Shade tree species effects on soil biogeochemistry and coffee bean quality in plantation coffee agroforestry

Merkebu Getachew[ab] (merkeb2020@gmail.com), Kris Verheyen[a], Kassaye Tolassa[c], Ayco J.M. Tack[d], Kristoffer Hylander[d], Biruk Ayalew[d], Pascal Boeckx[e], Pieter De Frenne[a]

aForest & Nature Lab, Department of Environment, Faculty of Bioscience Engineering, Ghent University, Belgium
bDepartment of Horticulture and Plant Sciences, College of Agriculture and Veterinary Medicine, Jimma University, Ethiopia
cEthiopian Institute of Agricultural Research, Addis Ababa, Ethiopia
dDepartment of Ecology, Environment and Plant Sciences, Stockholm University, Stockholm, Sweden
eIsotope Bioscience Laboratory, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Belgium

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. We quantified to what extent four widely used shade trees species (*Acacia abyssinica, Albizia gummifera, Cordia Africana* and *Croton macrostachyus*) in a plantation coffee agroforestry system in Ethiopia impact soil biogeochemistry, and how this in turn affects coffee quality, measured as cupping scores. We found especially significant negative impacts of N-fixing shade tree species on soil pH and base cation concentrations. Plant-available and total phosphorus was enhanced by the presence of *Albizia gummifera*. Thus, the present findings demonstrate that careful selection and integration of shade tree species such as *Acacia abyssinica* and *Albizia gummifera* into coffee production systems is a good practice for sustaining soil chemical properties in coffee agroecosystem. In spite of the impacts on soil characteristics, the shade tree species did not impact cupping scores of the resulting coffee beverage except some effect on the bean mass. Hence, further research should focus more on coffee-shade tree associations such that our understanding of the biogeochemical impacts can be improved, especially given the microclimatic importance of shade tree species in buffering the negative impacts from heatwaves and droughts due to climate change.

Keywords: Coffee quality, soil biogeochemistry, shade tree species identity, Ethiopia

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 (Montagnini *et al*. 2017; Tscharntke *et al*. 2011). 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 (Soils *et al*. 2020; Dhyani, 2017; Jose and Bardhan, 2012), and improved biodiversity conservation and soil fertility (Tscharntke *et al*. 2011).

Shade trees 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 (Muchane *et al*. 2020; Sileshi *et al*. 2020; Kuyah *et al*. 2019). These benefits would be predominantly important for coffee cultivation practiced with no/little external inputs, which tend to be nutrient-depleted systems because nutrients exported from the system may not be replaced through fertilization (Nzeyimana *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).

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 (Sileshi *et al*. 2020; Franklin *et al*. 2019; Hedin *et al*. 2009). Higher N content in litter favors microbial activity and diversity, which in turn increase N cycling (Braga *et al*. 2019; Lopez-Sampson *et al*. 2020). 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 was shown in coffee cultivation (Tully *et al*. 2012). Similarly, shade tree species enhanced the organic matter concentrations due to litter inputs, thereby potentially favoring microbial diversity (Soils *et al*. 2020; Velmourougane, 2017; Bagyaray *et al*. 2015). 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 (Muchane *et al*. 2020; Tully *et al*.

2013). Yet, Etafa (2022) reported an increased soil pH under *Acacia abyssinica* and *Albizia gummifera*. The density of soil bacteria is negatively affected by soil acidity (Neina, 2019; Tully *et al*. 2012). 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*. 2022; Soils *et al*. 2020; Notaro *et al*. 2014), 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 (Aleixo *et al*. 2020; Notaro *et al*. 2014; Xavier *et al*. 2011). 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 (Zhang *et al*. 2022; Ekqvist, 2015). P-cycling in a coffee shade tree mixed system depends on the specific characteristics such as location and management system (Sauvadet *et al*. 2020, Ekqvist, 2015). Aleixo *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. Soil pH is also related to plant available-P in the sense that at relatively higher pH, plant available-P increases (non-linearly) (Buczko *et al*. 2018). On the other hand, in high alkaline soils, phosphorus reacts with calcium and also becomes inaccessible.

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) (Sebuliba *et al*. 2022; Schwendenmann *et al* 2010; Lin *et al*. 2008). 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, Campanha (2004), reported that shade trees used part of the available nutrients for growth and development, while Sebuliba *et al*. (2022) and Siles *et al*. (2010) 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 cleanness are directly correlated with soil pH (Morales-Ramos *et al*. 2020; Castro-Tanzi *et al*.

2012). Excess N increases the caffeine content, resulting in a more bitter taste of the brew (Koehler, 2017; Petit, 2007). A recent study from southwest Ethiopia revealed that soil fertility variables affected coffee bean physical and cup quality in its natural habitat and shows that available P, K and the ratio between Mg and K were the most important soil chemical variables influencing coffee bean size (Yadessa *et al*. 2020), and cupping scores and green bean biochemistry (Getachew *et al*. 2022; Clemente *et al*. 2015). Excessive NPK fertilizer use and increased aluminum toxicity were shown to cause a reduction in coffee cup quality due to a reduced soil pH (Rekik *et al*. 2019; Castro-Tanzi *et al*. 2012). Another study shows that coffee cup quality was significantly associated with available P and K (Yadessa *et al*. 2020). To date, research linking soil biogeochemistry and coffee bean quality is, however, very scarce.

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. Hence, the objective of this study was to test the hypothesis, derived from the above studies, that shade tree species impact soil biogeochemistry and in turn could affect coffee bean quality. We here thus test whether and how shade tree species in plantation agroforestry systems impact soil biogeochemistry, and how this could be related to changes in coffee bean quality. To avoid effects of pre-existing soil nutrient differences, we used a common garden approach in which coffee was grown below shade trees of different species within one large coffee plantation.

3. Materials and Methods

3.1. 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. The locations where the coffee plants were sampled lie at a geographical coordinate ranging between 7.94 - 07.95 N latitude and 36.63 - 36.64 E longitudes (Fig. 1), with the elevation ranging between 1545 - 1570 m asl. 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 a yearly rainfall 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 with 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 (Geeraert *et al*. 2019; Denu *et al*. 2016). 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 H_2O) between 4.2 and 6.2 (Kebede *et al*. 2018; Kufa, 2011). 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 (Hundera *et al*. 2013; Davis *et al*. 2012). 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, Acacia abyssinica, Cordia africana, Croton macrostachyus,* and *Millettia ferruginea.* 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.

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* and *Albizia gummifera*), and two non-N-fixing shade tree species (*Cordia africana* and *Croton macrostachyus*).

Acacia abyssinica 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* (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* 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. Beehives are often placed in this tree and also is planted as a shade tree in coffee plantations. It is usually left in the fields, as it provides excellent shade for crops and a good source of firewood and Timber.

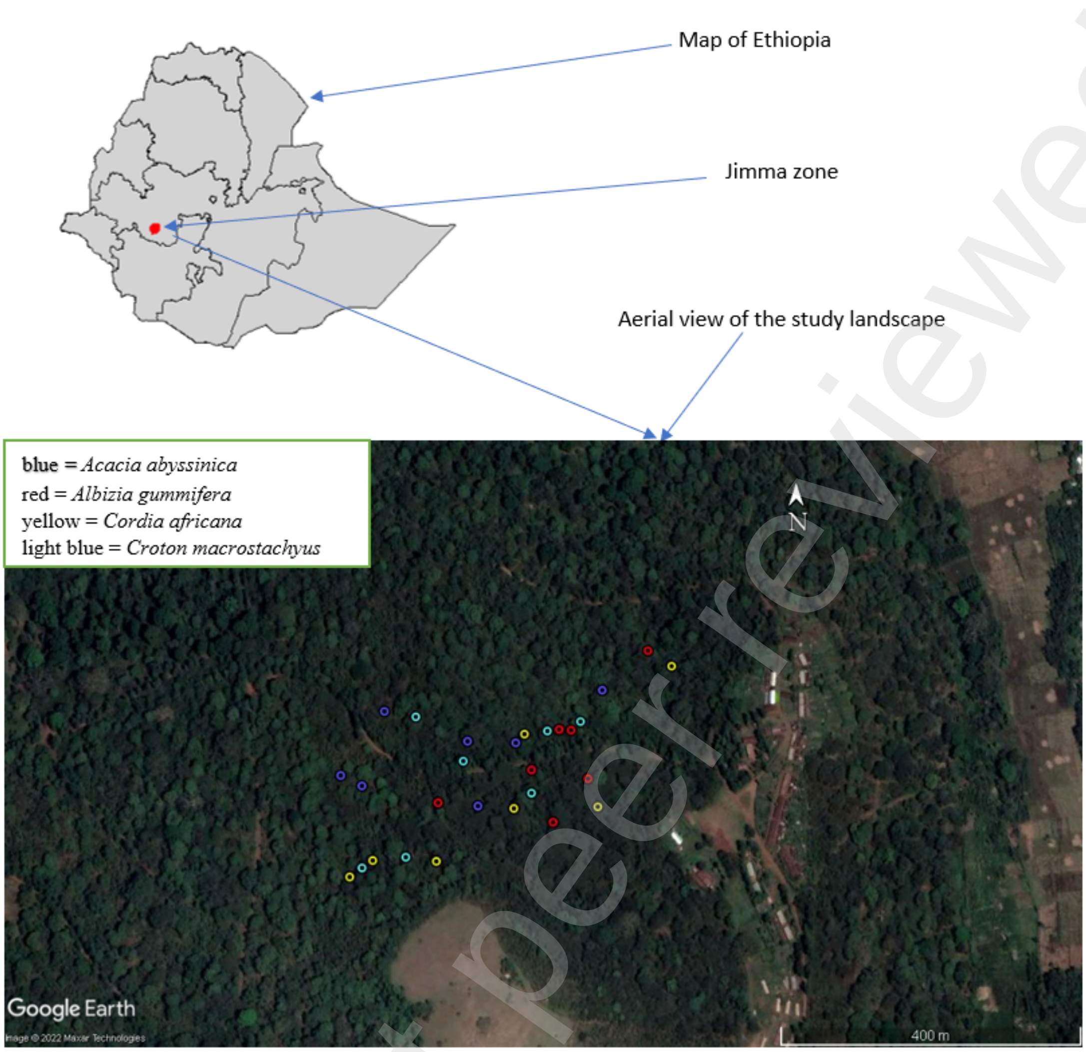


Fig 1. Study area showing an aerial view of the study landscape representing the distribution of shade tree species (28 locations).

Croton macrostachyus (*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 nectars. It also used for firewood, shade for crops, mulch, and soil conservation (Teketay and Tegineh, 1991). Each shade tree species was replicated seven times and a total of 28 shade tree species identity (from 28 locations) were considered. The canopies of 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). From each of these shade trees, three coffee plants that are completely positioned under the canopy of the shade trees were considered (Ayalew *et al*. 2022).

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 also to reduce the potential of leaching losses. On a hectare basis, this would be 250 kg NPK/ha (considering 1.5m between plants and 2m 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.

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 sub-sections describe the data collected at a coffee plant level.

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.

Measuring soil biogeochemistry

A cylindrical metal core sampler 5 cm in diameter and 15 cm long was used to sample the undisturbed soils in March 2020. The core was driven to the desired depth (10 cm) 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. The soil samples were taken during the measurement of the canopy cover. These three field samples per shrub 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.

Laboratory analysis of soil samples: The oven-dried soil samples were used for the measurements of soil organic carbon, soil total N, soil pH (H_2O), Olsen-P, lactate-P, oxalate-P, total-P, lactate-K, lactate-Mg, lactate-Ca, lactate-Al, oxalate-Al, and oxalate-Fe. The pH (in H_2O) 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 ($NaHCO_3$) 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 $HClO_4$ (65%), HNO_3 (70%) and H_2SO_4 (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.

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 ("Kesha"). The berries were dry-processed, i.e. sun-dried (on raised mesh 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 "Kesha") 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.

Bean physical 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.

Raw quality (40% of the total preliminary quality): A green coffee bean sample of 100 g was used for physical 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 to 10 for odor.

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 minutes 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 minutes 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 specialty 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).

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 shade tree species effects on soil biogeochemistry and coffee bean quality attributes. 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. 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 (Bates *et al*. 2018). Moreover, 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 (R^2) was quantified using the 'r.squaredGLMM' function in the package 'MuMIn' (Barton and Barton, 2015). Accordingly, both marginal and conditional R^2 values were determined to describe the proportion of variance explained by the fixed effects alone as well as the fixed and random factors together, respectively (Nakagawa and Schielzeth, 2017).

Secondly, first Principal Component Analyses (PCA) was performed on the soil chemical variables and then the first axes of the PCA then used to reveal relationships between soil biogeochemistry and coffee quality attributes. To select prominent variables for subsequent regression analyses, the first two principal components, accounting for 64.7% of the variation, from soil biogeochemistry were taken (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 the backward variable selection procedures using the function 'prcomp' in 'factoextra' package. In this hierarchal nested design, the 28 locations are considered as blocks (random variable) whereas the individual coffee plants are considered as replicates.

3. Results

3.1. Linking soil biogeochemistry 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 *Albizia gummifera* and *Cordia africana* were most often significantly different from *Acacia abyssinica* and *Croton macrostachyus* do (Table 1 & Fig. 2). Available-P (Olsen, lactate and oxalate) and total-P were higher under *Albizia* plots 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 weight was significantly affected by the shade tree species (Fig. 4).

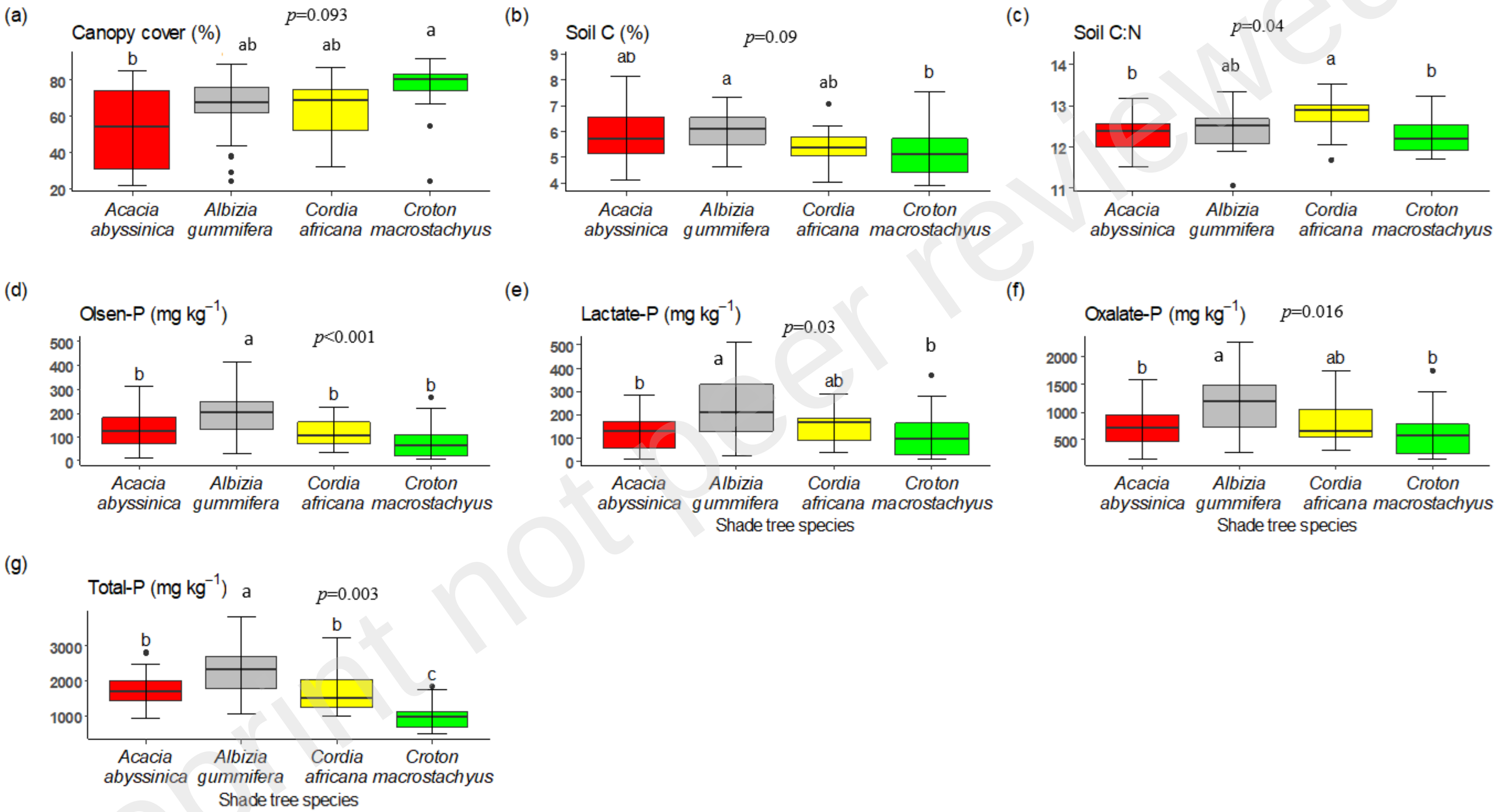
Table 1. Descriptive statistics of the studied shade tree species on soil biogeochemical variables

Shade tree species	Soil biogeochemical variables												
	%C	%C:N	pH (H_2O)	Lactate K	Lactate Mg	Lactate Ca	Lactate Al	Oxalate Al	Oxalate Fe	Olsen P	Oxalate P	Lactate P	Total P
Acacia abyssinica													
Mean	5.8	12.3	4.7	596.0	176.8	1233.7	758.3	2883.0	5854.0	126.9	713.3	121.6	1724.8
SE	0.2	0.1	0.1	38.7	15.2	122.0	32.6	82.6	127.9	17.9	80.5	18.1	107.2
Albizia gummifera													
Mean	6.1	12.5	4.8	678.6	167.8	1632.1	652.4	2693.8	6600.0	209.7	1147.4	223.3	2304.5
SE	0.2	0.1	0.1	44.2	14.2	223.1	17.4	50.3	175.8	25.8	118.9	28.8	154.3
Cordia africana													
Mean	5.5	12.8	5.6	952.1	343.9	2797.6	496.5	2385.6	5859.7	113.5	804.6	147.7	1682.3
SE	0.2	0.2	0.1	49.7	28.9	231.3	36.3	83.5	242.5	12.1	78.0	14.9	121.9
Croton macrostachyus													
Mean	5.1	12.3	5.7	931.4	361.2	2601.0	617.6	2823.8	5368.8	84.1	649.2	126.1	997.0
SE	0.2	0.2	0.1	44.1	26.0	262.8	39.3	89.6	166.9	15.9	97.4	26.6	88.1

SE = standard error

3.2. Linking coffee bean quality attributes to soil biogeochemistry

A PCA condensed soil chemical variables into axes representing a gradient of soil biogeochemistry, in which the length of the vector indicates the variance explained by the 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 high nutrient content of the plots (i.e. high lactate-Ca and Mg, and pH) to high P-rich plots (negative axis) (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 axis values) from Al-rich (negative axis values) plots. This axis seems to be mostly driven by Al, which in turn is negatively correlated to pH (Fig. 3). Moreover, the 1st and 2nd principal components were significantly related to all coffee quality attributes (Fig. 5).



(a)
Canopy cover (%)
p=0.093
b
ab
ab
a
20
40
60
80
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
(b)
Soil C (%)
p=0.09
ab
a
ab
b
4
5
6
7
8
9
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
(c)
Soil C:N
p=0.04
b
ab
a
b
11
12
13
14
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
(d)
Olsen-P (mg kg^{-1})
p<0.001
b
a
b
b
0
100
200
300
400
500
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
(e)
Lactate-P (mg kg^{-1})
p=0.03
b
a
ab
b
0
100
200
300
400
500
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
Shade tree species
(f)
Oxalate-P (mg kg^{-1})
p=0.016
b
a
ab
b
500
1000
1500
2000
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
Shade tree species
(g)
Total-P (mg kg^{-1})
p=0.003
b
a
b
c
1000
2000
3000
Acacia abyssinica
Albizia gummifera
Cordia africana
Croton macrostachyus
Shade tree species

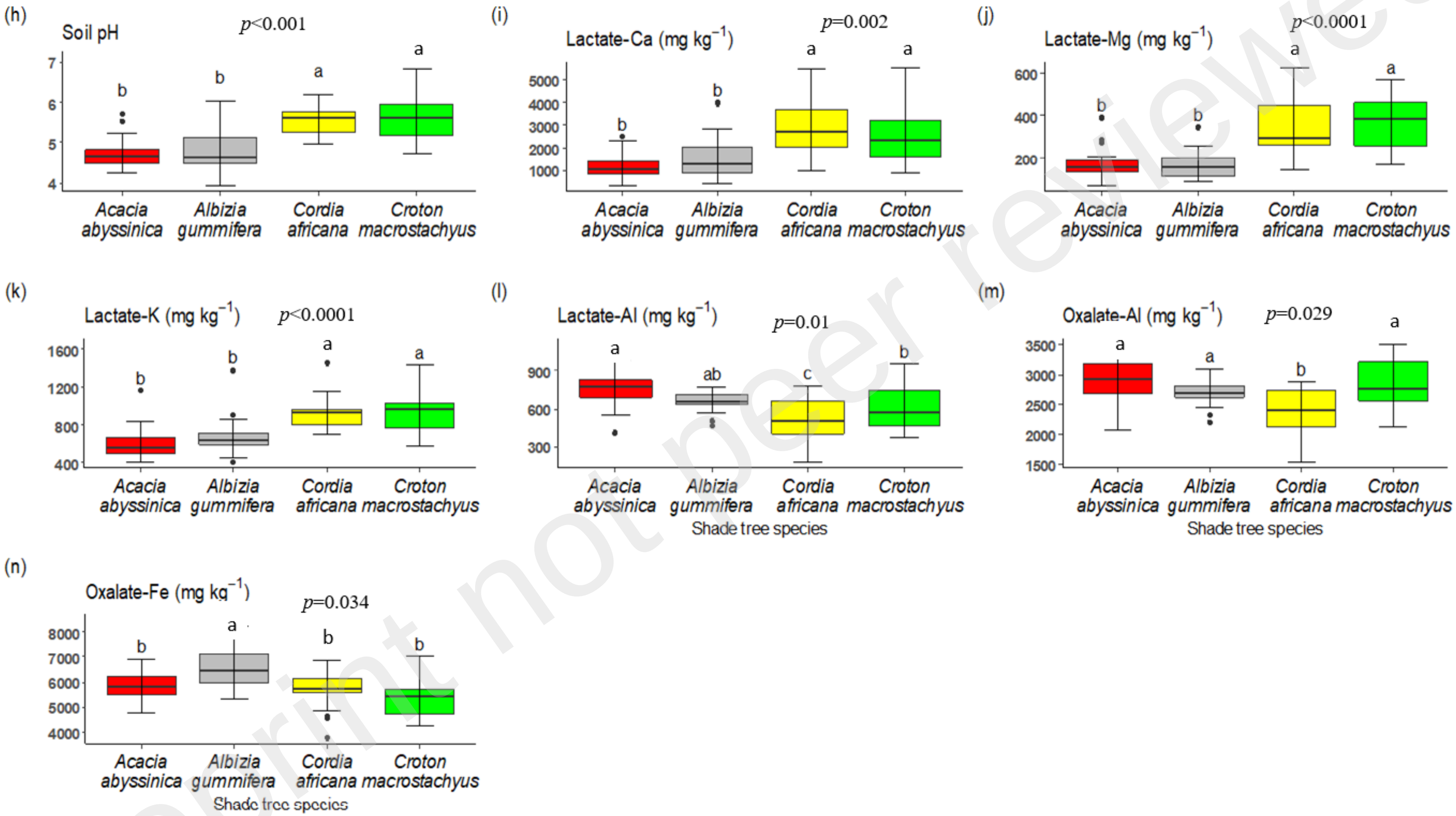


Fig 2. Effect of four shade tree species on various soil biogeochemistry and canopy cover. Bars denote standard errors and the different letters denote significant differences among shade tree species.

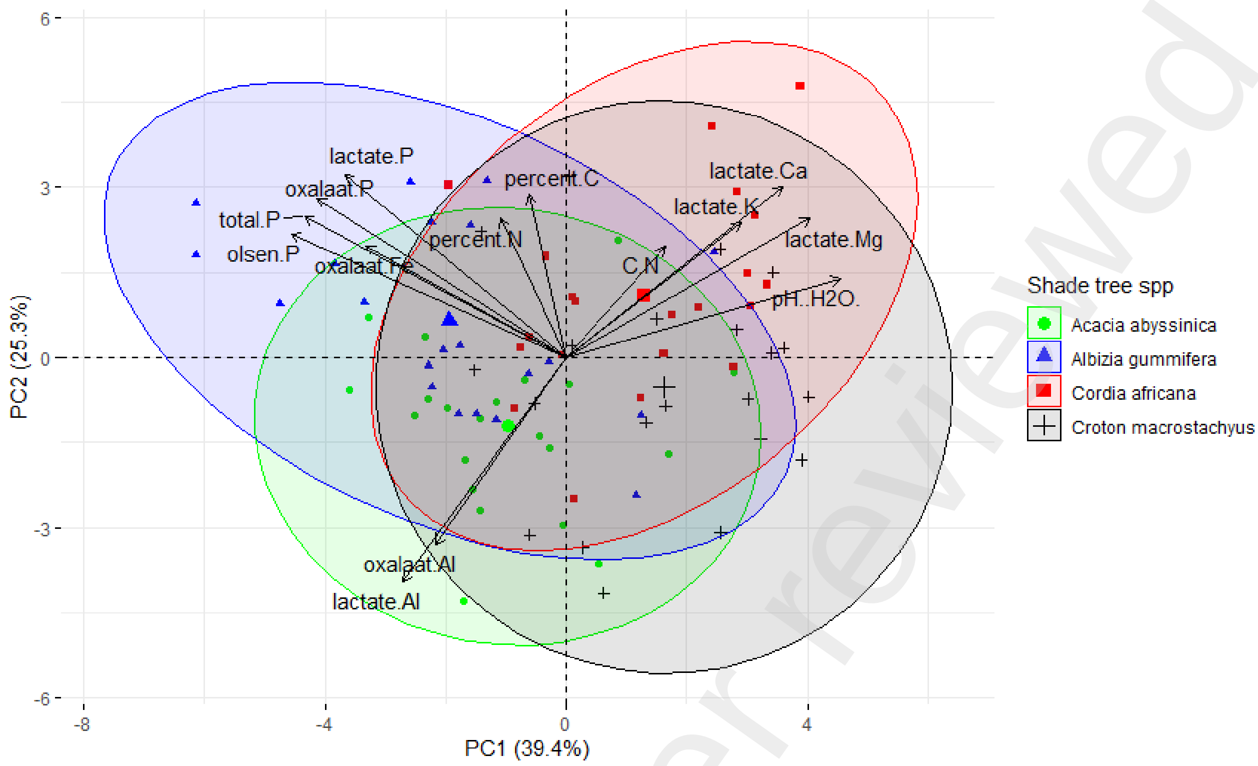


Fig 3. PCA biplot showing groupings and relationships among soil biogeochemical variables per shade tree species.

A significant effect of the first principal component (PC1) was observed on total preliminary quality (p=0.032, R^2m=0.054, R^2c=0.42) (Fig. 5). However, the effect size and beta-value are very small. Likewise, specialty quality was found to be significantly affected (p=0.046, R^2m=0.017, R^2c=0.15) by PC1, whereas hundred bean mass was found to be significantly affected (p=0.043, R^2m=0.048, R^2c=0.11) by PC1 (Fig. 5). There was also a significant effect of the second principal component (PC2) on total preliminary quality (p=0.012, R^2m=0.044, R^2c=0.34), specialty quality (p=0.033, R^2m=0.086, R^2c=0.23) and hundred bean mass (p=0.023, R^2m=0.18, R^2c=0.29) by PC2 (Fig. 5).

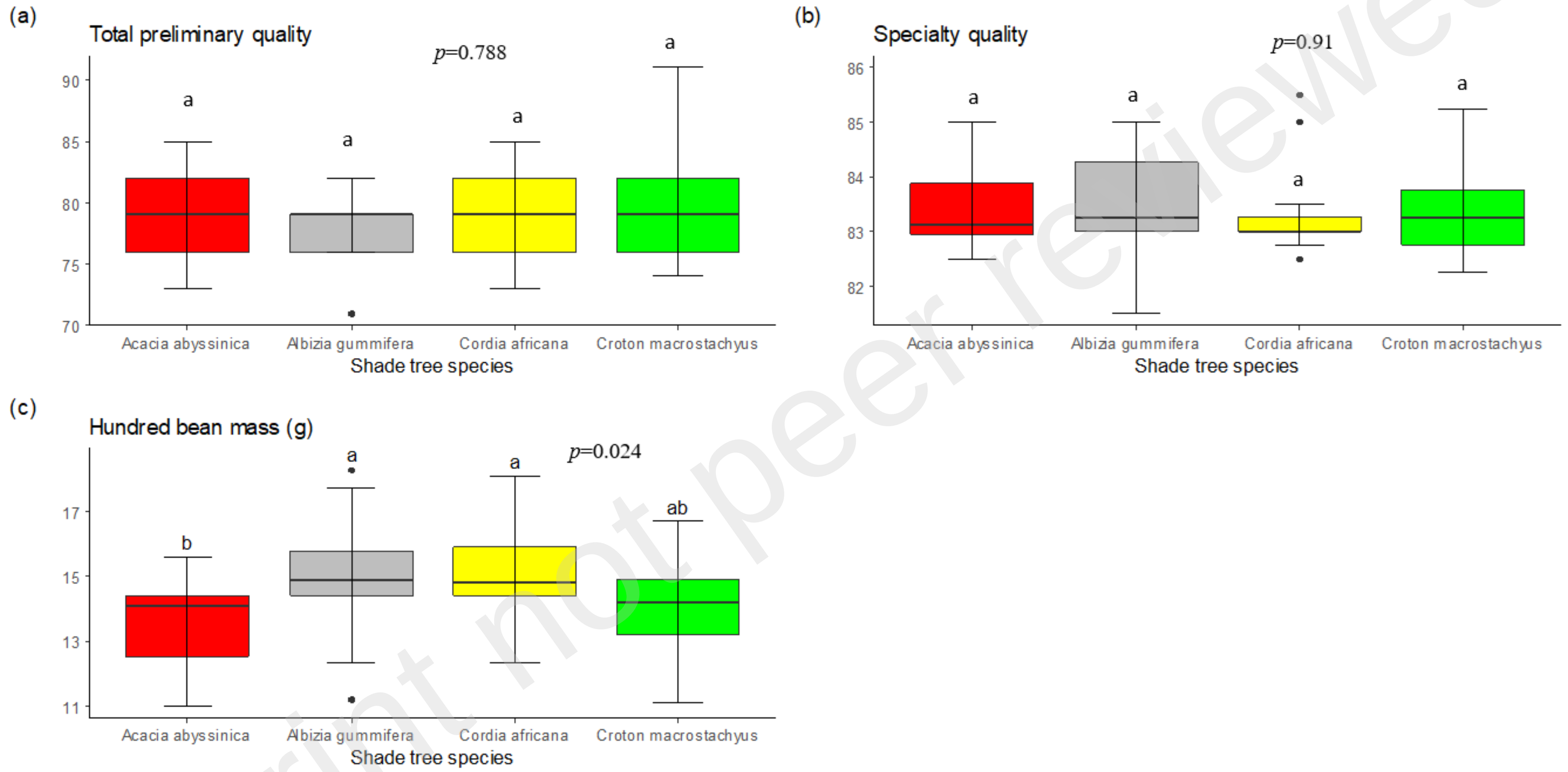


Fig 4. Boxplot representing the effect of four shade tree species in three coffee bean quality attributes. Mean values and standard error bars represent the total preliminary and specialty quality, and value of hundred bean mass (g).

4. Discussion

4.1. Shade tree species have a significant impact on soil biogeochemistry

Our 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 are higher under *Cordia africana*, implying that plots under these trees appeared to be less acidic as compared to the plots under N-fixing shade tree species. Although shade tree-coffee association has been shown to reduce soil acidity, the selection of specific shade tree species could have differing impact on the changes in pH (Muchane *et al*. 2020; Rigal, 2018). In this particular study, soils under leguminous shade trees (*Acacia* and *Albizia*) were found to be more acidic. Likewise, studies involving shade tree species have also reported a consistent result: that leguminous shade trees have been shown to contribute to a lower soil pH when compared to non-N-fixing tree species (Tully *et al*. 2012; Pinho *et al*. 2012). In contrast, a reduced soil acidification was reported under some N-fixing shade trees (Sileshi *et al*., 2014; Wang *et al*. 2010). This might be due to the fact that tropical leguminous shade trees could take-up less cations and this might have a reduced acidifying effect on the rhizosphere because the amino acids produced by N-fixation have a lower tendency to release protons (Wang *et al*. 2010). On the other hand, the release of H^+ during N-fixation must also be considered (Liu *et al*. 1989). Besides, trees could minimize soil acidification both by decreasing drainage and through uptake of otherwise leached nutrients. In tropical and sub-tropical forest ecosystems, a paradoxical relationship is commonly observed between shade tree species and soil acidification. For instance, a sub-tropical legume tree (*Senna siamea)* has been shown to recycle calcium from deeper soils and significantly reduce acidity of the top soil (Vanlauwe *et al*. 2005). Hence, the soil acidity alleviating effect of shade tree species depends on the litter chemical composition, together with N fixing ability (Wong *et al*., 2002).

C:N ratios were also highest under *Cordia africana*. 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 a negative influence on soil biology which in turn negatively affect the decomposition rates (Rowe *et al*. 2013; Aitkenhead-Peterson *et al*. 2012). Our present findings contradict the findings of Etafa (2022), who reported that soil organic matter, total N, available P, exchangeable K, and soil pH were generally greater under shade trees under study.

We also find that the N-fixing leguminous tree *Albizia* enhanced soil available P compared to the non-N-fixing shade tree species. This effect was also present in *Acacia*, but to a lesser extent. This agrees with the previous findings of Aleixo *et al*. (2020), who 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 association of N and P in agroforestry systems with N-fixing leguminous trees is very strong (Aleixo *et al*. 2020; Treseder and Vitousek, 2001). However, this depends on different environmental conditions (mainly climate and soil), cropping system and management practices (Aleixo *et al*. 2020). 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 (Qihua *et al*. 2020; Cross and Schlesinger, 1995). 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* (Fig. 2). 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 our 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 (Kang *et al*. 2009).

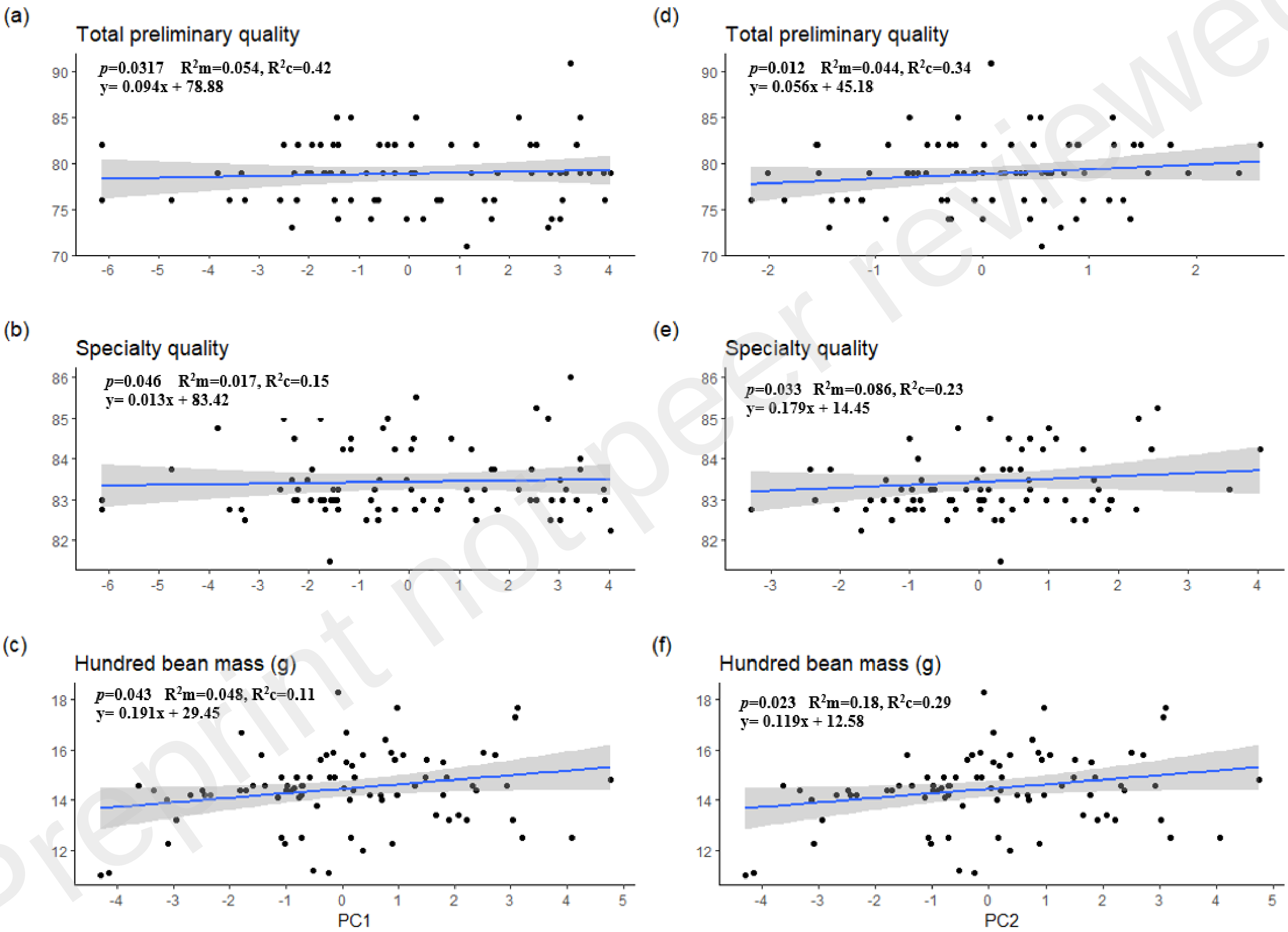

(a)
Total preliminary quality
p=0.0317 R²m=0.054, R²c=0.42
y= 0.094x + 78.88
(d)
Total preliminary quality
p=0.012 R²m=0.044, R²c=0.34
y= 0.056x + 45.18
(b)
Specialty quality
p=0.046 R²m=0.017, R²c=0.15
y= 0.013x + 83.42
(e)
Specialty quality
p=0.033 R²m=0.086, R²c=0.23
y= 0.179x + 14.45
(c)
Hundred bean mass (g)
p=0.043 R²m=0.048, R²c=0.11
y= 0.191x + 29.45
PC1
(f)
Hundred bean mass (g)
p=0.023 R²m=0.18, R²c=0.29
y= 0.119x + 12.58
PC2

Fig 5. 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 $p<0.05$. R^2m= marginal R^2 (is the proportion of variance explained by the PCA score values; R^2c= conditional R^2 (is the proportion of variance explained by the PCA score values and the random variable).

When correlating the different P-extraction methods with each other, the overall picture indicates that the three extraction methods are strongly correlated (Fig. 3). How these variables occur concurrently influences the solubility of phosphates and hence the extractability and efficiency 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 our present findings in that Al-rich plots and P-rich plots (Olsen-P, lactate-P, oxalate, and total-P) are negatively associated with each other.

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

Our present findings are consistent with that of our own previous work 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 (Yadessa *et al*. 2020; Clemente *et al*. 2015). 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 certainly 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, our results clearly indicate that the conditional R^2 values are far higher than the marginal R^2 values, implying that the spatial random variability is more important than the variability due to the fixed effects (Supplementary table 1 and Fig. 5).

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

Our 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 (Fig. 4). 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*. 2008). If soil characteristic improvements by the shade tree species were to improve coffee bean quality attributes, we would expect to find greater coffee bean quality in locations with better soil characteristics. However, we could not confirm from our 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 our study area. However, a limited effect of shade tree species identity was observed on hundred bean mass (Fig. 4), which could be due to the increasing competition for light as a shade canopy cover increases (Getachew *et al*. 2022, Lin, 2010). 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. Based on the evidence provided by the present findings, it appears easy to justify the implementation of shade trees for soil fertility improvements for a long-term coffee sustainability. 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. Implications for the coffee producers in the study area

Farmers' incentives for planting shade trees are diverse other than the cup quality of coffee. Besides the observed effect of shade tree species on physical bean quality, a coffee producer's decision to plant shade trees could also 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.

Our findings show that shade tree species had a significant effect on soil biogeochemistry but only a limited effect on coffee bean quality attributes (except in the bean mass). Although our data did not allow us to identify the mechanisms that caused the observed effects of soil biogeochemistry on coffee bean quality attributes, we found a positive and significant effect of soil nutrient status on total preliminary, specialty quality, and hundred bean mass. The findings of this study show that shade trees can be planted with the goal of improving soil biogeochemistry, and that tree species recommendation for coffee agroecosystem need to be associated to climate buffering, carbon sequestration and pathogen loads while taking into account a wide range of cropping systems and climatic zones. In the future, further research should focus more on coffee-shade tree associations such that our understanding of the biogeochemical impacts can be improved, especially given the microclimatic importance of shade tree species in buffering the negative impacts from heatwaves and droughts due to climate change.

Acknowledgements

This study has been supported by the Belgian Development Cooperation (VLIRUOS-NASCERE program) and Ethiopian Ministry of Science and Higher Education (MoSHE). The authors are profoundly grateful for the Ethiopian government for this support. P.D.F. received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC Starting Grant FORMICA 757833). We would like to thank coffee owners for allowing us to work in their coffee plots and the local and regional administration for providing the permits to work in the coffee farms. We also thank Beyene Zewdie for establishing the coffee plots. Lastly, we are very grateful to the ECX for their support in evaluating coffee cup quality and Ethiopian Institute of Agricultural research for analyzing our green bean biochemical compositions.

Code availability: Not applicable.

Authors' contribution: Conceptualization, M.G., P.D.F., K.V. and P.B.; methodology, M.G., K.T., K.V., K.H., A.T., B.A. and P.B.; formal analysis, M.G.; investigation, M.G. and K.T., writing—original draft, M.G. and P.D.F.; writing—review and editing, P.B., K.H., A.T., and K.V.; visualization, M.G., and B.A.; Funding Acquisition, P.B.; Supervision, K.V., P.B. and P.D.F.

Funding: This study has been supported by the Belgian Development Cooperation (VLIRUOS-NASCERE program) and Ethiopian Ministry of Science and Higher Education. The authors are profoundly grateful for the Ethiopian government for this support. P.D.F. received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC Starting Grant FORMICA 757833).

Data availability: The data will be made available via an online repository such as figshare.

Declarations: Not applicable.

Conflict of interest: The authors declare no potential conflict of interest.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

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