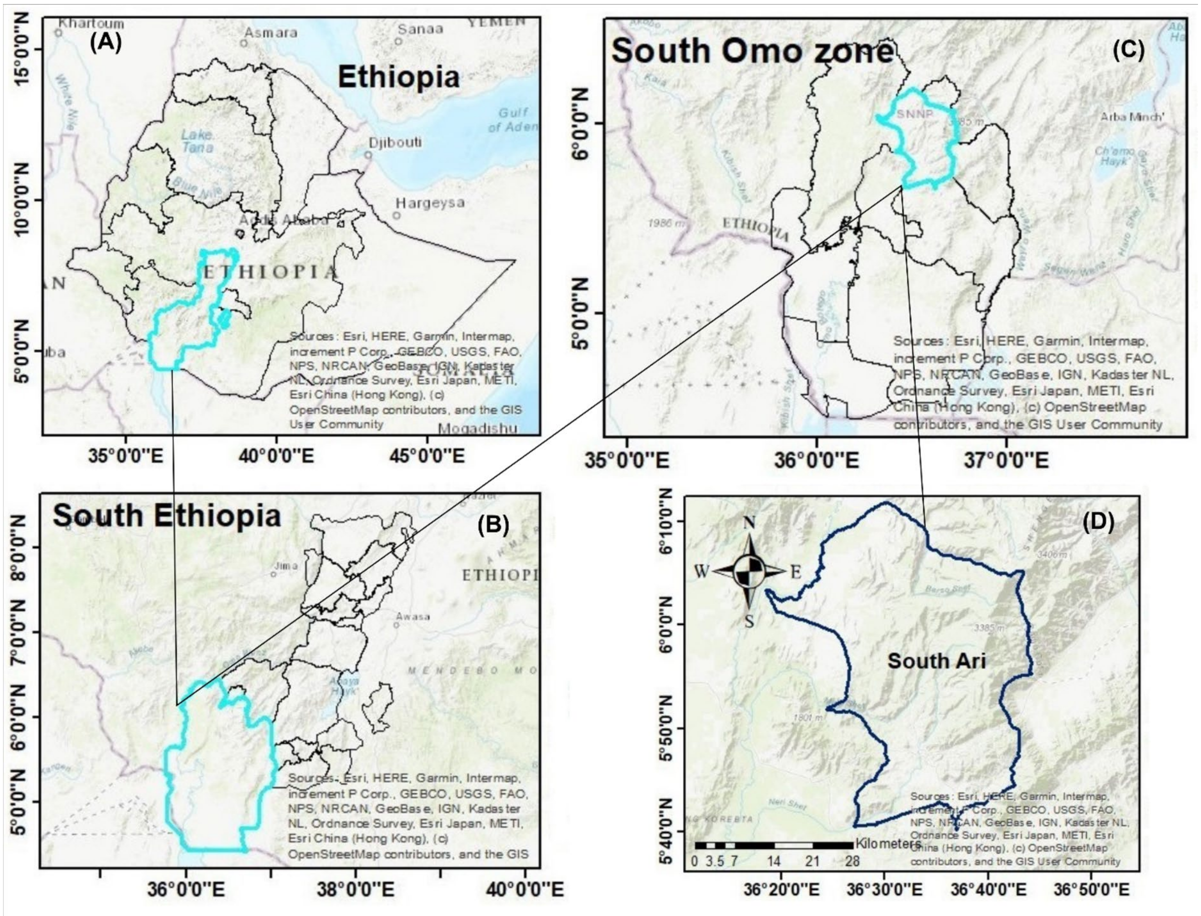


Fig. 1 The study area's map displays Ethiopia at the top left **A** in light green, emphasizing the South Ethiopia region **B**, South Omo Zone **C** at the top right and South Ari District **D** at the bottom right. *Source*: Esri, HERE, Garmin, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong) and OpenStreetMap Contributors and the GIS User Community

climates, the rainfall in the study area is influenced by the seasonal oscillation of the Inter-Tropical Convergence Zone (ITCZ). It has a bi-modal rainfall pattern, with a shorter rainy season from March to May and the longest rainy season from August to October (Lemma et al. 2020). The mean annual rainfall is 1272 mm. The mean monthly minimum and maximum temperatures are 16.3 °C and 27.7 °C, respectively (Handiso et al. 2023). Our actual study location is situated in the midland region with soil characterized as Cambisols, having a dark reddish brown to very dark brown color. The soil has a fine clay texture, low to medium organic carbon and phosphorus, and is slightly acidic, with a pH value ranging from 4.87 to 6.18 (Mesfin et al. 2017).

Tree management strategies

In the study area, farmers cultivate various shrubs and trees in their fields for multiple benefits. The most common tree is *Terminalia brownii*. Farmers conduct pruning, pollarding, and lopping annually during the field preparation season, typically at least one month before planting. This practice helps to reduce shading from the trees and aligns with local farming schedules. Pollarding involves cutting back the upper branches of a tree to encourage a dense head of foliage. This technique reduces shading and improves the balance between light availability and canopy structure. Pruning is selective removal of specific branches or stems, mainly from the sides, to shape the tree and enhance light penetration. Lopping focuses on the selective removal of medium-sized branches, allowing the tree to maintain its overall structure while improving light distribution to the crops growing beneath its canopy (Harmer 2004; Harris 1994).

Household survey data

To assess farmers' perceptions of *Terminalia brownii* tree management, household survey data were collected. Out of 28 rural and three urban lower administrative levels of the district (locally called Kebeles), only two Kebeles, namely Alga, and Beytsemal, were purposefully selected due to the extensive presence of *Terminalia brownii*. From 563 and 438 household heads in Alga and Beytsemal, respectively, sample households were stratified based on their wealth categories (poor, middle class, and rich) by the selected key informants (SI 1). Based on this, eight percent of the households from each wealth category in each Kebele were randomly selected for the survey by using the proportional sample size determination method by considering three criteria, such as the level of precision (±5%), the level of confidence or risk (95%), and the expected degree of variability in the information (Adam 2020; Gelan et al. 2016). Accordingly, 45 and 35 households from Alga and Beytsemal, respectively, making a total of 80 household respondents, were randomly selected (SI 2).

In this survey, structured questionnaires with both closed and open-ended questions were prepared and used (SI 3). Before implementing the actual survey, the questionnaire was tested and then organized to make the questions easy for the participants and enumerators, so to that they can capture all relevant information by employing face-to-face data collection techniques. Enumerators from the Jinka Agricultural Research Center, who know the local areas and speak the local language (Arigna), participated.

Sampling

Twenty key informants practicing agroforestry parkland and associated tree management were selected by local farmers randomly using snowball sampling techniques. To ensure consistency in the data *Terminalia brownii* were selected based on visual evidence that showed similarities in their diameters at breast height (DBH at 1.3 m), the spread of their canopies (crown diameter), their maturity level, and the cropping history of the farmland (SI 4).

Treatments and experimental design

Distances from the tree trunk and soil depth were considered in the present study as factors of the soil's physicochemical properties.

Factor I: Distances from the tree trunk

In four directions, three radial transects were drawn under the selected tree canopy extending from the tree trunk to the open field (Fig. 2) according to the procedure used by Agena et al. (2014) and Berhe et al. (2013). Briefly, D_1 (the radial distance from tree trunk to ½ crown radius or 0–4.1 m), D_2 (the radial distance from ½ crown radius to edge of the tree canopy or 4.1–8.2 m), and D_3 (open field or out of the tree canopy coverage at 15 m far from the tree trunk).

Factor II: Soil depth

Under each radial distance from four directions and two soil depths (0–20 and 20–40 cm deep), the soil was sampled to represent the surface and subsurface soil layers. The sampling was laid out in a randomized complete block design (RCBD) in three blocks (crop fields) with two soil depths under three radial distances and nine independent field replicates (trees, three in each block), resulting in 54 composite soil samples ($3*9*2=54$) in total.

Soil chemical analysis

A composite soil sample of 150 g was air-dried, ground, sieved (particle size < 2 mm diameter) and subjected to analysis for soil texture, pH, electrical conductivity (EC), soil organic carbon (SOC), total nitrogen (TN), plant-available phosphorus (P_{av}), cation exchange capacity (CEC), exchangeable cations (Ca^{2+}, Na^+, Mg^{2+}) and plant-available potassium (K_{av}) at the laboratory of the soil biogeochemistry

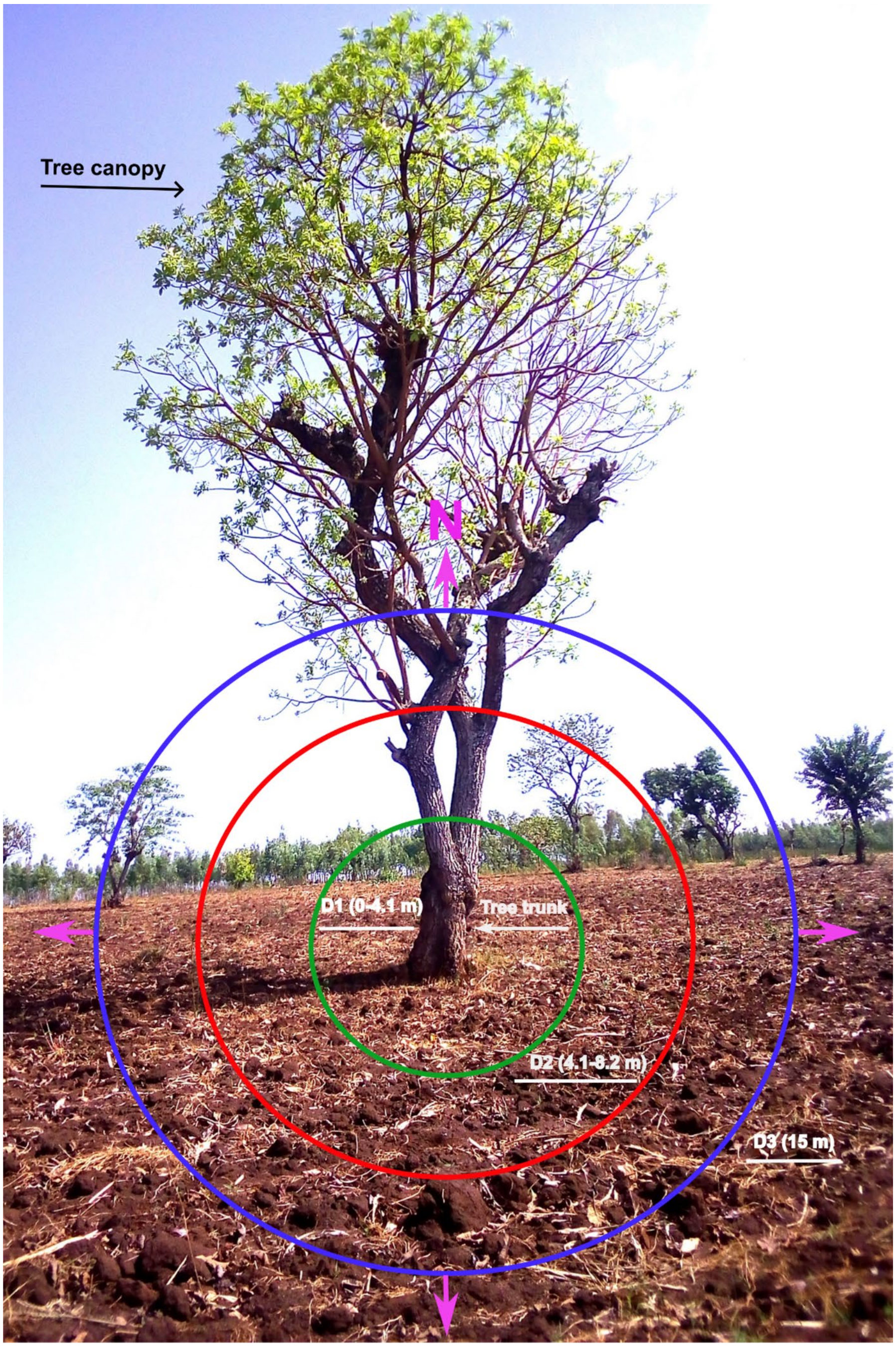


Fig. 2 Schematic drawing of experimental design for sampling under the *Terminalia brownii* tree in a crop field

department, Martin Luther University Halle-Wittenberg, Germany. Soil pH was measured with a combination electrode in a 1:2.5 (volume/volume) soil-to-water suspension. Plant-available P was analyzed by sodium bicarbonate ($NaHCO_3$) extract according to the standard method described by Olsen (1954). SOC and TN were determined by means of catalytic high-temperature combustion and thermal conductivity detection using an elementar vario MAX cube (Elementar Analysensysteme GmbH, Germany). Exchangeable base cations and CEC were extracted at pH 7 according to the ammonium acetate method proposed by Lavkulich (1981) and then quantified by inductively coupled plasma optical emission spectroscopy (ICP-OES, Ultima 2, HORIBA Europe GmbH, Germany). Percentage base saturation was calculated by dividing the sum of the mole of the base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) by the effective CEC of the soil and multiplying by 100.

Soil texture was determined quantitatively by using the hydrometer method. For soil bulk density, a core sampler was taken from each undisturbed plot at two depths (0–20 cm and 20–40 cm) before field preparation. Then, it was analyzed by gravimetric methods and then changed to a volumetric base. Initially, fresh soil was weighed and oven-dried at 105 °C for 24 h, and then dry soil was weighed. Afterward, the bulk density of the soil was calculated by the following formula.

$$BD = \frac{DSW}{SV}$$

where: BD is the bulk density (g/cm^3), DSW is the dry soil weight (g) and SV is the soil volume (cm^3).

Data evaluation

The household survey data were analyzed using SPSS software (version 21.0) to know the farmers' perceptions about the effects of *Terminalia brownii* management. All other collected data from experimental designs were subjected to the statistical analyses using parametric methods, specifically Factorial Analysis of Variance (ANOVA) for normally distributed data, as determined by tests for normality like Shapiro–Wilk test. Where data deviated from normality, non-parametric methods, such as the Kruskal–Wallis test, were employed. Least Significant Difference (LSD) was used to separate mean differences at $p\text{-value} < 0.05$ levels of significance using R software version 4.2.1 (R Core Team, 2022). A factorial ANOVA tested the independent variables, such as radial distances from tree trunks and their interactions, and dependent variables, such as soil depth and indicator parameters of the soil physicochemical property.

Results and discussion

Farmers' perception of *Terminalia brownii* management

In the study area, approximately 90% of farmers retain remnants of natural forest trees in their crop fields, demonstrating their intentional integration of these trees for multiple purposes (Table 1). Among the agroforestry trees, *Terminalia brownii* was identified as the most dominant species (86%), followed by *Vitex doniana* (81%) and *Cordia africana* (76%). These trees are particularly valued for their ecological, economic, and social benefits, including improving soil fertility through leaf litter deposition and nutrient turnover, which are highly preferred by farmers (Lemage and Hido 2021; Lemage and Anmaw 2022). The high percentage of farmers retaining *Terminalia brownii* highlights its perceived importance in enhancing agricultural sustainability and meeting household needs. Farmers' preference for *Terminalia brownii* as a soil fertility enhancer (93%) further supports its critical role in nutrient cycling through litterfall and decomposition. The preference of trees like *Acacia albida* and *Acacia abyssinica* (95%) for similar purposes demonstrates the general value of agroforestry trees in improving soil health in semiarid regions.

Farmers cultivate crops at varying distances from *Terminalia brownii*. Specifically, 50% of farmers prefer to plant their crops at the edge of the tree canopy, while 35% choose the area near the tree trunk, and 15% opt for open fields (Table 2). The highest crop yield was reported at the edge of the tree canopy by 76% of respondents, likely due to optimal light conditions and nutrient availability. In contrast, lower yields near the tree trunk were attributed to excessive shading, while lower fertility levels in open fields resulted in reduced yields in those areas. To minimize the adverse effect of shading, farmers in the study area exercised different tree management practices, including pruning (67%), pollarding (66%), and lopping (45%) (Table 2). According to farmers' responses, pruning (63%) is the most often used canopy management method for *Terminalia brownii* followed by pollarding (49%). Of the 80 farmers, 55% managed their trees at least one month before plowing. The pruned or pollarded branches were trodden to leave the leaf

Table 1 Summarized information about the presence, sources, uses, and preference of agroforestry trees by farmers in Alga (N = 45) and Beytsemal (N = 35) Kebeles, in South Ari district (N = 80)

Items	Response	Kebele		Total	Rank
		Alga (freq (%))	Beytsemal (freq (%))	Freq (%)	
Crop field trees presence	Yes	40 (89)	32 (91)	72 (90)	1
	No	5 (11)	3 (9)	8 (10)	2
Dominant trees	*Terminalia brownii*	38 (84)	31 (89)	69 (86)	1
	Vitex doniana	35 (78)	30 (86)	65 (81)	2
	Cordia africana	29 (78)	32 (91)	61 (76)	3
	Croton macrostachyus	29 (64)	26 (74)	55 (69)	4
	Acacia albida	19 (42)	11 (35)	30 (37)	5
	Acacia abyssinica	17 (38)	11 (31)	28 (35)	6
Sources	Natural forest	39 (87)	28 (80)	67 (84)	1
	Plantation	3 (7)	2 (6)	5 (6)	3
	Both	4 (9)	3 (9)	7 (9)	2
	Others (soil seed bank, bird dispersal, and other natural regeneration processes)	1 (2)	–	1 (1)	1
Major use categories of all species	Improving soil fertility	42 (93)	31 (89)	73 (91)	1
	Shading for livestock	41 (91)	29 (83)	70 (87)	2
	Keeping crops	34 (76)	19 (54)	53 (66)	6
	Charcoal	38 (84)	22 (83)	60 (75)	4
	Poles	35 (78)	26 (74)	56 (70)	5
	Medicine	29 (64)	18 (51)	47 (59)	7
	Others	38 (84)	30 (86)	68 (85)	3
Best preferred trees for improving soil fertility	*Terminalia brownii*	42 (93)	32 (91)	74 (92)	2
	Vitex doniana	41 (91)	30 (86)	71 (89)	4
	Cordia africana	37 (82)	29 (83)	66 (82)	3
	Croton macrostachyus	43 (95)	29 (83)	72 (90)	3
	Acacia albida	42 (93)	34 (97)	76 (95)	1
	Acacia abyssinica	43 (96)	33 (94)	76 (95)	1

biomass in the soil, and the woody parts were taken for different purposes. Proper pruning maintains tree structures that provide shade, which benefits livestock during the hot season (Badrulhisham and Othman 2016). In most semi-arid parts of Ethiopia, farmers maintain and manage trees on crop fields mainly to protect animals from heat stress (Muthuri et al. 2014; Mamo and Asfaw 2017). This effect is often mentioned as a strategy for mitigating climate stress because temperatures under tree canopies can be substantially lower than in an open field, potentially reducing heat stress for plants at temperature-sensitive crop development stages (Lin et al. 2015). Likewise, reduced wind speeds and increased air humidity beneath tree canopies can lessen crop transpiration and plant water stress (Cleugh and Hughes 2002) and decrease mechanical damage to crops, like leaf tearing and crop lodging (Luedeling et al. 2016; Lemage et al. 2022). Overall, the integration of *Terminalia brownii* and other trees into farmland demonstrates the multifunctional role of agroforestry systems as a climate-smart agriculture solution in improving soil fertility, supporting crop and livestock productivity, and mitigating climate stress in the study area.

Pollarding involves cutting back the tree's upper branches to promote dense foliage, reducing shading, and improving light balance. Pruning

Table 2 Local farmers' perception on *Terminalia brownii* tree management under parkland agroforestry practice at Alga (N = 45) and Beytsemal (N = 35) Kebeles, in South Ari district (N = 80)

Items	Response	Kebele		Total	Rank
		alga (freq (%))	Beytsemal (freq (%))	freq (%)	
Do you have *Terminalia brownii* in the agroforestry parkland?	Yes	41 (91)	31 (89)	72 (90)	1
	No	4 (9)	4 (11)	8 (10)	2
If yes, how far do you plant these crops?	Near the tree trunk	17 (38)	11 (31)	28 (35)	2
	At the edge of the tree canopy	24 (53)	16 (46)	40 (50)	1
	Open field	8 (18)	4 (11)	12 (15)	3
In which zone was, the highest crop yield observed	Near the tree trunk	5 (11)	3 (8.6)	8 (1)	3
	At the edge of the tree trunk	39 (87)	22 (63)	61 (76)	1
	Open field	7 (16)	4 (11)	11 (23)	2
To mitigate shading effects on crop yield, how can you manage the canopies of these trees?	*Pruning*	33 (73)	21 (60)	54 (67)	1
	Pollarding	32 (71)	21 (60)	53 (66)	2
	Lopping	24 (53)	12 (34)	36 (45)	3
Which management practice is relevant for *Terminalia brownii*?	*Pruning*	28 (62)	22 (63)	50 (62)	1
	Pollarding	19 (42)	20 (57)	39 (49)	2
	Lopping	12 (27)	10 (29)	22 (12)	3
Which time is relevant to manage *Terminalia brownii* tree canopy?	*At least one month before crop planting*	23 (51)	21 (60)	44 (55)	1
	At plowing start	19 (42)	11 (31)	30 (37)	2
	At any time	14 (31)	8 (23)	22 (27)	3

Table 3 The effects of *Terminalia brownii* on soil bulk density (BD), electric conductivity (EC) and on soil pH

Soil properties	Soil depth (cm)	Distance from a tree trunk (m) + SD			Overall depth (0–40)	*P-Value*
		D$_1$ (0–4.1)	D$_2$ (4.1–8.2)	D$_3$ (15)		
BD (g cm^{-3})	0–20	$1.0^{\mathbf{e}} \pm 0.04$	$1.3^{d} \pm 0.04$	$1.5^{b} \pm 0.04$	$1.3^{B} \pm 0.023$	0.000 of dep*dist
	20–40	$1.4^{c} \pm 0.04$	$1.6^{a} \pm 0.04$	$1.6^{\mathbf{a}} \pm 0.04$	$1.5^{A} \pm 0.023$	0.000 of depth
Overall distance		$1.2^{C} \pm 0.03$	$1.4^{B} \pm 0.03$	$1.6^{A} \pm 0.03$	–	0.000 of distance
EC (dS/m)	0–20	$84.7^{bc} \pm 42.7$	$118.5^{abc} \pm 42.7$	$72.2^{c} \pm 42.7$	$91.8^{B} \pm 24.7$	0.106 of dep*dist
	20–40	$164.5^{a} \pm 42.7$	$123.0^{ab} \pm 42.7$	$107.6^{bc} \pm 42.7$	$131.7^{A} \pm 24.7$	0.007 of depth
Overall distance		$124.6^{A} \pm 0.03$	$120.7^{A} \pm 0.03$	$89.9^{A} \pm 0.03$	–	0.104 of distance
pH	0–20	$5.7^{a} \pm 0.12$	$5.7^{a} \pm 0.12$	$5.6^{a} \pm 0.12$	$5.7^{A} \pm 0.07$	0.667 of dep*dist
(H$_2$O)	20–40	$5.8^{a} \pm 0.12$	$5.7^{a} \pm 0.12$	$5.6^{a} \pm 0.12$	$5.7^{A} \pm 0.07$	0.856 of depth
Overall distance		$5.7^{A} \pm 0.09$	$5.7^{A} \pm 0.09$	$5.6^{A} \pm 0.09$	–	0.333 of distance

Note that the superscript of the same letter indicates no significant difference at ($p < 0.05$), SD: standard deviation

selectively removes specific branches to shape the tree and enhance light penetration, while lopping targets medium-sized branches to maintain structure and improve light distribution for crops beneath the canopy.

Soil physicochemical properties

Bulk density

The results revealed a significant difference ($p < 0.05$) in soil bulk density (BD) across radial distances and soil depths (Table 3). Bulk density increased from the tree trunk (D$_1$) to the open field (D$_3$) and from surface (0–20 cm) to subsurface soil (20–40 cm). The mean bulk density ranged from 1.0 g cm^{-3} at the surface near the tree trunk to 1.6 g cm^{-3} in the subsurface open field. Trees enhance soil structure by lowering bulk density, increasing macro-porosity, and raising carbon content through root activity and organic matter inputs, especially near the trunk where root density is higher (Bargués Tobella et al. 2014). In addition to root activity, the incorporation of organic matter plays a significant role in reducing bulk density. Pruned or pollarded branches that are trodden and left as leaf biomass on the soil surface decompose over time, contributing to increased SOC levels. This organic matter improves soil structure by binding soil particles, increasing porosity, and reducing compaction near the tree canopy. These properties make agroforestry systems with *Terminalia brownii* a valuable component of climate-smart agriculture, as they enhance soil physical resilience under changing climatic conditions.

In line with our results, significantly lower soil bulk density under different tree canopies as compared to an open field and soil depths were reported for *Combretum apiculatum* and *Peltophorum africanum* (Aweto and Dikinya 2003), *Millettia ferruginea* (Hailu et al. 2000), *Acacia nilotica*, and *Ficus thonningii* (Berhe et al. 2013). The loosening of the soil and consequent decrease in soil bulk density could be influenced by the increased abundance of tree roots and organic matter around the trunk. Tree root density and organic matter correlated negatively with bulk density (Xie et al. 2020). This indicates that trees play a crucial role in loosening soil, enhancing water infiltration, and reducing soil compaction. This is essential for improving crop productivity, especially in semi-arid climates where soil compaction can be a limiting factor. By integrating *Terminalia brownii* into farmlands, farmers can improve the physical properties of the soil, supporting climate resilience by enhancing soil structure and reducing the risk of erosion (Fahad et al. 2022).

Electrical conductivity (EC)

The mean values of soil electrical conductivity (EC) showed no significant differences ($p < 0.05$) across various radial distances and between soil depths. Hence, the influence of the presence of *Terminalia brownii* on EC is minimal (Table 3). However, the average EC values decreased with increasing radial distance from the tree trunk, while they increased with soil depth. Surface soils closest to the tree trunk (D_1) had higher median EC values (84.7 dS/m) compared to those in open fields (72.2 dS/m). In contrast, subsurface soils near the tree trunk exhibited even higher EC values (164.5 dS/m). This indicates that the surface soil is less saline than the subsurface soil. Moreover, the microbial association and lower leaching of base-forming cations around a tree might contribute to higher values around the tree trunk. Our results are in good agreement with Kassa et al. (2010), who reported non-significant effects of *Balanites aegyptiaca* and *Ziziphus spina-christi* over EC in the arid areas of Humera and Hibru districts of Ethiopia, respectively. In line with this study, subsurface soil prevailed with a higher EC under trees, for instance, for *Faidherbia albida* (Abdella et al. 2020), *Cordia africana*, and *Croton macrostachyus* (Mohammed et al. 2018). The role of *Terminalia brownii* in moderating EC levels under its canopy contributes significantly to maintaining soil fertility, particularly in degraded landscapes where salinity and nutrient leaching are major concerns. By enhancing the availability of nutrients and reducing the risk of salinity stress, *Terminalia brownii* supports sustainable agricultural practices aligned with climate-smart agriculture. These findings underscore the importance of integrating *Terminalia brownii* into agroforestry systems to ensure soil health and productivity under changing climatic conditions (Lemage & Anmaw 2022; Muchane et al. 2020).

Soil pH

No significant differences ($p < 0.05$) in soil pH were observed across radial distances or soil depths (Table 3). However, mean values of soil pH exhibited a slightly decreasing trend as it went from tree trunk to open field, with the highest mean value (5.8) at D_1 within subsurface soil (20–40 cm) and the lowest (5.6) at D_3 within surface soil (0–20 cm). This might be due to higher litter deposition, decomposition, and subsequent mineralization that release cations to the soil system under the canopy than on open fields. Similar to this finding, Aweto and Dikinya (2003) reported no significant difference in soil pH under the canopy of scattered *Combretum apiculatum and Peltophorum africanum* compared to the open field. However, soil pH was significantly higher under the tree trunks of *Cordia africana* and *Croton macrostachyus* and decreased with increasing radial distances (Anbessa and Utaile 2024). The moderately acidic pH levels observed in this study (5.6–5.8) are favorable for most crops and microbial activities, which support nutrient cycling and overall soil health (Zhalnina et al. 2015). By maintaining these conditions through agroforestry practices, it is possible to buffer soils against acidification—a common consequence of climate changes—thus ensuring sustainable agricultural productivity.

Soil texture

The particle size distribution of the soils in the investigated samples was categorized as clay loam. There was no significant ($p < 0.05$) difference in the soil texture, i.e., the contribution of sand, silt, and clay fractions within the samples along the concentric radial distances and soil depths (Table 4). The highest (25%) mean values of the sand fraction were found in the open field at the subsurface (20–40 cm) soil depth, whereas the lowest (21%) were found near the tree trunk at the top surface (0–20 cm). Even if it is not statistically significant, the average contents of silt and clay fractions were slightly higher near the tree trunk on the surface (0–20 cm) and slightly lower at the open field in the subsurface (20–40 cm). The mean value of sand exhibited a slightly increasing trend, whereas silt and clay showed a slightly decreasing trend within the radial distance and soil depths. Thus, our results show that the effect of trees is not significant in changing the texture of the parent soil materials, which is in line with the findings of Hailu et al. (2000). As noted by Mohammed et al. (2018), several mechanisms can explain the observed trends. Trees affect soil properties through their canopies and root systems. The canopy mitigates the direct impact of raindrops, which helps minimize soil erosion, especially of finer particles like clay and silt that are more easily displaced in open fields. Also, tree roots contribute organic matter and enhance soil aggregation, which assists in retaining finer particles near the tree trunk. Over time, these processes may result in a lower sand fraction and a higher clay content under the tree canopy when compared to open fields. While these mechanisms could account for the trends reported in the literature, they were not statistically significant in our study.

Soil organic carbon (SOC) and total nitrogen (TN)

The SOC and TN contents exhibited statistically significant differences ($P < 0.05$) across radial distances and soil depths (Table 5). Generally, the SOC and TN showed a decreasing trend with increasing radial distances in both surface and subsurface soil depth. This pattern is attributed to the accumulation of organic matter around the tree trunk due to litterfall, root biomass, and microbial activity. The higher SOC and TN near the canopy zone highlight the vital role of *Terminalia brownii* in nutrient cycling and soil enrichment. Similarly, in southeastern Botswana, SOC is higher by 47% and 55% under the canopy of *C. apiculatum*

Table 4 The effects of *Terminalia brownii* on soil texture. Note that the superscript of the same letter indicates no significant difference at ($p < 0.05$)

Soil properties (%)	Soil depth (cm)	Distance from tree trunk (m) + SD			Overall depth (0–40)	*P-Value*
		D_1 (0–4.1)	D_2 (4.1–8.2)	D_3 (15)		
Clay	0–20	$56.8^{a} \pm 0.03$	$56.2^{a} \pm 0.03$	$55.5^{a} \pm 0.03$	$56.1^{a} \pm 0.01$	0.000 of dep*dist
	20–40	$55.4^{a} \pm 0.03$	$55.3^{a} \pm 0.03$	$55.1^{a} \pm 0.03$	$55.6^{a} \pm 0.01$	0.000 of depth
Overall distance		$56.1^{a} \pm 0.02$	$56.2^{a} \pm 0.02$	$55.3^{a} \pm 0.02$		0.000 of distance
Silt	0–20	$23.9^{a} \pm 0.04$	$22.5^{a} \pm 0.04$	$21.3^{a} \pm 0.04$	$22.6^{a} \pm 0.02$	0.000 of dep*dist
	20–40	$23.3^{a} \pm 0.04$	$22.1^{a} \pm 0.04$	$22.1^{a} \pm 0.04$	$22.5^{a} \pm 0.02$	0.001 of depth
Overall distance		$23.6^{a} \pm 0.01$	$22.3^{a} \pm 0.01$	$21.7^{a} \pm 0.01$		0.000 of distance
Sand	0–20	$21.0^{a} \pm 0.01$	$23.0^{a} \pm 0.01$	$23.9^{a} \pm 0.01$	$22.6^{a} \pm 0.01$	0.000 of dep*dist
	20–40	$22.9^{a} \pm 0.01$	$23.9^{a} \pm 0.01$	$25.0^{a} \pm 0.01$	$23.9^{a} \pm 0.01$	0.000 of depth
Overall distance		$21.9^{a} \pm 0.01$	$23.4^{a} \pm 0.01$	$24.4^{a} \pm 0.01$		0.000 of distance

Table 5 Effects of *Terminalia brownii* on SOC, TN, $K_{av,}$ and P_{av}. Note that the superscript of the same letter indicates no significant difference at ($p < 0.05$)

Soil properties	Soil depth	Distance from tree trunk (m) + SDE			Overall depth	*P*-Value
		D_1(0–4.1)	D_2 (4.1–8.2)	D_3 (15)		
TN (%)	0–20	$0.2^{a}\pm0.01$	$0.2^{a}\pm0.01$	$0.2^{b}\pm0.012$	$0.2^{A}\pm0.08$	0.012 of dep*dista
	20–40	$0.2^{b}\pm0.01$	$0.2^{b}\pm0.01$	$0.1^{c}\pm0.012$	$0.1^{B}\pm0.08$	0.000 of depth
Overall distance		$0.21^{A}\pm0.008$	$0.20^{A}\pm0.008$	$0.16^{B}\pm0.008$		0.000 of distance
SOC (%)	0–20	$3.3^{a}\pm0.22$	$3.3^{a}\pm0.22$	$2.7^{b}\pm0.22$	$3.10^{A}\pm0.13$	0.016 of dep*dista
	20–40	$2.6^{b}\pm0.22$	$2.7^{b}\pm0.22$	$1.5^{c}\pm0.22$	$2.3^{B}\pm0.13$	0.000 of depth
Overall distance		$3.0^{A}\pm0.16$	$3.0^{A}\pm0.16$	$2.1^{B}\pm0.16$		0.000 of distance
$K_{av(ppm)}$	0–20	$4.9^{ab}\pm1.13$	$6.6^{a}\pm1.13$	$5.1^{ab}\pm1.13$	$5.6^{A}\pm0.65$	0.485 of dep*dista
	20–40	$3.5^{bc}\pm1.13$	$3.5^{bc}\pm1.13$	$2.0^{c}\pm1.13$	$3.0^{B}\pm0.65$	0.000 of depth
Overall distance		$4.2^{B}\pm0.80$	$5.0^{A}\pm0.80$	$3.6^{B}\pm0.80$		0.199 of distance
$P_{av(ppm)}$	0–20	$2.6^{a}\pm0.32$	$1.9^{b}\pm0.32$	$0.8^{c}\pm0.32$	$1.8^{A}\pm0.18$	0.001 of dep*dista
	20–40	$0.6^{c}\pm0.32$	$0.5^{c}\pm0.32$	$0.5^{c}\pm0.32$	$0.5^{B}\pm0.18$	0.000 of depth
Overall distance		$1.6^{B}\pm0.22$	$1.2^{A}\pm0.22$	$0.7^{B}\pm0.22$		0.000 of distance

C

and *P. africanum* than in open fields (Aweto and Dikinya 2003). Furthermore, results from different tree species such as *F. albida, O. abyssinica, D. melanoxylon, A. seyal, C. africana, and C. macrostachyus* showed significantly higher SOC and TN under the canopy than outside the canopy zone (Gebrewahid et al. 2018; Mohammed et al. 2018; Tsegu 2019; Abdella et al. 2020; Anbessa and Utaile 2024).

These findings are crucial for agricultural productivity, particularly in semi-arid regions where nutrient-depleted soils restrict crop yields. Retaining *Terminalia brownii* in crop fields can enhance soil organic matter, which supports water retention, microbial activity, and nutrient availability, especially under changing climatic conditions. Such practices not only improve soil fertility but also contribute to carbon sequestration, an essential strategy for mitigating climate change.

Plant-available potassium (K_{av}) and phosphorus (P_{av})

The mean values of K_{av} and P_{av} depict a significant difference ($P < 0.05$) across various radial distances and soil depths (Table 5). The K_{av} and P_{av} on the soil surface and under the canopy of *Terminalia brownii* were higher as compared to subsurface soil and open fields. K_{av} was highest in the surface soil under the tree canopy at D_2, measuring 6.6 ppm, and decreased to 2.0 ppm in the subsurface soil of the open field at D_3. Similarly, P_{av} was notably higher in the surface soils near the canopy, with a value of 2.6 ppm at D_1, compared to 0.8 ppm at D_3 in the open field. Subsurface P_{av} values remained consistently low, averaging 0.5 ppm across all distances. The enrichment of K_{av} and P_{av} under the canopy of *Terminalia brownii* can be attributed to the accumulation of above- and below-ground biomass, including leaf litter and root turnover, which undergo microbial decomposition and release nutrients into the soil. The higher biological activity around the tree canopy accelerates the mineralization of organic matter, making potassium and phosphorus more available to plants. These findings are consistent with previous studies showing higher concentrations of K_{av} and P_{av} under agroforestry tree species like *A. tortilis, A. seyal*, *C. africana*, *C. macrostachyus*, *D.* melanoxylon, *F. albida*, *M. ferruginea*, *O. abyssinica*, and *V. doniana* exhibited a higher amount of K_{av} and P_{av} (Yadessa et al. 2009; Berhe et al. 2013; Agena et al. 2014; Gebrewahid et al. 2018; Mohammed et al. 2018; Tsegu 2019; Abdella et al. 2020; Lemage and Anmaw 2022; Anbessa and Utaile 2024). The role of potassium and phosphorus in maintaining soil fertility is crucial, especially in the context of changing climatic conditions. Potassium helps regulate water uptake and improves crop resistance to drought, while phosphorus is essential for root development and energy transfer. The ability of *Terminalia brownii* to enhance these nutrients beneath its canopy plays a significant role in creating climate-resilient agroforestry systems. These nutrient-rich soils decrease the reliance on synthetic fertilizers, which can be less accessible and more expensive for rural farmers, particularly during climate variability and economic challenges.

In contrast to our results, the mean values of K_{av} between radial distance from the canopy of *B. aegyptiaca* and soil depths did not show significant differences (Kassa et al. 2010). This discrepancy might have occurred due to differences like species, age variation, and site dissimilarity that affect nutrient release and cycling. By enhancing soil fertility and supporting nutrient availability, *Terminalia brownii* plays a pivotal role in sustainable agriculture. Its integration into agroforestry systems supports climate-smart agriculture by lowering input costs, reducing nutrient loss due to heavy rains, and improving soil resilience during prolonged droughts. Additionally, these trees promote nutrient cycling and buffer soils against degradation, ensuring sustained agricultural productivity in the face of climate variability.

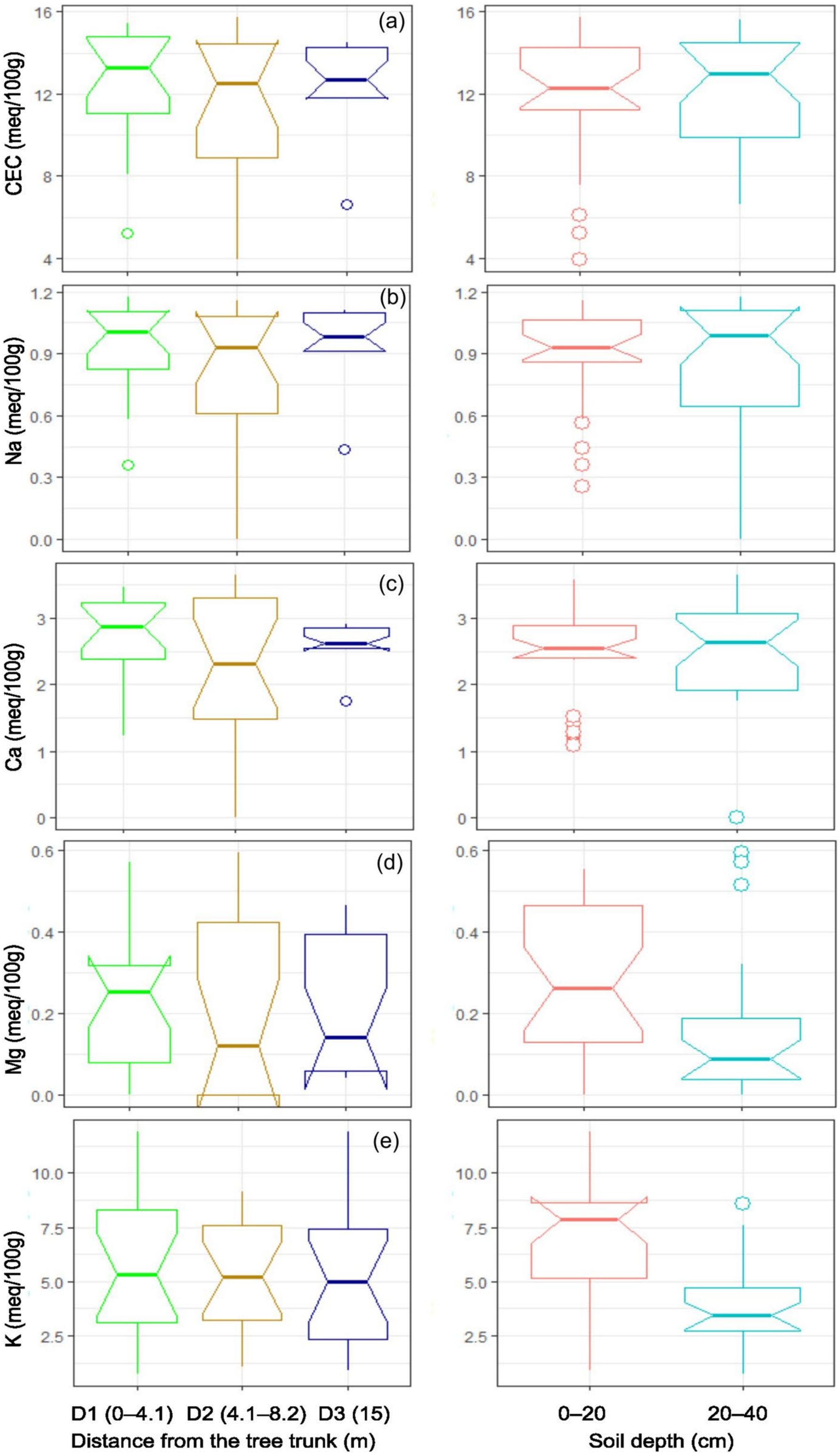
Cation exchange capacity (CEC) and exchangeable cations (Na^+, Ca^{2+}, Mg^{2+} and $K.^+$)

Figure 3a-e illustrates the cation exchange capacity (CEC) and levels of exchangeable cations—sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+)—at various radial distances and soil depths beneath the canopy of *Terminalia brownii*. Our results revealed no statistically significant differences ($P > 0.05$) in CEC and exchangeable cations (EC) across radial distances (D_1, D_2, and D3) or soil depths (0–20 cm and 20–40 cm). However, median values for CEC and EC were generally higher under the tree canopy when compared to open fields, suggesting improved soil fertility in these areas, which is beneficial for agroforestry systems (Fig. 3 a-e). The higher CEC values observed under the canopy of *Terminalia brownii* can be attributed to the accumulation of litter and organic matter, which decomposes and releases cations into the soil. This increases the soil's capacity to retain positively charged ions, thereby enhancing nutrient availability. Exchangeable cations such as Na^+, Ca^{2+}, Mg^{2+}, and K^+ contribute to improved soil structure, water retention, and nutrient cycling. These processes are crucial for maintaining soil fertility and resilience under changing climatic conditions. CEC tended to increase with depth, likely due to the higher clay content in subsurface soils, which inherently have a greater capacity to retain cations. However, variable patterns in Mg^{2+} and K^+ could result from leaching, differential root uptake, or site-specific soil properties. In line with our results, high values of CEC under the canopy of *A. senegal*, *C. macrostachyus*, and *C. africana* report (Aweto and Dikinya 2003; Yadessa et al. 2009; Anbessa and Utaile 2024). Similarly, high exchangeable cations were recorded under the canopy of native tree species such as *F. vasta* (Berhe et al. 2013), *F. albida*, and *C. africana* (Mohammed et al. 2018). Overall, the enhancement of CEC and exchangeable cations under the canopy of *Terminalia brownii* supports the principles of climate-smart agriculture by improving soil quality in degraded landscapes. Higher cation levels ensure that essential nutrients remain available for crops, reducing the need for chemical fertilizers, which are often costly and environmentally damaging. These findings highlight the potential of *Terminalia brownii* in addressing soil degradation and enhancing agricultural sustainability. Its role in improving soil fertility through increased CEC and exchangeable cations underscores its value as a cornerstone of climate-smart agroforestry practices.

Conclusions

Farmers consider *Terminalia brownii* essential in agroforestry due to its potential for soil fertility, its ability to regulate microclimates, and its provision of fodder, fuelwood, and timber. However, there are challenges associated with its cultivation, including competition with crops for resources and insufficient management practices. To address these issues, pollarding and pruning are preferred management methods by farmers. These techniques help maintain tree biomass over time, maximize the multifunctional benefits of the tree, and minimize shading effects on the crops growing beneath it. The soil's physical properties, like soil textural fractions (sand, silt, and clay), were not considerably influenced by the presence of *Terminalia brownii*. However, soil bulk density was notably lower under the canopy and increased with increasing radial distances and soil depth. The

Fig. 3 **a–e** The effect of *Terminalia brownii* on soil CEC and EC (Na^+, Ca^{2+}, Mg^{2+} and K^+). The notched box plots indicate the median (solid lines between the boxes), and interquartile range (IQR) with upper (75%) and lower (25%) quartiles as well as a 95% confidence interval of the median within $\pm 1.57*IQR/\sqrt{n}$. The scattered circles also indicate the outlier



soil chemical properties such as SOC, TN, P_{av}, and K_{av} were higher near the tree trunk than in the open field. Soil pH, CEC, EC and exchangeable bases were not significantly influenced by *Terminalia brownii*. Hence, retaining *Terminalia brownii* on crop fields is crucial for farmers to benefit from the multipurpose uses of the tree. The present study investigated the role of *Terminalia brownii* in soil physicochemical properties; however, its significance in crop yield and conditioning of the microclimate needs to be studied in the future.

Acknowledgements The authors are indebted to Aaron Tinschert for analyzing soil samples and Dr. Betelhem Mekonnen for her valuable comments and suggestions. We thank the Agricultural and Rural Development experts of South Ari District and the Alga Kebele Administrations for their unreserved support during site selection and data collection. We also extend our deepest gratitude to Belayneh Lemage for his support during field data collection and the Jinka Agricultural Research Center for the collaboration. Mr. Mitiku appreciates the in-country scholarship award for the German Academic Exchange Service (DAAD) and the Wondo Genet College of Forestry and Natural Resources, Hawassa University. We are grateful for the editorial support and comments from two anonymous reviewers.

Author Contributions Sample collection, Formal analysis and Investigation, Writing – original draft preparation: [Mitiku Ayele Handiso]; Writing – original draft preparation, review and editing, Supervision: [Bruk Lemma]; Conceptualization, Methodology, Writing –review and editing, Supervision: [Zebene Asfaw]; Writing – review and editing, Methodology, Supervision: [Tobias Bromm]; Writing – review and editing: [Beyene Teklu Mellisse]; Funding acquisition, Resources, Writing – review and editing, Supervision: [Bruno Glasser].

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interests The authors declare no competing interests.

References

Abdella M, Nigatu L, Akuma A (2020) Impact of Parkland Trees (Faidherbia albida Delile and Cordia Africana Lam) on selected soil properties and sorghum yield in Eastern Oromia. Ethiopia. Agric For Fish. 9:54

Adam AM (2020) Sample size determination in survey research. J Sci Res Rep. https://doi.org/10.9734/jsrr/2020/v26i530263

Agena AT, Tilahun FE, Bekele L (2014) Effects of three tree species on microclimate and soil amelioration in the central rift valley of Ethiopia. J Soil Sci Environ Manag 5:62–71. https://doi.org/10.5897/JSSEM12.060

Anbessa GN, Utaile YU (2024) Scattered trees in smallholder farms improve soil properties and litter decomposition in humid-agroecosystems in Ethiopia. Agrofor Syst. https://doi.org/10.1007/s10457-024-00982-z

Asfaw Z (2007) Farmers' local knowledge and topsoil properties of agroforestry practices in Sidama, Southern Ethiopia. Agrofor Syst 71:35–48. https://doi.org/10.1007/s10457-007-9087-0

Aweto A, Dikinya O (2003) The beneficial effects of two tree species on soil properties in a semi-arid savanna rangeland in Botswana. Land Contam Reclam 11:339–344

Ayres E, Steltzer H, Berg S et al (2009) Tree species traits influence soil physical, chemical, and biological properties in high elevation forests. PLoS ONE 4:e5964. https://doi.org/10.1371/journal.pone.0005964

Badrulhisham N, Othman N (2016) Knowledge in tree pruning for sustainable practices in urban setting: Improving our quality of life. Procedia-Soc Behav Sci 234:210–217

Bargués Tobella A, Reese H, Almaw A, Bayala J, Malmer A, Laudon H, Ilstedt U (2014) The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. Water Resources Research. https://doi.org/10.1002/2013WR015197

Bekele SE (2018) Parkland agroforestry of Ethiopia; key to production, productivity, biodiversity conservation and climate change mitigation: a review. Open J for 08:472–488. https://doi.org/10.4236/ojf.2018.84030

Berhe H, Anjulo A, Abdulkadir A, Edwards S (2013) Evaluation of the effect of ficus thonningii (blume) on soil physicochemical properties in ahferom district of Tigray, Ethiopia. J Soil Sci Environ Manag 4:35–45. https://doi.org/10.5897/JSSEM13.0369

Boffa JM (2000) West African agroforestry parklands: keys to conservation and sustainable management. Unasylva Engl Ed 51:11–17

Cleugh H, Hughes D (2002) Impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. Aust J Exp Agric 42:679–701

Dawid I, Mohammed F (2021) The status challenges and prospects of agricultural production and productivity in Ethiopia a review. Int J Res Agron. 4(2):108–114

Demelash M, Stahr K (2010) Assessment of integrated soil and water conservation measures on key soil properties in South Gonder. North-Western Highl Ethiop 1(7):164–176

Fahad S, Chavan SB, Chichaghare AR, Uthappa AR, Kumar M, Kakade V, Pradhan A, Jinger D, Rawale G, Yadav DK, Kumar V, Farooq TH, Ali B, Sawant AV, Saud S, Chen S, Poczai P (2022) Agroforestry systems for soil health improvement and maintenance. In Sustainability (Switzerland). 14(22):14877

Gebre-Selassie S (2004) The Roles of Agriculture in the Development Process: Recent Experiences and Lessons from Ethiopia.

Gebrewahid Y, Gebre-Egziabhier T-B, Teka K, Birhane E (2018) Carbon stock potential of scattered trees on farmland along an altitudinal gradient in Tigray. Northern Ethiop Ecol Process 7:40. https://doi.org/10.1186/s13717-018-0152-6

Gelan, D. T., Tilahun, S., Yousuf, J. (2016). Analysis of Livelihood Strategy Determinates Among Different Wealth Categories of Rural Households : A Case from Amhara Region of Ethiopia. Developing Country Studies, 6(2).

Hailu T, Negash L, Olsson M (2000) Millettia ferruginea from southern Ethiopia: impacts on soil fertility and growth of maize. Agrofor Syst 48:9–24

Handiso MA, Hemacho AH, Bongido BL, Anjulo MM (2023) Effect of conservation tillage on soil and water conservation, yield and yield components of Maize (Zea mays L) in South Ari District. Discov Agric, Southern Ethiopia. https://doi.org/10.1007/s44279-023-00008-9

Harmer R (2004) SILVICULTURE | coppice silviculture practiced in temperate regions. Encycl For Sci. https://doi.org/10.1016/b0-12-145160-7/00230-1

Harris R (1994) Clarifying certain pruning terminology thinning heading pollarding. Arboric Urban For. 20(1):50–54

Kassa H, Gebrehiwet K, Yamoah C (2010) Balanites aegyptiaca, a potential tree for parkland agroforestry systems with sorghum in Northern Ethiopia

Lavkulich LM (1981) Methods Manual, Pedology Laboratory. Department of Soil Science, University of British Columbia, Vancouver. Br Columbia Can

Lemage B, Hido A (2021) Assessing, evaluation and demonstration of highland indigenous fodder tree and shrub species in Debub Ari district. S Ethiop. 8(4):8

Lemage B, Anmaw Y (2022) Effect of farmland trees Terminalia brownie and Vitex doniana on soil physicochemical properties and maize yield. J Innov Agric. 9(4):1–9

Lemage B, Hegano A, Tesfaye A, Ayele M (2022) Evaluation of leaf litter nutrient composition, decomposition and releasing potential of Cordia Africana, Terminalia Brownie and, Vitex Doniana tree species. J Agric Aquac 4:

Lemma B, Kebede Gurmessa S, Nemomissa S et al (2020) Spatial and temporal 2H and 18O isotope variation of contemporary precipitation in the Bale Mountains, Ethiopia. Isotopes Environ Health Stud 56:122–135

Lin B, Burgess A, Murchie E. 2015. Adaptation for climate-sensitive crops using agroforestry. Case studies for coffee and rice In Tree-crop interactions. Agroforestry in a changing climate. CABI Wallingford. UK. 278-308

Luedeling E, Smethurst PJ, Baudron F et al (2016) Field-scale modeling of tree–crop interactions: challenges and development needs. Agric Syst 142:51–69. https://doi.org/10.1016/j.agsy.2015.11.005

Mamo D, Asfaw Z (2017) Assessment of farmers' management activities on scattered trees on crop fields at Gemechis district, West Hararge Zone, Oromia, Ethiopia. Int J Agric 2:41–57

Mekuria, W. 2018. The link between agricultural production and population dynamics in Ethiopia a review. Advances in Plants Agriculture Research. https://doi.org/10.15406/apar.2018.08.00336

Mesfin K, Tesfaye S, Girma K et al (2017) Description, characterization and classification of the major soils in jinka agricultural research center, South Western Ethiopia. J Soil Sci Environ Manag 8:61–69. https://doi.org/10.5897/JSSEM2015.0498

Mohammed M, Beyene A, Reshad M (2018) Influence of scattered cordiaafricana and crotonmacrostachyus trees on selected soil properties, microclimate and maize yield in Eastern Oromia. Ethiopia. Am J Agric for. 6:253–262

Muchane MN, Sileshi GW, Gripenberg S, Jonsson M, Pumariño L, Barrios E (2020) Agroforestry boosts soil health in the humid and sub-humid tropics: a meta-analysis. In Agricult, Ecosyst Environ. 295:106899

Muthuri C, Bayala J, Iiyama M, Ong C (2014) Trees and microclimate. Treesilience Assess Resil Provid Trees Drylands East Afr World Agrofor Cent Nairobi Kenya 81–85

Neglo KAW, Gebrekidan T, Lyu K (2021) The role of agriculture and non-farm economy in addressing food insecurity in ethiopia: a review. Sustainability 13:3874

Ogunkunle CO, Fatoba PO, Awotoye OO, Olorunmaiye KS (2013) Root-shoot partitioning of copper, chromium and zinc in lycopersicon esculentum and amaranthus hybridus grown in cement-polluted soil. Environ Exp Biol 11:131–136

Olsen SR (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture

R Core Team (2022) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. https://www.r-project.org/

Tesemma Bekele A, Birnie A, Tengnäs B (1993) Useful trees and shrubs for Ethiopia Identification, Propagation and Management for Agricultural and Pastoral Communities. Regional Soil Conservation Unit (RSCU), Swedish International Development Authority (SIDA)

Tolera M, Asfaw Z, Lemenih M, Karltun E (2008) Woody species diversity in a changing landscape in the south-central highlands of Ethiopia. Agric Ecosyst Environ 128:52–58

Tscharntke T, Clough Y, Bhagwat SA et al (2011) Multifunctional shade-tree management in tropical agroforestry landscapes–a review. J Appl Ecol 48:619–629

Tsegu E (2019) The role of Faidherbia albida tree species in parkland agroforestry and its management in Ethiopia. J Hortic for 11:42–47. https://doi.org/10.5897/JHF2018.0570

Xie C, Cai S, Yu B et al (2020) The effects of tree root density on water infiltration in urban soil based on a ground penetrating radar in shanghai. China Urban for Urban Green 50:126648. https://doi.org/10.1016/j.ufug.2020.126648

Yadessa A, Itanna F, Olsson M (2009) Scattered trees as modifiers of agricultural landscapes: the role of *waddeessa* (*Cordia africana* Lam.) trees in Bako area, Oromia. Ethiopia Afr J Ecol 47:78–83. https://doi.org/10.1111/j.1365-2028.2008.01053.x

Zhalnina K, Dias R, de Quadros PD et al (2015) Soil pH determines microbial diversity and composition in the park grass experiment. Microb Ecol 69:395–406. https://doi.org/10.1007/s00248-014-0530-2