Effects of shade tree species on soil biogeochemistry and coffee bean quality in plantation coffee

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ABSTRACT

Shade trees are used in many coffee production systems across the globe. Beyond the benefits on biodiversity conservation, climate buffering, carbon sequestration and pathogen regulation, shade trees can impact the soil nutrient status via, for instance, litter inputs and nitrogen fixation. Since soil nutrients affect coffee quality and taste, there is also a potential indirect effect of shade tree species on coffee quality. Yet, in spite of the potentially large impact of shade tree species, quantitative data on the effects of shade trees on (i) soil biogeochemistry and (ii) the associated coffee bean quality remain scarce. To what extent four widely used shade tree species (Acacia abyssinica L., Albizia gummifera L., Cordia africana L. and Croton macrostachyus L.) in a plantation coffee agroforestry system impact soil biogeochemistry, and how this in turn affects coffee quality, measured as cupping scores and bean size. A significant negative impact of N-fixing shade tree species on soil pH and base cation concentrations was found. Plant-available and total phosphorus was enhanced by the presence of Albizia gummifera L. Thus, the present findings demonstrate that careful selection and integration of shade tree species such as Acacia abyssinica L. and Albizia gummifera L. into coffee production systems is a good practice for sustaining soil chemical properties in coffee agroecosystem. Despite the impacts on soil chemical characteristics, the shade tree species had no effect on coffee cup quality but did affect the bean mass. In this particular study, an attempt was made to quantify the impacts of widely used shade tree species on soil biogeochemistry and the subsequent effect on coffee bean quality in a plantation agroforestry system over the course of one season in southwest Ethiopia. However, it might be feasible to accommodate both relatively sparse time-series experimental data consisting of coffee farms from plantations and smallholders, which needs to be the goal of future research to accurately examine the impacts on the outcome variables.

1. Introduction

Including shade trees in annual or perennial cropping systems has been promoted as a potential solution to bridge soil conservation efforts and improve crop yield in many tropical countries (Tscharntke et al., 2011; Montagnini et al., 2017). The positive effect of including shade trees with coffee include microclimate buffering against heatwaves and drought (Getachew et al., 2022; Merle et al., 2022), carbon sequestration (Jose and Bardhan, 2012; Dhyani, 2017; Solis et al., 2020), and improved biodiversity conservation and soil fertility (Tscharntke et al., 2011). Shade tree species can impact the soil nutrient status both directly (e.g. via litter inputs and nitrogen fixation), but also indirectly (e.g. via altered decomposition rates due to contrasting below-canopy temperatures) (Liu et al., 2021; Strukelj et al., 2021). The presence of shade tree species at the ecosystem level can improve resource use complementarity (Mahaut et al., 2020), minimize nutrient leaching (Cappelli et al., 2022), and improve nutrient recycling and nutrient availability for the crops (Kuyah et al., 2019; Muchane et al., 2020; Sileshi et al., 2020). These benefits would be predominantly important for coffee cultivation practiced with no/little external inputs, which tend

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to be nutrient-depleted systems because nutrients exported from the system may not be replaced through fertilization (Nzeiyimana et al., 2016). Besides, by harvesting coffee, nutrients are also exported from the system, and unless external inputs are added, several nutrients can become limiting (Kiup et al., 2017).

The effects of shade trees on soil physiochemical properties can be explained via different mechanisms. First of all, leaf litter and decomposing fine roots generate an important influx of nutrients into the soil, while carbon inputs from decomposing biomass such as fine roots, leaf litter, and other organic plant biomass can be sequestered in soil aggregates and contribute to carbon sequestration (Gama-Rodrigues et al., 2011). These effects on soil fertility can vary by shade tree species and this variation may be due to qualitative or quantitative differences in leaf litter (Sauvadet et al., 2020; Bai et al., 2022), particularly the C:N ratio, C:P ratio, concentrations of polyphenols, and presence of other nutrients that may be limiting (Bai et al., 2022). Second, N-fixing shade trees, due to symbiosis with root-nodulating bacteria, can significantly influence the soil nutrient status due to their N-fixing capability and effects on soil pH (Hedin et al., 2009; Franklin et al., 2019; Silesli et al., 2020). Moreover, increased microbial diversity and activity are favored by higher N content in litter, which, in turn, promotes N cycling (Braga et al., 2019; Lopez-Sampson et al., 2020). Therefore, integrating N-fixing shade trees in coffee agroecosystem is considered an important practice to maintain soil fertility. The provision of a sustainable N cycling in agroforestry systems is hence the result of these dynamics as it reduces N leaching (Karki et al., 2021). A linear decrease in N loss with increasing shade tree cover has already been detected for coffee cultivation systems (Tully et al., 2012). Similarly, shade tree species enhanced the organic matter concentrations due to litter inputs, thereby potentially favoring microbial diversity (Bagyaraj et al., 2015; Velmouroughane, 2017; Solis et al., 2020). Shade tree species may have varying effects on soil pH. N-fixing trees have been shown to reduce soil acidity as compared to non-N-fixing shade trees (Tully et al., 2013; Muchane et al., 2020). Yet, Etaha (2022) reported an increased soil pH under Acacia abyssinica L. and Albizia gummifera L. The density of soil bacteria is negatively affected by soil acidity (Tully et al., 2012; Neina, 2019). Meanwhile, both high and low soil pH negatively affect plant nutrient availability and uptake (Bidalia et al., 2019).

Because of changed soil nutrient status, litter inputs and soil acidity, also plant-available phosphorus (P) concentrations can be affected. P has been shown to be a limiting nutrient in many coffee agroecosystems (Notaro et al., 2014, 2022; Solis et al., 2020), and hence the contribution of litter from shade trees is suggested to have a considerable positive effect on P cycling to enhance the available P content in soils (Xavier et al., 2011; Notaro et al., 2014; Alexio et al., 2020). This is due to the higher degree of mycorrhizal symbiosis in the presence of shade trees and also because of the different canopy exchange processes that are strongly species-dependent (Ekqvist, 2015; Zhang et al., 2022). P-cycling in a coffee shade tree mixed system depends on the specific characteristics such as location and management system (Ekqvist, 2015; Sauvadet et al., 2020). Alexio et al. (2020) indicated that N-fixing shade trees can have a positive effect on plant-available P as compared to fields with non-N-fixing shade tree species.

Although the central goal of agroforestry is to create complementarity between shade trees and coffee plants, growing coffee in association with shade trees inevitably leads to some degree of competition for the aboveground (light) and belowground resources (water and nutrients) (Castro-Tanzi et al., 2012; Sauvadet et al., 2020; Sebuliba et al., 2022). Different shade tree species bring alterations in light, soil water content and nutrient competition with the coffee plants due to variations in canopy and root architecture. For instance, Schnabel et al. (2018), reported that shade trees used part of the available nutrients for growth and development, while Silesli et al. (2020) and Sebuliba et al. (2022) reported that shade trees competed with coffee for soil nutrients and soil moisture. However, the degree to which this occurs will be largely controlled through appropriate selection of the shade tree species and management if microclimatic protection and nutrient cycling are the main goals. Soil pH and the nutrient status can also impact coffee bean quality. Body, acidity and cup cleanliness are directly correlated with soil pH (Castro-Tanzi et al., 2012; Morales-Ramos et al., 2020). Excess N increases the caffeine content, resulting in a more bitter taste of the brew (Petit, 2007; Koehler, 2017). A recent study from southwest Ethiopia revealed that soil fertility variables affected coffee bean mass and cup quality in their natural habitat and showed that available P, K, and the ratio between Mg and K were the most important soil chemical variables influencing coffee bean size (Yadesa et al., 2020), cupping scores, and green bean biochemistry (Clemente et al., 2015; Getachew et al., 2022). Excessive NPK fertilizer use and increased aluminum toxicity were shown to cause a reduction in coffee cup quality due to a reduced soil pH (Castro-Tanzi et al., 2012; Reklk et al., 2019). Another study shows that coffee cup quality was significantly associated with available P and K (Yadesa et al., 2020).

Although several studies conducted in the tropics have quantified soil nutrient responses to shade tree species, quantitative data on individual nutrients, and linked with data on coffee quality, under different shade tree species remains limited. Thus, the impacts of shade tree species in a plantation agroforestry system on soil biogeochemistry and the subsequent effect on coffee bean quality were thoroughly investigated. To avoid the effects of pre-existing soil nutrient differences, a common garden approach was used, where coffee was grown below shade trees of different shade tree species within one large coffee plantation. Hence, this study aims to test the hypothesis that shade tree species impact soil biogeochemistry, which in turn could affect coffee bean quality.

2. Materials and methods

2.1. Study area and experimental design

The study was carried out at a commercial coffee plantation located on a flat plateau in the eastern wing of Horizon-2 coffee farm in the southwest region of Ethiopia (7.94–07.95 N latitude and 36.63–36.64 E longitudes), with the elevation ranging between 1545 – 1565 m asl, as shown in (Fig. 1). The region is part of the Eastern Afromontane Biodiversity Hotspot (Hundera et al., 2013) where the climate is conditioned by the Inter-Tropical Convergence Zone (Schmidt et al., 2014), with an average annual precipitation between 1500 and 2000 mm. Besides, the region is characterized by a unimodal rainfall, accounting for about 85% of the annual rainfall, with the main rainy season between May and September and the main dry season between December and March. Differences in temperature vary throughout the year, with a mean monthly temperature between 13 and 26 °C (Denu et al., 2016; Geeraert et al., 2019). The bulk of coffee growing soils in the region are classified as Eutric Nitisols, which are deep, red and well-drained soils with a clay content of more than 30% and a pH (measured in H2O) between 4.2 and 6.2 (Kufa, 2011; Kebede et al., 2018). In terms of farming systems, the southwestern region of the country is characterized by a mosaic of farmlands dominated mainly by Arabica coffee farming systems. The region is known as a primary center of origin and diversity of coffee, where the species grows naturally as understory tree in moist Afromontane forests (Davis et al., 2012; Hundera et al., 2013). Coffee in this region is mainly grown under shade trees, either within forest or forest-like environments, or in farming systems that deliberately incorporate specific shade trees. Common coffee shade tree species in this region include Albizia gummifera L., Acacia abyssinica L., Cordia africana L., Croton macrostachyus L., and Millettia ferruginea L. The intensively managed commercial coffee plantation is run by a private company in which regular field management activities including pruning, weeding (herbicide use) and fertilization are a regular practice.
2.2. Selection of individual shade tree species

In March 2020, four shade tree species were selected across the commercial plantation to study effects of these widely used shade tree species on soil biogeochemistry and coffee bean quality: two N-fixing shade tree species (Acacia abyssinica L. and Albizia gummifera L.), and two non-N-fixing shade tree species (Cordia africana L. and Croton macrostachyus L.).

Acacia abyssinica L. is N-fixing tree in the family Fabaceae. The tree is found in Africa from east to south. In Ethiopia it occurs in wooded grassland, highland forest edges of dry, moist and wet highlands of the agroclimatic zones. Its main uses among others are for firewood, charcoal, poles, fodder, bee forage, shade tree for coffee, soil conservation, and fence. Albizia gummifera L. (also Fabaceae) is commonly grown in lowland and upland rainforest, riverine forest, and in open habitats near forests. Its uses among others are shade tree for coffee (in Ethiopia), fuelwood, timber, and erosion control. Cordia africana L. occurs at medium to low elevations, in woodland, savannah, in warm and moist areas. It occurs in afro-montane rainforest along margins and in clearings. It provides good bee forage, as the flowers yield plenty of nectar.

Croton macrostachyus L. (Euphorbiaceae) is widespread in areas with high rainfall. It is commonly planted for shade and provides good bee forage, as the flowers yield plenty of nectar. It also used for firewood, shade for crops, mulch, and soil conservation (Teketay and Teginhe, 1991). Each shade tree species was replicated seven times, leading to a total selection of 28 study locations. The canopies of the selected shade trees were not overlapping with other tree canopies, and the selected shade trees were spaced at least 30 m from each other, and were also spatially intermixed to avoid spatial autocorrelation between trees belonging to the same species (Fig. 1). Below each of these shade trees, three coffee plants were selected that were completely covered by the canopy of the considered shade tree.

2.3. Characteristics of the commercial coffee plantation

The plantation commonly applies a compound NPK fertilizer (18–18–24) based on the productivity of the individual coffee trees/plots/year. The commercial fertilizers are mostly applied in spray forms and the application modality in the coffee farms is: NPK (75 g/tree/year) applied in two splits and urea (28 kg/ha) applied as a foliar spray once per year as a supplementary feed to reduce the potential of leaching losses. On a hectare basis, this would be 250 kg NPK/ha (considering 1.5 m between plants and 2 m between rows in a coffee plantation). Herbicides are commonly used to control weeds, and fungicides are also applied once per year on a plant basis based on the incidence of fungal disease.

2.4. Coffee plant-level measurements

Three randomly selected coffee plants that are completely positioned inside the canopy of the shade trees were marked for measurements. A total of 84 coffee plants were marked from the 28 shade trees (28 locations; Fig. 1) and all of the required samples (soil sampling, canopy cover measurements, and coffee cherry sampling) were taken from each of the coffee plants. The following subsections describe the data collected at coffee plant level.

2.4.1. Measuring shade tree canopy cover

Shade tree canopy cover over each coffee tree was quantified using a convex spherical crown densiometer (Forest densiometers, Model A, Bartlesville, Oklahoma, USA). The densiometer is made of a small wooden box with a convex mirror consisting of a grid of squares; shade tree canopy cover is then calculated as the proportion of 96 points that was intersected by vegetation times 1.04. The densiometer was held at breast height and the observer’s head was reflected from the edge of the mirror just outside the box. The curved mirror reflects the canopy above. Above the canopy of each sampled tree using a ladder all the time, two counts were recorded and their average was taken.

2.5. Measuring soil biogeochemistry

A cylindrical metal core sampler (IG-PAS core sampler, IG PAS, Italy) 5 cm in diameter and 15 cm long was used to sample the undisturbed soils in March 2020. The metal cylinder was driven to the desired depth (10 cm) to sample the surface mineral topsoil (0–10 cm) and samples were taken from three locations per coffee tree (10 cm away from the coffee stem in three cardinal directions). Then, the soil was carefully taken from the core sampler to preserve the known soil volume in situ. In doing so, surface litter and plant debris were carefully removed from the samples. These three field samples per coffee plant were pooled into one sample, immediately weighed and then oven-dried at 65°C for 48 hrs. Finally, the soil samples were sieved with a 2 mm mesh and stored for further soil nutrient analysis.

2.5.1. Laboratory analysis of the soil samples

The oven-dried soil samples were used for the measurements of soil
organic carbon, soil total N, soil pH (H₂O), Olsen-P, lactate-P, oxalate-P, total-P, lactate-K, lactate-Mg, lactate-Ca, lactate-Al, oxalate-Al, and oxalate-Fe. The pH (in H₂O) of the soil was measured using a calibrated glass electrode (model Ross sure-flow 8172 BNWP, Thermo Scientific Orion, USA). Dried soil samples without further preparations were combusted with elemental analyzer to analyze total C and N content. The samples were combusted at 1150 °C and the gases were measured by a thermal conductivity detector in a CNS elemental analyzer (vario Macro Cube, Elementar, Uberlingen, Germany). The CNS measures the content of C and N inorganic soil samples. Soil available phosphorus was analyzed using various extraction methods for a comparison of different methods. In so doing, three extraction methods were used: Olsen, lactate and oxalate and also total-P was also analyzed. In all cases P was analyzed colorimetrically with the malachite green procedure according to Lajtha et al. (1999)). For Olsen-P, sample extraction of 2.5 g dry soil with 50 mL 0.5 M sodium bicarbonate (NaHCO₃) was conducted at pH 8.5. For lactate-P, samples were extracted in a 1:5 soil: extractant ratio with ammonium lactate which consisted of lactic acid (88%), acetic acid (99%) and ammonium acetate (25%) at pH 3.74 according to the malachite green procedure (Lajtha et al. (1999)). For Oxalate-P, Oxalate-Al and Oxalate-Fe, Active P, which also includes P that can become available on the longer term and is adsorbed by Al and Fe. This P-fraction was extracted in ammonium oxalate-oxalic acid (according to NEN 5776:2006). P-contents were measured according to the malachite green procedure. Al and Fe contents were measured by atomic absorption spectrophotometry (AA240FS, Fast Sequential AAS) whereas total-P was measured after complete destruction of the soil samples with HClO₄ (65%), HNO₃ (70%) and H₂SO₄ (98%) in teflon bombs for 4 hrs at 150 °C. P-contents were measured colorimetrically according to the malachite green procedure (Lajtha et al. (1999)). Lactate Ca, Mg, K, and Al, was extracted in a 1:5 soil: extractant ratio with ammonium lactate which consisted of lactic acid (88%), acetic acid (99%) and ammonium acetate (25%) at pH 3.74. The cations (Ca, K, Mg, Al) were measured by atomic absorption spectrophotometry.

2.6. Coffee berry sampling and coffee quality assessment

All fully ripe, red-colored coffee berries were hand-picked once at peak harvest in November 2020 from each selected coffee tree using the local coffee bags (“Keshas”). The berries were dry-processed, i.e. sun-dried (on raised mash wire) immediately after harvest (harvesting was in the morning and subjected to drying started in the afternoon). The berries were returned to local coffee bags (“Keshas”) before sunset and stored in clean rooms (to prevent spoilage) and were exposed to the sun in the morning until green beans attained 11.5% moisture content measured using coffee moisture tester (mini GAC, Dickey - John, USA). The berries were regularly turned to maintain uniform drying and the dried coffee berries were separately labeled and packed for analysis. The dried coffee berries were dehusked using a hulling coffee machine (coffee huller, McKinnon, Scotland) at Jimma University, cleaned and stored at room temperature.

2.6.1. Bean physical quality attributes

Bean length (mm) and diameter (mm) were measured using a bean measuring caliper (Mitutoyo, IP 67, CD-20-PPX, Kawasaki, Japan) using 10 beans per sample. Additionally, the mass of the beans was recorded by taking 100 beans from each sample. Finally, the green bean samples were submitted to the Ethiopian Commodity Exchange (ECX) for raw and sensory quality analyses.

2.6.2. Raw quality

(40% of the total preliminary quality): A green coffee bean sample of 100 g was used for raw quality evaluation before roasting. Primary and secondary defects and odor, were assessed according to the procedures developed by the ECX (2011)). The rating was based on a scale from 0 to 15 for the defects and 0–10 for odor.

2.6.3. Cup quality

(60% of the total preliminary quality): Coffee bean samples were evaluated for cup quality attributes by a panel of three internationally trained, experienced and certified Q-grade cuppers in Jimma ECX center. Acidity, body, cup cleanness and flavor were assessed following a standard method (ECX (2011)). This Q-grade standard method involves Q-certified cuppers, i.e., cuppers licensed by the Specialty Coffee Association (SCA) Coffee Quality Institute (CQI). Roasting, grinding, and brew preparation: This was performed by the ECX laboratory in Jimma, Ethiopia. A roaster equipped with a cooling system, in which air was forced through a perforated plate, capable of roasting up to 500 g of coffee beans, was used for roasting the coffee beans. An amount of 100 g green beans was used for each sample and the beans were put into the roasting machine with six cylinders (Probat, 4 Barrel Roaster, Germany). They were carefully roasted for 7–8 min to medium roast at temperatures of 200 °C. Subsequently, the roasted bean samples were ground to a medium level using a Guatemala SB electrical grinder, which were cleaned well after each sample. The medium roasted coffee was tipped out into a cooling tray and allowed to cool down for 4 min rapidly by blowing cold air through it. Then, eight grams of coffee powder was put into a 250 mL cup and 5 cups per coffee sample were used. Next 125 mL boiled water (93 °C) was poured onto the ground coffee, followed by stirring the content to ensure homogeneity of the mixture. Then, the cups were filled with an additional 125 mL and left to settle. After three minutes, floating coffee was skimmed, and the brew was ready for cup tasting. Finally, the five prepared cups were cup tasted by three professional Q-grade cuppers operating in ECX. Each panelist gave their independent judgment using a cupping form and the average score of the three cuppers was used.

Finally, the total preliminary quality was calculated using raw and cup quality scores. Coffee samples of grades 1–3 (specialty 1, 2 and 3) were assessed for total speciality quality. Accordingly, aroma, flavor, acidity, body, uniformity, cup cleanness, overall preference, aftertaste, balance and sweetness were rated on a scale from 0 to 10. The sum of all these cup quality attributes gave a specialty quality ranging from 0 to 100 (https://sca.coffee/ research/protocols-best-practices). Hence, total preliminary quality is the sum of all raw bean quality scores (primary defects, secondary defects, and odor) and four cup quality attributes (acidity, body, flavor, and cup cleanness), whereas the speciality quality is the sum of ten cup quality attributes (aroma, flavor, aftertaste, acidity, body, balance, overall, cup cleanness, sweetness, and uniformity).

2.6.4. Statistical analyses

In order to establish the relationship between shade tree species and soil biogeochemistry, shade tree species and coffee quality attributes, and finally soil biogeochemical and coffee quality attributes, two statistical approaches were chosen to analyze the data.

First of all, a linear-mixed effect model was used to quantify the effects of shade tree species on soil biogeochemical variables and coffee bean quality attributes in a univariate model. The models were fitted using maximum-likelihood methods in the ‘lme4’ packages using the ‘lmer’ function (Harrison et al., 2018) and always included the location as random-intercept term to account for the spatial differences. The p-values of the fixed effect (shade tree species) was estimated based on the denominator degrees of freedom calculated with the Satterthwaite approximation, in the ‘lmerTest’ package in R (Bates et al., 2018). To test the differences among individual shade tree species identity on soil biogeochemical variables we performed a Tukey test for differences in shade tree species identity, multiple comparison of Kruskal-Wallis test was used. Multiple comparison analyses were performed using ‘multcompView’, ‘agricolae’ and ‘gghthemes’ packages in R. In order to show significant differences across shade tree species in soil biogeochemistry, standard error bars and letters were used at (p = 0.05). Model assumptions were checked after fitting the models. To test the explanatory power of several different predictor variables for the variation in response variables, the coefficient of determination (R²)
was quantified using the ‘r.squaredGLMM’ function in the package ‘MuMIn’ (Barton and Barton, 2015). Accordingly, both the marginal and conditional R² values were computed to quantify the proportion of variance explained by the fixed effects (shade tree species) alone as well as the fixed and random factors together, respectively (Nakagawa and Schielzeth, 2017).

To account for multicollinearity among soil biogeochemistry, a Principal Component Analysis (PCA) was conducted to be able to test the effects of soil biogeochemistry on coffee quality. Accordingly, the first two principal components were kept for subsequent regression analyses. The first two principal components (PC1 = 39.4%) and (PC2 = 25.3%), accounting for 64.7% of the variation, were kept (Fig. 3) and the scores obtained from the above considered principal components were utilized as independent variables in linear mixed-effect models (LMMs) to test their effects on coffee quality attributes using ‘factoextra’ package. In this hierarchical nested design, the 28 locations were considered as

![Fig. 2. Effect of four shade tree species on various soil biogeochemistry and canopy cover. Bars denote standard errors and the different letters denote significant differences among shade tree species.](image-url)
blocks (random term) whereas the individual coffee plants were considered as replicates.

In addition, a piecewise structural equation model (SEM) was fitted to better quantify the direct effect of shade tree species on coffee quality and the indirect effect via soil biogeochemistry on coffee quality. PiecewiseSEM is a statistical framework used to understand causalities within complex natural systems. All relations in the piecewise structural equation model were fitted using linear-mixed effect models in accordance with the nested design of the data with location (shade tree species) as random effect. PiecewiseSEM was built with six independent mixed-effect models: two PCA axes (PC1 and PC2) as dependent variables and shade tree species as explanatory variable, canopy cover as dependent variable and shade tree species as explanatory variable, and the remaining three coffee quality attributes (total preliminary quality, specialty quality and hundred bean mass) as dependent variables and shade tree species, canopy cover and the two PCA axes as independent variables. The means of the PC’s and coffee quality attributes were generated using function lme in the piecewiseSEM package. Path coefficients within the piecewiseSEM procedures were estimated with a restricted maximum likelihood approach, whereas the completeness of the models was assessed by means of Fisher’s C statistics (Lefcheck, 2016). The individual paths were estimated separately and then combined into a series of equations to estimate the direct and indirect effects within the system. The corresponding standardized regression coefficients were provided on each path. The direct influence is the path coefficient of the independent variable pointing directly to the dependent variable; the larger the path coefficient, the greater the influence. The piecewiseSEM analyses were performed using ‘nlme’ and ‘piecewiseSEM’ packages. All statistical analyses were performed in R software R-4.1.2 (R Core Team, 2022).

3. Results

3.1. Soil biogeochemistry in relation to shade tree species

Except for soil C, all the remaining soil chemical variables showed a significant shade tree-species effect (p < 0.05) (Supplementary table 1). Available and total phosphorus values were highest under *Albizia*, whereas the remaining shade tree species appear to have similar contents of available and total phosphorus (Fig. 2). Canopy cover as a response variable was included in supplementary table 1 and Fig. 2 to show whether shade tree species affect the canopy cover: canopy cover was unaffected by the shade tree species. Based on 13 soil chemical variables studied, shade tree species comparisons revealed that *Acacia abyssinica* and *Albizia gummifera* were most often significantly different from *Cordia africana* and *Croton macrostachys* do (Table 1 & Fig. 2). Available-P (Olsen, lactate and oxalate) and total-P were higher under *Albizia* than the other shade trees (Fig. 2). The four shade tree species mostly overlap also in the PCA analysis (Fig. 3), suggesting similarity between them in explaining soil chemical characteristics except soil available P, Ca and Mg. There were no significant effects of the shade tree species on the cupping quality. Only the 100-bean mass was significantly affected by the shade tree species (Fig. 4).

3.2. Association between coffee bean quality attributes and soil biogeochemistry

The PCA condensed soil chemical variables into axes representing the major gradients in soil biogeochemistry, in which the length of the vectors indicates the variance explained by each soil chemical variables (Fig. 3). Values of phosphorus obtained by different extraction methods (Olsen-P, lactate-P, oxalate-P and total-P) are strongly and positively correlated to each other. The 1st axis, explaining 39.4% of the variance, runs from P-rich plots (negative loading) to plots with a high N availability (low C/N), base cation concentration and pH (positive loading) (Fig. 3). Meanwhile, the soil chemical variables clustered to the right (lactate-Ca, lactate-Mg and pH) have large positive loadings on the first component, i.e., the relationship among these variables is strong and positive. The 2nd axis, explaining 25.3% of the variance, separated relatively N-rich/high OC content (positive loading) from Al-rich (negative loading) plots. This axis seems to be mostly driven by Al, which in turn is negatively correlated to pH (Fig. 3).

C (%) C/N (dimensionless); pH (dimensionless); all the remaining soil chemical variables (in ppm); SE = standard error.

A significant effect of the first principal component (PC1), mainly basic cations (lactate Ca, lactate Mg, and lactate K) and soil pH, was observed on total preliminary quality (p = 0.032, R^2=0.054, R^2=0.42) (Fig. 6). However, the effect size and beta-value are very small. Likewise, specialty quality was found to be significantly affected (p = 0.046, R^2=0.017, R^2=0.015) by PC1, whereas hundred bean mass was found to be significantly affected (p = 0.043, R^2=0.048, R^2=0.11) by PC1 (Fig. 6). There was also a significant effect of the second principal component (PC2), mainly available and total P, on total preliminary quality (p = 0.012, R^2=0.044, R^2=0.34), specialty quality (p = 0.033, R^2=0.086, R^2=0.23) and hundred bean mass (p = 0.023, R^2=0.18, R^2=0.29) by PC2 (Fig. 6).

3.3. The direct and indirect effects of shade tree species on coffee bean quality through soil biogeochemistry and canopy cover using piecewiseSEM

The piecewise SEM revealed that coffee bean quality attributes were not affected by shade tree species directly. Overall, several positive relationships between shade tree species and soil biogeochemistry were found, while the relationships between shade tree species and canopy cover were all non-significant (Fig. 5). The path analysis revealed only indirect effect of shade tree species on coffee bean quality through their influence on soil biogeochemistry and canopy cover, but these effects generally only explained a small part of the variability in coffee quality.

Table 1

Descriptive statistics of the studied shade tree species on soil biogeochemical variables.

<table>
<thead>
<tr>
<th>Shade tree species</th>
<th>Soil biogeochemical variables</th>
<th>C</th>
<th>C/N (H2O)</th>
<th>pH</th>
<th>Lactate K</th>
<th>Lactate Mg</th>
<th>Lactate Ca</th>
<th>Lactate Al</th>
<th>Oxalate Al</th>
<th>Oxalate Fe</th>
<th>Oxalate P</th>
<th>Olsen P</th>
<th>Oxalate P</th>
<th>Lactate P</th>
<th>Total P</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acacia abyssinica</em> L.</td>
<td>Mean</td>
<td>5.8</td>
<td>12.3</td>
<td>4.7</td>
<td>596.0</td>
<td>176.8</td>
<td>1233.7</td>
<td>758.3</td>
<td>2883.0</td>
<td>5854.0</td>
<td>126.9</td>
<td>713.3</td>
<td>121.6</td>
<td>1724.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>38.7</td>
<td>15.2</td>
<td>122.0</td>
<td>32.6</td>
<td>82.6</td>
<td>127.9</td>
<td>17.9</td>
<td>80.5</td>
<td>18.1</td>
<td>107.2</td>
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<tr>
<td><em>Albizia gummifera</em> L.</td>
<td>Mean</td>
<td>6.1</td>
<td>12.5</td>
<td>4.8</td>
<td>678.6</td>
<td>167.8</td>
<td>1632.1</td>
<td>652.4</td>
<td>2693.8</td>
<td>6600.0</td>
<td>209.7</td>
<td>1147.4</td>
<td>223.3</td>
<td>2304.5</td>
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</tr>
<tr>
<td></td>
<td>SE</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>44.2</td>
<td>14.2</td>
<td>223.1</td>
<td>17.4</td>
<td>50.3</td>
<td>175.8</td>
<td>25.8</td>
<td>118.9</td>
<td>28.8</td>
<td>154.3</td>
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<tr>
<td><em>Cordia africana</em> L.</td>
<td>Mean</td>
<td>5.5</td>
<td>12.8</td>
<td>5.6</td>
<td>952.1</td>
<td>343.9</td>
<td>2797.6</td>
<td>496.5</td>
<td>2385.6</td>
<td>5859.7</td>
<td>113.5</td>
<td>804.6</td>
<td>147.7</td>
<td>1682.3</td>
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</tr>
<tr>
<td></td>
<td>SE</td>
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<td>0.2</td>
<td>0.1</td>
<td>49.7</td>
<td>28.9</td>
<td>231.3</td>
<td>36.3</td>
<td>83.5</td>
<td>242.5</td>
<td>12.1</td>
<td>78.0</td>
<td>14.9</td>
<td>121.9</td>
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</tr>
<tr>
<td><em>Croton macrostachys</em> L.</td>
<td>Mean</td>
<td>5.1</td>
<td>12.3</td>
<td>5.7</td>
<td>931.4</td>
<td>361.2</td>
<td>2601.0</td>
<td>471.6</td>
<td>2823.8</td>
<td>5368.8</td>
<td>84.1</td>
<td>649.2</td>
<td>126.1</td>
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<td>26.0</td>
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scores. The variability in each of the coffee bean quality attributes was mainly explained by the spatial random effect, with conditional $R^2$ values for total preliminary quality, specialty quality, and hundred bean mass being 17%, 8%, and 32%, respectively. Only the presence of *Albizia gummifera* L. and *Cordia africana* L., had a positive effect on hundred bean mass. The direct effects of shade tree species on soil biogeochemistry and canopy cover were species-specific, as can be seen from Fig. 5. Shade tree species had significant positive, negative and no relationships with PC1, PC2 and canopy cover.

4. Discussion

This experiment was explicitly designed to investigate the impacts of shade tree species identity on soil biogeochemistry and coffee bean quality. It has been hypothesized that shade tree species can impact soil biogeochemistry, which in turn could have a positive effect on coffee bean quality. The data showed that these assumptions were only sometimes met.

4.1. Shade tree species have a significant impact on individual soil biogeochemical variables

The present study demonstrates that the individual shade tree species have a substantial effect on almost all selected soil chemical variables. Particularly, lactate- Ca and pH values are higher under *Cordia africana* L., implying that plots under these trees appeared to be less acidic as
The C:N ratio under *Acacia* and *Albizia* tree species implies high N-availability, and the more rapidly nitrogen will be released into the soil for immediate crop use. Meanwhile, carbon to nitrogen ratios (C:N) were also highest under *Cordia africana* L. This ratio is an important indicator of the rate of decomposition, particularly residue-cover on the soil and crop nutrient cycling (predominantly N) (Adetunji et al., 2020; Ashworth et al., 2020). The C:N ratio in this particular study had a negative relationship with Aluminum, implying that Aluminum-rich plots can have less soil biological activities and lower decomposition rates (Aitkenhead-Peterson et al., 2012; Rowe et al., 2015). The present findings are a bit inconsistent with the findings of Etafa (2022), who reported that soil organic matter, total N, available P, exchangeable K, and soil pH were generally higher under the specific shade tree species considered (*Acacia abyssinica* L., *Albizia gummifera* L., *Croton macrostachys* L., *Cordia africana* L., *Millettia ferruginea* L., and *Erythrina abyssinica* L.).

The findings in the current study indicated that the N-fixing leguminous tree ‘*Albizia*’ enhanced soil available P compared to the non-N-fixing shade tree species. This effect was also observed in *Acacia*, but to a lesser extent. The findings of Turner et al. (2018) and Aleixo et al. (2020), reported that soil P availability was improved by N-fixing leguminous trees. This positive association between soil P availability and N-fixing leguminous trees could be due to the conditions favoring the production of extracellular phosphatase enzymes by N-rich plant and microorganism species in the rhizosphere and bulk soils. As a result of such environmental conditions, P mineralization could increase, and, thus P-availability in the soils would increase. In general, the tight coupling between N and P in agroforestry systems with N-fixing leguminous trees is very strong (Aleixo et al., 2020; Sauvadet et al., 2020). However, this depends on different environmental conditions (mainly climate and soil), cropping system and management practices (Aleixo et al., 2020).

The N-fixing shade tree species (*Albizia gummifera* and *Acacia abyssinica*) can sustain or improve chemical properties in coffee production system given that soil acidity in these two N-fixing tree species is high. One potential explanation for this paradox is that the ability to symbiotically fix N allows greater root phosphatase enzyme activity to enhance P acquisition from organic sources, since enzymes are N-rich compared to the plots under N-fixing shade tree species. Although shade tree-coffee association has been shown to reduce soil acidity, different shade tree species could have differing impacts on changes in soil pH (Rigal, 2018; Muchane et al., 2020). In this particular study, soils under leguminous shade trees (*Acacia* and *Albizia*) were found to be more acidic. Likewise, other studies have found that leguminous shade trees give rise to a lower soil pH when compared to non-N-fixing tree species (Pinho et al., 2012; Tully et al., 2012). In contrast, a reduced soil acidification has also been reported under N-fixing shade trees (Wang et al., 2015; Sileshi et al., 2020). This might be due to the fact that tropical leguminous shade trees could take-up less cations and this might have a paradoxical relationship is commonly observed between shade tree species and soil acidification. For instance, a sub-tropical legume tree (*Senya siamea* L.) has been shown to recycle calcium from deeper soils and significantly reduce acidity of the top soil (Meylan et al., 2017). Hence, the soil acidity alleviating effect of shade tree species depends on the litter chemical composition, together with N-fixing ability (Sauvadet et al., 2020).
organic molecules (Batterman et al., 2018). Phosphatase enzymes catalyze the hydrolysis of organic P esters, releasing more orthophosphates (inorganic P) for uptake by plant roots (Png et al., 2017; Turner et al., 2018). This phenomenon is more important in many ecosystems with strongly weathered, P-deficient soils such as lowland tropical rainforest trees, where organic P can make up a significant portion of the total P in these soils, and plant productivity is more likely to be restricted by P than N. The buffering capacity of the soils where the study was conducted could be another possible explanation. Nitisols, as strongly weathered and well-drained tropical soils, have a greater tendency to buffer acidity than sandy soils. On the other hand, some shade tree species have the tendency of re-cycling nutrients from the deep horizons and build-up of OM through time can enhance exchangeable cations and hence increase soil nutrient compositions. For instance, a sub-tropical legume tree (*Senna siamea* L.) has been shown to recycle calcium from deeper soils and significantly reduce acidity of the top soil. Hence, the soil acidity alleviating effect of shade tree species depends on the nutrient re-cycling tendency, litter chemical composition, together with N-fixing ability. Meanwhile, the lower C:N ratio implies high N-availability (organic matter), and the more rapidly nitrogen will be released into the soil. In sum, nitrogen fixing tree species can improve the soil chemistry by supplying nitrogen-rich organic matter.

Although soils differ widely in their P content, generally the range of total-P in many soils is in the range of 200–800 mg/kg (Cross and Schlesinger, 1995; Qihua et al., 2020). However, the quantities of soil total-P in the present study was considerably higher than expected (600–2500 mg/kg soils) under N-fixing shade trees, *Acacia* and *Albizia*. This could be associated with the application of large quantities of chemical inputs to the soils of the plantation coffee in the study plots. Most importantly, too much application of phosphatic and potassium fertilizers (75 g NPK/tree/year), which is equivalent to 250 kg NPK/ha, in the study plots most likely is the consequence for the high values of total-P. In addition to this, the high total-P values obtained in this particular study could be partly explained by the high values of percent soil organic carbon. Soil organic carbon content has an important role in relation to the content of P in soils: a strong positive correlation exists between P content and organic carbon of the soils under study (Zhang et al., 2020).

Given that the benefits of shade tree species on soil characteristics are localized and that there is a nutrient imbalance in many small-scale farming systems (Wortmann and Kaizzi, 1998; Nkonya et al., 2005), shade tree species alone are unlikely to be able to sustain sufficient levels of soil nutrients for coffee production and bean quality improvements. Although the present study demonstrates that the individual shade tree species have a substantial effect on individual soil chemical variables, the effects shade trees have on the overall nutrient dynamics is limited and the findings suggest that shade trees might ultimately have limited benefits for soil fertility at the level of the coffee farming system. Hence, it is unlikely that growing coffee in an agroforestry system will entirely avoid the use of mineral fertilizers.

When correlating the different P-extraction methods with each other, the overall picture indicates that the three extraction methods are strongly correlated. How these variables occur concurrently influences the solubility of phosphates and hence the extractability and efficiency.

Fig. 6. Relationship between coffee quality attributes and soil chemical characteristics (quantified via PC1 and PC2 from the soil chemical PCA depicted in Fig. 3). Data points represent a particular response variable at a single coffee tree (n = 84) in which the fitted regression lines and 95% confidence intervals are from linear mixed-effect models at p < 0.05. R²m= marginal R² (is the proportion of variance explained by the PCA score values; R²c= conditional R² (is the proportion of variance explained by the PCA score values and the random variable).
of different extraction methods are required to estimate plant-available soil P (Fath et al., 2019; Penn and Camberato, 2019). The availability of P in soils is influenced by soil pH and the presence of Fe and Al (Penn and Camberato, 2019). This was shown by the present findings: Al and P concentration (Olsen-P, lactate-P, oxalate-P, and total-P) were found to be negatively associated with each other.

4.2. Soil biogeochemistry affect coffee bean quality in a plantation coffee

The present findings are consistent with that of the previous work of the authors in the same region in the sense that most soil chemical variables were found to have a significant positive association with hundred bean mass (Getachew et al., 2022). Similarly, total preliminary and specialty quality had a significant positive relationship with soil chemical variables (Getachew et al., 2022). Besides, recent studies from southwest Ethiopia revealed that soil fertility variables affected cup quality of wild arabica coffee in its natural habitat and that available P, K and the ratio between Mg and K were the most important soil chemical variables that influenced bean size, cupping scores, and green bean biochemistry (Clemente et al., 2015; Yadessa et al., 2020). They primarily reported that coffee with improved cup quality was collected from coffee farms with greater available P, K, Mg, and Zn levels. These compounds are considered important for the brew quality and also N and K played a significant role in the final bean quality (Clemente et al., 2015). Castro-Tanzi et al. (2012) have pointed out that, excessive NPK fertilizer use and increased aluminum toxicity were linked to a lower coffee cup quality. Another study shows that coffee cup quality was significantly and Positively associated with available P and K (Yadessa et al., 2020). Meanwhile, the findings clearly indicate that the conditional R² values are far higher than the marginal R² values, implying that the spatial random variability is more important than the variability due to the fixed effects (Supplementary table 1).

4.3. Shade tree species have limited benefits for coffee bean quality improvement

The data suggest that shade tree species have a limited effect on coffee bean quality attributes. Except hundred bean mass, no associations were found between coffee bean quality attributes and shade tree species identity. This contrasts with previously reported findings from the same region but from different coffee agroecosystems that found significant effect of shade tree species on coffee bean quality attributes (Yadessa et al., 2020). If improvements in soil characteristics by the shade tree species were to improve coffee bean quality attributes, the expectation would be to find greater coffee bean quality in locations with better soil characteristics. However, this could not be confirmed from the present data whether the observed effect of soil biogeochemistry on bean quality attributes are associated with the shade tree species or not. This indicates that, shade tree species are unlikely to be the factor most limiting coffee bean quality attributes in the study area. However, a limited effect of shade tree species identity was observed on hundred bean mass, which could be due to the increasing competition for light as a shade canopy cover increases (Lin, 2010; Getachew et al., 2022). Lack of significant effects of the shade tree species on coffee cup quality is not unexpected because of two basic reasons: 1) the sensitivity of coffee bean quality to other biophysical variables, mainly climate; and 2) as the study was a one-season experiment, a longer-term study consisting of both spatial and temporal experiments might bring about a change in bean quality in response to the shade tree species. Meanwhile, if shade trees are to be included in coffee agroforestry systems, the tree shade cover need to be taken into consideration, while maintaining other benefits of shade trees like microclimate buffering. The present findings mainly suggest that selecting shade tree species based on their positive effects on soil fertility can be considered a good practice towards achieving sustainable coffee production systems, while shade tree species effects on coffee quality can be largely neglected. Yet, also the interaction between the elevation where the coffee tree is grown and the shade tree canopy cover need to be considered as an important environmental driver (Getachew et al., 2022).

4.4. Quantifying the direct and indirect effects of shade tree species on coffee bean quality via soil biogeochemistry and canopy cover

The piecewiseSEM demonstrated the presence of only indirect effects of shade tree species on coffee bean quality through soil biogeochemistry and canopy cover. According to the path analysis, shade tree species had no direct effect on total preliminary quality, specialty quality, and hundred bean mass, with the exception of the presence of Albizia gummifera L. and Cordia africana L., which both of them had a direct positive effect on hundred bean mass.

The present study also highlights the need to address both direct and indirect effects of the shade tree species to improve the understanding of the influence of shade trees on coffee quality. The direct effects of the shade tree species on coffee bean quality showed that the effects are limited to bean mass and direct effects are negligible for total preliminary and specialty quality. The effects of shade tree species on soil biogeochemistry were not directly linked to coffee bean quality, suggests that shade tree species are unlikely to be the factor limiting coffee bean quality in the study area within the study periods.

4.5. Implications for the coffee producers in the study area

Farmers’ incentives for planting shade trees go beyond improving the cup quality of coffee. Besides, the effect of shade tree species on productivity (as observed here for hundred bean mass), a coffee producer’s decision to plant a specific shade trees will depend on a number of factors, such as certification opportunities (e.g. Rainforest Alliance, etc.), temperature buffering, management considerations related to agronomic inputs, and the need for alternative products from the trees. Hence, there is a need to weigh the effects of shade tree species from multiple perspectives. The findings show that shade tree species had a significant effect on soil biogeochemistry but only a limited effect on coffee bean quality attributes (except for hundred bean mass). Although the data did not allow for the identification of the mechanisms that caused the observed effects of soil biogeochemistry on coffee bean quality attributes, a positive and significant effect of soil nutrient status on total preliminary, specialty quality, and bean mass was found. Meanwhile, the findings show that shade trees can be planted with the goal of improving soil chemical characteristics and that tree species recommendations for coffee agroecosystems need to be associated with climate buffering, carbon sequestration, and pathogen loads while taking into account a wide range of cropping systems and climatic zones. In this particular study, an attempt was made to quantify the impacts of widely used shade tree species on soil biogeochemistry and the subsequent effect on coffee bean quality in a plantation agroforestry system over the course of one season in southwest Ethiopia. However, it might be feasible to accommodate both relatively sparse time-series experimental data consisting of coffee farms from plantations and small-holders, which needs to be the goal of future research to accurately examine the impacts on the outcome variables.

Consent to participate
Not applicable.

Consent for publication
Not applicable.

Ethics approval
Not applicable.
Declaration of Competing 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.

Data Availability

Data will be made available on request.

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