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ORIGINAL PAPER

# Soil Physicochemical Properties under Selected Avocado Cultivars in Ethiopian Smallholder Agroforestry

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**Abstract**
This study investigated the impact of three avocado cultivars on selected soil physicochemical properties in Central Ethiopia, to enhance the knowledge on the influence of avocado cultivars on soil physicochemical properties, and assist smallholders in cultivar selection in agroforestry. Trees planted in farmers′ fields 8 years earlier were revisited. Soil samples were collected from 0–20 cm and 20–40 cm depth at three radial distances from trees (1 m and 2 m from tree trunk, and at 5 m from the canopy edge as a control). Soil texture, bulk density, moisture content, pH, electrical conductivity, soil organic carbon, total nitrogen and available phosphorus were determined. Soil moisture content and electrical conductivity were overall higher and bulk density was lower ($p < 0.05$) under the canopies of the avocado trees than in the control and soil organic carbon, total nitrogen and available phosphorus tended to increase in spite of nutrient inputs to the control whilst the trees were unfertilized. Differences between the studied cultivars were small, but Hass tended to have the largest impact on soil nutrient levels, whilst Ettinger and Nabal tended to have a somewhat larger effect on the soil organic carbon concentration. Integrating these avocado cultivars on farms can improve soil fertility in the study area. However, for optimal agricultural soil health and sustainable avocado production, cultivar and site-specific soil management practices must be applied.

**Keywords** Home garden · Organic carbon · Nitrogen · Phosphorus · Hass · Nabal · Ettinger

## 1 Introduction

Sustainable agroforestry produces a range of economic, environmental and social benefits beyond those provided by sole-crop farming (Catacutan et al. 2017; Do et al. 2020). Integrated fruit tree-crop agroforestry can enhance soil fertility by adding organic matter to the soil organic carbon pool (Tsufac et al. 2021). Tree inclusion in the cropping system can optimize nutrient cycling and improve soil chemical and physical properties (Pinho et al. 2012) by adding tree leaves, roots, flowers and fruit biomass to the soil (Sarvade et al. 2019). However, a productive agroforestry system relies on tree-crop-soil interactions that minimize competition and maximize complementarity in the use of available natural resources (Rathore et al. 2022). It also requires soil physical and chemical properties that underpin nutrient availability and accessibility for absorption by plants (Freitas and Silva 2022).

Avocado cultivars can grow in tropical and subtropical areas and have been adapted for cultivation in more than 60 countries worldwide (Araújo et al. 2018; Nyakang'i et al. 2023). Cultivars found in Ethiopia were initially brought from Israel in 1986 (EIAR, 2010) and are now commonly grown as part of coffee and enset systems in home garden agroforestry in Ethiopia (Emire et al. 2021). However, there is increasing interest among smallholder farmers in integrating avocado cultivars onto their farmland, alongside annual crops such as maize. Therefore, it is crucial to research the

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effect of avocado trees on soil, to ensure the sustainability of on-farm productivity.

Avocado naturally accumulates litter on the soil surface and thus provides organic matter, which can improve soil structure and water-holding capacity (Grunennvaldt 2022). In addition, the dense shallow root system of avocados strongly promotes accumulation of organic matter in the topsoil (Crowley 2007). This is an important effect, as high evapotranspiration in avocado cultivation leads to high water consumption in the dry season. Although avocado growers in tropical and subtropical climates often use irrigation, information on the water footprint and exact requirement of avocado production is not accessible in most countries (Sommaruga and Eldridge 2021). However, it has been shown to limit access to water for subsistence agriculture (De la Vega-Rivera and Merino-Pérez 2021).

The elderly avocado cultivar 'Hass' has a relatively high canopy density and litter accumulates over time, which can continuously improve soil structure in the tree root zone (Kotze 2022). However, while the litter contains nutrients, avocado trees also take up soil nutrients, which are exported from the field through fruit harvesting (Crowley 2007). For instance, Hass has been shown to remove 0.22 kg of nitrogen, 0.04 kg of phosphorus and 0.3 kg of potassium per 100 kg of fruit (Rosecrance et al. 2012). Therefore, a better understanding of the net effect of avocado cultivars on the soil is important to support rational crop and soil management decisions, in order to maintain nutrient levels and soil physical properties and increase avocado production and quality on farms (Selladurai and Awachare 2020; Wolstenholme 2004).

Previous studies on avocado production have focused mainly on the commercial cultivar Hass, with emphasis on the effects of soil conditions, low soil oxygen due to flooding or low soil aeration (Wolstenholme 2013) and soil type (Kaneko et al. 2022) on tree growth. Others have examined the effects of soil texture on calcium absorption by Hass avocados (Bonomelli et al. 2019), waterlogged conditions on the nutritional status of avocados (Tzatzani et al. 2020) and soil water content on fruit yield and mineral nutrition in avocados (Gil et al., 2012; Ferreyra et al. 2014). A few studies have also examined the effect of local avocado (non-grafted) on soil properties (Kassa et al. 2014; Ketema and Abayineh 2015). However, the effect of improved avocado cultivars on soil properties has rarely been investigated.

Recently, Abebe et al. (2022) and Sora (2023) investigated growth and fruit yield of six improved avocado cultivars (Hass, Bacon, Ettinger, Pinkerton, Nabal and Fuerte) in the lowland and warm-humid agroecological zone in Ethiopia. In addition, the World Agroforestry Centre (CIFOR-ICRAF) has tested the ecological adaptation of five improved avocado cultivars (Hass, Ettinger, Nabal, Fuerte and Reed) in the mid-highland zone of Ethiopia (Mokria et al. 2022). However, the influence of these avocado cultivars on soil physicochemical properties has not been studied to date. Therefore, the aim of the present study was to examine the effect on selected soil physicochemical properties of the three avocado cultivars most preferred by local farmers in Ethiopia. The hypothesis tested was that improved avocado cultivars have differing effects on soil physicochemical properties. The intention was to contribute to existing knowledge on the influence of avocado cultivars on soil physical and chemical properties, and thus assist smallholders in cultivar selection and cultivar-specific soil management in agroforestry.

## 2 Materials and Methods

### 2.1 Site Description

The study was conducted in the central southern region of Ethiopia, in Jewe kebele (the lowest administrative unit in the country) and Upper Gana kebele, Lemo district (Fig. 1a, b). This region is geographically located at 7°22'00"-7°39'59 N, 37°40'00"-38°00'00"E and has rugged topography, with 2–35% slope. In Jewe (altitude 2,100-2,244 m a.s.l.), annual rainfall is normally 900-1,400 mm, while Upper Gana (altitude 2,129-2,400 m a.s.l) normally receives 900-1,300 mm. Both sites have a bimodal rainfall pattern. Mean annual maximum temperatures in Jewe and Upper Gana is 23°C and 18°C, respectively. Nitisols are the predominant soil type in Jewe, whereas in Upper Gana, Nitisols and Cambisols are the primary soil types (ILRI 2015). The mean percentage of clay, silt, and sand in soils at the farms of both study sites was 20, 34 and 46%, respectively, and the soils at both sites were classified as loams (Table 1). The clay content at both sites was higher at 20–40 cm depth than at 0–20 cm depth (Table 1).

### 2.2 Cultivar and Farm Selection

The World Agroforestry Centre (CIFOR-ICRAF), through the Africa RISING project, conducted participatory research on integration of avocado trees with annual crops in Jewe and Upper Gana in 2014. One tree each of five improved avocado cultivars (Hass, Ettinger, Nabal, Fuerte and Reed) were introduced to 70 households at both sites (Mokria et al. 2022), planted with 8 m spacing between trees. At the time of the present study, in 2022, these avocado trees were eight years old, which allowed analysis of their effect on soil fertility parameters. Of the five cultivars present, Hass, Ettinger and Nabal were selected based on a reconnaissance survey of farmers' preferences. To minimize variation

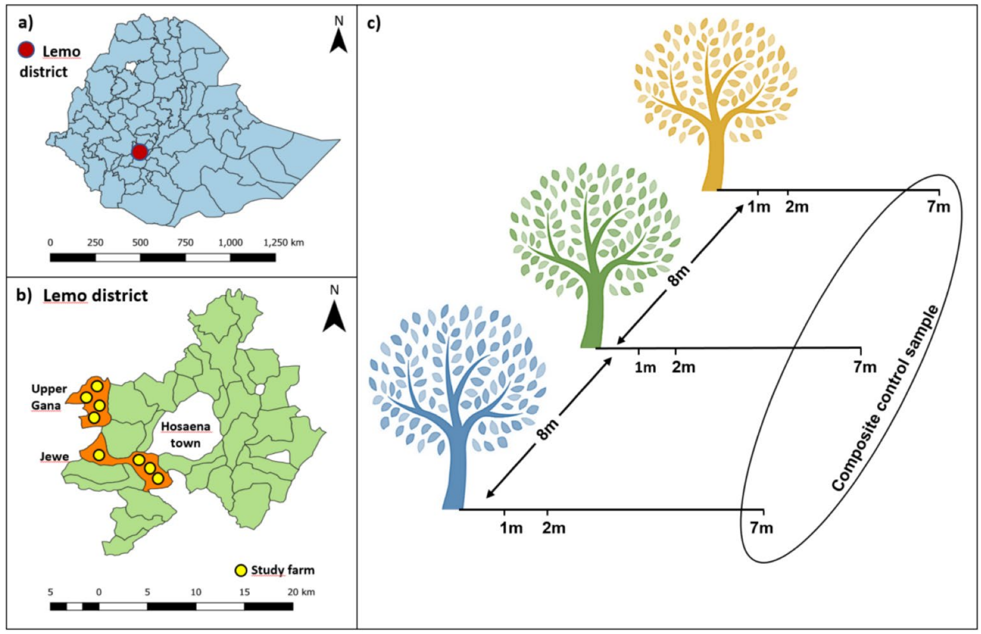


**Fig. 1** Experimental design applied in soil sampling. (**a**) Location of Lemo district; (**b**) locations of Jewe and Upper Gana kebele, and schematic nesting of farms within the respective kebele; and (**c**) arrangement of the trees and soil sampling points within each farm. Different colours refer to different cultivars. 1 m represents mid-canopy, 2 m represents canopy edge and 7 m represents the control area, approx. 5 m from the canopy edge and unaffected by the canopy. The order in which the avocado cultivars were planted differed between farms, depending on the individual farmer's decision when planting

**Table 1** Average soil texture at the study sites

| Variable | Description | Clay % | Silt % | Sand % | Texture class |
|---|---|---|---|---|---|
| Soil layer | 0–20 cm | 17 | 37 | 45 | Loam |
| | 20–40 cm | 21 | 31 | 46 | Loam |
| Site | Jewe | 21 | 35 | 44 | Loam |
| | Upper Gana | 18 | 34 | 48 | Loam |

**Table 2** Growth parameters (mean ± SD) of the three selected avocado cultivars at the time of soil sampling. Trunk ⌀ A = trunk diameter above the graft union point; trunk ⌀ B = trunk diameter below the graft union point

| Cultivar | Trunk ⌀ A[1] (cm) | Trunk ⌀ B (cm) | Height[2] (m) | Canopy diameter[3] (m) |
|---|---|---|---|---|
| Hass | 17.9 ± 5.3a | 14.4 ± 5.6a | 3.8 ± 0.1b | 3.7 ± 0.0b |
| Nabal | 17.8 ± 4.8a | 14.1 ± 2.7a | 4.3 ± 0.2a | 4.0 ± 0.1a |
| Ettinger | 17.2 ± 4.0a | 12.4 ± 2.0a | 4.1 ± 0.1a | 3.6 ± 0.0b |
| *p*-value | 0.9415 | 0.5445 | < 0.001*** | < 0.001*** |

[1] Trunk diameter was determined at 10 cm above and below the graft union using a digital calliper

[2] Tree height was measured using a meter stick

[3] Canopy diameter (east-west and north-south direction) was measured using a meter tape

between farms, neighboring farms with similar agronomic practices and no fertilizer applied to the trees were purposively chosen. In each area, four farms on which all three selected cultivars were still present were selected for participation in the study (Fig. 1b). Common crops intercropped with the avocado trees in the home gardens of the study were maize, faba beans and vegetables which were rotated over the years in both study sites.

## 2.3 Sample Tree Growth Performance

All avocado cultivars studied were growing under rainfed conditions. Fencing, weeding, supplementary watering, mulching, litterfall retention and manual harvesting were used on all farms to improve tree performance. Basic growth parameters for avocado cultivars were assessed, as a basis for deciding the soil sampling pattern. The results revealed that stem diameter growth was comparable in all trees, but that Nabal had a higher and wider canopy than Ettinger and Hass (Table 2).

## 2.4 Soil Sampling Method

Soil samples were collected in early April 2022 at 1 m (mid-canopy) and 2 m from the tree trunk (approx. edge of the canopy), and at 5 m away from the edge of the tree canopy (control) (Fig. 1c). Samples were collected from the topsoil (0–20 cm) and subsoil (20–40 cm), using an Edelman combination soil auger (10 cm core diameter). The sampling points were arranged in a design that encompassed the three cultivars and three distances from the tree trunk, with topsoil and subsoil samples taken at the same sampling point. The control samples were pooled to give one sample per soil layer and farm. Farms functioned as blocks. Soil bulk density was measured by collecting undisturbed soil samples at each sampling point using a core sampler (6 cm diameter, 4 cm height). All soil physical and chemical analyses were carried out at Debrezite National Agricultural Research Centre laboratory.

### 2.5 Soil Physiochemical Analysis

The soil samples were air-dried and sieved using a 2 mm mesh. The fine fraction was analyzed using the following methods: Soil texture was determined by hydrometric measurements (Gee and Bauder 1986). Soil pH was measured in a 1:2.5 water suspension (soil:liquid ratio) (Jackson 1958). Soil electrical conductivity (EC) was determined from a saturated paste extract, using an EC meter (FAO 2020). Total nitrogen was determined using a modified Kjeldahl method of digestion and distillation (Bremner 1965). Soil organic carbon was determined following the method by Walkley and Black (1934), with a correction factor of 1.29. Available phosphorus was determined using the Olsen method (Olsen 1954). Soil moisture content was determined by oven-drying at 105℃ for 24 h (Benke and Kearfott 1999).

### 2.6 Statistical Analysis

Statistical tests were performed to determine the influence of independent factors (avocado cultivar, radial distance, soil depth) on dependent variables (soil physiochemical parameters). The data were analyzed using a linear mixed effect model. Soil properties (bulk density, moisture content, soil pH, organic carbon, EC, total nitrogen, available phosphorus, carbon:nitrogen (C:N) ratio) were treated as the response variable, avocado cultivar with seven levels (combination of three cultivars with two radial distances + control) and soil depth (two levels) were treated as fixed effect factors, and site (two levels), farm (eight levels) and soil sampling point were treated as random effect factors to account for possible variations across different locations. Similarly, to compare the avocado-influenced sampling points overall with the control, soil properties were treated as the response variable, avocado cultivar with three levels (combination of all avocado cultivars with two radial distances + control) and soil depth (two levels) were treated as fixed effect factors, and site (two levels), farm (eight levels) and soil sampling point were treated as random effect factors. To identify significant differences between cultivar interaction with soil depth and radial distance on soil total nitrogen and available phosphorus, total nitrogen and available phosphorus were treated as the response variable, avocado cultivar with six levels (combination of three cultivar with two radial distance) and soil depth (two levels) were treated as fixed effect factors, and site (two levels), farm (eight levels) and soil sampling point were treated as random effect factors. Means were compared using the Tukey post hoc test, with significance level set at $p < 0.05$. All statistical analyses were carried out using R version 4.2.2.

## 3 Results

### 3.1 Effects of Avocado Cultivars on Soil Physicochemical Properties

#### 3.1.1 Soil Bulk Density

Soil bulk density under the avocado trees was significantly lower than in the control soil, while there was no difference between the mid-canopy (1 m) and canopy edge (2 m from the trunk) sampling points (Table 3). Soil bulk density was similar under the three different cultivars (Fig. 2a) and in both soil layers sampled (Fig. 2b).

#### 3.1.2 Soil Moisture Content

Soil moisture content under the avocado tree canopy was overall higher than in the control soil (Table 3, top part), and was also significantly higher under the Ettinger canopy at 1 m distance from the tree trunk than in the control (Fig. 3a). The topsoil was slightly drier than the subsoil under all three cultivars (Fig. 3b).

#### 3.1.3 Soil pH

Soil pH under the avocado trees tended to be somewhat higher than in the control soil, but the difference was not significant (Table 3). Nevertheless, there was a trend for higher soil pH especially under Hass (at 1 and 2 m) and Nabal (at 1 m) canopies than in the control soil, while soil pH under Ettinger canopy at (1 m) was similar to that in the control (i.e. slightly acidic) (Fig. 4a). There was also a tendency for soil pH to decrease successively from mid-canopy (1 m) to the open control area (Table 3). Soil pH was overall lower in the subsoil than in the topsoil (Fig. 4b).

#### 3.1.4 Soil Electrical Conductivity

There was also a trend for soil under the avocado trees to have higher EC values than the control soil, and EC decreased significantly from mid-canopy (1 m from the tree trunk) to the control (5 m) (Table 3). There were also differences in soil EC between the three avocado cultivars, with Hass showing the highest average values (Fig. 5a). Moreover, the topsoil had higher EC than the subsoil (Fig. 5b).

#### 3.1.5 Soil Organic Carbon

Soil organic carbon content was significantly higher under the avocado trees than in control soil, particularly at the tree mid-canopy (1 m from trunk) (Table 3). In soil under cv. Nabal canopy, mean soil carbon concentration was

**Table 3** Main effects of avocado trees, avocado cultivar, soil layer and radial distance from tree trunk, and the interactions of cultivar with radial distance and soil depth, on physicochemical properties of soil. Cultivar mean refers to the mean value at 1 and 2 m distance from tree trunk; BD = bulk density; MC = moisture content; pH = hydrogen ion concentration; OC = soil organic carbon; EC = electrical conductivity; TN = total nitrogen; av. P = available phosphorus; C:N = carbon to nitrogen ratio. Means within each comparison are significantly different ($p < 0.05$) if followed by different letters

| Treatment level | BD (kg $dm^{-3}$) Mean (SE) | MC (%) Mean (SE) | pH Mean (SE) | EC (dS $m^{-1}$) Mean (SE) | OC (%) Mean (SE) | Av. *P* (mg $kg^{-1}$) Mean (SE) | TN (%) Mean (SE) | C: *N* Mean (SE) |
|---|---|---|---|---|---|---|---|---|
| Between-overall avocado and control variation | | | | | | | | |
| Avocado | 1.17 (0.01) b | 19.2 (0.75) a | 6.44 (0.11) a | 0.21 (0.02) a | 3.11 (0.10) a | 11.9 (4.16) a | 0.23 (0.01) a | 13.5 (0.49) a |
| Control | 1.25 (0.02) a | 15.2 (1.45) b | 6.17 (0.17) a | 0.13 (0.04) a | 2.68 (0.17) b | 11.3 (4.51) a | 0.24 (0.01) a | 11.5 (0.88) b |
| *p*-value | 0.007* | 0.008* | 0.137 | 0.070 | 0.014* | 0.794 | 0.481 | 0.028 * |
| Between-cultivar variation | | | | | | | | |
| Control 5 m | 1.25 (0.02) a | 15.2 (1.43) b | 6.17 (0.19 ) a | 0.13 (0.04) b | 2.68 (0.17) a | 11.34 (4.54) a | 0.24 (0.01) a | 11.5 (0.87) a |
| Ettinger 1 m | 1.17 (0.02) a | 21.8 (1.43) a | 6.13 (0.19 ) a | 0.17 (0.04) ab | 3.30 (0.17) a | 12.69 (4.54) a | 0.24 (0.01) a | 13.6 (0.87) a |
| Ettinger 2 m | 1.17 (0.02) a | 17.4 (1.43) ab | 6.33 (0.19 ) a | 0.18 (0.04) ab | 2.90 (0.17) a | 9.92 (4.54) a | 0.22 (0.01) a | 13.0 (0.87) a |
| Hass 1 m | 1.17 (0.02) a | 19.5 (1.43) ab | 6.81 (0.19 ) a | 0.35 (0.04) a | 3.18 (0.17) a | 16.86 (4.54) a | 0.26 (0.01) a | 12.5 (0.87) a |
| Hass 2 m | 1.16 (0.02) a | 20.7 (1.43) ab | 6.49 (0.19 ) a | 0.20 (0.04) ab | 2.82 (0.17) a | 15.04 (4.54) a | 0.22 (0.01) a | 12.7 (0.87) a |
| Nabal 1 m | 1.15 (0.02) a | 18.4 (1.43) ab | 6.53 (0.19 ) a | 0.22 (0.04) ab | 3.35 (0.17) a | 8.12 (4.54) a | 0.22 (0.01) a | 15.1 (0.87) a |
| Nabal 2 m | 1.19 (0.02) a | 17.4 (1.43) ab | 6.32 (0.19 ) a | 0.16 (0.04) b | 3.09 (0.17) a | 8.85 (4.54) a | 0.21 (0.01) a | 14.0 (0.87) a |
| *p*-value | 0.198 | 0.024* | 0.090 | 0.008** | 0.029* | 0.032* | 0.040* | 0.070 |
| Between-soil layer variation | | | | | | | | |
| 0–20 cm | 1.20 (0.02) a | 18.6 (0.84) a | 6.58(0.11) a | 0.24 (0.02) a | 3.62 (0.11) a | 17.25 (4.17) a | 0.26 (0.004) a | 13.9 (0.54) a |
| 20–40 cm | 1.17 (0.02) a | 18.6 (0.84) a | 6.22 (0.11) b | 0.16 (0.02) b | 2.48 (0.11) b | 6.42 (4.17) b | 0.20 (0.004) b | 12.6 (0.54) b |
| *p*-value | 0.088 | 0.996 | < 0.001*** | < 0.001*** | < 0.001*** | < 0.001*** | < 0.001*** | 0.035* |
| Between-radial distance variation | | | | | | | | |
| Mid-canopy (1 m) | 1.17 (0.02) b | 19.9 (0.91) a | 6.50 (0.13) a | 0.25 (0.02) a | 3.28 (0.12)a | 12.6 (4.22) a | 0.24 (0.01) a | 13.8 (0.58) a |
| Canopy edge (2 m) | 1.18 (0.02) b | 18.5 (0.91) ab | 6.38 (0.13) a | 0.18 (0.02) ab | 2.94 (0.12) ab | 11.3 (4.22) a | 0.22 (0.01) a | 13.2 (0.58) a |
| Control (5 m) | 1.25 (0.02) a | 15.2 (1.45) b | 6.17 (0.17) a | 0.13 (0.04) b | 2.68 (0.17) b | 11.3 (4.51) a | 0.24 (0.01) a | 11.5 (0.87) a |
| *p*-value | 0.026* | 0.015* | 0.235 | 0.021* | 0.002* | 0.714 | 0.045* | 0.067 |
| Cultivar: Radial distance: Soil depth interaction, *p*-value | | | | | | | | |
| Cultivar: Radial distance | 0.777 | 0.137 | 0.382 | 0.063 | 0.111 | 0.726 | 0.025* | 0.738 |
| Cultivar: Depth | 0.934 | 0.156 | 0.099 | 0.170 | 0.995 | 0.001** | 0.014* | 0.415 |
| Cultivar: Radial distance: Depth | 0.788 | 0.442 | 0.588 | 0.381 | 0.966 | 0.203 | 0.150 | 0.485 |

approximately 20% higher than in the control, but the difference was not significant. There was no significant difference between the cultivars (Fig. 6a).

### 3.1.6 Available Phosphorus

Mean available phosphorus concentration in soil under the avocado cultivars was similar to that in the control soil (Table 3). However, there were differences between the cultivars ($p = 0.032$), with soil under Hass canopy tending to have higher available phosphorus concentrations than soil under Nabal canopy, while soil under Ettinger canopy was intermediate (Fig. 7a). Concentrations of available phosphorus were lower in the subsoil than in the topsoil (Fig. 7b), but the average difference between the soil layers was smaller for Nabal than for the other cultivars (Table 4).

### 3.1.7 Total Nitrogen

Mean total nitrogen concentration in soil was similar under avocado trees and in the control (Table 3). However, there was some variation in soil total nitrogen content between

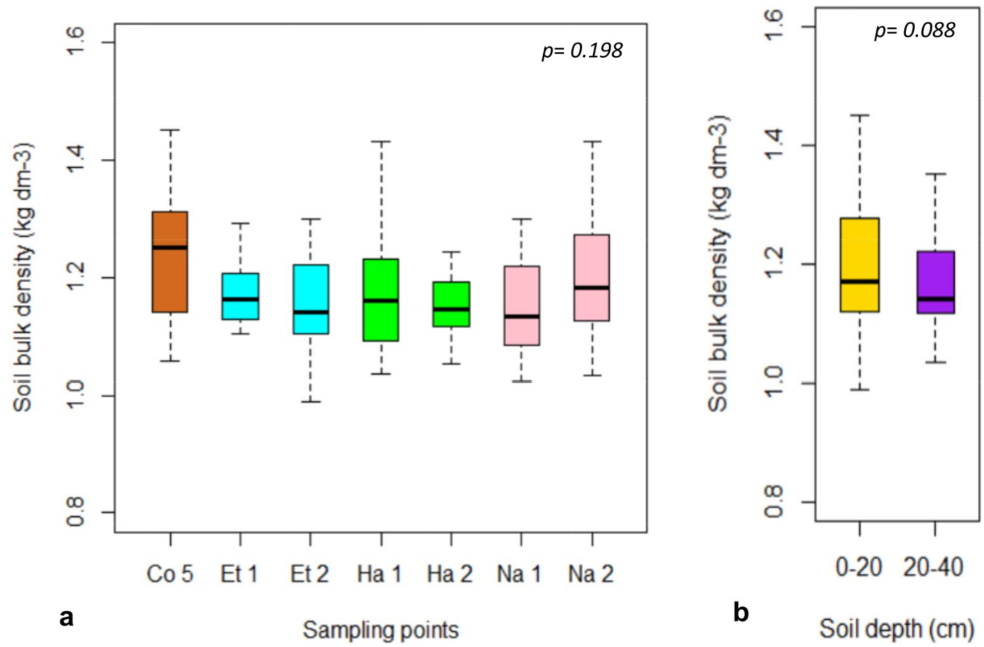


**Fig. 2** Soil bulk density at (**a**) the control sampling point + points affected by avocado cultivars (at different radial distances, across soil depths) and (**b**) in the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. The black line in the middle of each box refers to the median value

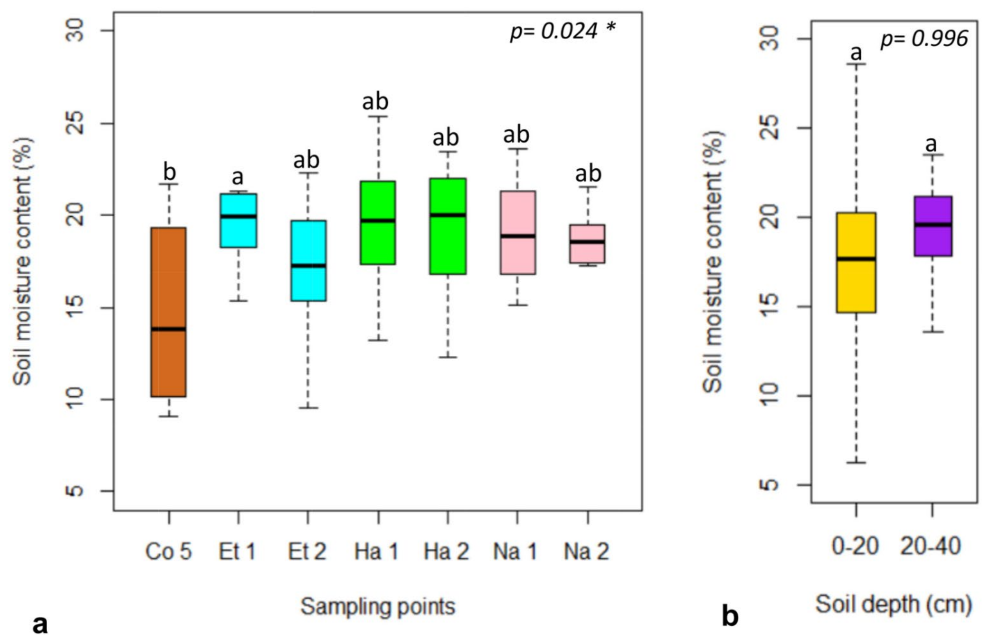


**Fig. 3** Soil moisture content of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

the avocado cultivars (Fig. 8a), where soil under Hass canopy (at 1 m distance from the trunk) tended to have higher average values than soil under Nabal canopy. There was a general tendency for higher total nitrogen concentration in soil at mid-canopy (1 m) than at the canopy edge (2 m) (Table 3), but Hass was the only cultivar for which the effect was significant (Table 4). Total nitrogen concentration was significantly lower in the subsoil than in the topsoil (Fig. 8b), with soil under Hass canopy tending to show the largest difference (Table 4).

#### 3.1.8 Carbon to Nitrogen Ratio (C:N)

Overall, the C:N ratio was significantly higher under the avocado trees than in the control soil (Table 3), and the soil under Nabal canopy tended to have the highest C:N ratio (Fig. 9a). The C:N ratio was significantly higher in the topsoil than in the subsoil (Fig. 9b).

#### 3.1.9 Soil Variable Correlation

Pearson correlation analysis revealed positive correlations between soil organic carbon and soil moisture content,

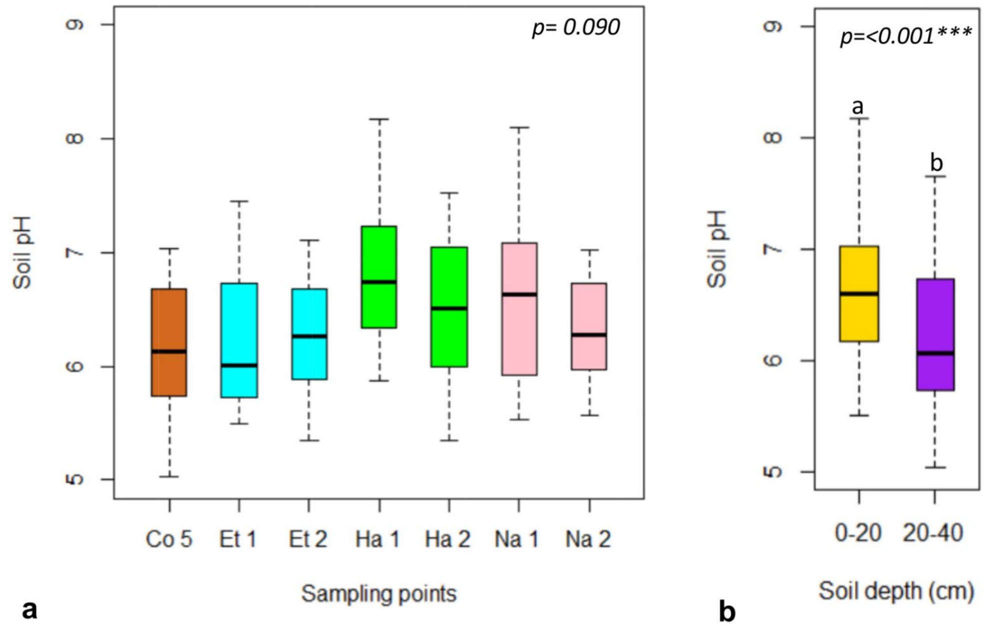


**Fig. 4** Soil pH of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

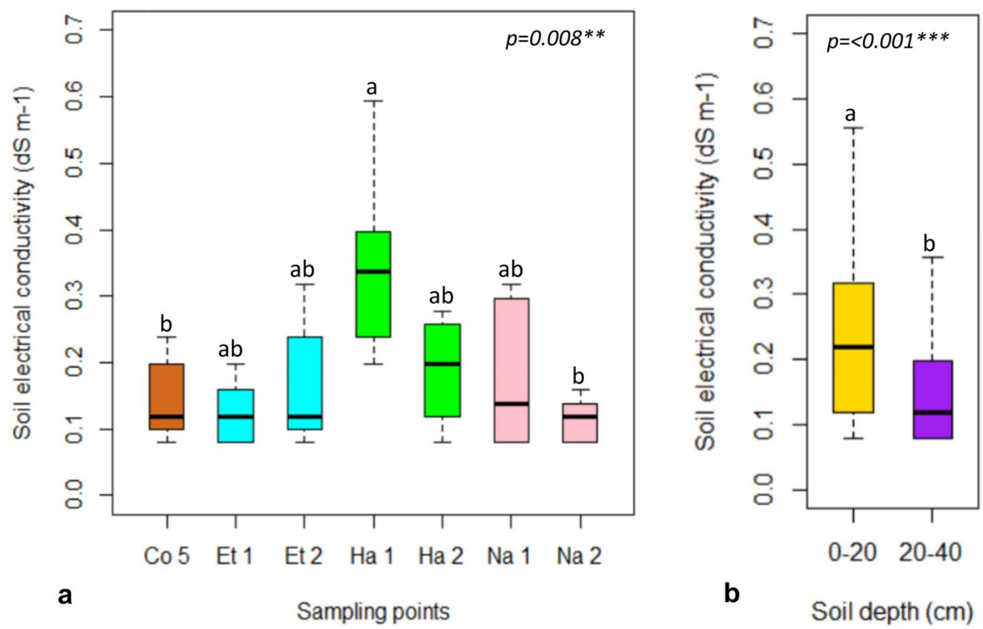


**Fig. 5** Soil electrical conductivity of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

pH, EC, available phosphorus, and total nitrogen (Supplementary Table S1). Similarly, available phosphorus, total nitrogen and EC were all positively correlated with soil pH (Table S1). However, soil organic carbon and soil bulk density showed a negative correlation.

## 4 Discussion

This study investigated the effects of three avocado cultivars most preferred by local farmers in Ethiopia on the physical and chemical properties of the soil, in order to understand the longer-term implications for farms and help farmers make more informed cultivar choices when integrating avocado trees into their cropping system. The results revealed that soil beneath avocado tree canopy had a higher moisture content and lower soil bulk density than the control. The mulch provided by the avocado leaf litter, and possibly the shade from the canopy, apparently reduced evaporation and helped retain soil moisture compared with the control, even though water consumption by the avocado trees themselves may be high since their cultivation is known to demand a reliable water supply (Frankowska et al. 2019). Soil organic matter content was elevated below the tree canopy, which can reduce soil bulk density (Fahad et al. 2022) and improve infiltration of precipitation through increased

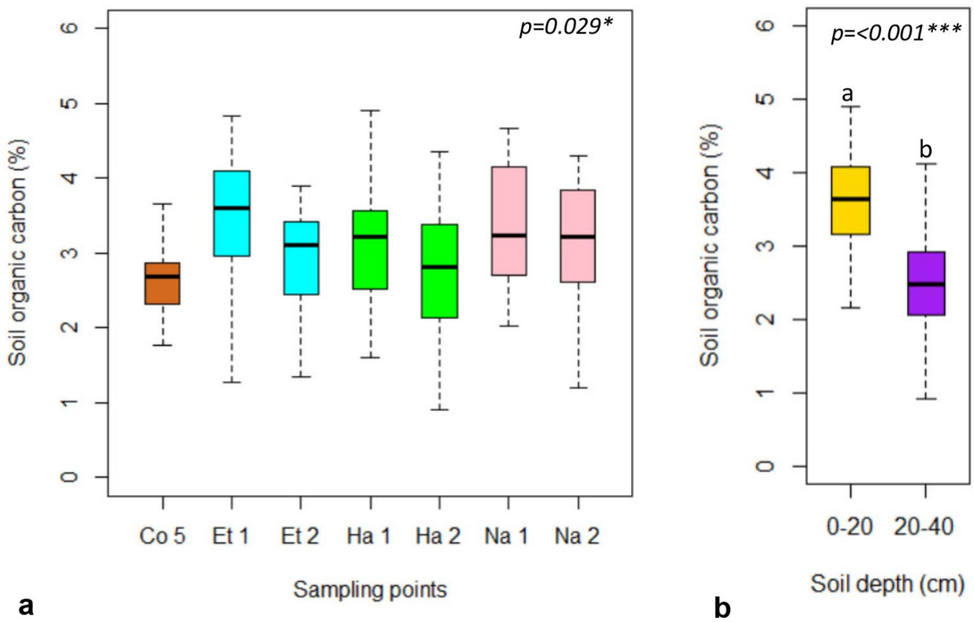


**Fig. 6** Soil organic carbon of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

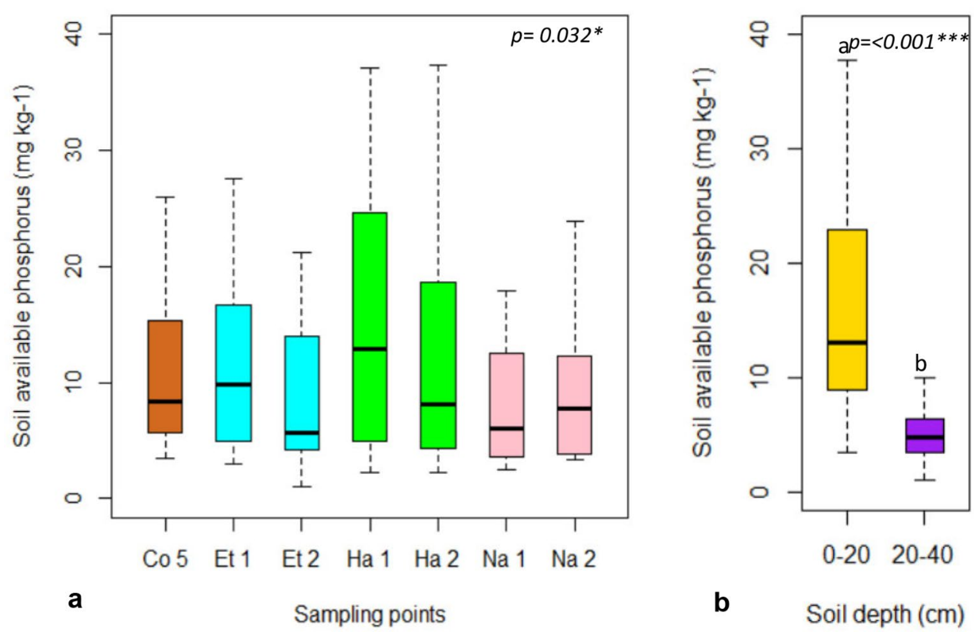


**Fig. 7** Soil available phosphorus of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

aggregate stability (Blanco-Canqui and Benjamin 2015). It is also likely to increase the water-holding capacity of the soil, further improving water availability. These differences suggest that avocado trees may perform well in terms of soil moisture retention under rainfed cultivation in the Ethiopian highlands. Soil moisture content was similar under all three cultivars studied, despite relatively large differences in tree size, suggesting that their water use efficiency may differ. Water use efficiency has been found previously to vary between avocado cultivars (Acosta-Rangel et al. 2018), while rainfed avocado cultivation has been found to use less water than irrigated avocado cultivation (Gómez-Tagle et al. 2022). Harnessing the potential of cultivar differences in improving soil physical properties and conserving water through high use efficiency in rainfed production areas could satisfy global demand for avocado without the negative consequences that arise in the many avocado-growing areas worldwide that require irrigation (Sommaruga and Eldridge 2021).

One of the most important findings in this study was that soil organic carbon content was higher under the avocado canopy than in the open control area. This can be attributed to high carbon inputs beneath the canopy through spontaneous litterfall from this vigorously growing species and its dense root system in the topsoil (Salazar-Garcia and Cortés-Flores 1986; Durand and Claassens 2010). Avocado trees

**Table 4** Interactive effects of avocado cultivar, soil layer and radial distance on available phosphorus (av. P) and total nitrogen (TN) content in soil. Means within cultivar are significantly different ($p < 0.05$) if followed by different letters. In the cultivar versus depth comparisons, cultivar mean refers to the mean value at 1 m and 2 m radial distance from the tree trunk. In the cultivar versus radial distance comparisons, depth mean refers to the mean value in the 0–20 cm and 20–40 cm soil layer

| Cultivar versus Depth (over radial distances) | | | Cultivar versus Radial distance (over depths) | |
|---|---|---|---|---|
| Cultivar | Av. P (mg kg$^{-1}$) Mean (SE) | TN (%) Mean (SE) | Cultivar | TN (%) Mean (SE) |
| Ettinger 0–20 cm | 18.27 (4.31) a | 0.26 (0.01) a | Ettinger 1 m | 0.24 (0.01) a |
| Ettinger 20–40 cm | 4.34 (4.31) b | 0.19 (0.01) b | Ettinger 2 m | 0.22 (0.01) a |
| Hass 0–20 cm | 24.72 (4.31) a | 0.29 (0.01) a | Hass 1 m | 0.26 (0.01) a |
| Hass 20–40 cm | 7.18 (4.31) b | 0.19 (0.01) b | Hass 2 m | 0.22 (0.01) b |
| Nabal 0–20 cm | 11.35 (4.31) a | 0.25 (0.01) a | Nabal 1 m | 0.22 (0.01) a |
| Nabal 20–40 cm | 5.62 (4.31) b | 0.19 (0.01) b | Nabal 2 m | 0.21 (0.01) a |
| *p*-value | 0.001 ** | 0.014 * | *p*-value | 0.025 * |

often have two or three growth flushes per year (Silva et al. 2017; Thorp et al. 1995; Whiley 1994), while minimal soil disturbance through avoiding tillage under the trees decreases turnover of soil organic matter (Zikeli et al. 2013). Furthermore, avocado trees form substantial arbuscular mycorrhizal fungi (AMF) associations (Bárcenas et al. 2007), which constitute another entry route of photosynthates and thus carbon into the soil. These AMF associations are formed due to growth 'dependence' of the fungi on the avocado plant (Montoya and Osorio 2009) owing to lack of root hairs or very small cell size (Lara-Chávez et al. 2013). Through these associations, AMF contribute to soil fertility by producing organic acids and glomalin, which protect soil from erosion, improve carbon sequestration and stabilize soil macro-aggregation (Fall et al. 2022). The lack of soil tillage also benefits the AMF, creating concurrent interactions that boost overall soil fertility (Verbruggen et al. 2012).

Among the three avocado cultivars studied, Nabal tended to have higher soil organic carbon than the others. This may be due to the larger canopies of Nabal, leading to higher organic matter input than from Ettinger and Hass. The findings in this study are in agreement with those in a study by Reddy et al. (2014), where soil organic carbon content under avocado cultivars ranged from 2.4 to 5.3%, and suggest that selection of cultivar can influence soil organic matter level and the multitude of related soil variables. However, the C:N ratio was still within the range where net nitrogen mineralization can be expected and, given the larger organic matter pool, this most likely did not affect nitrogen availability to the trees.

Soil pH was generally similar under the avocado cultivars and in the control and was within the optimal range for avocado production, indicating conditions supporting soil microbial biomass and activity (Msimbira and Smith 2020) and availability of nutrients in the soil (Penn and Camberato 2019). Soil EC were higher under the central avocado tree canopy than in the control, while available phosphorus and total nitrogen concentrations did not differ. This suggests that overall soil fertility under the tree canopy was similar to that in control soil, despite the fact that farmers applied no nutrient inputs to the trees, whereas the control area received e.g. domestic wastes and had a crop rotation

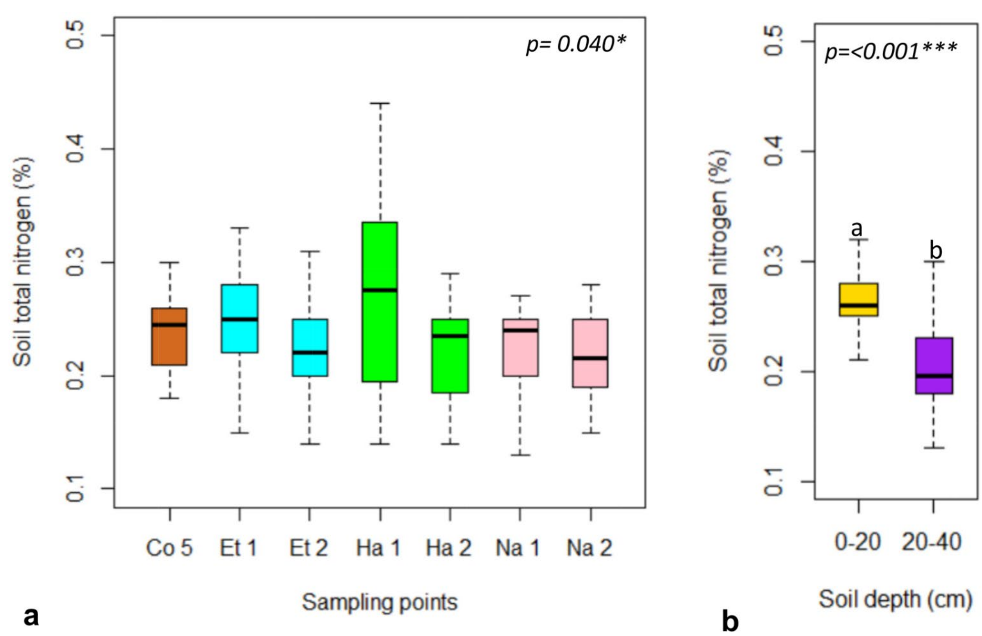


**Fig. 8** Soil total nitrogen of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

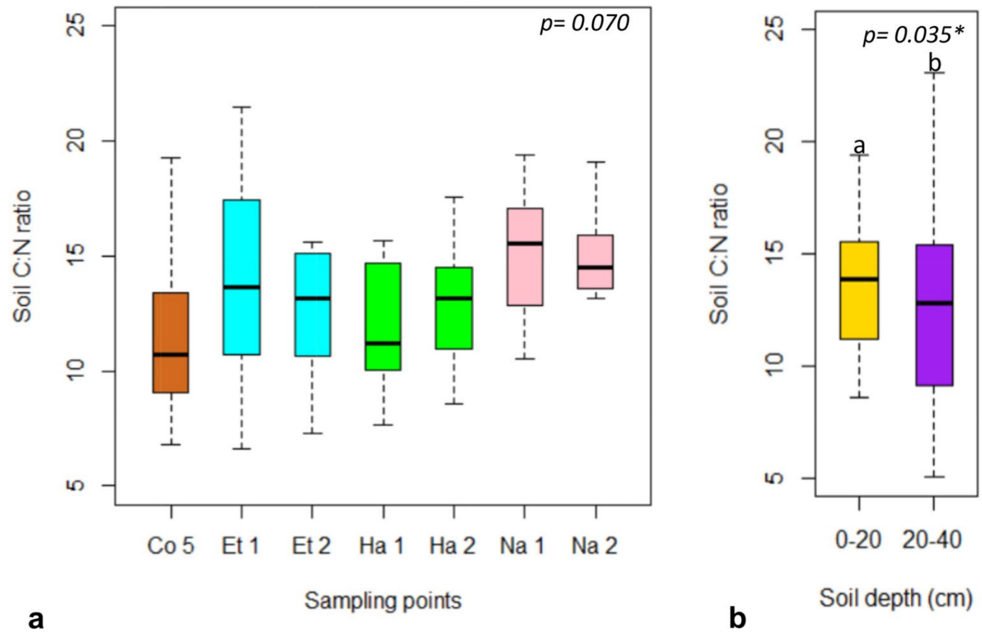


**Fig. 9** Carbon to nitrogen ratio of (**a**) control + avocado cultivars (at different radial distances, across soil depths) and (**b**) the 0–20 cm and 20–40 cm soil layers (across cultivars + control and radial distances). Co 5 = control (5 m from tree canopy); Et = cv. Ettinger, Ha = cv. Hass, Na = cv. Nabal. 1, 2 = 1 and 2 m distance from tree trunk. Boxes with different letters are significantly different ($p < 0.05$). The black line in the middle of each box refers to the median value

that included legumes. This might be due to nutrient mining by tree roots from deep layers and deposition in the topsoil via litterfall decomposition (Agena et al. 2014; Kumar 2011) and to the higher level of soil organic matter providing increased nutrient-holding capacity.

In general, this study showed that avocado trees have the potential to improve soil properties by increasing organic matter content and improving some other soil properties. Smallholder farmers can therefore include avocado production for farm diversification without risking negative side-effects on soil health. The effect of the three studied cultivars on the soil differed in some respects, with Hass tending to give higher soil nutrient concentrations and Nabal tending to give higher soil organic carbon concentration. Each farmer's preferences for enhancing these aspects of soil quality may thus inform cultivar selection. However, farmers in the study area maintained close spacing when growing avocados on their small land-holdings. Therefore, other factors such as tree size, time of fruit set, yield potential, competition with companion crops and size of the growing area, proper spacing and tree density are likely to be more important for farmers when selecting cultivars to plant.

## 5 Conclusions

In general, the three avocado cultivars studied had important effects in improving the physicochemical properties of the soil through organic matter addition and can improve the soil nutrient availability under the canopy. However, the three cultivars apparently differed somewhat in their potential to improve soil properties. In general, Hass tended to make the greatest contribution to the soil nutrient status (total nitrogen, available phosphorus), but Nabal tended to give the greatest increase in soil organic carbon. Hass and Nabal cultivars thus appear to have the potential to significantly increase physicochemical properties with time. Smallholder farmers in the study area in Ethiopia may thus benefit in particular from integration of Hass into their cropping system, as it may provide most benefits in terms of nutrient status of the soil and has relatively small trees. However, for optimal soil nutrient balance and sustained avocado production, avocado cultivars with beneficial effects on soil properties should be combined with wider spacing and with cultivar and site-specific soil and tree management practices.

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**Data Availability** The datasets generated during the current study are available from the corresponding author on request.

## Declarations

**Conflict of Interest** The authors declare that they have no conflict of interest.

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## References

FAO (2020) Soil testing methods: global soil doctors Programme- A farmer to farmer training programme. Rome. https://doi.org/10.4060/ca2796en

Abebe H, Biratu W, Tesfay K, Berhe M, Gebremeskel H (2022) Growth and yield evaluation of Avocado (*Persea americana*) varieties in Lowland Agro Ecology of Raya Azebo, Southern Zone of Tigray Region, Northern Ethiopia. Agro Bali Agric J 5:263–273. https://doi.org/10.37637/ab.v5i2.919

Acosta-Rangel A, Ávila-Lovera E, De Guzman ME, Torres L, Haro R, Arpaia ML, Focht E, Santiago LS (2018) Evaluation of leaf carbon isotopes and functional traits in avocado reveals water-use efficient cultivars. Agric Ecosyst Environ 263:60–66. https://doi.org/10.1016/j.agee.2018.04.021

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

Araújo RG, Rodriguez-Jasso RM, Ruiz HA, Pintado MME, Aguilar CN (2018) Avocado by-products: Nutritional and functional properties. Trends Food Sci Technol 80:51–60. https://doi.org/10.1016/j.tifs.2018.07.027

Bárcenas A, Almaraz C, Reyes L, Varela L, Lara B, Guillén A, Carreón Y, Aguirre S, Chávez A (2007) Diversity of arbuscular mycorrhizal fungi on avocado orchards from Michoacan. In Proceedings VI World Avocado Congress. Viña del Mar, Chile

Benke RR, Kearfott KJ (1999) Soil sample moisture content as a function of time during oven drying for gamma-ray spectroscopic measurements. Nucl Instruments Methods Phys Res Sect Accel Spectrometers Detect Assoc Equip 422:817–819. https://doi.org/10.1016/S0168-9002(98)01004-3

Blanco-Canqui H, Benjamin JG (2015) Impacts of soil organic carbon on soil physical behavior. Quantifying Model Soil Struct Dyn 3:11–40. https://doi.org/10.2134/advagricsystmodel3.c2

Bonomelli C, Gil PM, Schaffer B (2019) Effect of soil type on calcium absorption and partitioning in young avocado (*Persea americana* Mill.) Trees. Agronomy 9:837. https://doi.org/10.3390/agronomy9120837

Bremner JT (1965) Inorganic forms of nitrogen. In Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties 9: 1179–1237. American Society of Agronomy, Soil Science Society of America

Catacutan DC, Van Noordwijk M, Nguyen TH, Öborn I, Mercado AR (2017) Agroforestry: contribution to food security and climate-change adaptation and mitigation in Southeast Asia. White Paper. ISBN: 978-979-3198-95-8. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program 1–28

Crowley D (2007) Managing soils for avocado production and root health. Calif Avocado Soc Yearbook 90:107–130. http://avocadosource.com/cas_yearbooks/cas_90_2007/cas_2007_v90_pg_107-130.pdf

De la Vega-Rivera A, Merino-Pérez L (2021) Socio-environmental impacts of the avocado boom in the Meseta Purépecha, Michoacán. Mexico Sustain 13:7247. https://doi.org/10.3390/su13137247

Do VH, La N, Mulia R, Bergkvist G, Dahlin AS, Nguyen VT, Pham HT, Öborn I (2020) Fruit tree-based agroforestry systems for smallholder farmers in Northwest Vietnam - a quantitative and qualitative assessment. Land 9:1–23. https://doi.org/10.3390/land9110451

Durand BJ, Claassens NJF (2010) Root distribution of avocado trees in different soil types. Distribution 15–19. South African Avocado Growers' Association Yearbook 1987. 10:15–19. Proceedings of the First World Avocado Congress. https://www.avocadosource.com/WAC1/WAC1_p015.pdf

EIAR (2010) Registration of Plant varieties. Ethiop J Agric Sci 20:179–194

Emire A, Demise S, Giri T (2021) Growth and Yield Performance of Avocado (*Persea americana*) Tree Varieties at Midland Agro-ecology of Guji Zone, Southern Ethiopia. International Journal of Advanced Research and Review 6:7–15. https://www.ijarr.in/finder.aspx?author=&title=Growth%20and%20yield%20performance%20of%20avocado

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. Sustain 14:14877. https://doi.org/10.3390/su142214877

Fall AF, Nakabonge G, Ssekandi J, Founoune-Mboup H, Apori SO, Ndiaye A, Badji A, Ngom K (2022) Roles of Arbuscular Mycorrhizal Fungi on Soil Fertility: Contribution in the improvement of Physical, Chemical, and Biological properties of the Soil. Front Fungal Biol 3:1–11. https://doi.org/10.3389/ffunb.2022.723892

Ferreyra R, Selles G, Gil P, Celedon J, Maldonado P (2014) Effect of soil available water depletion on plant water status, fruit size and yield of avocado trees cv. 'Hass'. Acta Hortic 1038:393–400. https://doi.org/10.17660/ActaHortic.2014.1038.47

Frankowska A, Jeswani HK, Azapagic A (2019) Life cycle environmental impacts of fruits consumption in the UK. J Environ Manage 248:109111. https://doi.org/10.1016/j.jenvman.2019.06.012

Freitas J, Silva P (2022) Sustainable Agricultural Systems for Fruit orchards: the influence of Plant Growth promoting Bacteria on the Soil Biodiversity and Nutrient Management. Sustain 14:13952. https://doi.org/10.3390/su142113952

Gee GW, Bauder JW (1986) Particle-size analysis. Methods of Soil Analysis: part 1 physical and mineralogical methods, vol 5. American Society of Agronomy, Soil Science Society of America, pp 383–411

Gil PM, Bonomelli C, Schaffer B, Ferreyra R, Gentina C (2012) Effect of soil water-to-air ratio on biomass and mineral nutrition of avocado trees. J Soil Sci Plant Nutr 12:609–630. https://doi.org/10.4067/s0718-95162012005000020

Gómez-Tagle AF, Gómez-Tagle A, Fuerte-Velázquez DJ, Barajas-Alcalá AG, Quiroz-Rivera F, Alarcón-Chaires PE, Guerrero-García-Rojas H (2022) Blue and Green Water Footprint of Agro-industrial Avocado Production in Central Mexico. Sustain 14:1–20. https://doi.org/10.3390/su14159664

Grunennvaldt R (2022) Avocado soil health literature review. Extension horticulturist Queensland Department of Agriculture and Fisheries. Queensland, Australia. https://avocado.org.au/wp-content/uploads/2022/11/Soil-health-literature-review_NOV-22.pdf

ILRI (2015) Africa RISING Ethiopia project in Southern Nations, Nationalities and Peoples region Lemo, Jawe and Upper Gana. 9:1–2. https://cgspace.cgiar.org/bitstreams/4eeb3a72-d8b3-4a04-9fd0-14820a8c0dd3/download

Jackson (1958) Determining nutrient availability in forest soils. Soil Sampl Methods Anal Second Ed 317–329. https://doi.org/10.1201/9781420005271.ch27

Kaneko T, Gould N, Campbell D, Snelgar P, Clearwater MJ (2022) The effect of soil type, fruit load and shaded area on 'Hass' avocado (*Persea americana* Mill.) water use and crop coefficients. Agric Water Manag 264:107519. https://doi.org/10.1016/j.agwat.2022.107519

Kassa M, Asfaw Z, Beyene S (2014) On-farm management of Persea americana (avocado) and its influence on some soil physicochemical properties and maize yield: a case of Damot Gale, South Ethiopia. Adv Life Sci Technol 23:83–9

Ketema H, Abayineh D (2015) The effect of avocado tree (*Persea americana* Mill.) on Selected soil properties and under storey plants in Southern Ethiopia. Int J Res 2:1093–1116. https://web.archive.org/web/20181126043542/http://nadre.ethernet.edu.et:80/record/232/files/PUBBLICATIONSDU-2018-001.pdf

Kotze R (2022) An Investigative soil health analysis of avocado orchards in Eastern Zimbabwe. BSc (Hons) Agriculture Dissertation, Royal Agricultural University, Cirencester, England

Kumar BM (2011) Quarter century of agroforestry research in Kerala: an overview. J Trop Agric 49:1–18. https://jtropag.kau.in/index.php/ojs2/article/view/231

Lara-Chávez MBN, del Ávila-Val C, Aguirre-Paleo T, Vargas-Sandoval S M (2013) Arbuscular mycorrhizal fungi identification in avocado trees infected with Phytophthora Cinnamomi Rands under Biocontrol. Trop Subtrop Agroecosystems 16:415–421. https://www.researchgate.net/publication/285189146_Arbuscular_mycorrhizal_fungi_identification_in_avocado_trees_infected_with_phytophthora_cinnamomi_rands_under_biocontrol

Mokria M, Gebrekirstos A, Said H, Hadgu K, Hagazi N, Dubale W, Bräuning A (2022) Fruit weight and yield estimation models for five avocado cultivars in Ethiopia. Environ Res Commun 4:075013

Montoya B, Osorio W (2009) Mycorrhizal dependency of avocado at different levels of soil solution phosphorus. Suelos Ecuatoriales 39:143–147. https://www.bioedafologia.com/sites/default/files/documentos/pdf/39%202%206%20Mycorrhizal%20dependency%20of%20avocado%20MONTOYA%20Y%20OSORIO_0.pdf

Msimbira LA, Smith DL (2020) The roles of Plant Growth Promoting Microbes in Enhancing Plant Tolerance to Acidity and Alkalinity stresses. Front Sustain Food Syst 4:1–14. https://doi.org/10.3389/fsufs.2020.00106

Nyakang'i CO, Ebere R, Marete E, Arimi JM (2023) Avocado production in Kenya in relation to the world, Avocado by-products (seeds and peels) functionality and utilization in food products. Appl Food Res 3:100275. https://doi.org/10.1016/j.afres.2023.100275

Olsen SR (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939). US Department of Agriculture, Washington

Penn CJ, Camberato JJ (2019) A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agric 9:1–18. https://doi.org/10.3390/agriculture9060120

Pinho RC, Miller RP, Alfaia SS (2012) Agroforestry and the improvement of soil fertility: a view from Amazonia. 616383. Applied and environmental soil science. https://doi.org/10.1155/2012/616383

Rathore SS, Babu S, El-Sappah AH, Shekhawat K, Singh VK, Singh RK, Upadhyay PK, Singh R (2022) Integrated agroforestry systems improve soil carbon storage, water productivity, and economic returns in the marginal land of the semi-arid region. Saudi J Biol Sci 29:103427. https://doi.org/10.1016/j.sjbs.2022.103427

Reddy M, Moodley R, Jonnalagadda SB (2014) Elemental uptake and distribution of nutrients in avocado mesocarp and the impact of soil quality. Environ Monit Assess 186:4519–4529. https://doi.org/10.1007/s10661-014-3716-7

Rosecrance R, Faber B, Lovatt C (2012) Patterns of nutrient accumulation in 'Hass' avocado fruit. Better Crop 96:12–13. http://www.ipni.net/publication/bettercrops.nsf/0/F2E59118B155B269062579AC005AE171/$FILE/Better%20Crops%202012-1%20p.12-13.pdf

Salazar-Garcia S, Cortés-Flores JI (1986) Root distribution of mature avocado trees growing in soils of different texture. Calif Avocado Soc Yearbook 70:165–174. https://www.avocadosource.com/CAS_Yearbooks/CAS_70_1986/CAS_1986_PG_165-174.pdf

Sarvade S, Gautam DS, Upadhyay VB, Sahu RK, Shrivastava AK, Kaushal R, Singh R, Yewale AG (2019) Agroforestry and soil health: an overview. Agroforestry for climate resilience and rural livelihood. Scientific Publishers India 275– 97, Jodhpur, India

Selladurai R, Awachare CM (2020) Nutrient management for avocado (Persea americana Miller). J Plant Nutr 43:138–147. https://doi.org/10.1080/01904167.2019.1659322

Silva SRD, Cantuarias-Avilés TE, Chiavelli B, Martins MA, Oliveira MS (2017) Phenological models for implementing management practices in rain-fed avocado orchards. Pesqui Agropecuária Trop 47:321–327. https://doi.org/10.1590/1983-40632016v4747140

Sommaruga R, Eldridge HM (2021) Avocado Production: Water Footprint and Socio-economic implications. EuroChoices 20:48–53. https://doi.org/10.1111/1746-692X.12289

Sora SA (2023) Evaluation of Avocado (*Persea americana*) for growth and yield at Teppi, Southwestern Ethiopia. Int J Fruit Sci 23:46–50. https://doi.org/10.1080/15538362.2023.2178595

Thorp TG, Anderson P, Camilleri M (1995) Avocado tree growth cycles - a quantitative model. Proc World Avocado Congr III 76–79. https://www.avocadosource.com/WAC3/wac3_p076.pdf

Tsufac AR, Awazi NP, Yerima BPK (2021) Characterization of agroforestry systems and their effectiveness in soil fertility enhancement in the south-west region of Cameroon. Curr Res Environ Sustain 3:100024. https://doi.org/10.1016/j.crsust.2020.100024

Tzatzani TT, Kavroulakis N, Doupis G, Psarras G, Papadakis IE (2020) Nutritional status of 'Hass' and 'Fuerte' avocado (*Persea americana* Mill.) Plants subjected to high soil moisture. J Plant Nutr 43:327–334. https://doi.org/10.1080/01904167.2019.1683192

Verbruggen E, Kiers ET, Bakelaar PN, Röling WF, van der Heijden MG (2012) Provision of contrasting ecosystem services by soil communities from different agricultural fields. Plant Soil 350:43–55. https://doi.org/10.1007/s11104-011-0828-5

Walkley AJ, Black IA (1934) Estimation of soil organic carbon by the chromic acid titration method. Soil Sci 37:29–38. https://doi.org/10.1097/00010694-193401000-00003

Whiley AW (1994) Ecophysiological studies and tree manipulation for maximization of yield potential in avocado (*Persea americana* Mill.). Ph.D. Thesis. University of Natal. Pietermaritzburg, South Africa. 175pp

Wolstenholme BN (2004) Nitrogen the manipulator element: managing inputs and outputs in different environments. South Afr Avocado Growers' Association Yearbook 27:45–61. https://www.avocadosource.com/Journals/SAAGA/SAAGA_2004/SAAGA_2004_PG_45-61.pdf

Wolstenholme BN (2013) Ecology: climate and soils. The avocado: botany, production and uses 86–117. CABI, Wallingford UK

Zikeli S, Gruber S, Teufel CF, Hartung K, Claupein W (2013) Effects of reduced tillage on crop yield, plant available nutrients and soil organic matter in a 12-year long-term trial under organic management. Sustain 5:3876–3894. https://doi.org/10.3390/su5093876

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