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Fertilizer type and species composition affect leachate nutrient concentrations in coffee agroecosystems

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Abstract Intensification of coffee (*Coffea arabica*) production is associated with increases in inorganic fertilizer application and decreases in species diversity. Both the use of organic fertilizers and the incorporation of trees on farms can, in theory, reduce nutrient loss in comparison with intensified practices. To test this, we measured nutrient concentrations in leachate at 15 and 100 cm depths on working farms. We examined (1) organically managed coffee agroforests (38 kg N ha^{-1} year^{-1}; $n = 4$), (2) conventionally managed coffee agroforests (96 kg N ha^{-1} year^{-1}; $n = 4$), and (3) one conventionally managed monoculture coffee farm in Costa Rica (300 kg N ha^{-1} year^{-1}). Concentrations of nitrate (NO_3^--N) and phosphate (PO_4^{3-}-P) were higher in the monoculture compared to agroforests at both depths. Nitrate concentrations were higher in conventional than organic agroforests at 15 cm only. Soil solutions collected under nitrogen (N)-fixing *Erythrina poeppigiana* had elevated NO_3^--N concentrations at 15 cm compared to *Musa acuminata* (banana) or *Coffea*. Total soil N and carbon (C) were also higher under *Erythrina*. This research shows that both fertilizer type and species affect concentrations of N and P in leachate in coffee agroecosystems.

Keywords Agroforestry · Monoculture · Coffee · Leaching · Lysimeters · Fertilizer · Organic agriculture

Introduction

In Latin America coffee (*Coffea arabica*) is traditionally cultivated in an agroforest, cropped under the shade of a variety of overstory tree species. However, in response to increases in global demand, coffee farming has intensified through the adoption of high-yielding varieties, elimination of shade trees to reduce competition for resources and light, and addition of large quantities of mineral nitrogen (N) fertilizer (200–300 kg N ha^{-1} year^{-1} as a conservative estimate of upward bounds; Reynolds-Vargas and Richter 1995). Isotopic tracer studies from these intensified coffee agroecosystems indicate that only 30–40 % of the applied N is incorporated into aboveground biomass, and as much as 50 % of the nitrate (NO_3^--N) applied is leached below the crop root zone (Sommer 1978; Salas et al. 2002). Annual NO_3^- -N leaching losses tend to be higher in conventional coffee

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monocultures than in agroforests that receive similar quantities of mineral N (Babbar and Zak 1995; Harmand et al. 2007). Unlike NO_3^--N, phosphate (PO_4^{3-}-P) has received less attention. In phosphorus (P)-poor tropical soils, PO_4^{3-}-P leaching is assumed to be negligible (Radulovich and Sollins 1991). However, in agricultural systems, where P additions can vary by an order of magnitude among farms, leaching may be substantial; therefore, it is important to assess the effects of different management strategies on this process.

The form in which N is applied may differentially impact leaching since mineral fertilizers are applied in a form that is both readily available to plants and highly susceptible to leaching. Thus, NO_3^--N is likely to move quickly through these systems. Organic fertilizers, by contrast, must undergo chemical transformations before they can be assimilated by plants, making them less susceptible to leaching. Many studies in temperate regions have shown that the addition of organic fertilizers can have positive impacts on soil organic matter (SOM; Clark et al. 1999), microbial biomass (Fließach and Mader 2000), soil biological activity (Fließach et al. 2007), mineralizable N (Clark et al. 1998), cation exchange capacity (Reganold et al. 1993), water-holding capacity (Liebig and Doran 1999), and permeability (Drinkwater et al. 1995). Very few studies evaluating the impacts of organic farming practices have been conducted in tropical regions (but see Payán et al. 2009). This study will assess how organic and conventional farming practices (specifically the application of organic vs. mineral fertilizers) alter leachate and soil nutrient dynamics in coffee agroecosystems.

In addition to fertilizer form, biotic factors, such as community composition, are likely to control the amount of nutrients that leach through the soil profile. Agroforests are distinguished from monocultures by their structural and species diversity. Greater aboveground biomass and niche complementarity leads to resource partitioning among functionally different species that can use resources in different ways (Cardinale et al. 2007, 2012; Reich et al. 2012). Increased species diversity (even at low levels) should therefore lead to lower amounts of leaching through increased resource use efficiency at the community scale (Ewel and Bigelow 2011). Deeply rooted shade trees in agroforests can access water and nutrients stored beyond the reach of coffee plants reducing leaching (Berendse 1979; Seyfried and Rao 1991; Van Noordwijk et al. 1996; Schroth et al. 2001). Nutrient dynamics in these systems will be affected by the diversity of functional traits present and expressed (Hillebrand and Matthiessen 2009). The diversity of 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). There is also tentative evidence that plant community composition and diversity can alter microbial communities, with potential implications for nutrient cycling (Innes et al. 2004; Carney and Matson 2004; Bremer et al. 2007; Lamb et al. 2011).

Finally, hardly any research (temperate or tropical) has measured leaching losses from organic and conventional farming systems, and leaching estimates are typically based on nutrient budgets (but see Stopes et al. 2002 and Torstensson et al. 2006). Many factors in the soil that are not reflected in nutrient budgets may be crucial to the processes regulating N and P leaching (Ulén et al. 2005; Aronsson et al. 2007). We measured several of these soil characteristics to determine their ability to predict leachate nutrients across different management scenarios.

Although a spectrum of management systems exists for coffee agroecosystems, no research has explored how multiple factors—in this case, fertilizer form, species composition, and soil characteristics (i.e. C, N, P, gravimetric soil moisture, and pH)—drive patterns in nutrient concentrations in leachate. Understanding how these factors regulate leaching losses is critical for the design and implementation of sustainable agricultural practices and policies in the tropics.

Materials and methods

Study sites

This study was conducted in three locations near Turrialba, Costa Rica (9°53′N 83°41′–83°42′W; Fig. 1). Farms were located within three km of each other (9°51′–9°54′N, 83°41′–83°42′W). The altitude of sites ranged from 783 to 1,017 m above sea level. Soils are of volcanic origin and are characterized as Typic Humitropepts (Selvaradjou et al. 2005) with a clay-loam texture. The study region receives on average 2,600 mm of rainfall per year and has a mean annual temperature of 22.6 °C (CATIE meteorological data). Rainfall is seasonal, and the dry season extends from February through May. This study was conducted between September 2008 and October 2009, over a year that was wetter than average, with a cumulative rainfall of 3,530 mm from lysimeter installation to final collection. During the study period, the region experienced an unusually wet December (708 mm) and February (544 mm) and an extremely dry April (39 mm; Fig. 7 in Appendix). When soils are at field capacity, monthly evapotranspiration in coffee agroforests is roughly 70–75 mm (2–3 mm per day; Goméz-Delgado et al. 2011); therefore, plants likely experienced water stress between April and May of 2009. Soil solutions were difficult to collect at this time due to highly negative capillary pressure of remaining soil water.

After farmer interviews and preliminary sampling (Tully and Lawrence 2011), four organically managed and four conventionally managed coffee agroforests, and one conventionally managed coffee monoculture were selected for instrumentation (Table 1). Thus, we examined three farm management types: (1) organic agroforests (OAF) where *Coffea* is cultivated under the canopy of shade trees in the absence of synthetic fertilizers and pesticides; (2) conventional agroforests (CAF) where *Coffea* is cultivated under the canopy of shade trees in the presence of synthetic fertilizers and pesticides; (3) conventional monocultures (MONO) where *Coffea* is grown in the absence of other species (trees) and in the presence of synthetic fertilizers and pesticides. In the agroforests, *Coffea* is cultivated at a density of 3,300–6,600 plants ha^{-1} (Table 1) under a combination of *Erythrina poeppigiana* and *Musa acuminata* (banana). Nitrogen-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* (Table 1). Shade trees are pruned two to three times a year, which can provide as much as 70–90 kg of N ha^{-1} year^{-1} (Tully and Lawrence 2011, but see Tully et al. 2012 for timing of pruning). On average, conventional agroforests received 96 kg (±16) of N and 18 kg (±5) of P ha^{-1} year^{-1} in the form of mineral fertilizer (Table 1; Tully et al. 2013). Organic agroforests received an average of 38 kg (±20) of N and 16 kg (±7) of P ha^{-1} year^{-1} in the form of manure, compost, and/or fermented coffee husks (called *broza* locally). The conventional monoculture received 300 kg N and 62 kg of P ha^{-1} year^{-1}. Farmers in this region tend to apply fertilizer at one time (basal application), typically in January (Tully et al. 2012).

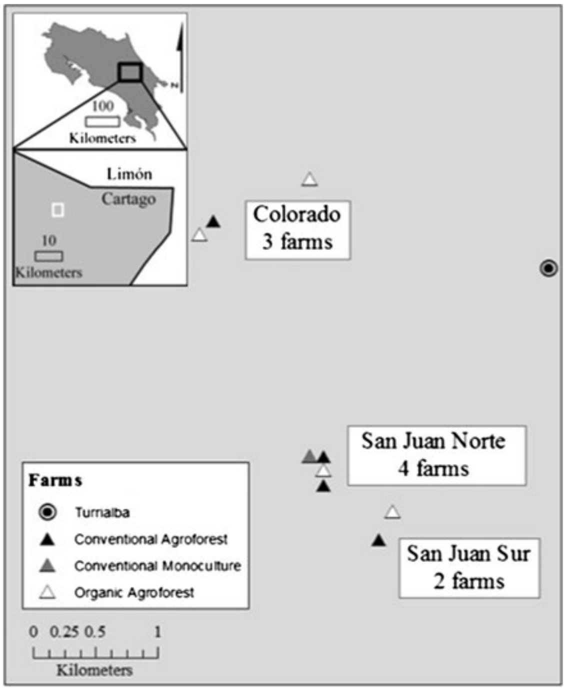

Fig. 1 Map of farm locations in Central Valley of Costa Rica indicating the locations of the three regions where coffee farms were selected for instrumentation in 2008. All farms are located between 783 and 1,017 masl. Four are conventional agroforests, four are organic agroforests, and one is a conventional coffee monoculture

Tension lysimeters

Tension lysimeters use suction to collect water from the soil matrix and were constructed by attaching ceramic cups (SoilMoisture Corp., Goleta, CA) to a 4.2-cm diameter (Schedule 40) polyvinyl chloride (PVC) pipe tube sealed at the end with a rubber stopper (1-hole, #7.5). Farmers apply organic and mineral fertilizer directly to the base of *Coffea* plants. In order to capture fertilizer dynamics, we placed lysimeters within 30 cm of the base of *Coffea* plants in all farms. Conventional agroforests were heavily instrumented with additional lysimeters installed within 30 cm of the stems of *Erythrina* and *Musa* (2 depths per

Table 1 Characteristics of coffee farms selected for lysimeter instrumentation in Costa Rica

Farm description						Density (plants ha^{-1})			Soil nutrient pools to 80 cm (Mg ha^{-1})			Fluxes (kg ha^{-1} year^{-1})		
Management	Prior land use	Years in current land use	Area (ha)	Location	Prunings year^{-1}	*Coffea*	*Erythrina*	*Musa*	C	N	P	Yield	Fert N	Fert P
OAF	Managed[ab]	20	2	SJN	2	5,586	400	833	254	20	8	1,800	58	29
OAF	Managed[a]	30	8.5	SJS	2	4,881	204	333	249	18	10	1,193	0.5	0.2
OAF	Forest	44	2.8	COL	2	5,292	100	50	135	16	14	900	84	27
OAF	Forest	20	0.7	COL	2	3,286	400	571	132	16	9	514	10	8
CAF	Managed[b]	50	2	SJN	3	5,000	400	833	274	22	7	2,160	46	13
CAF	Managed[b]	30	2.1	SJN	2	4,762	278	100	213	19	11	4,114	115	32
CAF	Forest	20	2	SJS	2	3,950	278	278	204	24	6	2,250	121	18
CAF	Forest	50	3	COL	2	5,000	300	417	177	18	8	1,800	100	8
MONO	Managed[a]	15	14	SJN	0	5,000	0	0	–	–	–	4,719	300	62

Farm characteristics, plant density, and nutrient fluxes in organic agroforests (OAF), conventional agroforests (CAF), and the conventional coffee monoculture (MONO)

SJN San Juan Norte, *SJS* San Juan Sur, *COL* Colorado

[a] Sugarcane

[b] Pasture

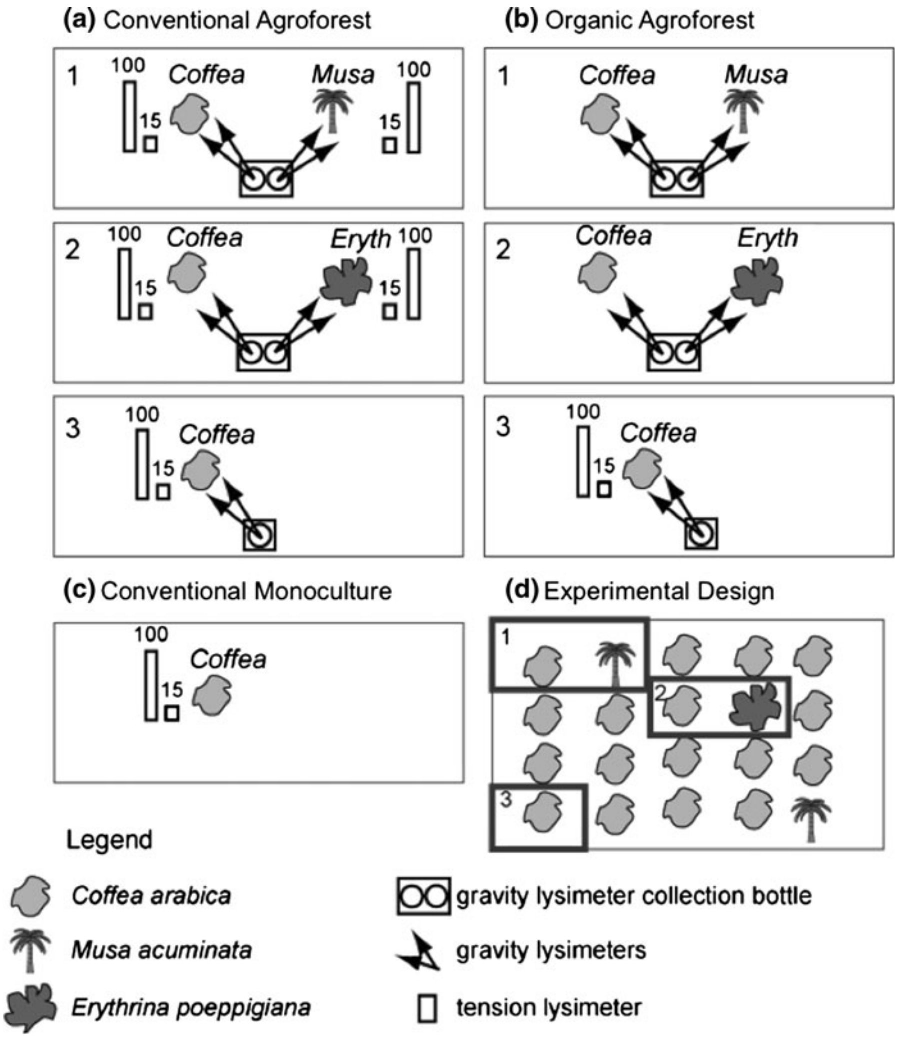

Fig. 2 Diagram of lysimeter sampling design in coffee farms in Costa Rica. Lysimeter sampling design in **a** conventional agroforests, **b** organic agroforests, and **c** the conventional monoculture. The design at the farm level is shown in **d** Locations of gravity lysimeters are indicated by black triangles (all at 15 cm) and rectangles indicate locations of tension lysimeters (at 15 and 100 cm depth). In agroforests, a pair of gravity lysimeters was installed at 15 cm below *Coffea* and adjacent *Musa*, *Coffea* and adjacent *Erythrina*, and *Coffea* 5 m from the nearest shade tree. Only tension lysimeters were installed in the monoculture

plant × 5 species combinations; $n = 10$ per farm; Fig. 2a). We examined soil solutions at 100 cm as (1) 75 % of total fine root biomass in *Coffea* is was concentrated in the top 100 cm of soil (Siles et al. 2010); (2) 80 % of *Erythrina* roots are concentrated in the first 20 cm (Chesney 2008); and (3) 70 % *Musa* roots are concentrated in the first 40 cm (Draye 2002). Roots of both *Erythrina* and *Musa* can extend below the *Coffea* rooting zone of 60 cm (Chesney 2008; Araya 2005), but become rare at 100 cm depth. Thus, we assumed that soil solutions collected at 100 cm were indicative of the soluble nutrient concentrations lost from the system. In organic agroforests, a pair of tension lysimeters (15 and 100 cm) was installed within 30 cm of the base of the previously selected "distant *Coffea* plant" (a plant located at least 5 m from nearest shade tree; Fig. 2b), but tension lysimeters were not installed in the other species combinations. Lysimeter pairs were installed under two different *Coffea* plants in the conventional monoculture farm (Fig. 2c).

Tension lysimeters were allowed to equilibrate with their surroundings for one month before collection, after which samples were collected every 4 weeks (starting in September 2008). Lysimeters were filled with distilled water before each sampling period in order to maintain good contact between the lysimeters and the surrounding soil. The day before sample collection, tension lysimeters were purged of any remaining water, and an internal pressure of −0.05 to −0.06 MPa was applied using a hand-held vacuum pump. Soil solutions were extracted from the lysimeters on the following day and were re-filled with distilled water. All samples were frozen until analysis to minimize the conversion of inorganic N to organic N by microbes.

Gravity lysimeters

Gravity lysimeters are frequently used in tropical systems where rainfall is high (Russell and Ewel 1985; Radulovich and Sollins 1991; Campo et al. 2001). To examine the effect of management and species on nutrient concentrations in leachate in surface soils, three lysimeter stations were established in the eight agroforests. A pit was excavated to roughly 80 cm within 50 cm of the bases of (1) *Coffea* beside *Erythrina*, (2) *Coffea* beside *Musa* and (3) the "distant" *Coffea* plant (Fig. 2a, b). Soil samples were taken at six depths within each pit in order to quantify total soil nutrient pools (Table 1). Gravity lysimeters were not installed in the conventional monoculture, as the owner did not agree to pit excavation in his farm.

Gravity lysimeters were constructed from 4.2-cm PVC tubes cut on an angle to create an oval opening with semi-axis of 10.16 and 5.08 cm. The surface area of the lysimeter exposed to leachate was 40.45 cm^2 such that 10 mm of leachate should yield 40.45 mL. Trenches were dug and lysimeters were installed 15 cm below the soil surface and roughly 15 cm from the base of the trunk. Two lysimeters were installed under each species in the pair (e.g. *Coffea* and adjacent shade tree), and lysimeters from each species were connected to a single one-liter volumetric high-density polyethylene (HDPE) collection bottle by PVC tubing. For example, the two lysimeters under *Erythrina* were connected to one bottle and the two lysimeters under *Coffea* were connected to another. A wooden box (internal dimensions: 85 cm × 10 cm × 20 cm) was installed in the pit to prevent back-filling, and the HDPE bottles were placed at the bottom of the box. Bottles were treated with three drops of chloroform ($CHCl_3$) to prevent bacterial growth, and all parts of the lysimeter were washed in 5 % HCl prior to deployment. Gravity lysimeters were allowed to equilibrate with their surroundings for one month before collecting the first sample, after which water was allowed to accumulate in the bottle and samples were collected every four weeks (starting in September 2008). At each collection, the volume in the bottles was measured and a sub-sample of soil water was collected for nutrient analysis. Old bottles were replaced with acid-washed (10 % HCl), chloroform-treated bottles. All samples were frozen prior to analysis.

Soils collection

Every four weeks (on the same day that tension was applied), soil samples (0–10 cm depth) were collected from within 1 m of each lysimeter station. Eight soil cores were collected from each station and composited for a total of three samples per farm, and 14 collections over the course of a year. Field-moist sub-samples of soils were weighed on the same day as collection, oven-dried at 105 °C until a constant mass was attained, then re-weighed to determine gravimetric soil moisture content ($\mathrm{mass_{water}/mass_{soil}}$). Remaining soils were air-dried for three days in an air-conditioned room, and then passed through a 2 mm mesh sieve. Soil pH was determined on air-dried sub-samples using a 2:1 water-to-soil slurry.

Nutrient analysis

Leachate samples from gravity and tension lysimeters were transported to the University of Virginia for nutrient analysis. Samples were filtered through a Whatman filter (No. 42; 2.5 μm) to remove any debris. Inorganic NO_3^-, NH_4^+, and PO_4^{3-} in leachate were analyzed on a LACHAT QuikChem (LACHAT Instruments Loveland, CO) on filtered samples. A potassium persulfate digestion (also on filtered samples) converted organic P to an inorganic form (Hosomi and Sudo 1986). Analyzing this solution on a LACHAT yielded total P concentrations, which allowed us to calculate organic P. All nutrient concentrations are reported in mg L^{-1} (where mass values pertain to N or P component of NO_3^-, NH_4^+, PO_4^{3-}).

Bioavailable soil P was determined using a modified Bray-extraction on sub-samples of air-dried soil. Approximately three grams of sieved, air-dried soils were shaken for one minute in 25 mL of a 0.03 mol L^{-1} NH_4F and 0.025 mol L^{-1} HCl solution (Bray and Kurtz 1945). Extracts were filtered and P concentration was determined colorimetrically using a molybdate blue methodology on an Alpkem Flow Solution IV Autoanalyzer (OI Analytical, College Station, Texas, USA). A portion of soil was also ground to <145 μm and dry-combusted on an elemental analyzer to determine total N and C. All data are reported on an oven-dry mass basis. Nutrient ratios (C:N or N:P) are reported on a molar basis.

Statistical approach

Tension lysimeters

We used a generalized linear mixed model (GLMM) approach to assess the effect of management on nutrient concentrations in leachate, measured in tension lysimeters (Fig. 2 a3, b3, and c). Because of a non-Gaussian error structure, we fit our GLMMs with a Poisson distribution, which best fit the data. Since Poisson distributions require an integer response, we multiplied the leachate concentration values by 100 and rounded. This preserved the two significant digits with which the original, non-integer data were reported, but allowed the data to be run in a Poisson model. We also tested lognormal and Gaussian error structures, none of which significantly impacted the results. We decided to use the Poisson model because it had the best qualitative fit to the data.

A second motivation for the selection of the GLMM was to account for the unbalanced study design. We identified four replicate farms of each type of agroforest with one tension lysimeter pair each (one at 15 cm and one at 100 cm; four conventional agroforests and four organic agroforests). However, only one conventional monoculture farmer agreed to participate in the study, so we installed two lysimeter pairs on this farm (Note: the monoculture farm is on average five times larger than individual agroforests). The GLMM, unlike an analysis of variance (ANOVA)-based approach, is flexible enough for unbalanced designs. We included two random effects: date and individual lysimeter, nested within farm, to account for variability among instruments. In all models, the leaching response variables were restricted to values greater than zero. In some cases, concentrations of inorganic P were calculated to be slightly higher than total P (leading to a negative value for organic P) due to variation in colorimeter calibration and low concentrations of P in leachate. Any negative organic P values were dropped from the analysis as were the inorganic and total P values associated with them.

The GLMM models were fit using a Markov Chain Monte Carlo (MCMC) approach (Zuur et al. 2009; see Clark 2005 for an explanation of MCMC in an ecological context) using the “MCMCglmm” package (Hadfield 2010) for the R statistical programming environment (R Development Team 2012). We selected the MCMC approach to modeling GLMMs because the F-statistics associated with GLMMs in the widely used “lme4” package are not considered valid because they assume fixed denominator degrees of freedom in the calculation of the F-statistic, which varies as a function of degrees of freedom, thus making associated *P* values anti-conservative (Baayen et al. 2008). Researchers have begun to circumvent this challenge by assessing significance of these GLMMs with MCMC approaches (Bradford et al. 2012). MCMC techniques offer a robust alternative strategy for marginalizing the model random effects and identifying response variable likelihood (Browne and Draper 2006). The MCMCglmm package has the added benefit of allowing for alternative random effects structures, including the nested random effects used in this study. We report *P* values derived from the MCMC estimation of a posterior distribution; these *P* values have similar interpretation to classical *P* values. We considered coefficients with $P < 0.05$ significant and coefficients with $P < 0.10$ marginally significant (Hurlbert and Lombardi 2009).

To examine species effects, nutrient concentrations in leachate collected from tension lysimeters (at both depths) in conventional agroforests, we used GLMMs with a Poisson error structure (with species and depth as main effects, time as random effect, and lysimeters nested within farms; Fig. 2b). We tested five species and/or species combinations: *Erythrina, Musa,* distant *Coffea plant, Coffea* adjacent to *Erythrina,* and *Coffea* adjacent to *Musa.* Each of the models we used is represented in Fig. 8 in Appendix.

Gravity lysimeters

We also used GLMMs to assess the impact of both management type and species on nutrient concentrations in leachate, measured by gravity lysimeters. Time was included as a random effect and individual lysimeters were nested within farm. We used the same MCMC approach to estimate significance values as was used in the tension lysimeter models.

Comparing tension and gravity lysimeters

We fit a LMM using a similar approach to compare nutrient concentrations collected at 15 cm from tension and gravity lysimeters. All of the data were lognormally distributed, so they were log-transformed (for leachates from both tension and gravity lysimeters) before entering the model.

Soil characteristics

We were interested in assessing (1) the effect of management and species on soil characteristics (e.g. total N, total C, Bray-P, gravimetric soil moisture, and pH) and (2) the relationship between soil characteristics and nutrient concentrations in leachate. For the first analysis, we used a linear mixed model (LMM) approach with management and species as main effects and time and farm as random effects. In this case, farms were blocked by location in order to account for inherent differences in substrate (even though all farms were located within 3 km of one another; Fig. 1). To disaggregate the effect of different species combinations, which is a three-level variable, on soil properties, we used pairwise *t* tests with Tukey comparisons between each combination. For pH, we converted to the concentration of H^+ ions to eliminate confounding results due to the logarithmic scale of the data. Soil data were cleaned by removing any observations of total N and C where total carbon was less than 2.5 %. These low values for percent carbon are suggestive of instrumentation error.

In the second analysis, we sought to examine the relationship between surface soil (0–10 cm depth) characteristics and leachate nutrient concentrations in both gravity and tension lysimeters to explain potential drivers of nutrient loss. We used a GLMM to assess the impact of soil properties on nutrient concentrations in leachate, measured by gravity lysimeters. Fixed effects were reduced from a full model based solely on significance, rather than an information criterion approach. Information criteria, such Akaike's Information Criterion (AIC) penalize models for the number of included variables and are useful when trying to select a parsimonious model; given the small number of possible covariates in our model, we did not feel it was necessary to penalize variable inclusion. Further, we were principally interested in understanding which soil properties affected leachate concentrations, rather than optimize overall model performance, thus making variable significance a more appropriate approach than model information criterion. All statistical analyses were conducted using the R statistical package (www.rproject.org).

Results

Effects of management on leachate and soil

Nitrate concentrations in leachate were significantly higher in the conventional monoculture compared to the agroforests at both depths ($P = 0.02$ at 15 cm and $P = 0.04$ at 100 cm in tension lysimeters; Fig. 3a; Table 2). These concentrations were nearly three times higher (27 mg NO_3^--N L^{-1}) than the World Health Organization standards for drinking of 10 mg NO_3^--N L^{-1} (WHO 1996) in the conventional monoculture at 100 cm. Despite greater N inputs, conventional agroforests did not have higher NO_3^--N concentrations than organic agroforests at either depth in tension lysimeters. Concentrations of organic P were also significantly higher at 15 cm in the conventional

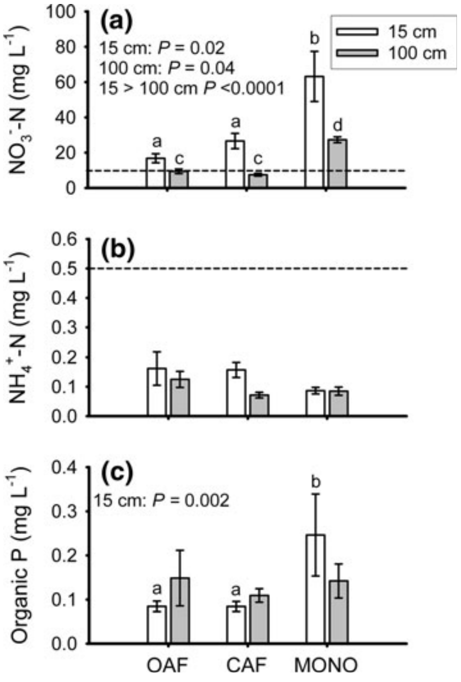

Fig. 3 Mean monthly concentrations of **a** NO_3^--N, **b** NH_4^+-N, and **c** Organic P in leachate collected from tension lysimeters at 15 (*white bars*) and 100 cm (*grey bars*) depth in organic agroforests (OAF), conventional agroforests (CAF), and coffee monocultures (MONO). Dashed lines represent the World Health Organization standards for drinking water quality (10 mg NO_3^--N L^{-1} and 0.5 mg NH_4^+-N L^{-1}). Values presented are means across farms (within the same management type) and sampling ($n = 13$). Bars represent standard error of the mean. Values that were significantly different at $P < 0.05$ are indicated by different letters

Table 2 Regression table of model coefficients relating nutrient concentrations (in mg L^{-1}) in tension lysimeters to depth and farm management

Variable	NO_3^--N		NH_4^+-N		Inorganic PO_4^{3-}-P		Organic P		Total P	
	Coefficient estimate	*P* value	Coefficient estimate	*P* value	Coefficient estimate	*P* value	Coefficient estimate	*P* value	Coefficient estimate	*P* value
Depth	**−0.89**	**0.01**	**−0.44**	**<0.001**	0.19	0.37	0.09	0.3	**0.4**	**0.02**
Monoculture	**1.32**	**0.04**	−0.13	0.45	0.05	0.83	**0.49**	**0.002**	0.29	0.232
Organic agroforests	−0.31	0.35	0.09	0.48	0.21	0.37	0.13	0.15	0.06	0.77

The coefficient estimate is the mean posterior value from the Markov Chain Monte Carlo simulation and can be interpreted as the marginal effect of each independent variable on the response variable. The *P* values are MCMC *P*-values, but have a similar interpretation as frequentist *P*-values. Management, which is a three-level factor, fit only two levels to avoid multi-collinearity (the conventional monoculture and organic agroforests). The coefficient for each can be interpreted as the effect of the given management practice relative to the other two. Values in bold are significant at $P < 0.05$

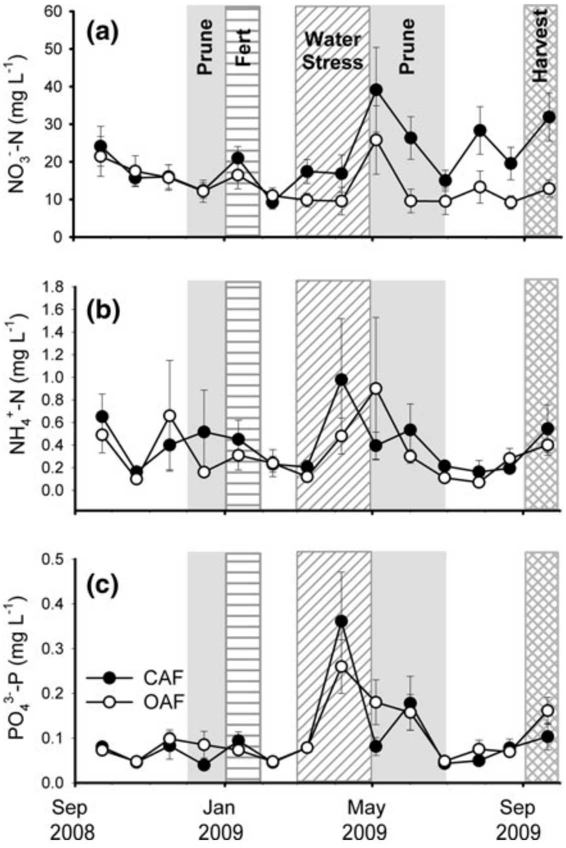

Fig. 4 Nutrient concentrations in gravity lysimeter leachate in coffee agroforests in Costa Rica. Mean concentrations of inorganic **a** NO_3^--N, **b** NH_4^+-N, and **c** PO_4^{3-}-P in leachate (15 cm; gravity lysimeters) in conventional and organic agroforests (across species) throughout the study period (September 2008–October 2009). Closed circles indicate conventional agroforests (CAF; $n = 4$), and open circles indicate organic agroforests (OAF; $n = 4$). Bars represent standard error of the mean. Diagonal lines represent period of water stress <100 mm per month (March through May), shaded areas represent pruning periods (December–January and May–July), horizontal lines indicate the primary fertilization event (January–February), and cross-hatches represent harvest period (beginning in September with the harvest peak in November)

monoculture compared to the agroforests ($P = 0.001$; Fig. 3c; Table 2). Concentrations of NH_4^+-N did not differ significantly among management types in tension lysimeters (Fig. 3b). Nitrate concentrations in leachate were about two-and-a-half times higher at 15 cm than they were at 100 cm (36 vs. 15 mg NO_3^--N L^{-1}; $P < 0.0001$), and were drawn down by 71, 44, and 57 % from original concentrations in conventional agroforests, organic agroforests, and the conventional monoculture, respectively. The greatest unit reduction in NO_3^--N concentrations between 15 and 100 cm occurred in the conventional monoculture (36 mg NO_3^--N L^{-1} difference), with similar reductions in concentrations among organic and conventional agroforests (7 and 19 mg NO_3^--N L^{-1} difference, respectively). As expected, NH_4^+-N concentrations were almost two orders of magnitude lower than NO_3^--N concentrations, and therefore negligible in terms of N losses to the system. Concentrations were also below the standard limit of 0.5 mg NH_4^+-N L^{-1} (WHO 1996) at both depths in all management types (Fig. 3b). Phosphate-P concentrations were also two orders of magnitude lower than NO_3^--N concentrations, which is not surprising as P is strongly adsorbed onto the clay minerals of tropical soils.

Gravity lysimeters were only installed at 15 cm and only in the agroforests, and unlike the tension lysimeters, detected difference between the agroforests. Nitrate concentrations were significantly higher in leachate collected in conventional agroforests (23 mg NO_3^--N L^{-1}) than organic agroforests (15 mg NO_3^--N L^{-1}; $P = 0.02$; Fig. 4a), but not for any NH_4^+-N or any form of PO_4^{3-}-P (Fig. 4b and c; Table 3). There were no significant effects of management on soil properties in organic and conventional agroforests (Fig. 5; Table 5; Fig. 9 in Appendix).

Nitrate concentrations were significantly higher in leachate collected from the tension compared to gravity lysimeters at 15 cm ($P = 0.0001$, mean of 22 and 15 mg NO_3^--N L^{-1}, respectively). There were no other significant differences in nutrient concentrations in leachate collected from tension and gravity lysimeters.

Effects of species on leachate and soil

There was no significant effect of species on nutrient concentrations in leachate at 15 or 100 cm collected from tension lysimeters in the conventional farms. Unlike tension lysimeters, gravity lysimeters were installed at the species-level in both conventional and organic agroforests (at 15 cm; Fig. 2a and b). We observed significantly higher NO_3^--N concentrations under *Erythrina* (28 mg NO_3^--N L^{-1}) than any other species or their combination (mean of 17 mg NO_3^--N L^{-1} across other species; $P = 0.01$; Table 3). Organic P was significantly higher under the *Coffea–Erythrina* combination (0.16 mg organic P L^{-1}) than any other species or their combination (mean of

Table 3 Regression table of coefficients of the model relating nutrient concentrations (in mg L^{-1}) in gravity lysimeters to species and management

Variable	NO_3^--N		NH_4^+-N		Inorganic PO_4^{3-}-P		Organic P		Total P	
	Coefficient estimate	*P*-value	Coefficient estimate	*P*-value	Coefficient estimate	*P*-value	Coefficient estimate	*P*-value	Coefficient estimate	*P*-value
Management	**−0.56**	**0.02**	−0.16	0.29	0.19	0.29	0.11	0.25	0.11	0.28
Coffea	−0.08	0.84	0.06	0.81	−0.17	0.55	0.09	0.56	−0.03	0.85
Erythrina	**0.90**	**0.02**	0.38	0.12	0.06	0.80	0.05	0.72	0.01	0.97
Coffea–Musa	−0.30	0.41	−0.01	0.96	0.01	0.99	−0.01	0.94	−0.03	0.86
Coffea–Erythrina	0.41	0.27	0.09	0.70	0.12	0.69	*0.28*	*0.05*	0.20	0.22

The coefficient estimate is the mean posterior value from the Markov Chain Monte Carlo simulation and can be interpreted as the marginal effect of each independent variable on the response variable. The *P*-values are MCMC *P*-values, but have a similar interpretation as frequentist *P*-values. Management has two levels (organic and conventional), with species has five levels (*Coffea, Musa, Erythrina, Coffea–Musa, Coffea–Erythrina*), though only four are estimated to avoid multi-collinearity. The coefficient for each can be interpreted as the effect of the given species composition relative to the other four. Values in bold are significant at $P < 0.05$

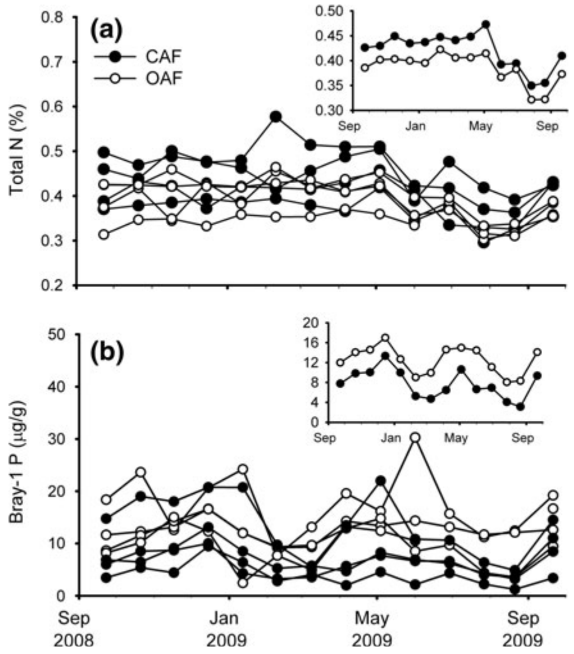

Fig. 5 Soil N and P in top 10 cm in coffee agroforests in Costa Rica. Mean **a** total N and **b** Bray-1 P in soils collected from 0 to 10 cm in organic and conventional coffee agroforests (across species) throughout the study period (September 2008–October 2009). Closed circles indicate conventional agroforests (CAF; $n = 4$), and open circles indicate organic agroforests (OAF; $n = 4$). Inset of mean soil N and P dynamics across farms are also presented

0.14 mg organic P L^{-1} across other species; $P = 0.05$; Table 3).

Although there were no significant effects of fertilizer type on surface soils, we observed strong species effects on soil characteristics. Total soil C and N concentrations were significantly higher (by 14 %) in the *Coffea–Erythrina* combination than in *Coffea–Musa* or in *Coffea* alone ($P < 0.0001$ in both cases; Table 4). Bray P concentrations were significantly lower (by 25 %) under *Coffea* plants alone than in combination with either *Erythrina* or *Musa* ($P = 0.03$ and $P = 0.02$, respectively; Table 4). Gravimetric soil moisture was significantly lower (by 7 %) under *Coffea–Erythrina* combinations than *Coffea–Musa* combinations or *Coffea* alone ($P = 0.01$ and $P < 0.0001$, respectively). Finally, soil pH was significantly higher (by 10 %) under the *Coffea–Musa* combination ($P < 0.0001$) compared to other species (Table 4).

Effects of soil characteristics on nutrient concentrations in leachate

We wanted to determine if leachate concentrations could be predicted by surface soil nutrient concentrations and properties. Inorganic PO_4^{3-}-P concentrations in leachate (in gravity lysimeters at 15 cm) were negatively correlated with pH ($P < 0.0001$, $r = -0.22$). Organic P concentrations in leachate (at 15 cm) were significantly positively correlated with C:N in soils ($P < 0.0001$, $r = 0.24$).

Discussion

Management affects leachate but not soil

Fertilizer N inputs were three times higher in the monoculture farm compared to the agroforests (see

Table 4 Soil characteristics among species (0–10 cm) averaged across study period

Species	Total C (%)	Total N (%)	C:N	Bray-1 P (µg/g)	Gravimetric soil moisture (%)	pH	Bulk density (g/cm^3)
Coffea	4.4 (0.09) a	0.38 (0.005) a	14 (0.15)	8.3 (0.59) a	59.4 (1.0) a	5.1 (0.07) a	0.87 (0.03)
Coffea + *Musa*	4.8 (0.12) a	0.40 (0.007) a	14 (0.19)	11.1 (0.82) b	61.0 (1.0) a	5.6 (0.08) b	0.88 (0.04)
Coffea + *Erythrina*	5.2 (0.15) b	0.44 (0.009) b	14 (0.15)	10.9 (0.77) b	66.0 (1.5) b	5.0 (0.06) a	0.86 (0.03)

Differences in nutrient concentrations, soil moisture (mass$_{water}$/mass$_{soil}$), and pH among the three species combinations were tested by LMM. Means are reported for each species (±SE), and values that were significantly different at $P < 0.05$ are indicated by different letters. Bulk density values are provided for scaling purposes

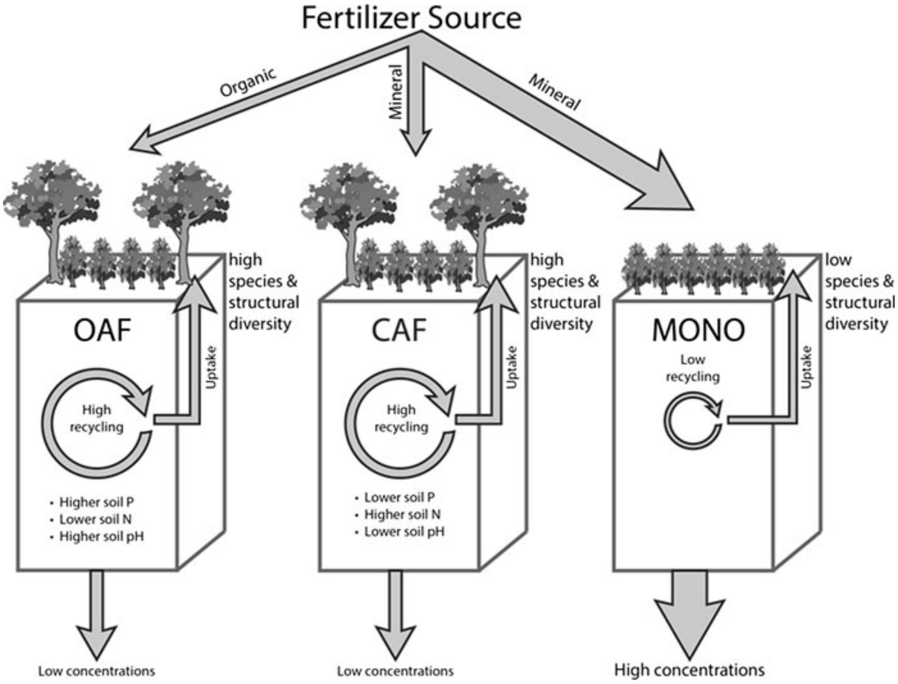

Fig. 6 Conceptual diagram of the relationships between nutrient inputs and species and structural diversity on soil characteristics and leachate concentrations in organic agroforests (OAF), conventional agroforests (CAF), and conventional monocultures (MONO). The size of arrows are indicative of the magnitude of the flux

Table 5 Soil characteristics between conventional and organic agroforests (0–10 cm) averaged across study period

Management	Total C (%)	Total N (%)	C:N	Bray-1 P (µg/g)	Gravimetric soil moisture (%)	pH	Bulk density (g/cm^3)
Organic	4.5 (0.12)	0.39 (0.005)	14 (0.14)	12.5 (0.70)	60.3 (0.009)	5.4 (0.06)	0.88 (0.03)
Conventional	5.1 (0.08)	0.42 (0.007)	13 (0.12)	8.0 (0.45)	63.8 (0.011)	5.0 (0.06)	0.82 (0.02)

Differences in nutrient concentrations, soil moisture (mass$_{water}$/mass$_{soil}$), and pH between the management types were tested by LMM. Means are reported for each species (±SE), and no significant differences were detected between management types. Bulk density values are provided for scaling purposes

Table 1). Therefore, it is not surprising that leachate NO_3^--N concentrations were higher in the monoculture than the agroforests (tension lysimeters, at 15 and 100 cm; Fig. 3a). Further, although NO_3^--N concentrations were significantly reduced at depth in the monoculture, due to its (1) high N inputs, and (2) reduced plant uptake (no trees), concentrations exceeded the public health standard limit (WHO 1996; Figs. 3a, 6). Nitrate concentrations in gravity lysimeters (15 cm) were significantly higher in conventional compared to organic agroforests (Fig. 4a), and it should be noted that although not significant in the tension lysimeters, this trend was still apparent at 15 cm depth. Elevated NO_3^--N concentrations in shallow leachate concentrations are likely driven by the larger N inputs in conventional agroforests through mineral fertilizers. However, NO_3^--N concentrations at 100 cm in the organic and conventional agroforests were very similar and below the standard limit. Even though conventional agroforests received about 2.5 times as much N as organic agroforests, NO_3^--N concentrations were very similar at 100 cm, which suggests that trees (density was also similar among agroforests) can draw concentrations down to around 8 mg NO_3^--N L^{-1} (a concentration that is still higher than found in near-by tree plantations (0.66 mg NO_3^--N L^{-1}; Ewel and Bigelow 2011; Fig. 6). The similarity among agroforests receiving different forms and amounts of inputs suggests that may trees have a “neutralizing effect”, and lower concentrations to levels which meet drinking water standards for nitrate (WHO 1996).

Although two orders of magnitude lower than nitrate concentrations, leachate organic P concentrations varied among farm management types. The monoculture received over three and a half times as much fertilizer P as the agroforests, and lost about three times as much P, primarily in organic form (at 15 cm; Fig. 3c). Although fertilizer was added in inorganic form in the monoculture, studies have shown that the application of fertilizer N tends to increase P leaching and that up to 80 % of the total P lost is in organic form (Monaghan et al. 2000, 2002). Unlike N, P concentrations in leachate were neither lower at depth nor different among management types at depth. Phosphorus is very conservatively cycled in tropical soils (Jordan 1982; Vitousek 1984), and P in solution is quickly adsorbed onto clay minerals. Thus organic P concentrations in leachate appear to be driven by inherent chemical mechanisms, which may also explain why solutions are similar at 15 and 100 cm. In these systems, it seems that regardless of management, additional P is either (1) being adsorbed onto clay minerals and effectively removed from the P cycle (Uehara and Gillman 1981), and/or (2) quickly assimilated by plants and microbes.

Although we observed significant effects of management on leachate concentrations, this was not the case for soil properties (Fig. 5; Table 5; Fig. 9 in Appendix). Due to the formulation of the statistical model, the effects of species overwhelm any management effects. Nevertheless, some trends are apparent. Soil P tends to be higher in organic agroforests where soil N tends to be higher in conventional agroforests (Fig. 6). This pattern is significant at deeper soil layers on these farms (Tully et al. 2013). Higher soil N in conventional agroforests is likely the result of greater N inputs and subsequent transport (via leaching) to deeper soil layers. Higher soil P in conventional farms may be due to lower yields (Tully and Lawrence 2011) and therefore lower demand of P compared to higher yielding conventional agroforests (see Tully et al. 2013).

Temporal variation in leachate and soils

Shallow leachate concentrations increased slightly in January following the first prune and during fertilization. However, the highest NO_3^--N concentrations followed the prolonged dry period (Fig. 4a). High rates of mineralization and nitrification are often observed in topsoil with the onset of rains (known as the “birch effect”; Birch 1964; Chikowo et al. 2004). The birch effect may explain the sudden pulse in NO_3^--N concentrations that we observed at the beginning of the rainy season. As fertilizer is typically added in January, it is unlikely that this pulse is the result of fertilizer application, although it is possible that residual water-soluble fertilizer NO_3^--N is mobilized when water passes through the soil.

Phosphate (and ammonium) concentrations increased tenfold during the driest period (about one month before the peak in NO_3^--N concentrations; Fig. 4c). As PO_4^{3-}-P is tightly bound to soil colloids, and only a small fraction is mobile, in a typical month this soluble fraction was diluted to a mean concentration of 0.08 mg PO_4^{3-}-P L^{-1}. However, in dry months (<3.5 mm rainfall per day) soluble P was diluted in less water leading to higher concentrations at the end of the dry period (0.31 mg PO_4^{3-}-P L^{-1}).

Temporal variations in soil C, N, and P tracked plant nutrient demand. The draw-down of soil N and P between June and September may be the result of enhanced *Coffea* uptake as the crop matures (i.e. berries ripen), which appears to demand high quantities of nutrients. Soil P also declined from January to April, increasing again in May. This pattern may be better explained by changes in soil chemistry as a result of nutrient additions in the form of pruning residues (December/January) and fertilizer (January/February).

Following nutrient inputs, microbial and plant activity increases, and in tropical soils, P often limits plant and microbial uptake of other nutrients (Vitousek 1982), which may explain why soil P declined following nutrient additions, but soil N remained high. This is further supported by the fact that decomposition of pruning residues is P-limited, especially in the initial stages (Tully and Lawrence 2012).

Higher concentrations in tension lysimeters

Nitrate concentrations were higher in tension lysimeters than in gravity lysimeters, which may be due, in part, to the sampling protocol. Monthly water collection from tension lysimeters may not have captured some of the short-term variations in leachate concentrations that may follow large rainfall events (dilution of nutrient concentrations) or management interventions such as fertilizer application and shade tree pruning (sudden spikes in nutrient concentrations). Gravity lysimeters, on the other hand, provide an "average" concentration across the month as the bottles continuously collect water across that time period. Tension lysimeters use suction to collect leachate, which allows for the water sampling even during relatively dry periods (when no water may be moving vertically through the soil column). Therefore, tension lysimeters have access to the more concentrated solutions that tend to occur during dry periods.

Species affect leachate and soil

Farmers are keenly aware of the benefits imparted by the presence of N-fixers (Albertin and Nair 2004). Enhanced N availability in the soil (Table 4) and higher concentrations in soil solution under *Erythrina* trees is the result of N-fixation and subsequent transfer of fixed N partly through high quality leaves during annual prunings (see Payán et al. 2009 for more detailed spatial effects). *Erythrina* leaves have high N and P concentrations and decompose quickly, rapidly releasing nutrients to the soil (Tully and Lawrence 2012). Nitrogen fixed by *Erythrina* may elevate surface soil solution concentrations, potentially transferring more N to deeper soil layers.

The elevated organic P concentrations found in leachate under *Coffea*–*Erythrina* combinations suggest that *Erythrina* may play an important role in P cycling (Tully and Lawrence 2012), potentially as a result of mychorrhizal activity (Danso et al. 1992). For example, bioavailable soil P was higher under *Coffea* near shade trees compared to distant *Coffea* plants. Phosphorus availability may be greater in species mixtures as mychorrizal fungi are capable of liberating P not available to plants through enhanced mineral weathering (Jongmans et al. 1997) and by associating with bacteria that secrete phosphatases or excrete organic acids (Smith et al. 1997). In addition, greater quantities of nutrient-rich litter and pruning residues can be produced under species mixtures, which may enhance the quality of surrounding soils over time. For example, initial P-release from decomposing *Coffea* leaves is much higher when mixed with *Musa* and *Erythrina* (Tully and Lawrence 2012). The higher concentrations of both C and N in soils under the *Coffea*–*Erythrina* combinations (Table 4) further support the theory that the presence of multiple species (especially N-fixers) can improve soil quality.

Soil characteristics do not predict leachate concentrations

Available soil P was a good predictor of inorganic PO_4^{3-}-P in leachate at 15 cm suggesting that Bray extractions may be useful in determining concentrations of P in shallow leachate. However, we did not identify any surface soil properties that were able to predict nutrient concentrations at depth. Potassium chloride (KCl) is used to extract soil N and predict NO_3^--N concentrations in leachate. Although we did not perform KCl extractions, we expect that the surface concentration of KCl-extractable N, will not likely make a good proxy for deep leachate concentrations.

Conclusions

Both farm management and species composition affected leachate nutrient concentrations and soil properties in coffee agroecosystems. Overall, the monoculture farm, which received higher fertilizer N, also had higher nutrient concentrations in leachate than the agroforests. At depth, agroforests had very similar concentrations of nutrients in leachate despite large differences in nutrient inputs, which suggests that the presence of trees may draw concentrations down to levels that meet the WHO standards for drinking water. Both soil and leachate nutrient concentrations were elevated under the N-fixing species, supporting the critical role this functional group plays in sustaining agroforests. Finally, the soil nutrient concentrations (C, N, and P) and properties (soil moisture and pH) we measured were not strong predictors of nutrient concentrations in leachate.

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Appendix

See Figs. 7, 8, 9.

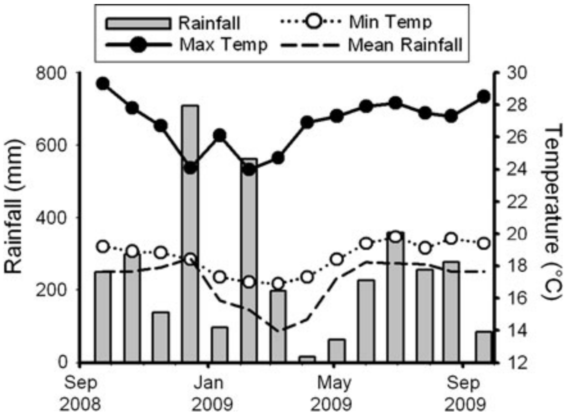

Fig. 7 Rainfall and temperature throughout the study period (September 2008–October 2009) in the Central Valley of Costa Rica. Cumulative rainfall and mean daily minimum and maximum temperatures for each 28-day period prior to sample collection. Dashed line represents the mean monthly rainfall from 1942–2009 (CATIE meteorological data)

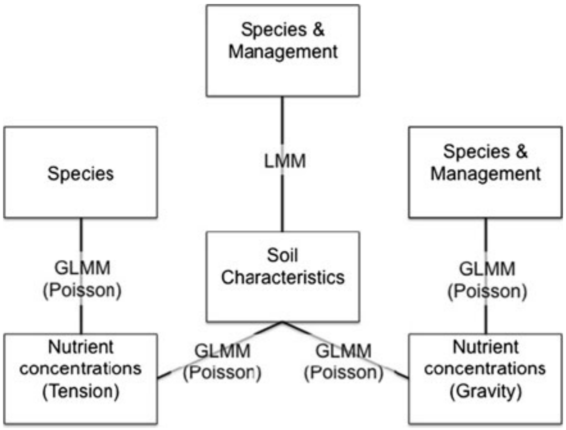

Fig. 8 Each statistical model run during the analysis. The *boxes* represent key variables. The *lines* connect the response variables, which are higher up, to the dependent variables, which are lower in the diagram. The text describes the type of linear model used

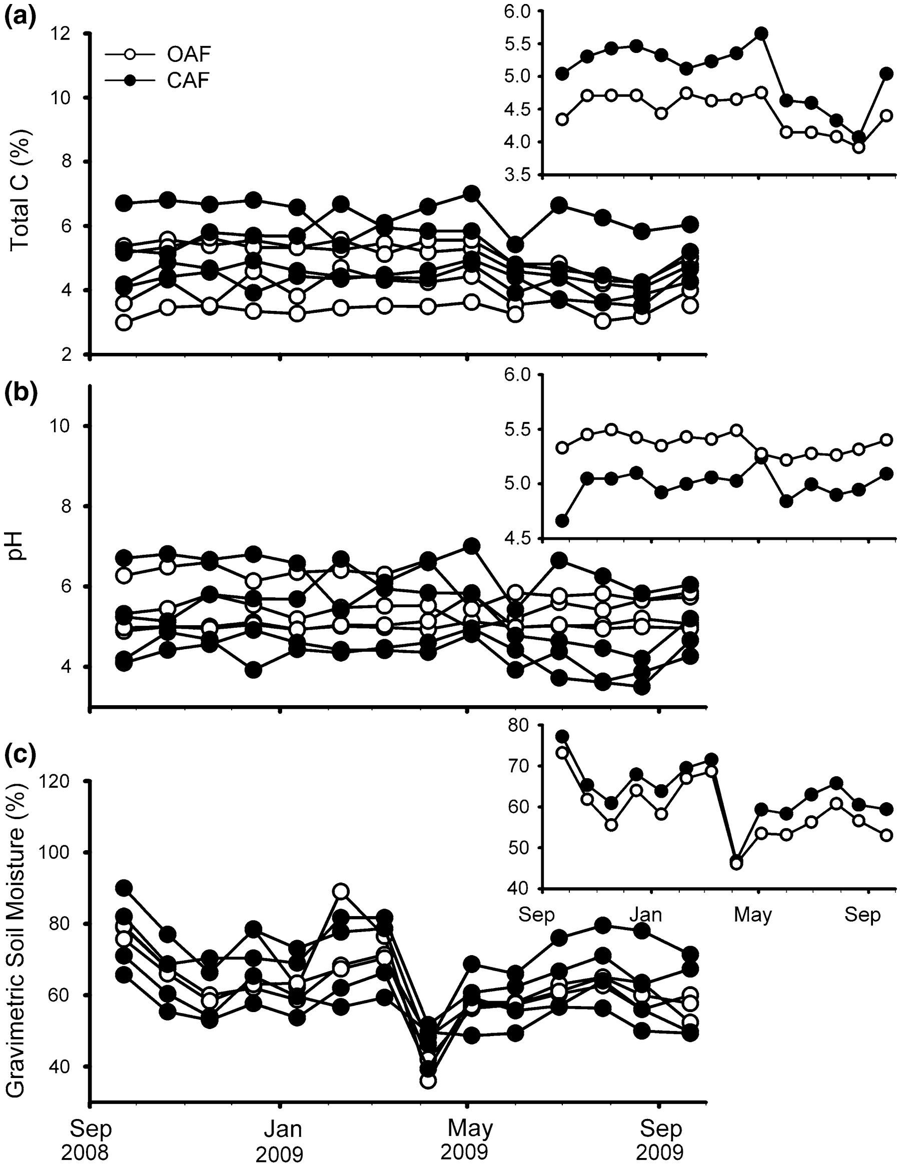

Fig. 9 Soil C, pH, and soil moisture in the top 10 cm in coffee agroforests in Costa Rica. Mean **a** total C, **b** pH, and **c** gravimetric soil moisture in soils collected from 0 to 10 cm in organic and conventional coffee agroforests (across species) throughout the study period (September 2008–October 2009). Closed circles indicate conventional agroforests (CAF; $n = 4$), and open circles indicate organic agroforests (OAF; $n = 4$). Inset of mean soil C, pH, and moisture dynamics across farms are also presented

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