J Arid Land (2024) 16(1): 1–13
https://doi.org/10.1007/s40333-024-0002-6

Science Press Springer-Verlag

Parkland trees on smallholder farms ameliorate soil physical-chemical properties in the semi-arid area of Tigray, Ethiopia

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Abstract: Proposed agroforestry options should begin with the species that farmers are most familiar with, which would be the native multipurpose trees that have evolved under smallholder farms and socioeconomic conditions. The African birch (*Anogeissus leiocarpa* (DC.) Guill. & Perr.) and pink jacaranda (*Stereospermum kunthianum* Cham.) trees are the dominant species in the agroforestry parkland system in the drylands of Tigray, Ethiopia. Smallholder farmers highly value these trees for their multifunctional uses including timber, firewood, charcoal, medicine, etc. These trees also could improve soil fertility. However, the amount of soil physical and chemical properties enhanced by the two species must be determined to maintain the sustainable conservation of the species in the parklands and to scale up to similar agro-ecological systems. Hence, we selected twelve isolated trees, six from each species that had similar dendrometric characteristics and were growing in similar environmental conditions. We divided the canopy cover of each tree into three radial distances: mid-canopy, canopy edge, and canopy gap (control). At each distance, we took soil samples from three different depths. We collected 216 soil samples (half disturbed and the other half undisturbed) from each canopy position and soil depth. Bulk density (BD), soil moisture content (SMC), soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), available potassium (AK), pH, electrical conductivity (EC), and cation exchange capacity (CEC) were analysed. Results revealed that soil physical and chemical properties significantly improved except for soil texture and EC under both species, CEC under *A. leiocarpus*, and soil pH under *S. kunthianum,* all the studied soils were improved under both species canopy as compared with canopy gap. SMC, TN, AP, and AK under canopy of these trees were respectively 24.1%, 11.1%, 55.0%, and 9.3% higher than those soils under control. The two parkland agroforestry species significantly enhanced soil fertility near the canopy of topsoil through improving soil physical and chemical properties. These two species were recommended in the drylands with similar agro-ecological systems.

Keywords: agroforestry; bulk density; carbon stock; dispersed tree; soil texture; tree canopy

Citation: Selam LJALEM, Emiru BIRHANE, Kassa TEKA, Daniel H BERHE. 2024. Parkland trees on smallholder farms ameliorate soil physical-chemical properties in the semi-arid area of Tigray, Ethiopia. Journal of Arid Land, 16(1): 1–13. https://doi.org/10.1007/s40333-024-0002-6

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Received 2023-08-23; revised 2023-11-28; accepted 2023-12-18

1 Introduction

Declining soil fertility is a major impediment to crop production (Ajayi et al., 2007; Hadgu et al., 2009; Berhe et al., 2013; Gebrewahid et al., 2019) and a major problem for the drylands in the sub-Saharan Africa (Ajayi et al., 2007). The soils in Ethiopia, for example, are being depleted at rates of 122 kg/hm^2 for nitrogen (N), 13 kg/hm^2 for phosphorus (P), and 82 kg/hm^2 for potassium (K). On top of this, soil organic matter (SOM) content is also declining (Woldu et al., 2021; Kahsay et al., 2023). The main reasons for soil nutrient depletion include continued cultivation and nutrient mining without adequate replenishment (Mafongoya et al., 2006; Woldu et al., 2021), limited external inputs, soil erosion, nutrient leaching, free stubble grazing after harvest, and forest degradation (Hadgu et al., 2009; Berhe et al., 2013; Kahsay et al., 2023). Thus, the main issue for improving agricultural productivity in drylands lies in how to build up and maintain soil fertility (Mafongoya et al., 2006).

To maintain and recover soil fertility, many agricultural measures exists with agroforestry being one of them (Berhe et al., 2013; Gebrewahid et al., 2019; An et al., 2023; Felton et al., 2023). Agroforestry combines trees and/or shrubs with crops and/or livestock on the same piece of land either simultaneously, as in intercropping, or sequentially, as in rotational fallow systems (Rhoades, 1996; Birhane et al., 2019; Kuyah et al., 2019; Felton et al., 2023), and play an important role in sustainable agro-ecological systems (An et al., 2023). The integration of trees into farms has the potential to enhance soil fertility and structure, enhance carbon sequestration (biogenic carbon capture and storage), reduce erosion and surface run-off, improve water quality, enhance biodiversity, and increase soil organic carbon (SOC) (An et al., 2023; Felton et al., 2023). Planting trees on farmlands depends on the provisioning and protection function of the specific tree species (Gindaba et al., 2005; Melaku et al., 2022; Felton et al., 2023). As such, candidate agroforestry options should start with the species that farmers are most familiar (Gebrehiwot, 2004; Berhe et al., 2013; Birhane et al., 2019). These species would be the indigenous multipurpose trees that have evolved under smallholder farms and socioeconomic conditions (Berhe et al., 2013; Gebrewahid et al., 2019). Many studies witness the presence of indigenous tree species with great untapped potential for growing with agricultural crops (Kassa et al., 2010; Berhe et al., 2013; Berhe and Anjulo, 2013; Gebrewahid et al., 2019) in Tigray. Thus, in order to encourage tree planting by individual farmers, investigating the potential contribution of trees to soil fertility is vital (Gindaba et al., 2005; Berhe et al., 2013; Birhane et al., 2019; Mesfin and Haileselassie, 2022).

Trees can potentially improve soils through numerous processes including maintenance or increase of SOM, biological N_2 fixation, uptake of nutrients, increased water infiltration and storage, reduced loss of nutrients by erosion and leaching, physical properties, reduced soil acidity, and improved soil biological activity (Buresh and Tian, 1997; Berhe and Retta, 2015). Trees can increase the availability of nutrients through increased release of nutrients from SOM and recycled organic residues (Buresh and Tian, 1997).

Parkland trees are characteristics of many agricultural landscapes in drylands (Tiruneh, 2017; Zoungrana et al., 2023). These trees have been either purposely planted or naturally grown on farmlands and left to stand for supporting agricultural production (Kassa et al., 2010; Tiruneh, 2017; Gebrewahid et al., 2019) through maintaining SOM, promoting nutrient cycling and microclimate amelioration, and other uses (Berhe et al., 2013; Bayala et al., 2014; Felton et al., 2023).

The African birch (*Anogeissus leiocarpa*) and pink jacaranda (*Stereospermum kunthianum*) are among the dominant multipurpose tree species that are deliberately retained on farmland in the Tselemti district of northwestern Tigray in Ethiopia. *A. leiocarpus* is a deciduous tree species that can grow up to 18 m in height and 1 m in diameter and belongs to the family Combretaceae (Bein et al., 1996; Arbab, 2014). *S. kunthianum* is a small deciduous tree reaching up to 13 m and belongs to the family Bignoniaceae (Bein et al., 1996). These trees are known for their importance in providing animal feed during the dry season, cultural medicine, and soil erosion control (Bein et al., 1996). These trees are mostly found with the integration of crops such as *Eleusine coracana* (L.) Gaertn, *Eragrostis tef* (Zuccagni) Trotter, and *Sorghum bicolor* (L.) Moench as a parkland agroforestry system. Studies on the contribution of these species to soil fertility improvement are lacking. Therefore, this study was undertaken to investigate the impacts of these parkland trees on selected physical-chemical properties of the soil within and outside their canopy in the Tselemti district of Tigray, Ethiopia. The present study is significant for the promotion and better management of *S. kunthianum* and *A. leiocarpus* in other arid and semi-arid areas of the world.

2 Materials and methods

2.1 Study area

The study was conducted in Tselemti district, situated in the northwestern Tigray, Ethiopia (13°37′45″N–13°44′45″N, 38°03′00″E–38°13′30″E; 800–1370 m a.s.l.) (Gebrtsadkan and Assefa, 2015). Agro-ecologically, the study district is categorized as dry-moist lowland (Darcha, 2015; Redda and Abay, 2015). The dry season is from October to February with an annual temperature ranging from 15.6°C (November to January) to 38.6°C (February to May). Rainfall occurrence in the area is mono-modal, which is concentrated during the months of June to September. The mean annual precipitation for five years is estimated at 1170 mm (Ethiopian Metrological Agency, 2016). The geological formation of the study area is Tsaliet Group basalt, and the dominant soil group is Eutric Cambisols (Gebrtsadkan and Assefa, 2015). Dryland regions (e.g., in equatorial Africa) may receive on average precipitation more than 1000 mm/a (Davis et al., 2017). However, high mean temperatures and prolonged dry season exacerbate the rate of evapotranspiration, causing aridity (Kuyah et al., 2023).

The area is also characterized by a mixed farming system composed of crop and livestock production, where these components are highly complementary to each other. The major crop types grown are *S. bicolor*, *E. coracana*, *Zea mays* L., and *E. tef*. The main woody floras grown in the farmland areas are *Faihderbia albida* (Del.) A. Chev, *Anogeissus leiocarpus* (DC.) Gull & Perr, *Balanites aegyptiaca* (L) Delile, *Combretum* species, *Cordia Africana* (Lam.), *Croton macrostachyus* (Hochst), *Ficus sycomorus* (Linn), *Ficus thonningii* (Blume), *Ficus vasta* (Forssk), *Stereospermum kunthianum* (Cham), *Ziziphus mauritiana* (Lam.), and *Ziziphus spina-christi* (L.).

2.2 Species selection and description

We selected species purposefully based on the occurrence, dominance, and abundance of *A. leiocarpus* and *S. kunthianum*. Both trees come from a representative area with similar tree management practices such as pruning, geological formation, and soil type. The tree species have similar diameter at breast height (DBH), total height, canopy cover, and similar ages. *A. leiocarpus* tree had an average stem diameter of 36.5 cm, a canopy radius of 5.3 m, and a height of 9.2 m, while *S. kunthianum* had an average stem diameter of 46.8 cm, a canopy radius of 5.3 m, and a height of 8.0 m. The mean area for both species is around 88.2 m^2.

2.3 Soil sampling and experimental layout

For soil sample, 12 trees (6 from each tree species) were selected. Soil sampling transects were laid in four directions from tree base (at an angle of 90° in the west, east, south, and north directions). Then, soil sampling spots were laid along the transects at three distances: at half of canopy radius under the tree, at the canopy edge (radius of the canopy), and at three times the canopy radius away from the trunk as outlined in similar studies (Pandey et al., 2000; Gindaba et al., 2005; Berhe et al., 2013). At each distance, soils were sampled from three depths: 0–30 cm (surface soil represents the tillage and rooting zone), 31–60 cm (subsurface represents the beyond tillage zone), and 61–90 cm (subsurface) for bulk density and carbon stock analysis.

From each sampling spot, disturbed and undisturbed soil samples were collected. The undisturbed soil sample was collected using a cylindrical soil corer of 5-cm internal diameter and was used for BD analysis, while the disturbed soil sample was used for soil chemical property analysis. Soil samples from the same radial distance and depth under each sample tree were merged to form nine replicates of composite samples. For the set of samples used for BD analysis, the soil was taken to the laboratory, and oven-dried at 105°C for 24 h to measure dry weight. BD was calculated as the weight of the corer content divided by corer internal volume.

2.4 Soil analysis

Collected soil samples were analysed for soil texture, SMC, soil pH, total nitrogen (TN), available phosphorus (AP), available potassium (AK), pH, electrical conductivity (EC), and cation exchange capacity (CEC), and SOC. Both soil BD and SMC were determined using gravimetric method as proposed by Estefan et al. (2013). Soil texture was analysed by the hydrometer method (Bouyoucos, 1962; Estefan et al., 2013); TN by the Kjeldahl method (Jackson, 1958); AP by the Olsen method (Olsen et al., 1982); and AK by the flame photometric method (Jackson, 1958; Estefan et al., 2013). Moreover, CEC, EC, and SOC were respectively determined using ammonium acetate extraction method at pH 7.0 (Chapman, 1965), EC meter (Hanlon and Bartos, 1993), and wet-oxidation using the Walkley-Black (1934) method. We estimated SOC stock (SOCS), which is the result of soil layer thickness, BD, and SOC concentration (Pearson et al., 2007; Broos and Baldock, 2008; Marín-Spiotta and Sharma, 2013) for 0–90 cm soil depth according to the method described by Pearson et al. (2007):

$$\text{SOCS} = \text{depth} \times \text{bulk density} \times \text{soil organic carbon content.} \tag{1}$$

2.5 Data analysis

Soil data were initially tested for normality, homogeneity, and equality of variances. Then, soil data (CEC, pH, AK, AP, and SOC) with normality problems were log transformed. A one-way analysis of variance (ANOVA) was conducted to compare different soil parameters. Moreover, to determine the effects of selected trees on the SMC, BD, and SOCS, we subjected data to a two-way ANOVA with general linear model (GLM) procedure using a fixed factor model at a confidence interval of 95% ($P<0.05$). Statistical software (SPSS v.20.0) was applied to analyse the data obtained from the laboratory. Furthermore, the mean value differences of the treatments were verified using least significance difference (LSD) and significant levels were taken at $P<0.05$ level.

3 Results

3.1 Effects of *S. kunthianum* and *A. leiocarpus* on soil physical properties

Soil texture (the proportions of sand, silt, and clay) was not significantly affected by the presence of both *S. kunthianum* and *A. leiocarpus* trees in the agricultural landscape ($P>0.05$; Table 1). The soils under the canopy of the tree and away from the canopy were texturally similar with a textural class of clay for both species. Though non-significant, the soil clay content showed a decreasing trend with increasing radial distance for both tree species.

Unlike soil texture, BD significantly increased with increasing radial distance from the tree trunk for both tree species ($P<0.05$; Table 1). BD increased from 1.35 to 1.38 g/cm^3 and from 1.23 to 1.25 g/cm^3 for *A. leiocarpus* and *S. kunthianum*, respectively. In addition to radial distance, BD was also significantly affected ($P<0.05$) by soil depth (data not shown). Lower values of BD were recorded in the surface soil as compared with the subsurface soils for both tree species.

SMC showed a significant decrease with increasing radial distance ($P<0.05$; Table 1). SMC decreased from 21.09% under the canopy of *A. leiocarpus* to 16.99% under the canopy gap while it reduced from 33.75% under the canopy of *S. kunthianum* to 31.76% under the canopy gap.

3.2 Effects of *S. kunthianum* and *A. leiocarpus* on soil chemical properties

TN significantly decreased with increasing radial distance from the base of both tree species ($P<0.05$; Table 2). It decreased from 0.196% under the canopy of *A. leiocarpus* to 0.193% under

Table 1 Effect of *Anogeissus leiocarpa* and *Stereospermum kunthianum* on soil physical properties

Tree species	Radial distance	Soil physical property					
		Sand (%)	Silt (%)	Clay (%)	Texture class	Bulk density (g/cm^{3})	Soil moisture content (%)
A. leiocarpus	Mid-canopy	33.50±2.1^{a}	18.00±1.3^{a}	48.50±1.6^{a}	Clay	1.35±0.006^{a}	21.09±0.81^{a}
	Canopy edge	35.83±2.0^{a}	16.83±2.0^{a}	47.33±0.6^{a}	Clay	1.37±0.006^{ab}	19.36±1.06^{ab}
	Canopy gap	36.83±0.7^{a}	17.00±0.8^{a}	46.00±0.7^{a}	Clay	1.38±0.006^{b}	16.99±0.85^{b}
	P value	0.409	0.827	0.297		0.013	0.022
S. kunthianum	Mid-canopy	15.83±0.6^{a}	19.83±0.7^{a}	64.33±0.7^{a}	Clay	1.23±0.006^{a}	33.75±0.37^{a}
	Canopy edge	17.00±1.0^{a}	19.50±0.9^{a}	63.50±0.8^{a}	Clay	1.24±0.005^{ab}	32.83±0.41^{ab}
	Canopy gap	16.17±0.5^{a}	21.67±0.6^{a}	62.17±0.3^{a}	Clay	1.25±0.007^{b}	31.76±0.55^{b}
	P value	0.547	0.136	0.099		0.013	0.024

Note: Different lowercase letters within the same column and same species indicate significant difference at $P<0.05$ level. Mean±SE.

Table 2 Effects of *A. leiocarpus* and *S. kunthianum* on soil chemical properties

Tree species	Radial distance	Soil chemical property					
		TN (%)	AP (mg/kg)	AK (mg/kg)	pH	EC (dS/m)	CEC (cmol/kg)
A. leiocarpus	Mid-canopy	0.196±0.0060^{a}	8.34±0.26^{a}	64.74±2.449^{a}	5.84±0.05^{a}	0.13±0.008^{a}	37.05±0.58^{a}
	Canopy edge	0.193±0.0007^{b}	7.28±0.32^{b}	52.55±1.368^{b}	5.59±0.05^{b}	0.11±0.009^{a}	35.85±0.53^{a}
	Canopy gap	0.193±0.0005^{b}	6.13±0.24^{c}	51.16±0.863^{b}	5.57±0.10^{b}	0.10±0.006^{a}	35.21±0.43^{a}
	P value	0.004	<0.001	<0.001	0.029	0.096	0.070
S. kunthianum	Mid-canopy	0.210±0.0020^{a}	6.51±0.32^{a}	69.77±1.82^{a}	7.25±0.19^{a}	0.15±0.001^{a}	36.01±1.36^{a}
	Canopy edge	0.190±0.0030^{b}	5.74±0.28^{ab}	66.47±0.76^{ab}	6.61±0.26^{a}	0.15±0.001^{a}	32.36±1.70^{a}
	Canopy gap	0.180±0.0020^{b}	4.20±0.21^{b}	64.03±1.13^{b}	6.38±0.32^{a}	0.15±0.001^{a}	27.40±0.84^{b}
	P value	<0.001	<0.001	0.024	0.080	0.087	0.002

Note: Different lowercase letters within the same column and same species indicate significant difference at $P<0.05$ level. Mean±SE. TN, total nitrogen; AP, available phosphorus; AK, available potassium; EC, electrical conductivity; CEC, cation exchange capacity.

the canopy gap and from 0.210% under the canopy of *S. kunthianum* to 0.180% under the canopy gap (Table 2). Similar to TN, the mean AP decreased with increasing radial distance from the base of both tree species ($P<0.05$). AP under the canopies of *A. leiocarpus* and *S. kunthianum* was respectively 36.05% and 55.00% higher than those of the canopy gap. In addition, AP was 1.83 mg/kg higher under the canopy of *A. leiocarpus* as compared with *S. kunthianum*. AK also showed a significant decrease with increasing radial distance from the tree trunk for both species ($P<0.05$). AK under the canopy of *A. leiocarpus* and *S. kunthianum* was respectively 26.54% and 8.96% higher than those of the canopy gap. In addition, AK under the canopy of *S. kunthianum* was 5.03 mg/kg higher than that of *A. leiocarpus*.

Soil pH significantly decreased with increasing distance from the base of *A. leiocarpus* ($P<0.05$). It was non-significant for *S. kunthianum* although it showed a decreasing trend with increasing radial distance ($P>0.05$). However, soil pH under the canopy edge of *A. leiocarpus* was on par with the soil under the canopy gap. ANOVA results for soil EC revealed that soil EC was not significantly affected by distance from the tree trunk for both species ($P>0.05$). EC under *A. leiocarpus* showed a decreasing trend with increasing radial distance while EC under *S. kunthianum* was similar for all radial distances.

ANOVA results for CEC showed a significantly decreasing trend with increasing radial distance from the trunk of *S. kunthianum*, but was not significantly different in *A. leiocarpus* although it showed a decreasing trend. CEC under the canopy of *S. kunthianum* was 31.42% higher than that of the canopy gap.

For both species, SOC and SOCS were significantly affected by both radial distance from the tree and soil depth ($P<0.05$), except for SOC under *S. kunthianum*, which was not significantly affected by depth ($P>0.05$; Table 3). The interaction effect of soil depth and radial distance from the base of both trees had no effect on both SOC and SOCS ($P>0.05$). In general, both SOC and SOCS decreased with increasing radial distance from the base of the trees and soil depth.

Table 3 Soil organic carbon (SOC) and SOC stock (SOCS) under *A. leiocarpus* and *S. kunthianum*

Tree species	Factor	Index	Soil fertility parameter	
			SOC (%)	SOCS (t/hm^2)
A. leiocarpus	Radial distance	Mid-canopy	1.35±0.0057^{a}	55.64±0.40^{a}
		Canopy edge	1.34±0.0085^{a}	54.96±0.29^{a}
		Canopy gap	1.32±0.0050^{b}	53.89±0.36^{b}
		P value	<0.001	<0.001
	Soil depth	0–30	1.37±0.0060^{a}	56.31±0.28^{a}
		30–60	1.32±0.0070^{b}	54.56±0.32^{b}
		60–90	1.30±0.0085^{c}	53.61±0.27^{c}
		P value	<0.001	<0.001
	Radial distance×soil depth	*P* value	0.584	0.706
S. kunthianum	Radial distance	Mid-canopy	1.67±0.0090^{a}	61.97±0.27^{a}
		Canopy edge	1.66±0.0080^{a}	61.65±0.37^{a}
		Canopy gap	1.62±0.0120^{b}	61.17±0.39^{a}
		P value	<0.001	0.196
	Soil depth	0–30	61.97±0.2690^{a}	62.54±0.286^{a}
		30–60	61.65±0.3740^{a}	61.56±0.36^{b}
		60–90	61.17±0.3910^{a}	60.69±0.28^{b}
		P value	0.196	0.001
	Radial distance×soil depth	*P* value	0.584	0.706

Note: Different lowercase letters within the same factor and same species indicate significant difference at $P<0.05$ level. Mean±SE.

3.3 Comparison of soil physical-chemical properties under *A. leiocarpus* and *S. kunthianum*

Except for soil TN, soil physical-chemical parameters were significantly different between the two trees ($P<0.05$; Fig. 1). Significantly higher values were recorded under the canopy of *S. kunthianum*. Soil nutrients were higher by 71.17% in SMC, by 20.33% in silt, 63.33% in clay, 21.46% in AK, 6.75% in soil pH, 0.153 dS/m in EC, 23.20% in SOM, 20.87% in the percentage of total C to N ratio and 12.34% in SOCS under the canopy of *S. kunthianum* than under the canopy of *A. leiocarpus*. Whereas higher values (higher by 32.29% and 12.83%, respectively) of AP and CEC were recorded under the canopy of *A. leiocarpus* (Fig. 1).

4 Discussion

Soil is the complex manifestation of physical, chemical, and biological processes occurring across spatial and temporal scales (Weil and Brady, 2017). Soil properties at a specific location integrate and reflect both past and present conditions (Rhoades, 1996; Weil and Brady, 2017). Trees alter chemical, physical, and biological soil properties through their impacts on energy and nutrient fluxes into, out of, and within ecosystems. The premise of agroforestry is that soil improvement

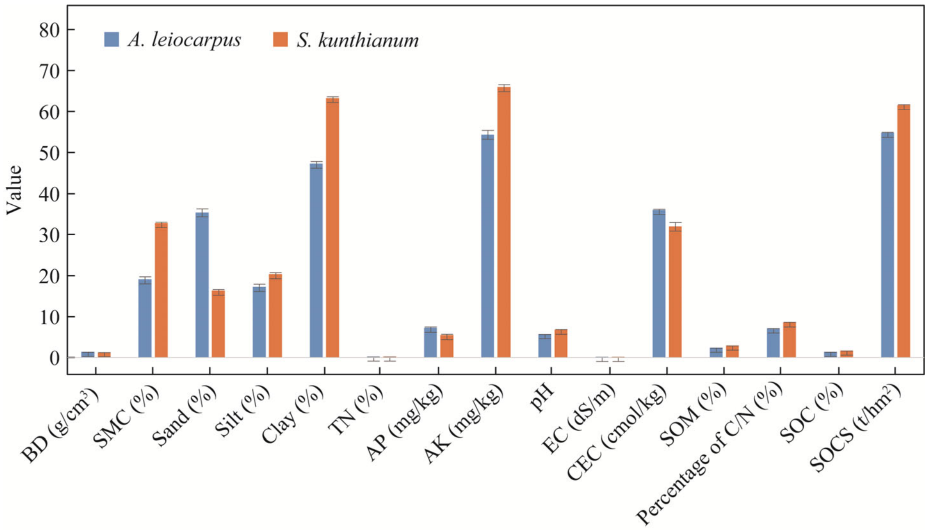

Fig. 1 Comparison of soil physical and chemical properties between *Anogeissus leiocarpa* and *Stereospermum kunthianum*. BD, bulk density; SMC, soil moisture content; TN, total nitrogen; AP, available phosphorus; AK, available potassium; EC, electrical conductivity; CEC, cation exchange capacity; SOM, soil organic matter; C, carbon; N, nitrogen; SOC, soil organic carbon; SOCS, SOC stock. Bars are standard errors.

generated by trees can be exploited within production systems, either simultaneously, as in intercropping, or sequentially, as in rotational fallow systems (Rhoades, 1996). Trees can influence both the supply and availability of nutrients in the soil (Buresh and Tian, 1997).

In the present study, the presence of scattered parkland trees had no effect on soil texture. The non-significant difference in the average proportions of sand, silt, and clay fractions between the soils under the canopies of both trees and in the open farmland (control) suggests that the soils are texturally similar (clay), having been derived from the same parent material, under the same climatic conditions with similar topography and vegetation cover (Pandey et al., 2000; Berhe et al., 2013; Birhane et al., 2019; Abdella and Nigatu, 2021). As such, any observed variation between the soils under both trees' canopies and in the open farmland is most likely as a result of the effects of these trees on the soil underneath rather than to the mineralogical or textural differences between these soils (Berhe et al., 2013). As a result, the prevailing variation in other soil fertility parameters is discussed as it is induced by the presence of both tree species in the landscape. Despite difficulty in comparing the results of the present study with other studies due to lack of information on both species, studies conducted on other species revealed similar results (Bhojvaiw et al., 1996; Aweto and Dikinya, 2003; Berhe et al., 2013).

4.1 Effects of *S. kunthianum* and *A. leiocarpus* on soil physical properties

Soil texture class was classified as clay with no significant difference in the relative proportions of sand, silt, and clay under both trees. The non-significant difference under both species might be attributed that texture class is less affected by management but other soil properties (Esmaeilzadeh and Ahangar, 2014). In the present study, soil BD increased with increasing radial distance (P<0.05) and soil depth (P<0.05) in the canopies of both tree species when compared with the bulk soils away from their canopy. The recorded amounts were within the range (1.1–1.6 g/cm^3) of the ideal soil BD in agricultural soils and the change in values in soil BD could be attributed to organic matter amendment and elimination of surface soil disturbance under canopy (Faleyimu and Akinyemi, 2010). In addition, it is known that incorporation of SOM in soil improves physical (aggregate stability, BD, and water retention) and biological properties (nutrients availability, CEC, and reduction of toxic elements) of soils (Kewessa et al., 2015). Lower soil BD under both tree species' canopies compared with the canopy gap is presumably due to the effect of litter addition to the soil. This has resulted in SOM building up in the soil under the canopies relative to levels in the soil outside the canopies. Also, the higher concentration of tree roots near the base of trees may have had the effect of loosening the soil, thereby reducing soil BD. Furthermore, the soil outside the tree canopies dries out more, being exposed to direct solar radiation. This not only accelerates thermally induced SOM decomposition, but also results in the shrinking of SOM and clay colloids, thereby making the soil more compact (Aweto and Dikinya, 2003).

In agreement to the present finding, Kewessa et al. (2015) and Mamo (2017) reported lower soil BD amount under the near distances from canopy cover of *Croton macrostachyus* Hochst. and *Hypericum revolutum* Vahl., respectively. In addition, similar decreasing trend in BD was documented in other dryland areas (Hailu et al., 2000; Pandey et al., 2000; Aweto and Dikinya, 2003; Gindaba et al., 2005; Berhe et al., 2013; Kewessa et al., 2015; Molla and Linger, 2017; Birhane et al., 2019; Abdella and Nigatu, 2021; Amare et al., 2022). In contrast, Kassa et al. (2010) and Birhane et al. (2019) found non-significant variation in BD from their study on *B. aegyptiaca* (Kassa et al., 2010) and *Acacia polyacantha* Willd (Birhane et al., 2019) in northern Ethiopia.

ANOVA results for SMC demonstrated a significant variation as the radial distance increased. SMC amount for both *S. kunthianum and A. leiocarpus* trees decreased as increased in the distance from the canopy ($P<0.05$; Table 1). The higher SMC in the canopy of both tree species as compared with the canopy gap might be due to variations in SOM. SOM makes the soil retain more water by increasing its surface area and improving soil structure. It might also be due to the shading effect of the tree. The soil outside the tree canopies might dry out more, being exposed to direct solar radiation whereas the shade provided by both trees might have enhanced SMC under their canopy. Furthermore, value reduction under the canopy gap could be because of the tree's contribution to the advanced increment in infiltration rate at the time when rain falls and moderating the release of moisture through evaporation process as a result of shading effect and organic matter accumulation (Esmaeilzadeh and Ahangar, 2014).

4.2 Effects of *S. kunthianum* and *A. leiocarpus* on soil chemical properties

For both species, significant difference in the TN concentration was observed ($P<0.05$). Lower TN concentration was estimated under the canopy gap for both species. Soils taken from the *S. kunthianum* showed higher TN accumulation under the mid-canopy by 7.14% and 11.10% than the canopy edge and the canopy gap, respectively. *S. kunthianum* has good fodder quality (Orwa et al., 2009). Thus, the deep rooting system and nitrogen availability in the leaf attributes the increase in TN concentration under *S. kunthianum*. Statistically the percentage change in TN under the mid-canopy and the canopy gap of *A. leiocarpus* was 1.55%. The observed high soil TN beneath both trees' canopy compared with the canopy gap could also be attributed to the high accumulation of SOM and slow decomposition due to the lower temperature under the tree canopy compared with the canopy gap and nutrient addition due to leaching from the leaves because trees that are better for fodder may usually increase the soil nitrogen availability (Schroth and Sinclair, 2003).

In accordance to the present study, Kassa et al. (2010) reported a greater TN by 8.2% under the canopy cover of *B. aegyptica* than the open area in the dryland. Similar decreasing trend in soil TN was also reported by other studies on different trees (Gindaba et al., 2005; Noumi and Chaieb, 2012; Berhe et al., 2013; Manjur et al., 2014; Berhe and Retta, 2015; Gebrewahid et al., 2019). The results for AP concentration also showed a significant ($P<0.05$) decrease with increasing radial distance from the bole of both trees (Table 2). Soils under mid-canopy and edge of the canopy of *A. leiocarpus* were 14.56% and 36. 05% higher in AP as compared with the soil at canopy gap, while the soils under canopy edge and canopy gap of *S. kunthianum* were equal. Although these values estimated are low for optimal growth of crop (Loch, 2006; Horneck et al., 2011), the higher AP accumulation under the canopy zone as compared with the outside canopy zone could be due to the high accumulation of SOM, the trees' ability to alter soil pH, and soil moisture contents and secrete organic acids to solubilize phosphorus and nutrients in the leaves washed up during rainfall and added to the soil for the fact that *A. leiocarpus* has a crucial value on soil and water conservation and improving soil moisture content (Neba, 2009). The present study is in line with studies conducted on different drylands of Ethiopia and different species such as *Ficus thonninigii* Blume (Berhe et al., 2013), *Oxytenanthera abyssinica* A. Rich. Munro (Gebrewahid et al., 2019), *Dalbergia melanoxylon* Guill. & Perr. (Gebrewahid et al., 2019), *C. africana* (Gindaba et al., 2005; Manjur et al., 2014), *A. polyacantha* (Birhane et al., 2019), *A. tortilis* (Noumi and Chaieb, 2012; Tiruneh, 2017) and *C. macrostachyus* (Gindaba et al., 2005; Manjur et al., 2014).

ANOVA results of this study indicated a clear significant variation in AK concentration. Although the concentration of AK at the canopy edge and canopy gap was on par with each other, AK concentrations under the mid-canopy were 26.54% and 8.96% higher than those of the canopy gap for *A. leiocarpus* and *S. kunthianum*, respectively. Even though the observed concentration of AK is higher under the mid-canopy than under the canopy gap, it was rated as low (Loch, 2006; Horneck et al., 2011). The change in AK concentration under the canopy as compared with the outside canopy of the present study could be due to the high accumulation of SOM, SMC increment, natural litter droppings, and the addition of different soil nutrients during tree pruning and rainfall (Schroth and Sinclair, 2003; Neba, 2009). Noticeably, higher percentage of AK under the tree canopy compared with the canopy gap was obtained in other studies (Aweto and Dikinya, 2003; Gindaba et al., 2005; Berhe et al., 2013; Manjur et al., 2014).

A simultaneously varied soil pH was observed on the soils taken from different radial distances under the canopy ($P<0.05$). Statistically the difference was not significant in *S. kunthianum*. The soils under the canopy edge in *A. leiocarpus* were similar to the soils under the canopy gap. A pH of 5.84 was observed under the mid-canopy and canopy edge of *A. leiocarpus*, which indicated the trees litter fall played an essential effect on the availability of hydrolysing cations and the ions that can stabilize the availability of pH (Mueller et al., 2012). However, Gindaba et al. (2005) and Amare et al. (2022) reported a higher pH value under the tree canopy as compared with the canopy gap, while other studies (Pandey et al., 2000; Kassa et al., 2010; Berhe et al., 2013; Berhe and Retta, 2015) reported the reverse.

Soil EC is highly correlated with soil size distribution and SMC under the tree canopy cover. Mean value of EC was slightly higher under the trees canopy than under the canopy edge, but was not statistically significant, which imply that the soil under the trees is salt free. Clay soils are expected to have relatively higher ability to transmit electric current within the soil (Faleyimu and Akinyemi, 2010). Gebrewahid et al. (2019) found that soils taken at different distances from *O. abyssinica* and *D. melanoxylon* were not significantly different. However, significantly higher EC under the canopy as compared with the canopy gap was reported for *F. albida* and *C. africana* (Abdella and Nigatu, 2021) and for *A. tortilis* (Tiruneh, 2017). ANOVA results in this study indicated that distance variation showed differences in the numerical concentration of available CEC under *A. leiocarpus*, but was not statistically significant, while the soils under *S. kunthianum* showed the significant variation with a higher CEC value under the canopy as compared with the canopy gap. For *S. kunthianum*, it was reported 31.42% higher under the mid-canopy than that under the canopy gap. The higher CEC under the tree canopy as compared with the canopy gap could be attributed to the SOM accumulation under the canopy of trees, which in return can influence the parameters such as pH, EC, and plant growth. The variation in availability of CEC under other species with distance differences was also reported in different agroforestry landscapes (Aweto and Dikinya, 2003; Manjur et al., 2014; Berhe and Retta, 2015; Gebrewahid et al., 2019).

This study found that a noticeably higher SOC concentration and SOCS under the canopy of both trees as compared with the canopy gap (Table 3). The addition of root exudates and extracts within the soil horizon can be attributed the increases in SOC and SOCS (Nsabimana et al., 2008). Carbon stock under trees is noticeably flexible with respect to the tree species, soil type, climatic condition, and inherent soil status. Values of 55.64 and 56.31 t/hm^2 SOCS were observed inside the canopy (mid-canopy) and the top soil layer of *A. leiocarpus*, respectively, which were higher than those of the canopy gap (53.89 t/hm^2) and deep layer (53.61 t/hm^2). In addition, SOCS value in *S. kunthianum* was also found to be higher at the 0–30 cm top layer than at the deep soil layer (60–90 cm). SOC and SOCS increment could be due to maintenance or an increase in SOM (Buresh and Tian, 1998). Agroforestry trees such as *B. aegyptiaca*, *Acacia tortilis* (Forssk.), *Acacia seyal* Del., and *F. thonningii* showed a higher SOC content too (Noumi and Chaieb, 2012; Berhe et al., 2013; Manjur et al., 2014; Gebrewahid et al., 2019; Abdella and Nigatu, 2021).

This study compared the soil physical and chemical properties under both species and results showed that except for TN all the studied soil parameters were noticeably varied. According to ANOVA result, all parameters except AP and CEC were higher in the soils taken from *S. kunthianum*. However, AP and CEC contents were recorded higher in *A. leiocarpus* by 32.29% and 12.83%, respectively. These differences in soil nutrients between both trees might be due to the ability of these trees to conserve soil nutrient loss through leaching and erosion, the litter fall volume that improves SOM, other soil nutrients, and rooting structures of these trees (Frouz et al., 2013; Berhe and Retta, 2015).

5 Conclusions

This study investigated the soil amelioration effects of two scattered parkland agroforestry trees (*A. leiocarpus* and *S. kunthianum*) grown on smallholder farms. ANOVA results revealed that the steadily decline in TN, AP, AK, and CEC concentrations as the distance from the trees increased can be an indicator for the good potential of these trees on soil amelioration. Soil parameters flexibility and improvement depends on soil inherent type, silvicultural practices, tree species, and climatic condition. This study revealed considerable difference in soil parameters in both trees as a result of species difference. As a result, it is highly recommended to retain *A. leiocarpus* and *S. kunthianum* in agricultural landscapes and promote their planting in degraded areas with similar environmental conditions. Furthermore, future researches on these species should consider investigating their association with beneficial soil microorganisms, as well as evaluating crop yield attributes and foliar nutrient concentrations for livestock feed purposes.

Conflict of interest

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

Acknowledgements

This research was supported by the Sustainable Forest Management Project with the Local Communities in Tigray, northern Ethiopia, which was funded by the Norwegian Agency for Development Cooperation (NORAD) under the Norwegian Programme for Capacity Development in Higher Education and Research for Development (NORHED) Programme (ETH 13/0018) and the Ecological Organic Agriculture Project, Mekelle University, Ethiopia. We acknowledged the Institute of International Education-Scholars Rescue Fund (IIE-SRF), Norwegian University of Life Sciences (NMBU), Faculty of Environmental Sciences and Natural Resource Management (MINA), and NORGLOBAL 2 Project in Ethiopia (303600) for supporting the research.

Author contributions

Conceptualization: Selam LJALEM, Kassa TEKA, Emiru BIRHANE; Methodology: Selam LJALEM; Formal analysis: Selam LJALEM; Writing - original draft preparation: Selam LJALEM; Writing - review and editing: Selam LJALEM, Kassa TEKA; Emiru BIRHANE, Daniel H BERHE; Funding acquisition: Selam LJALEM, Kassa TEKA; Emiru BIRHANE. All authors approved the manuscript.

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