

Organically managed coffee agroforests have larger soil phosphorus but smaller soil nitrogen pools than conventionally managed agroforests

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Abstract The cultivation of crops in the presence of trees (agroforestry) and organic agriculture are management strategies thought to reduce nutrient losses to the environment and increase soil organic matter. Little is known, however, about the differences between organic and conventionally managed agroforests. This research examines how soil nutrient pools and mechanisms for nutrient retention may vary between these two different types of coffee agroforests. We determined variation in soil nutrient pools and nutrient retention capacity among (1) coffee farms in Costa Rica receiving mineral (conventional management) and organic inputs (organic management) and (2) different combinations of shade tree species. Soil nutrient pools and retention capacity were altered by fertilizer management. Soil nitrogen (N) and carbon (C) pools were significantly larger in conventional agroforests, but C:N ratios were similar among agroforests. Soil phosphorus (P) pools were

significantly higher in organic agroforests. Overall, C and N concentrations were strongly positively correlated with oxalate-extractable aluminum concentrations. We did not observe many strong species effects; however, soil cation exchange capacity was higher under *Coffea–Musa* combinations than under *Coffea* and N-fixing *Erythrina* combinations. Thus, mechanisms are in place to promote nutrient retention in agroforestry systems, but these mechanisms can be altered by management practices with consequences for long-term nutrient storage.

Keywords Agroforestry · Coffee · Nutrient pools · Nutrient retention capacity · Organic agriculture

Introduction

It is well known that the addition of mineral fertilizers to agricultural systems can improve crop yields, but can have negative consequences for ecosystems downstream (Vitousek et al. 2009). Agroforestry (intercropping with trees) and organic agriculture (cultivation in the absence of synthetic pesticides or fertilizers), have been promoted for their ability to reduce nutrient losses from runoff and leaching by increasing evapotranspiration, biomass, and nutrient accumulation, which can increase the retention of carbon (C), nitrogen (N), and phosphorus (P) in the soil.

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In general, nutrient retention (and by extension, soil fertility) in soils is controlled by texture, organic carbon, cation exchange capacity (CEC), pH, and the presence of iron (Fe) and aluminum (Al) oxides (Arshad and Coen 1992; Seybold et al. 1997). Past research has shown that compared to single-crop systems (monocultures), agroforestry can support nutrient retention and promote soil fertility by (1) preventing erosion and soil compaction due to complex root systems (Young 1986, 1989; Lal 1989), (2) maintaining soil organic matter (SOM) through tree pruning and leaf litter fall (Chander et al. 1998; Lal 2004), and (3) reducing nitrate (NO_3) leaching by increasing evapotranspiration, total aboveground biomass, and nutrient accumulation (Babbar and Zak 1995; Harmand et al. 2007; Tully et al. 2012).

The fate of mineral fertilizer will be affected by changes in the size of the soil nutrient pool and by the capacity of the soil to retain nutrients. The size of soil nutrient pools is a direct function of the inputs—whether mineral or organic—that are applied to the farm (Clark et al. 1998). Mineral fertilizers have a much higher N content (18 %) than organic fertilizers (1.5–3 %; Tully and Lawrence 2011), and are applied at higher rates than organic fertilizers. Therefore, we expect conventionally managed soils to have larger N pools. On the other hand, long-term studies have shown that the application of mineral fertilizers can diminish soil nutrient pools and negatively affect their capacity to retain nutrients (Cassman 1999; Sanchez et al. 2003). The application of mineral N fertilizers can also acidify soils (Fließbach et al. 2007) and thereby reduce CEC compared to organic fertilizers (Haynes and Naidu 1998). When CEC is reduced, the number of binding sites for cations (including Ca^{2+} , Mg^{2+} , N^+ , K^+ , and NH_4^+) declines. Thus, we expect soil amended with organic fertilizers to be more basic and have a higher CEC.

Most research on organic farming has focused on agricultural systems of minimal biological structural diversity (e.g. monocultures or polycultures of similar size class). We hypothesize that tree species will affect soil nutrient pools and nutrient retention capacity; specifically, we expect soil N and P to be higher under N-fixing species than non N-fixing species due to the high quality of their leaves compared to the other species (Tully et al. 2012). Different plant functional traits (e.g. N-fixation, water use efficiency, foliar C:N ratios, etc.) can alter the physical environment and

microclimate through effects on percent shade cover (Vanlauwe et al. 1997) and standing biomass (Eviner and Chapin 2003). Thus, different tree species may have varying effects on soil nutrient retention and pools either through the direct effect of plant functional traits or through indirect control of related processes, such as decomposition and nutrient release (Haggar et al. 1993; Palm 1995; Mafongoya et al. 1997; Teklay 2007; Tully et al. 2012), thus potentially altering the residence time of nutrients in the litter pool.

In this research, we pose two hypotheses. First, soils in conventional agroforests will have larger soil N pools, but lower pH, and CEC than soils in organic agroforests. Second, soil N and P will be higher under N-fixing *Erythrina* than the other species present. We tested these hypotheses by collecting soils at different depths from coffee agroforests of varying management type in the Central Valley of Costa Rica.

Methods

Study sites

The Central Valley of Costa Rica has a humid tropical climate favorable to coffee (*Coffea arabica*) agroforestry. This study was conducted in three locations (Colorado, San Juan Norte, and San Juan Sur) near Turrialba, Costa Rica ($9^{\circ}53'N$ $83^{\circ}40'W$). All coffee farms were located within 3 km of one another between 9.89 and 9.91 and between -83.70 and -83.69 (decimal degrees). The altitude of farms ranged from 858 to 986 m above sea level (Table 1). The study region in the Central Valley receives on average 2,600 mm of rainfall per year with a mean annual temperature of 22.6°C . Rainfall is seasonal, and the dry season extends from February through May with March being the driest month. The region received 2,660 mm of rainfall in the year prior to sampling (June 2007–May 2008), with a mean temperature of 22.0°C (Centro Agronómico Tropical de Investigación y Enseñanza [CATIE] meteorological data).

Soils are of volcanic origin and are characterized as a Typic Humitropept (Selvaradjou et al. 2005) with a clay-loam texture. After interviews and initial sampling on 28 farms (Tully and Lawrence 2011), four organic and four conventional coffee agroforests were selected for additional sampling as the same fertilizer

Table 1 Management characteristics of coffee agroforests selected for sampling near Turrialba, Costa Rica

Farm description						Fertilizer		
Mgmt	Location	Area (ha)	Age (years)	Prior land use	Prunings (year ⁻¹)	kg N (ha ⁻¹ year ^{-1c})	kg P (ha ⁻¹ year ^{-1c})	Timing
Org	SJN	2.0	20	Managed ^{ab}	2	58	29	January
Conv	SJN	2.1	30	Managed ^b	2	115	32	April
Org	COL	0.7	20	Forest	2	10	8	May
Conv	COL	3.0	50	Forest	2	100	8	March
Org	SJS	8.5	30	Managed ^a	3	0.5	0.2	January
Conv	SJS	2.0	20	Forest	2	121	18	February
Org	COL	2.8	44	Forest	2	84	27	January
Conv	SJN	2.0	50	Managed ^b	3	46	13	January

Parts of this table originally appeared in Tully et al. (2012). Note that farms were paired by location with exception of the last set of farms

^a Sugarcane

^b Pasture

^c Fertilizer additions were calculated by multiplying the mass of fertilizer (mineral or organic) by known N and P concentrations. Nutrient concentrations in organic fertilizers are reported in Tully and Lawrence (2011)

management practices had been in place for at least 20 years (Tully et al. 2012). We tried to find an equal number of organic and conventional farms in each of the three locations; however, due to a scarcity of organic farms in San Juan Norte, we had to identify an organic farm in Colorado to complete the set (Table 1). In these agroforests, a common Brazilian dwarf cultivar, Caturra, was cultivated at a density 3,300–6,000 plants ha⁻¹ under the shade of *Erythrina poeppigiana* and *Musa acuminata*. N-fixing *Erythrina* represents 49 % of the total shade stem (non-*Coffea*) density in conventional agroforests and 45 % of the total shade stem density in organic agroforests, with the rest consisting of *Musa*. On average, the four conventional agroforests received 96 kg of N and 18 kg of P ha⁻¹ year⁻¹ in the form of mineral fertilizer (18-5-15 NPK by percent). The organic agroforests received an average of 38 kg of N and 16 kg of P ha⁻¹ year⁻¹ in the form of manure, compost, and fermented coffee husks (Table 1).

Soil sampling and initial processing

Early in the wet season (June) of 2008, soil pits to 80 cm were excavated in three locations in each agroforest (Tully and Lawrence 2011). The pits were located within 50 cm of the base of (1) *Coffea* adjacent to *Erythrina* (henceforth called *Coffea-Erythrina*), (2)

Coffea adjacent to *Musa* (henceforth called *Coffea-Musa*), and (3) *Coffea* at least 5 m from the nearest shade tree (henceforth called *Coffea*). ‘Adjacent’ means that the coffee and the shade tree were within 2 m of each other. Soil samples were taken at six depths along the soil profile: 0–5; 5–10; 10–15; 15–30; 30–50; and 50–80 cm using a metal cylinder (5 cm in diameter and 5 cm tall) inserted horizontally (one sample per depth between 0 and 15 cm; two samples per depth between 15 and 80 cm). Once the cylinder was full of soil, samples were bagged to retain moisture and immediately returned to the lab for processing.

Soil properties and nutrient analysis

Upon returning to the lab at CATIE, the entire soil sample was weighed wet and a subsample was weighed wet, dried until a constant mass was attained (~24 h) at 105 °C, and re-weighed to determine moisture content. This wet-to-dry conversion factor was applied to the total sample wet weight, and the product was divided by the total volume of the core to determine bulk density. Rocks and roots >2 mm were separated; we measured both the mass and the volume (by displacement) to correct bulk density for space occupied by rocks and roots. The remaining soil was air-dried and sieved (2 mm) prior to transport back to the University of Virginia.

Sub-samples of the processed soils were ground to <149 μm , weighed into foil capsules, and dry-combusted on an elemental analyzer using atropine as a standard (Carlo Erba, Model NA 2500; Milan, Italy) to determine total N and C. Soil texture analysis was performed by Brookside Laboratories, Inc. using the hydrometer method (New Knoxville, OH) on composite samples from 0 to 15 cm (Appendix Table 5).

We used a barium chloride (BaCl_2) extraction to determine CEC; agricultural soils are regularly amended with calcium (Ca), and studies have shown BaCl_2 is a more efficient replacer of exchangeable Ca, magnesium (Mg), and sodium (Na) than ammonium acetate in these soils (Gillman 1979). In this method, the basic exchangeable cations are removed by successive washings of 0.1 and 0.002 M BaCl_2 until exchange sites are completely saturated with magnesium sulfate (0.005 M MgSO_4). Final solutions were decanted using Whatman filters (No. 42; 2.5 μm), and analyzed on an atomic absorption spectrometer for Mg (AAAnalyst 100; Perkin Elmer; Connecticut, USA). CEC is estimated from the difference in Mg concentration before and after addition to the Ba-saturated soil. That is, total CEC is equivalent to the mass (in millequivalents) of Mg^{2+} removed from solution divided by the soil weight.

Non-crystalline (amorphous) and crystalline Al and Fe were estimated by the method of Darke and Walbridge (1994). A sequential acid ammonium oxalate extraction followed by NaOH extraction was used to estimate non-crystalline Al and Fe (Ox-Al and Ox-Fe) and crystalline Al (NaOH-Al), respectively on air-dried soils. Non-crystalline plus crystalline (total) Fe was estimated by a separate dithionite-citrate-bicarbonate extraction (DCB-Fe). Resulting solutions were analyzed on an atomic absorption spectrometer for Al and Fe. Soil subsamples were digested using a modified Kjeldhal protocol (18 M sulfuric acid plus 30 % hydrogen peroxide), and total P in resulting solutions was determined colorimetrically using the molybdate blue methodology on an Alpkem Flow Solution IV Autoanalyzer (OI Analytical, College Station, Texas, USA). Sodium hydroxide (NaOH) extracts (P sorbed to Al and Fe oxides) were also analyzed for P on an Alpkem. We refer to this pool as NaOH-P, but as more labile pools were not sequentially extracted (e.g. resin P, bicarbonate-extractable P; Tiessen and Moir 1983), the NaOH fraction in this

study represents both the plant-available P pool as well as the less labile P associated with non-crystalline Fe and Al phosphates (Cross and Schlesinger 1995). The bioavailable P pool (resin + bicarbonate) is likely to be approximately 6 % of the pool we extracted (Szott and Melendez 2001). Finally, primary Ca-associated P was determined by extracting soils with 1 M HCl; extracts were analyzed for P on an Alpkem. HCl and NaOH concentrations did not differ statistically suggesting that the majority of P is bound to Fe and Al oxides.

Soil nutrient pools were calculated for each depth using bulk density and profile thickness to scale up C, N, and P concentrations to pools on a per hectare basis. Concentrations are reported in Appendix Tables 6 and 7, but we chose to focus on soil pools in the text. We examined soil nutrient pools (and properties) at three depths: (1) “surface soils” comprising the most active root layer (0–15 cm); “mid soils” comprising the rest of primary rooting zone (15–50 cm); and “lower soils” extending below the primary coffee rooting zone (50–80 cm). For each depth, we calculated the total soil N, C, and P pools and the weighted average of CEC and concentrations. All data are reported on a dry mass basis. We reported soil C:N:P ratios on a molar basis.

Because samples were of variable thickness (0–5 cm compared to 30–50 cm), we examined the vertical distribution of nutrient pools on a relative basis at each soil depth (Jobbágy and Jackson 2001). First, nutrient pools were calculated on a volumetric basis using bulk density (e.g. Mg N m^{-3}). Then we estimated the normalized pool size in 5 cm of soil (Eq. 1).

$$P = C \times B \times D \times U \quad (1)$$

where P is the size of the nutrient pool in Mg ha^{-1} , C is the nutrient concentration in mg g^{-1} , B is the bulk density of the soil in g cm^{-3} , D is a standardized depth of 5 cm of soil, and U is 10^{-1} —the conversion factor to Mg ha^{-1} . Henceforth, we refer to these pools in the text as “normalized pools”.

Statistical approach

Initially, we determined the effect of location on soil texture, pH, CEC, bulk density, and Ox-Al in lower soils using a one-way ANOVA (results are presented

in Table 2). Significant differences among plots led us to believe it necessary to include location as a random effect. At each of the three depths (0–15, 15–30, and 50–80 cm) we examined the effects of management on soil N, C, and P pools as well as weighted averages (by depth) of CEC, and concentrations of N, C, P, HCl-P, NaOH-P, Ox-Al, Ox-Fe, and DCB-Fe (results of ANCOVA with C, N, and P concentrations are reported in Appendix Table 6). Data distributions were tested for normality and log-transformed where necessary to meet basic model assumptions. In the first model, we performed a two-way analysis of covariance (ANCOVA) on soil pools and properties with fertilizer management and previous land use as main effects and location (i.e. Colorado, San Juan Norte, or San Juan Sur) as a random effect. We fit a second model with species and previous land use as main effects and location as a random effect (results of ANCOVA with C, N, and P concentrations are reported in Appendix Table 7). To account for inherent soil variability at the “pit-level”, Ox-Al at 50–80 cm was also included as a covariate in both models. Ox-Al at this depth is not likely affected by management practices due to its depth and is instead related to inherent soil characteristics such as soil texture and lithology, and therefore is a good way to control for within-farm variability. We tested for the effect of age and N fertilizer rates, but neither was significant in the models. At the farm level (mean of 3 pits for each of 8 farms), we also used linear regression to determine the relationship between Ox-Al at each depth and soil C, N, and P pools at the same depth to determine if this property provided a mechanism for nutrient retention.

Results

The effects of fertilizer management on soils

Organically and conventionally managed agroforests had similar surface soil nutrient pools and properties. There were no significant differences in soil N and C at 0–15 cm although soil P tended to be higher in organic agroforests ($P = 0.07$; Table 3). Surface soil N:P, also tended to be higher in conventional compared to organic agroforests ($P = 0.06$; Table 3), but there were no significant differences in soil C:N, CEC, or pH between organically and conventionally managed agroforests. Soil texture and pH (which was only characterized in surface soils) also did not differ significantly between organic and conventional agroforests.

The effect of management became apparent in mid soils (15–50 cm), where soil N and C pools were significantly larger in conventional compared to organic agroforests ($P = 0.001$ and $P = 0.002$, respectively; Fig. 1a, b display data with depth), but C:N ratios were similar (around 12). The total soil P and the NaOH-P pools, on the other hand, were significantly larger in organically compared to conventionally managed soils ($P = 0.02$ and $P = 0.05$, respectively; Table 3; Fig. 1c). Soil N:P ratios were significantly higher in conventional compared to organic agroforests ($P = 0.0005$; Table 3). Soil CEC tended to be higher in organic agroforests ($P = 0.08$; Fig. 2 displays CEC data with depth). Differences in soil C, N and P pools were driven by differences in soil nutrient concentrations rather than bulk density (Appendix Table 6).

Table 2 Soil properties at the three sampling locations near Turrialba, Costa Rica

	Colorado ($n = 3$)	San Juan Norte ($n = 3$)	San Juan Sur ($n = 2$)	<i>P</i> value
Percent sand (0–10 cm)	13.4 (2.6) ^a	28.6 (2.6) ^b	26.5 (3.2) ^b	0.02
Percent silt (0–10 cm)	48.1 (1.5) ^a	45.7 (1.5) ^{ab}	38.8 (1.9) ^b	0.03
Percent clay (0–10 cm)	38.5 (3.0)	25.7 (3.0)	34.7 (3.7)	0.07
pH (0–10 cm)	5.0 (0.4)	5.6 (0.4)	4.6 (0.4)	0.3
0–80 cm CEC (cmol + kg ⁻¹)	3.45 (0.07) ^a	3.09 (0.2) ^b	3.11 (0.1) ^b	0.008
0–80 cm bulk density (g cm ⁻¹)	1.00 (0.01) ^a	0.92 (0.03) ^{ab}	0.92 (0.02) ^b	0.009
50–80 cm Ox-Al (mg g ⁻¹)	4.6 (0.4) ^a	5.83 (0.8) ^{ab}	6.75 (0.6) ^b	0.02
50–80 cm Ox-Fe (mg g ⁻¹)	7.04 (0.7)	8.06 (1.6)	7.73 (1.1)	0.8

Differences in soil properties among the three locations were tested by ANOVA. Values are least squares means weighted by depth (\pm SE). Values that were significantly different at $P < 0.05$ are indicated by different letters (post hoc Tukey comparisons), and *P* values are in bold

Table 3 Soil nutrient pools and properties in coffee agroforests near Turrialba, Costa Rica by fertilizer management

	Conventional	Organic	<i>P</i> value
0–15 cm			
N (Mg ha ⁻¹)	4.6 (0.4)	4.3 (0.4)	0.3
C (Mg ha ⁻¹)	52.2 (8.0)	51.8 (8.0)	0.9
P (Mg ha ⁻¹)	1.7 (0.2)	2.2 (0.2)	0.07
NaOH-P (Mg ha ⁻¹)	0.22 (0.04)	0.22 (0.04)	0.8
HCl-P (Mg ha ⁻¹)	0.18 (0.07)	0.28 (0.07)	0.2
C:N	13 (1.0)	13 (1.0)	0.7
N:P	6 (0.7)	4 (0.7)	0.06
CEC (cmol + kg soil ⁻¹)	3.6 (0.2)	3.9 (0.2)	0.2
DCB-Fe (mg g ⁻¹)	69.6 (4.8)	61.6 (4.7)	0.4
Ox-Fe (mg g ⁻¹)	7.5 (0.7)	8.5 (0.7)	0.3
15–50 cm			
N (Mg ha ⁻¹)	9.6 (0.3)	7.3 (0.4)	0.001
C (Mg ha ⁻¹)	110.2 (19)	77.6 (18.0)	0.002
P (Mg ha ⁻¹)	3.3 (0.4)	4.6 (0.4)	0.02
NaOH-P (Mg ha ⁻¹)	0.39 (0.08)	0.49 (0.07)	0.05
HCl-P (Mg ha ⁻¹)	0.18 (0.02)	0.35 (0.01)	0.07
C:N	12 (1.2)	12 (0.9)	0.9
N:P	7 (1.1)	4 (1.0)	0.0005
CEC (cmol + kg soil ⁻¹)	3.1 (0.3)	3.6 (0.2)	0.08
DCB-Fe (mg g ⁻¹)	73.7 (8.2)	63.7 (6.4)	0.3
Ox-Fe (mg g ⁻¹)	82 (1.1)	8.3 (0.7)	1.0
50–80 cm			
N (Mg ha ⁻¹)	7.6 (0.7)	6.3 (0.6)	0.005
C (Mg ha ⁻¹)	70.4 (8.6)	60.9 (6.6)	0.2
P (Mg ha ⁻¹)	2.1 (0.7)	3.1 (0.6)	0.009
NaOH-P (Mg ha ⁻¹)	0.28 (0.07)	0.35 (0.06)	0.2
HCl-P (Mg ha ⁻¹)	0.09 (0.004)	0.19 (0.004)	0.009
C:N	11 (0.7)	12 (0.8)	0.09
N:P	6 (0.6)	4 (0.6)	0.05
CEC (cmol + kg soil ⁻¹)	3.0 (0.2)	3.3 (0.2)	0.4
DCB-Fe (mg g ⁻¹)	64.1 (9.5)	63.9 (6.4)	0.4
Ox-Fe (mg g ⁻¹)	7.0 (0.5)	7.0 (0.7)	0.9

Characteristics of surface (0–15 cm), mid (15–50 cm), and lower (50–80 cm) soils. Pools have been summed across each depth, and other values are least squares means weighted by depth (\pm SE) where species and previous land use are main effects, Ox-Al in lower soils is a covariate, and location is a random effect. Bold numbers indicate significance at $P < 0.05$

Soil N pools were still significantly higher in conventionally managed agroforests in deeper soil layers (50–80 cm; $P = 0.005$; Table 3). Total and

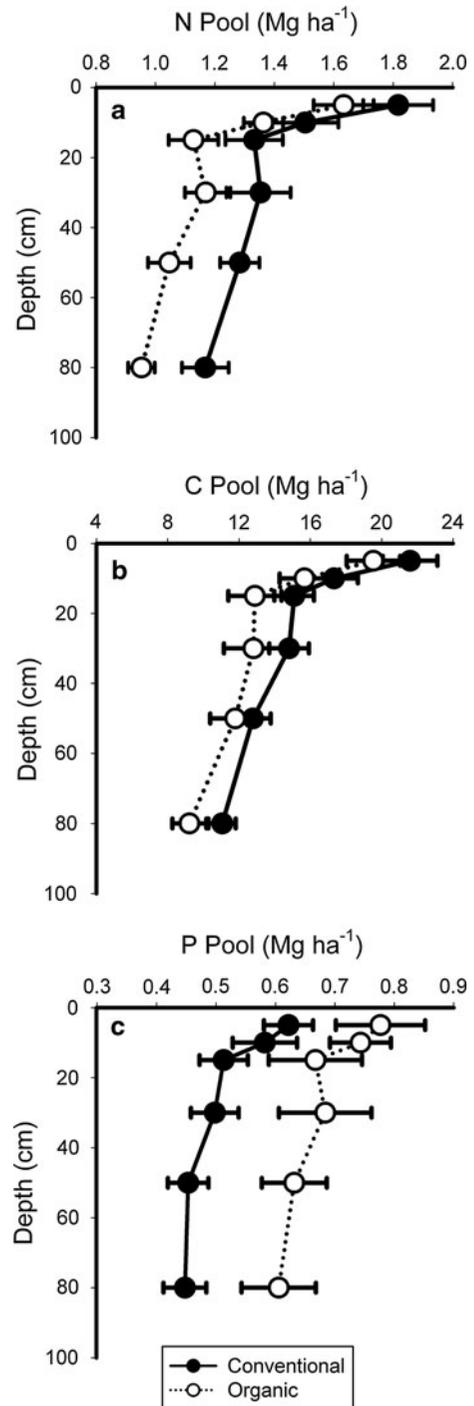


Fig. 1 Vertical patterns in normalized **a** nitrogen, **b** carbon and **c** total phosphorus pools in coffee agroforests near Turrialba, Costa Rica. Each point represents a mean pool at fixed depth interval of 5 cm each (See Eq. 1). Solid lines with closed circles indicate conventional agroforests and dotted lines with open circles indicate organic agroforests. Error bars are standard errors of the mean

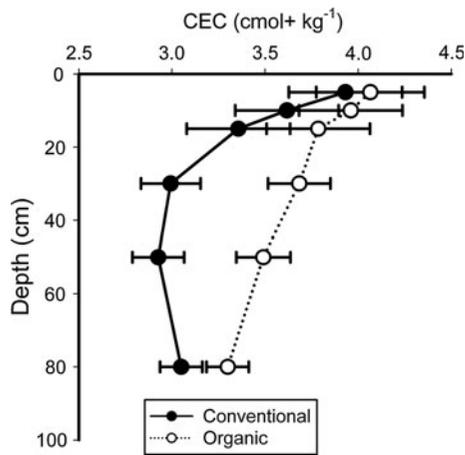
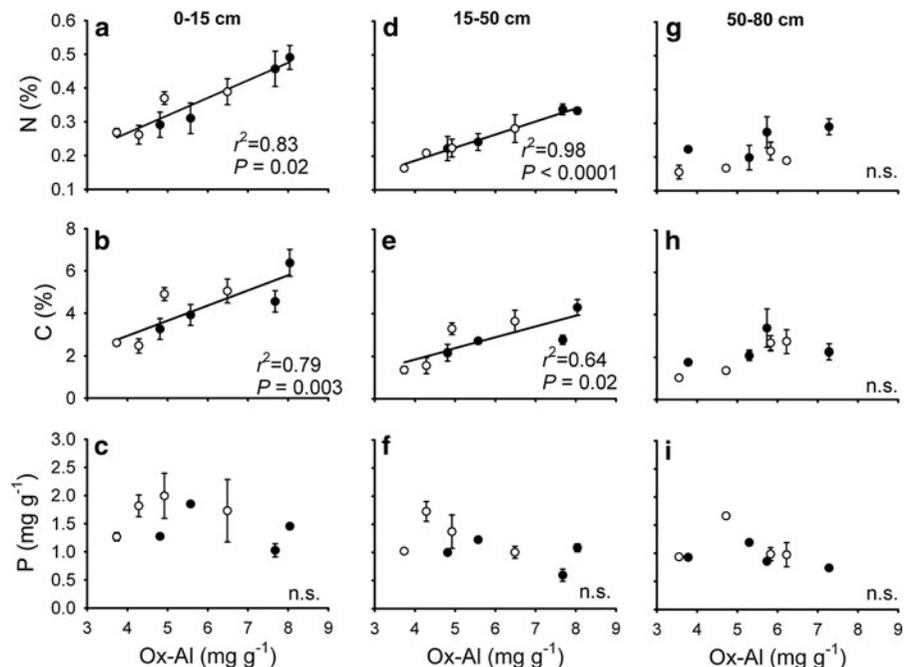


Fig. 2 Vertical patterns of mean cation exchange capacity (CEC) in coffee agroforests near Turrialba, Costa Rica. Each point represents a weighted mean by depth. Solid lines with closed circles indicate conventional agroforests and dotted lines with open circles indicate organic agroforests. Error bars are standard errors of the mean

HCl-extractable soil P were higher in organic compared to conventional agroforests ($P = 0.009$ in both cases). Lower soils N:P was significantly higher in conventional compared to organic agroforests ($P = 0.05$; Table 3).

Fig. 3 Soil nitrogen, carbon, and phosphorus pools as a function of oxalate-extractable aluminum concentrations at a–c 0–15 cm, d–f 15–50 cm, and g–i 50–80 cm depth in coffee agroforests near Turrialba, Costa Rica. Closed circles represent conventional agroforests and open circles represent organic agroforests. Lines of best fit are displayed, based on the means for all eight agroforests. Error bars are standard errors of the mean



Oxalate-extractable Al and soil pools

Oxalate-extractable Al was significantly, positively correlated with soil N pools in surface and mid soils ($r^2 = 0.83$, $P = 0.02$ and $r^2 = 0.98$, $P < 0.0001$, respectively; Fig. 3a, d). Ox-Al concentrations were also significantly positively correlated with soil C concentrations in surface and mid soils ($r^2 = 0.79$, $P = 0.003$; $r^2 = 0.64$, $P = 0.02$, respectively; Fig. 3b, e). Surprisingly, neither Ox-Al nor Ox-Fe concentrations were significantly related to soil P pools at any depth (Fig. 3 c, f, g). However, NaOH-P pools were strongly positively correlated with Ox-Al in surface soils, when data were not averaged at the farm-level ($r^2 = 0.32$, $P = 0.006$).

The effects of species on soils

Unlike the effects of management, species effects were only observed in surface soils. CEC was significantly higher under *Coffea-Musa* compared to *Coffea-Erythrina* combinations ($P = 0.03$; Table 4) in surface soils (0–15 cm). Surface HCl-P pools (primary Ca-associated P) tended to be low under *Coffea* alone compared to either *Coffea-Musa* or *Coffea-Erythrina* combinations ($P = 0.06$; Table 4). There was no

Table 4 Soil nutrient pools and properties in coffee agroforests near Turrialba, Costa Rica by species

	<i>Coffea</i>	<i>Coffea + musa</i>	<i>Coffea + erythrina</i>	<i>P</i> value
0–15 cm				
N (Mg ha ⁻¹)	4.2 (4.9)	4.7 (4.9)	4.5 (4.9)	0.3
C (Mg ha ⁻¹)	49.0 (8.1)	54.4 (8.1)	53. (8.2)	0.4
P (Mg ha ⁻¹)	2.1 (0.2)	2.1 (0.2)	1.9 (0.2)	0.7
NaOH-P (Mg ha ⁻¹)	0.21 (0.04)	0.21 (0.04)	0.25 (0.04)	0.4
HCl-P (Mg ha ⁻¹)	0.18 (0.08)	0.27 (0.08)	0.23 (0.08)	0.06
C:N	13 (1.2)	13 (1.1)	14 (1.2)	0.9
N:P	5 (1.0)	5 (1.0)	5 (1.0)	1.0
CEC (cmol + kg soil ⁻¹)	3.7 (0.2) ab	4.0 (0.2) a	3.5 (0.2) b	0.03
DCB-Fe (mg g ⁻¹)	64.9 (5.3)	65.0 (5.3)	68.2 (5.4)	0.8
Ox-Fe (mg g ⁻¹)	8.2 (0.7)	7.3 (0.7)	8.5 (0.8)	0.5
15–50 cm				
N (Mg ha ⁻¹)	7.9 (1.0)	8.6 (1.0)	8.0 (0.9)	0.7
C (Mg ha ⁻¹)	87.7 (21.7)	89.8 (21.6)	88.1 (21.4)	1.0
P (Mg ha ⁻¹)	3.9 (0.4)	3.7 (0.4)	4.0 (0.5)	0.9
NaOH-P (Mg ha ⁻¹)	0.46 (0.7)	0.44 (0.7)	0.45 (0.7)	0.9
HCl-P (Mg ha ⁻¹)	0.25 (0.23)	0.26 (0.23)	0.23 (0.14)	1.0
C:N	13 (0.8)	12 (0.8)	13 (0.8)	0.6
N:P	4.4 (0.6)	5.7 (0.7)	3.8 (0.6)	0.2
CEC (cmol + kg soil ⁻¹)	3.2 (90.2)	3.4 (0.2)	3.2 (0.2)	0.6
DCB-Fe (mg g ⁻¹)	65.7 (6.0)	48.0 (6.2)	73.5 (6.0)	0.4
Ox-Fe (mg g ⁻¹)	8.4 (0.9)	7.8 (0.9)	8.5 (0.9)	0.9
50–80 cm				
N (Mg ha ⁻¹)	6.3 (0.5)	7.0 (0.5)	5.9 (0.5)	0.3
C (Mg ha ⁻¹)	62.7 (5.0)	54.9 (5.1)	60.6 (5.0)	0.8
P (Mg ha ⁻¹)	2.7 (0.5)	3.1 (0.5)	2.7 (0.5)	0.6
NaOH-P (Mg ha ⁻¹)	0.35 (0.06)	0.35 (0.06)	0.28 (0.6)	0.3
HCl-P (Mg ha ⁻¹)	0.18 (0.1)	0.16 (0.1)	0.13 (0.1)	0.7
C:N	11 (0.8)	11 (0.9)	13 (0.9)	0.5
N:P	4 (1.0)	6 (1.0)	5 (1.3)	0.4
CEC (cmol + kg soil ⁻¹)	3.11 (0.2)	3.0 (0.2)	3.4 (0.2)	0.4
DCB-Fe (mg g ⁻¹)	33.0 (7.0)	70.7 (6.7)	64.7 (7.1)	0.2
Ox-Fe (mg g ⁻¹)	6.8 (0.8)	7.8 (0.8)	6.4 (0.7)	0.6

Characteristics of surface (0–15 cm), mid (15–50 cm), and lower (50–80 cm) soils. Pools have been summed across each depth, and other values are least squares means weighted by depth (\pm SE) as reported by ANCOVA where species and previous land use are main effects, Ox-Al in lower soils is a covariate, and location is a random effect. Values that were significantly different at $P < 0.05$ are indicated by different letters (post hoc Tukey comparisons), and P values are in bold

effect of species on soil pH, N, C, and P pools (or concentrations) at any depth (Table 4 and Appendix Table 7).

Discussion

Fertilizer management affects the size of soil N and P pools

Surface soils were remarkably similar among agroforests regardless of fertilizer management. However,

differences between organically and conventionally managed agroforests were apparent in mid and lower soils. Although soil N pools are relatively larger in surface soils (Fig. 1a), some of the added N (not utilized by plants) is moving downward to lower soil layers. This is supported by recent findings that show much higher concentrations of NO₃ in soil solution in fertilized agroforests compared to unfertilized tree plantations (8.5 compared to 0.38 mg NO₃⁻-N L⁻¹ at 1 m; Tully et al. *in review*; Ewel and Bigelow 2011). As conventional farms received 2.5 times more N in mineral fertilizer than the organic farms (Table 1), it is

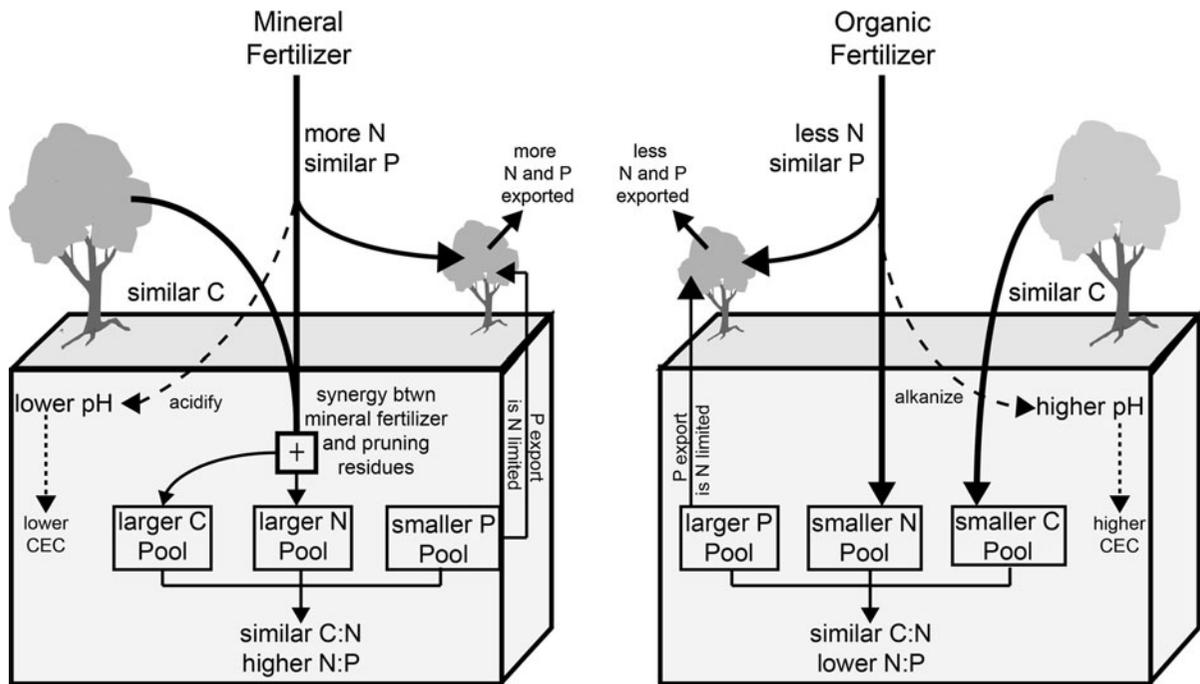


Fig. 4 Conceptual diagram of the effects of fertilizer management on soil nutrient retention capacity and nutrient pools in coffee agroforests near Turrialba, Costa Rica. Diagram depicts

the effects of nitrogen and phosphorus inputs (via fertilizer) and carbon transfer (via pruning) on soil nutrient pools and retention capacity in organic and conventional coffee agroforests

not surprising that soil N pools would be larger at depth. Further, at 1 m, N fluxes were similar between organic and conventional agroforests (127 and 111 kg N ha⁻¹ year⁻¹, respectively; Tully et al. 2012), which suggests that these soils are capable of storing excess N. NO₃ adsorption has been reported in tropical Andisols (Matson et al. 1987; Gonzales-Pradas et al. 1993; Ryan et al. 2001), which is the predominant soil order in this region. Therefore, since more NO₃ is added to conventional farms, more NO₃ builds up in lower soil layers as long as there remain open exchange sites (anion adsorption capacity; Ryan et al. 2001; Fig. 4).

Conventional agroforests had larger soil C pools in mid soils than organic agroforests even though past research shows larger C pools in organic farms (Fig. 1b; Clark et al. 1998; Drinkwater et al. 1995; Reganold et al. 1993). Shade tree pruning schedules were similar among organic and conventional agroforests in this study (Table 1), and the quantity of C added through pruning residues was double that added via organic fertilizers (3 vs. 6 Mg C ha⁻¹ year⁻¹;

Tully unpublished data). Thus, it follows that our results would differ from studies where conventional farms receive no organic inputs. It is well known that soil C accumulation depends on the availability of other key, limiting nutrients (e.g., Kirkby et al. 2013; Tittonell et al. 2008; Fig. 4). Thus, larger soil C pools in conventional agroforests may be evidence of a positive interaction between mineral fertilizers and C inputs.

Phosphorus pools were larger in organic farms compared to conventional farms even though agroforests were fertilized with comparable quantities of P (16 and 18 kg P ha⁻¹ year⁻¹, respectively; Table 1). Coffee yields are lower in organic farms, and thus fewer nutrients are exported in the organic coffee harvest (Tully and Lawrence 2011). In this system, the production of coffee is primarily N-limited, and thus the removal of P is also N-limited in organic farms due to low N inputs (Fig. 4). Phosphorus is not particularly mobile in solution, and P fluxes at 100 cm were low (and the same, 1.5 kg P ha⁻¹ year⁻¹) in the organic and conventional agroforests (Tully et al. 2012). Most

excess P is tightly held in the mineral structure of soils leading to an accumulation of P in both surface and lower soils in organically managed farms as less P is removed in the harvest.

Oxalate-extractable Al predicts soil C and N pools

There was a strong positive relationship between Ox-Al and soil C and N pools in surface and mid soils. Al can serve as a bridging cation between organic substances and clay minerals and can alter soil properties that control nutrient retention (Vance et al. 1996). As Ox-Al concentrations increase, so do the number of positively charged binding sites for negatively charged particles (NO_3^-), and organic matter in particular. It appears that regardless of farm management, soils in this region have a large capacity to retain N and C simply due to their high Al content. This is supported by the similar nitrate concentrations and leaching rates in these organically and conventionally managed agroforests (Tully et al. 2012; Tully et al. *in review*). We did not observe a strong positive relationship with Al and total soil P pools. However, the positive relationship between NaOH-P and Ox-Al is typical in highly weathered tropical soils since this P pool tends to be geochemically fixed to Fe and Al oxides (Sharpley et al. 1987; Cross and Schlesinger 1995).

No strong species effects observed

We did not observe a strong species effect on soil nutrient pools or mechanisms for nutrient retention. Although a recent longitudinal study in the same farms indicated higher soil N concentrations in surface soils under *Coffea-Erythrina* combinations (Tully et al. *in review*), we did not observe such a pattern in this study. This may have to do with the timing of collection as we would expect soil N concentrations to be highest shortly following pruning of N-fixing *Erythrina* when a pulse of N is made available to plants and microbes (Tully et al. 2012).

CEC was higher under *Coffea-Musa* combinations compared to *Coffea-Erythrina* combinations. Although not significant in this study, a longitudinal study evinced that soils under *Musa* plants are more basic (Tully et al. *in review*). Basic soils are associated with higher CEC. Further, *Musa* has very large potassium (K) requirements (Lahav 1995); relatively

high quantities of K tend to accumulate in their tissues (45–50 mg K g^{-1} ; Martin-Prevel et al. 1968) compared to either *Coffea* (10 mg K g^{-1} ; Glover and Beer 1986) or *Coffea-Erythrina* (20 mg K g^{-1} ; Glover and Beer 1986). As these leaves senesce or are pruned, they transfer more cation-rich tissues to the surrounding soils leading to the more basic conditions observed under *Musa* plants compared to the other species studied.

Conclusions

The cultivation of perennial crops such as coffee, which are not subject to total annual biomass removal or tilling, prevents erosion and soil compaction compared to annual crops. Intercropping the permanent crop with shade trees enhances these benefits. This research examined fertilizer- and species-specific effects on soil nutrient pools and soil nutrient retention capacity. While it appears that there are strong fertilizer effects, species effects are minimal. In shade-grown coffee, organic management enhances soil P, likely as a result of N-limited P removal in the harvest. On the other hand, conventional farms have larger N and C pools due to (1) larger N inputs, and (2) synergistic effect of the addition of mineral fertilizers and pruning residues. In both systems, Al oxides provide a mechanism for N and C retention. Combinations of *Coffea-Musa* had higher CEC than other combinations, which may be the result of *Musa*'s high K concentrations in tissues. Thus we show that fertilizer management may have consequences for long-term nutrient storage.

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Appendix

See Table 5, 6, 7.

Table 5 Soil texture and bulk density (0–15 cm) of coffee agroforests selected for sampling near Turrialba, Costa Rica

Mgmt	Location	Silt (%)	Clay (%)	Sand (%)	Bulk density (g cm ⁻³)
Org	SJN	47.34	24.57	28.09	0.84
Org	SJS	37.47	31.67	30.86	0.81
Org	COL	51.29	38.26	10.45	0.87
Org	COL	48.75	31.21	20.04	1.03
Conv	SJN	46.22	24.37	29.41	0.74
Conv	SJN	43.66	28.18	28.16	0.85
Conv	SJS	40.07	37.73	22.20	0.80
Conv	COL	44.39	45.89	9.72	0.86

Table 6 Weighted mean soil nutrient concentrations in coffee agroforests near Turrialba, Costa Rica by fertilizer management

	Conventional	Organic	P value
0–15 cm			
N (%)	0.38 (0.5)	0.34 (0.5)	0.2
C (%)	4.32 (0.8)	4.06 (0.8)	0.6
P (mg g ⁻¹)	1.4 (0.2)	1.7 (0.2)	0.1
NaOH-P (mg g ⁻¹)	0.18 (0.2)	0.18 (0.2)	0.9
HCl-P (mg g ⁻¹)	0.14 (0.2)	0.22 (0.2)	0.2
15–50 cm			
N (%)	0.30 (0.03)	0.21 (0.03)	0.01
C (%)	2.9 (0.4)	2.5 (0.2)	0.3
P (mg g ⁻¹)	0.93 (0.2)	1.21 (0.2)	0.003
NaOH-P (mg g ⁻¹)	0.12 (0.01)	0.14 (0.01)	0.1
HCl-P (mg g ⁻¹)	0.03 (0.6)	0.08 (0.1)	0.002
50–80 cm			
N (%)	0.25 (0.3)	0.19 (0.2)	0.04
C (%)	2.1 (1.0)	1.8 (1.0)	0.1
P (mg g ⁻¹)	0.76 (0.2)	1.03 (0.2)	0.007
NaOH-P (mg g ⁻¹)	0.10 (0.02)	0.11 (0.02)	0.3
HCl-P (mg g ⁻¹)	0.03 (0.04)	0.06 (0.4)	0.05

Characteristics of surface (0–15 cm), mid (15–50 cm), and lower (50–80 cm) soils. Values are weighted least squares means (\pm SE) as reported by ANCOVA where management and previous land use are main effects, soil Ox-Al (50–80 cm) is a covariate, and location is a random effect. Bold numbers indicate significance at $P < 0.05$

Table 7 Weighted mean nutrient concentrations by species in soils at each depth in coffee agroforests near Turrialba, Costa Rica

	<i>Coffea</i>	<i>Coffea + Musa</i>	<i>Coffea + Erythrina</i>	P value
0–15 cm				
N (%)	0.33 (0.06)	0.37 (0.06)	0.39 (0.06)	0.3
C (%)	3.8 (0.9)	4.3 (0.9)	4.6 (0.9)	0.3
P (mg g ⁻¹)	1.4 (0.2)	1.6 (0.2)	1.5 (0.2)	0.7
NaOH-P (mg g ⁻¹)	0.16 (0.04)	0.16 (0.04)	0.21 (0.04)	0.2
HCl-P (mg g ⁻¹)	0.12 (0.07)	0.21 (0.07)	0.19 (0.08)	0.6
15–50 cm				
N (%)	0.24 (0.02)	0.25 (0.03)	0.24 (0.03)	1.0
C (%)	2.3 (0.7)	2.9 (0.3)	2.7 (0.3)	0.9
P (mg g ⁻¹)	1.1 (0.2)	1.1 (0.2)	1.2 (0.2)	0.8
NaOH-P (mg g ⁻¹)	0.13 (0.01)	0.13 (0.01)	0.13 (0.01)	0.6
HCl-P (mg g ⁻¹)	0.06 (0.05)	0.08 (0.04)	0.06 (0.05)	0.9
50–80 cm				
N (%)	0.20 (0.02)	0.24 (0.02)	0.20 (0.02)	0.5
C (%)	1.8 (0.2)	2.2 (0.2)	1.9 (0.2)	0.4
P (mg g ⁻¹)	0.98 (0.15)	0.87 (0.15)	1.0 (0.15)	0.6
NaOH-P (mg g ⁻¹)	0.11 (0.03)	0.11 (0.02)	0.10 (0.02)	0.8
HCl-P (mg g ⁻¹)	0.05 (0.04)	0.05 (0.04)	0.05 (0.04)	0.9

Characteristics of surface (0–15 cm), mid (15–50 cm), and lower (50–80 cm) soils. Values are weighted least squares means (\pm SE) as reported by ANCOVA where species and previous land use are main effects, soil Ox-Al (50–80 cm) is a covariate, and location is a random effect

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