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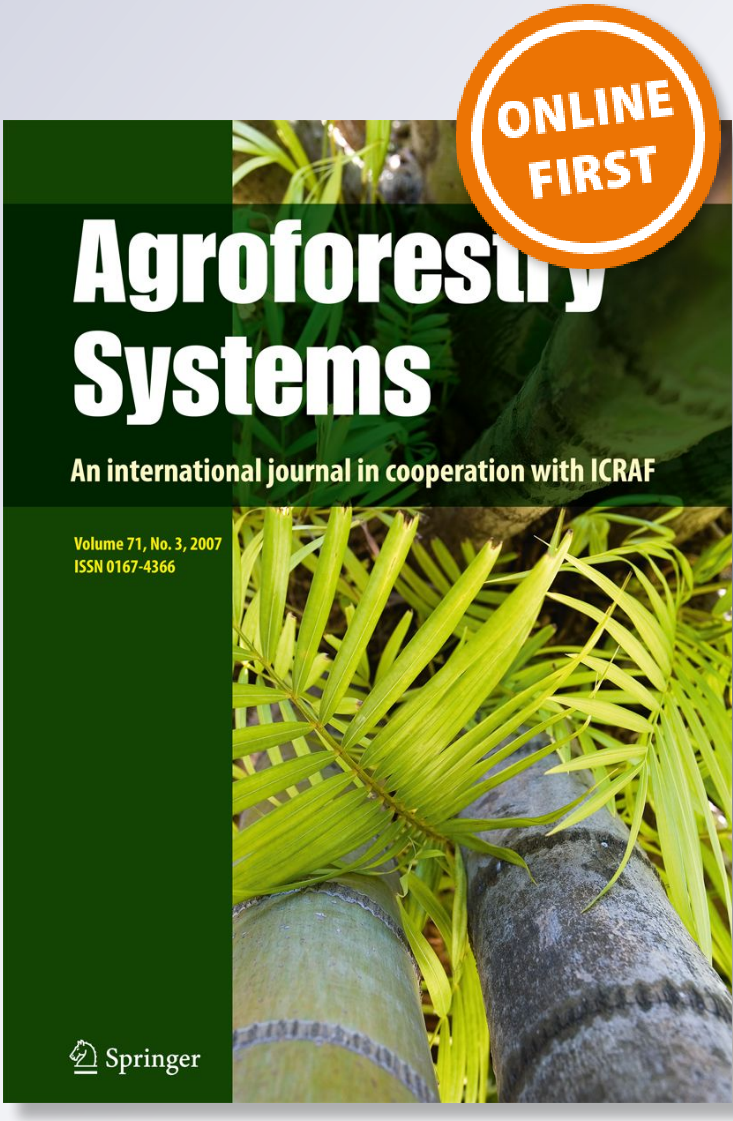

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Abstract Spatial relationships between root length density of *Coffea arabica* (coffee RLD) and soil nutrient- related factors at plot scale in a coffee-*Erythrina poeppigiana* system was studied by geostatistics. In a 24 × 29 m area, (organic and conventional management), coffee and Erythrina fine roots and soil chemical properties were sampled on an irregular grid in the topsoil. A factor analysis explained 83 % of the total variation of the soil attributes. Soil factors were identified: Chemical fertility (CF), Micronutrients, Organic matter, and Acidity (Ac). Based on the spherical model, all the attributes presented a strong spatial structure. The scale of spatial correlation for CF was lesser than for Ac, but similar to coffee RLD. Erythrina RLD had a short-range variation. Patchy areas of high spots of coffee RLD were greater in organic plot. Cross-semivariogram analysis estimated a correlation between soil factors and coffee RLD over a scale of 5.50 m; but 4.23 m with Erythrina RLD. Nutrients linked to P, Zn, exchangeable bases and acidity soil affected the scale of spatial aggregation pattern of coffee RLD. The spatial response of coffee RLD suggests a differential nutrient uptake strategy for acquiring soil nutrients induced by the quality of organic and inorganic fertilizer inputs. The fact that coffee RLD had higher scale of spatial variation than Erythrina RLD and a negative spatial correlation indicate that pruned Erythrina trees are not so competitive for acquiring shared nutrients in an agroforestry system.

Keywords *Coffea arabica* · Fine root length density · Spatial correlation · Acid soils · Organic management

A. Mora (✉)
Instituto de Investigaciones para el Desarrollo Forestal (INDEFOR), Facultad de Ciencias Forestales y Ambientales, Universidad de Los Andes, Conjunto Forestal vía Chorros de Milla, Merida, Estado Merida, Venezuela
e-mail: amora@ula.ve

J. Beer
Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica

Introduction

Belowground interaction studies are fundamental to understand the development and distribution of crop and tree fine roots in agroforestry systems (Jat and Poonia 2006). Assuming that at equal supply of growth resources in the soil, the nutrient and water uptake of each plant component is related to the amount its root length per unit soil volume, irrespective of species (Schaller et al. 2003). For example, a negative relationship between total fine root biomass and soil fertility was found in forested wetland ecosystems (Neatrour et al. 2005). Small-scale nutrient heterogeneity could have a strong effect on belowground interactions. The spatial variability of

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coffee fine roots depends on nutrient availability and can be influenced by both the manner of fertilizer application and distance from the shade tree (Schaller et al. 2003). It has been demonstrated that fertilized areas with available nutrients (i.e., high Ca and Mg concentrations) stimulate the proliferation of coffee fine root length in shaded coffee plantations (Schaller et al. 2003; van Kanten et al. 2005).

The scale of spatial heterogeneity estimated by the range in a semivariogram, describes the distance over which changes in the value of some variable can be detected (Kleb and Wilson 1999). Cheng (2004) sought to establish the relationships between plant fine root response and soil nutrient spatial heterogeneity. In response to this spatial variation, many plants selectively increase fine root biomass within enriched patches in order to forage efficiently for nutrients (Hodge 2006). Root length density (RLD) can be interpreted as a regionalized variable, showing spatial correlation (Jackson and Caldwell 1993; Vamerali et al. 2008; Gwenzi et al. 2011). Many attributes (e.g., soil properties, plant occurrence, biotic factors, etc.) can exhibit differential spatial heterogeneity as a spatial arrangement (pattern) of high and low values across the field or plot (Ettema and Wardle 2002); for instance, in soil attributes (Utset and Cid 2001; Paz- Gonzalez et al. 2000), or mirid insect density in cocoa agroforests (Babin et al. 2010). In particular, geostatistical studies on spatial heterogeneity of coffee fine roots and soil nutrients under shade trees are not known. This paper reports the results of a study on the scale of the spatial heterogeneity (aggregation pattern) of coffee fine root length density (RLD, $d < 2.0$ mm) and soil nutrients in experimental plots of a coffee- shade tree association (*Coffea arabica* shaded by *Erythrina poeppigiana*) with conventional and organic managements. It was hypothesized that coffee RLD is positively and spatially correlated with soil fertility factors; thus, coffee fine root foraging is influenced by the distribution of enriched patches of available nutrients or by limiting conditions—e.g., high content of Aluminum.

Materials and methods

Site description

The study was carried out in a long- term experiment of alternative coffee production systems established in 2000 and leaded by "Centro Agronómico Tropical de Investigación y Enseñanza" (CATIE), Turrialba, Costa Rica (Haggar et al. 2011). This experimental area represents a low altitude (685 m) for coffee growing, 2,700 mm annual of precipitation (1948 –2005) with few dry months (February–march). Prior to the establishment of the trial, the site was used (commercial farm) for sugar cane (*Saccharum officinarum*) production and soils were classified as Typic Endoaquepts and Typic Endoaquults (Sánchez- de León et al. 2006), and characterized as mixed alluvial with a poor or medium fertility and a water table ranging between 40 and 120 cm (Aguirre 1971). The study site is relatively flat (slope of < 1 %). *Coffea arabica* cv. "Caturra" and shade trees (*E. poeppigiana*) were planted during August and October 2000. Coffee planting holes were spaced 1×2 m apart with trees planted at 4×6 m. In November 2000, coffee replanting had to be done because of mortality due to the initial impeded drainage problem on some plots, which was resolved by establishing deep principal drainage channels during coffee replanting (> 1.0 m).

For the purposes of the present study two types of coffee managements were considered: i.e., conventional and organic. The conventional management corresponded to standard levels of input and management used at that time by local farmers; e.g., chemical weed and pest control plus mineral fertilizer (Table 1). The annual inputs of N, P, and K for conventional plot were 300, 20, and 150 kg ha^{-1} year^{-1}; respectively. The organic system included manual weed control and nutrients were supplied in the form of composted manure and foliar applications of botanical and biological composts; annual inputs of nutrients were 287, 205, and 326 kg ha^{-1} year^{-1} of N, P, and K; respectively. *Erythrina* tree shade was varied according to management treatment. In the conventional, total pruning was applied leaving only the main trunk to a height of about 1.8–2.0 m (a common practice by Costa Rican farmers). Whereas under organic management, trees were partially pruned (minimum of three branches were left). In both cases, pruning was applied twice a year and the pruned material was left on site.

Spatial sampling scheme and sample processing

In order to study the spatial variability of coffee RLD and of soil nutrients, an irregular grid was marked on

Table 1 Fertilizer and herbicide applications and other inputs[a] in the conventional and organic sub- treatments of the experimental coffee -based agroforestry systems- Bonilla experimental station, CATIE-MIP-AF-NORAD project, Costa Rica

Inputs	Organic	Conventional
Soil amendment	20 tons ha^{-1} $year^{-1}$ coffee pulp	400 kg ha^{-1} $year^{-1}$ 18–15–6–2 (N,P, K, Mg and B)
	chicken manure 7.5 tons $ha^{-1}year^{-1}$	45 kg ha^{-1} $year^{-1}$ NH_4HO_3
	200 kg Kmag ha^{-1} $year^{-1}$	Foliar application: B, Zn
	200 kg Phosphoric rock ha^{-1} $year^{-1}$	(once a year)
Weed control	No application of herbicides. Weeds were removed manually and mechanically with a string trimmer	10 ml l^{-1} Roundup to eliminate herbaceous species among coffee plants within a row
Pest control	No application of fungicides	fungicides: 2.5 g l^{-1} H_2O per block of Atemi or copper sulfate (once a year)

[a] Nutrient inputs from decomposition of shade tree biomass were not considered

two contiguous plots (Fig. 1, total area 24 × 29 m): one with organic and the other with conventional management. Points were systematically located following coffee and tree rows (40 points). An additional 24 points were randomly arrayed on inter-coffee row. The sampling design optimized the number of lag classes for semivariogram analyses where the minimum sampling interval was 0.5 m and permitted estimate the potential changes in coffee RLD (at small and large scales) that may occur along and between coffee rows. All sampling points were identified according to *X* and *Y* coordinates.

After litter layer was carefully removed, soil cores (0–20 cm) were taken by hammering an auger into the soil (internal diameter 6 cm). The samples were collected in July and August 2005 during the initial harvest period and after pruning of the *Erythrina* trees. Soil cores were bagged and transported from the field to the CATIE root laboratory and processed immediately. Each soil–root sample was weighed and homogenized; stones and other impurities were removed and roots cut to a length < 3 cm with scissors. A subsample (on average 50 % or ~400 g) was separated for fine root extraction and the remainder was sent for soil analyses: pH in H_2O; exchangeable bases (Ca, Mg, K); exchangeable acidity determined in 1.0 N KCl; organic carbon and total nitrogen was determined by combustion method using auto- analyzer equipment; available P and micronutrients (Cu, Zn, Mn, and, Fe) were extracted by modified Olsen method (pH 8.5).

All root samples were soaked in water overnight. Fine roots were gently washed with tap water to minimize loss or damage and to remove soil particles. Nested 1.5 and 0.5 mm sieves were used to recover

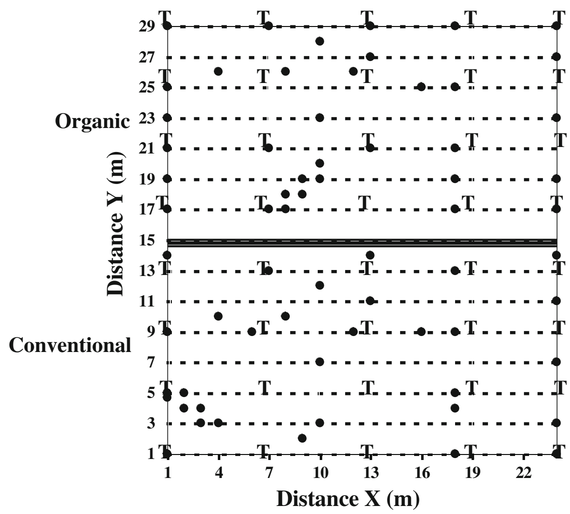

Fig. 1 Sampling scheme in organic and conventional plots of the *Coffea arabica- Erythrina poeppigiana* association. *Black dots*, *dash*, and, "**T**" denote sample cores, coffee rows, and, the location of *E. poeppigiana* trees, respectively

fine roots. Under a stereoscope (8×), tree and coffee roots were separated based on morphological characteristics. The *C. arabica* roots were brown- reddish and showed smooth branching. *E. poeppigiana* roots were brown- yellowish and showed pigments dark brown to black; nodules were almost spherical and slightly reddish to brown- yellowish. The total fine root length from coffee was determined by scanning in water with the software package WinRHIZO™ (Regent Instrument Inc., Quebec City, Canada). After scanning, the same samples of fine roots were dried to constant weight at 65 °C and weighed in a precision scale with three digits. The density of fine root length (RLD, cm cm^{-3}) was computed for coffee.

Statistical analysis

Shapiro–Wilk tests were applied on the data for normal distribution (Shapiro and Wilk 1965). In addition to descriptive statistics, a factor analysis (FA) of the soil chemical attributes was conducted to summarize and investigate the relationships between the soil chemical properties and coffee RLD. The central aim of FA is to explain the variation in a multivariate data set by extracting as few ''factors'' (called latent factors) as possible and to detect hidden multivariate data structures based on the correlation structure of the soil variables. Thus, theoretically, FA should be ideally suited to provide a clear presentation of the relevant information inherent in a data set with many analyzed elements (e.g., soil attributes). The possibility of detecting common processes determining the variability of soil attributes are improved by using FA (Reimann et al. 2002). Factors were extracted using the principal factor analysis and the varimax rotation method (Dallas 1998). The values of each new latent factor are presented as scores.

To study the relationships between the soil factors, Erythrina RLD and coffee RLD, a multiple regression model was fitted, using the scores of the latent factors as independent variables and coffee RLD as a dependent variable. Semivariograms are necessary because the values from samples within a grid are used repeatedly and are not independent (Isaaks and Srivastava 1989). For coffee RLD data, semivariograms ($\gamma_{(h)}$) of the observed residuals were built after fitting a spatial model for the mean of coffee RLD (Diggle and Ribeiro 2007) using those covariates that were significantly correlated with coffee RLD and management types (potential covariates). This approach permits modeling the potential spatial relationships between them.

The linear regression model fitted was

$$Z_s = \beta_0 + \sum_{j=1}^{p} X_j(s)\beta_j + e(s) \quad (1)$$

where Z_s is the coffee RLD values observed at spatial location s, X_{j} are the covariates (i.e., soil factors extracted by factor analysis as well as management types), β's are parameters and $e(s)$ residuals. This approach permits modeling any spatial trend attributed to spatially referenced covariates (Diggle and Ribeiro 2007). The semivariance statistic was estimated using the following expression

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{k=1}^{N(h)} [Z_k - Z_{k+h}]^2, \quad (2)$$

where $N(h)$ is the number of observation pairs separated by distance h, $Z_{(k)}$ is the value of the residual estimated at location k, and $Z_{(k+h)}$ is its value at a location at distance h from k.

Likewise, in order to determine the magnitude of spatial correlations between coffee RLD and soil factors, cross- semivariograms were estimated by

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{k=1}^{N(h)} \left[Z_{i(k)} - Z_{i(k+h)}\right]\left[Z_{j(k)} - Z_{j(k+h)}\right], \quad (3)$$

where, $Z_{i(k)}$ and $Z_{j(k)}$ represent the value of the residuals of the coffee RLD and soil factors scored at a location at distance h from k (Isaaks and Srivastava 1989).

Prior to constructing each semivariogram or cross-semivariogram, the data was segregated into distance classes by setting the appropriate number of bins and bin width (lag distance). The procedure permitted finding the maximum resolution of the semivariograms at small sampling distances (Franklin and Mills 2003). Each of experimental semivariogram was modeled using the spatial spherical model:

$$\hat{\gamma}(h) = \left\{C_0 + C\left(1.5\frac{h}{A_0} + 0.5\frac{h^3}{A_0^3}\right)\right\}; \quad \text{If } h < A_o, \quad (4)$$

where, C_0 is the nugget variance, C is the sill, A_o is the range, and h is the lagged distance.

In the analysis, when spatial dependence was detected, the ordinary kriging estimator was used to estimate the coffee RLD and soil factors at unsampled locations in the experimental plot. Visual maps were created using a grid specification of 1 × 1 m to describe local patterns of variation. All the geostatistical analyses were carried out with the geostatistical package gstat (Pebesma 2004) under the statistical environment R (R Development Core Team 2010).

Table 2 Summary statistics of soil chemical attributes and coffee fine root length density (RLD) in mineral soil (0–20 cm) of a coffee- tree association (*Coffea arabica* shaded by *Erythrina poeppigiana*) under organic and conventional management

	Conventional			Organic		
Soil attribute	Mean	SE	CV	Mean	SE	CV
pH (water)	4.8	0.1	5.4	6.1	0.1	12.8
Exch- Al (cmol(+) l^{-1})	2.1	0.2	39.0	0.4	0.1	134.9
Exch- (Ca cmol(+) l^{-1})	2.8	0.2	30.2	7.7	0.5	37.4
Exch- Mg (cmol(+) l^{-1})	1.2	0.1	23.8	2.1	0.1	24.6
Exch- K (cmol(+) l^{-1})	0.4	0.03	52.7	0.7	0.04	42.2
Fe (mg l^{-1})	194.5	8.3	23.5	129.2	10.4	44.0
Cu (mg l^{-1})	10.6	0.2	11.3	9.4	0.3	14.8
Mn (mg l^{-1})	31.8	3.1	53.5	19.4	2.0	55.2
Zn (mg l^{-1})	1.8	0.1	22.4	4.5	0.4	51.9
Available P (mg l^{-1})	8.2	0.6	42.2	76.2	12.6	94.2
Total N (%)	0.25	0.01	9.8	0.27	0.01	14.1
Organic C (%)	2.52	0.04	9.3	2.64	0.06	14.5
Erythrina RLD (cm cm^{-3})	0.18	0.10	188.0	0.55	0.15	134.5
Coffee RLD (cm cm^{-3})	1.41	0.17	63.5	1.32	0.16	77.3

SE Standard error, *CV* coefficient of variation (%)

Results

Descriptive statistics of soil chemical properties and coffee fine root density

In general, the soil chemical fertility in the organic plot was markedly improved compared to the conventional plot (Table 2). The organic inputs dramatically reduced the acidity of soils: i.e., pH of 6.1 versus 4.8 in the organic and conventional plots, respectively. Ca contents (exchangeable bases in general) were higher in the organic plot ($p < 0.001$). The Available P contents differed markedly between management systems ($p < 0.001$). Fe contents were very high in both organic and conventional management but was lower in the organic plots ($p = 0.005$). Organic C values observed in the soils of this study are considered relatively low ($\sim$2.5 %) with no difference between management systems.

The mean value of the coffee RLD was similar ($p = 0.2769$) for conventional and organic plots; i.e., 1.41 and 1.32 cm cm^{-3}, respectively (Table 2). This was comparable with previously reported values (0–20 cm) under different shade- tree species in Costa Rica (Morales and Beer 1998; Schaller et al. 2003; van Kanten et al. 2005). However, the Erythrina fine RLD varied between organic and conventional plots; for conventional, Erythrina RLD was estimated in 0.18 $\pm$ 0.10 cm cm^{-3}, but under the organic plot, 0.55 $\pm$ 0.15 cm cm^{-3}. These means were different statistically ($p = 0.0456$). Using the coefficient of variation (CV) as in index of dispersion, it was possible to establish the within- plot relative variability of RLD data. As it was expected, it shows the highest dispersion (CV's were estimated above 60 %) around the mean evidencing its high spatial variability. For geostatistical analysis, RLD data were transformed.

Determining soil nutrient- related factors and relationship with coffee RLD

The factor analysis provides a synthesis of the information obtained respect the soil attributes. Communality refers to the part of the variance explained by the common factors. A high value (e.g., > 0.5) indicates that a variable was well explained by the factor model. Manganese was the soil attribute least explained by a four factor model and hence was excluded from the subsequent analyses (Table 3).

The model using the four factors explained 83.4 % of the total variance. Based on the factor loadings after varimax rotation, which was used to increase the interpretability of the factors, factor 1 was called "exchangeable bases or chemical fertility factor" and comprised the exchangeable bases, P and Zn with

Table 3 Factor loadings and percentage of the total variance explained by the four-factor model in the factorial analysis applied on the soil chemical attributes

Soil attribute	Factor 1: fertility	Factor 2: micronutrient	Factor 3: organic matter	Factor 4: acidity	Communality
Exch-Al	−0.422	0.527	−0.175	**−0.554**	0.794
Exch-Ca	**0.645**	−0.48	0.248	**0.508**	0.966
Carbon	0.000	−0.103	**0.989**	0.000	0.995
Cu	0.000	**0.799**	−0.194	0.000	0.678
Fe	−0.367	**0.909**	0.000	−0.182	0.995
Exch-K	**0.716**	0.000	0.000	0.000	0.525
Exch-Mg	**0.696**	−0.283	0.000	0.499	0.818
Mn	−0.286	0.000	0.168	−0.544	**0.407**
N	0.119	−0.123	**0.951**	0.000	0.933
P	**−0.955**	0.119	0.000	0.231	0.979
pH	**0.718**	−0.408	0.000	**0.527**	0.969
Zn	**0.919**	−0.132	0.000	0.295	0.949
Cumulative percent of variance explained by factors					
	34.1	53.1	70.3	83.4	

Values for loadings > 0.6 and communality < 0.5 are highlighted in bold

loadings >0.60. The high and positive scores for this factor mean enhanced availability of exchangeable bases and high P and Zn concentration. Factor 2 comprised the variables available Cu and Fe (Micronutrient factor). Factor 3 was related to the organic matter status of the soil (high loadings for C and total N) and was referred to as "the organic matter factor". Factor 4 shows that increased exchangeable Al was associated with decreased pH and Ca; thus this factor was designated the "Acidity factor". In this way, the variation of the soil chemical properties was summarized using a reduced number of factors, which were independent of each other.

In order to display the spatial distribution of the soil factors, Erythrina RLD, and coffee RLD in the organic and conventional plots, "bubble" type plots were built based on the scores of each soil factor and the coffee and Erythrina RLD for each position sampled (Fig. 2); spatial aggregation of high density RLD values can be seen (Fig. 2a, f). Under conventional management (plot bottom), nothing or few Erythrina fine roots were found compared to organic plot (top). As expected from the preceding discussion, the chemical fertility factor was higher in the organic plot (Student T based test, $p = 0.004$) but was not spatially homogenous (highest in the upper right of the plot; bigger black circles, Fig. 2b). This factor includes available P, which is a relatively immobile element in the soil.

In addition, this pattern seems to be inversely related to average available Cu and Fe contents (Fig. 2c), which appear to be negatively correlated to the chemical fertility factor including relatively high values in the conventional plot ($p = 0.0129$). The organic matter factor seems to be higher in the organic plot (Fig. 2d) but no difference was detected between organic and conventional plots ($p = 0.1154$). As previously discussed, acidity was lower in the organic plots ($p < 0.0001$); higher scores (bigger black points) covered most of this plot. A similar but reversed spatial pattern to that of coffee RLD was observed; i.e., the aggregated or patchy distributions suggested an inverse spatial relationship between coffee RLD and the acidity factors (pH, exchangeable Al).

Stepwise multiple regression analysis was carried out to determine the effect of the soil factors and Erythrina RLD on the coffee RLD. In this analysis, the best fit (F- statistic $= 4.92$; $p < 0.01$; $R^2 = 0.33$) was obtained using the chemical fertility (CF), acidity (Ac) factors, and Erythrina RLD (ERLD):

$$\text{Coffee RLD} = 1.09 + 0.154(\text{CF}) - 0.117(\text{Ac}) - 0.193(\text{ERLD}) \quad (5)$$

It should be noted that coffee RLD showed a weak but significant relationship (non-spatial) with exchangeable bases, P, Zn, pH, and exchangeable Al at the plot scale that was studied. High coffee RLD

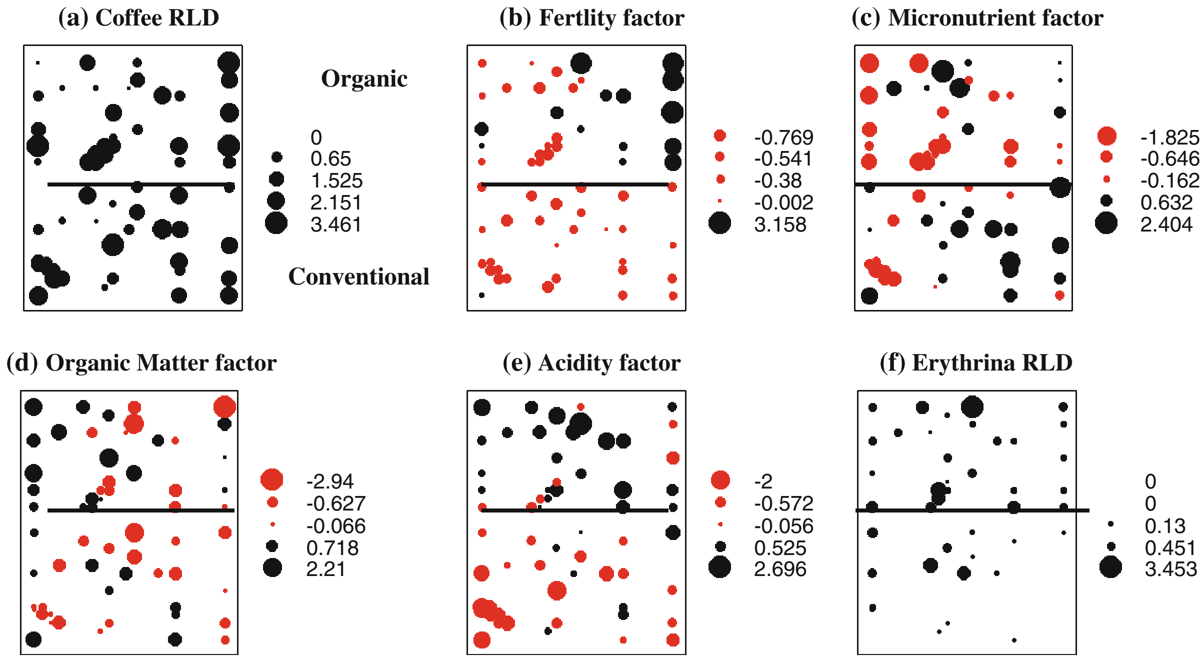

Fig. 2 Bubble plots for coffee fine root density (RLD, cm cm^{-3}), *Erythrina poeppigiana* RLD, and soil factor scores for different locations in the *Coffea arabica- Erythrina poeppigiana* association in organic (*top*) and conventional (*bottom*) plots. Point sizes are proportional to data values

was related to high exchangeable bases and amounts of available P and Zn.

Effects of the factors derived from soil nutrient variables on the spatial heterogeneity of coffee RLD

Based on stepwise multiple regression analysis of coffee RLD, semivariogram for coffee RLD was estimated using residuals from model (1) in order to determine the scale of spatial heterogeneity. For the chemical fertility (CF), acidity (Ac) factors, and Erythrina RLD (ERLD) semivariograms were estimated using only management types as covariates.

All the variables presented a spatial autocorrelation and semivariograms were well fitted with spherical model (Figs. 4, 5). A model spherical first rises from comparisons of neighboring samples that are similar and spatially correlated and then levels off at the sill semivariance, indicating the distance beyond which samples are independent. Thus, statistics from the spherical model indicate the range over which samples show spatial correlation, an index of the scale of spatial pattern in the studied plot. Besides, semivariance that exists at scale finer than field sampling is found at 0 lag distance and is known as the nugget effect (variation occurred over short distances). Comparing the semivariograms, the range over which there was a strong spatial dependence was different between coffee RLD and Erythrina RLD (8.41 and 3.5 m; respectively).

For coffee RLD, the structural variance or partial sill (C_p) represents 55 % of the total spatial variance implying a strong spatial correlation among sampling points separated by 8.4 m or less. This fact is reflected on the kriged map of coffee RLD that shows a patchy spatial pattern of density values in both organic and conventional plots. Furthermore, it seems that areas of high coffee RLD are somewhat greater in conventional than organic plots (Fig. 3a, right side). In contrast, the spatial heterogeneity scale of Erythrina RLD was lesser (3.5 m) and only a 24 % of the total spatial variance was estimated. The kriged map of Erythrina RLD describes clearly small clusters or short-range spatial structures and the occurrence of values below 0.22 cm cm^{-3}, under conventional plot (Fig. 3b). On the other hand, the range of spatial correlation for the chemical fertility factor (CF) was less than that for the acidity factor (Ac); 5.08 and 8.17 m, respectively. As a result, the spatial pattern of

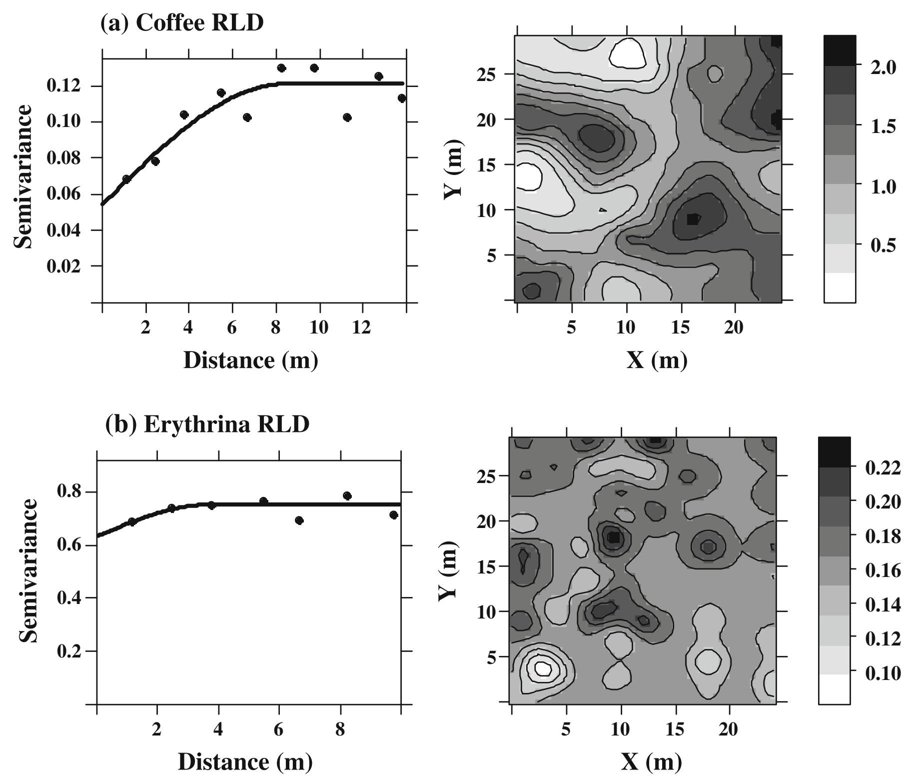

Fig. 3 Semivariograms of residuals from the linear model of density of coffee fine root length (RLD, cm cm^{-3}) on soil factors extracted by factorial analysis (*left*). Kriged maps for coffee RLD and Erythrina RLD estimated across the organic and conventional plots (*right*). In kriged maps, above 15 m on the *Y* axe represents the organic plot, below the conventional plot

the CF factor showed patches smaller and more numerous than for the Ac factor (Fig. 4a, b). Patches with the highest scores (i.e., high exchangeable bases and P content) were found in the organic plot.

Cross-semivariograms fitted (Fig. 5) confirmed the spatial relationship between the soil factors and coffee RLD over a spatial scale of 5.50 m. The spatial correlation estimated between coffee RLD and the CF factor was 0.61; it was −0.70 between coffee RLD and the Ac factor (Table 4). Besides, Erythrina RLD showed a negative spatial relationship to coffee RLD. This type of correlation could not be detected using the Pearson correlation coefficient (0.31, −0.24 and −0.14, respectively) because the Pearson statistic does not take into account the spatial locations of the soil cores.

Discussion

The present study is the first research of the spatial distribution of coffee fine roots, and their spatial relationship with soil attributes on a coffee- shade tree association by using geostatistic analysis. When comparing managements, low exchangeable Al in the organic plot can be attributed to the increase of pH values; it is also likely that there was a reaction of Al with organic compost (Juo and Franzluebbers 2003), which was provided in high quantities (Table 1). In contrast, under the conventional management, low pH could be associated with the application of nitrogen-based fertilizers, especially Urea (Theodoro et al. 2003). Phosphorus is a limiting nutrient for crop production in tropical soils. This limitation is mainly caused by strong adsorption of $H_2PO_4^-$ to Aluminum and Iron (hydr) oxides, which transform large proportions of total P into a form that is unavailable to plants (Juo and Franzluebbers 2003). Transformations and availability of soil P not only depend on soil characteristics, but also on interactions with plants and associations of plants with microorganisms. Correlations between spore production of vesicular arbuscular mycorrhiza (VAM) and the abundance of coffee fine roots have been found in coffee- based agroforestry systems (Cuenca et al. 1983; Cardoso et al. 2003).

The contribution of the acidity factor implies that high acidity or low pH and low Ca content were associated with lower coffee RLD. In Costa Rica,

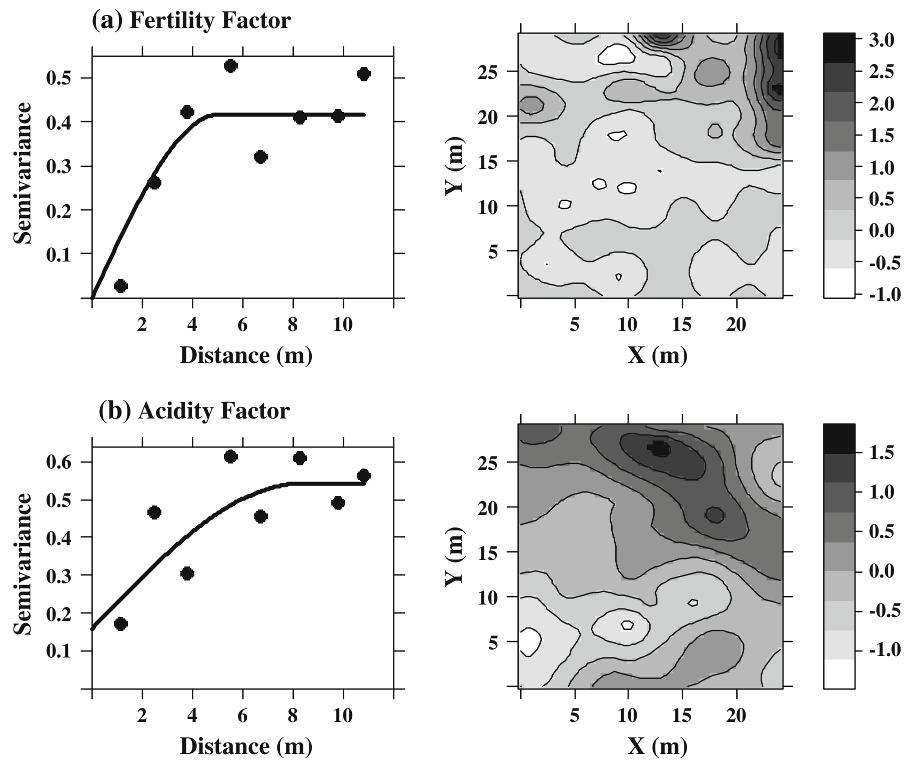

Fig. 4 Semivariograms of soil factors extracted by factorial analysis (*left*). Kriged maps for soil factor scores estimated across the organic and conventional plots (*right*). In kriged maps, above 15 m on the *Y* axe represents the organic plot, below the conventional plot

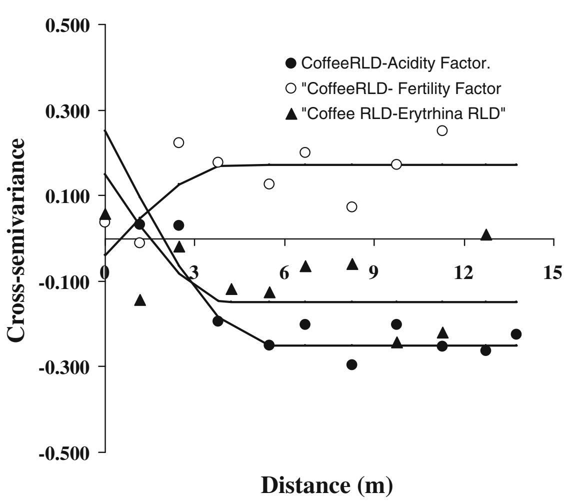

Fig. 5 Cross- semivariograms between coffee (*Coffea arabica*) fine root length (RLD) and *Erythrina poeppigiana* RLD, and soil factors

fertilizer and limestone applications on the soil surface are common practices used to correct acidity and increase coffee productivity. Even though it is recognized that coffee plants are tolerant to acid soils (pH 5–6.5 and up to 60 % of Al saturation), some coffee varieties are very sensitive to high Al concentrations (Cardoso et al. 2003) leading to decreases of root dry weight and root length percent in the inferior horizons of the soil. However, this may be compensated by higher fine root concentration in the mineral top soil layer or in litter layer as was reported in Mora (2011). It is possible that Cu emerged as an important element in the factor analysis because the conventional plot reflected the use of Cu-based fungicides, a common practice in coffee management during the last 4 decades in Costa Rica (Cabalceta et al. 1996). For the Ac factor, patches associated with elevated scores (i.e., less acidity) are broadly distributed on the organic plot while conversely, in the conventional plot high acidity is evident. The occurrence of such spatial patterns has been reported previously for soils cultivated with unshaded coffee (Ochoa et al. 2003; Silva et al. 2007). Silva et al. (2007) determined that some soil chemical attributes, such as cation exchangeable capacity and bases, showed little continuity in andisols and recommended localized fertilizer application in coffee plantations (precision agriculture management).

Table 4 Parameters of the spherical models fitted to the semivariograms of the scores of the samples for the chemical fertility and acidity factors and residuals of coffee fine root length density (RLD) in mineral soil (0–20 cm) of a coffee-tree association (*Coffea arabica* shaded by *Erythrina poeppigiana*) under organic and conventional managements

	Nugget (*Co*)	Partial sill (C_p)	Range (*Ao*, m)	Spatial correlation Structure (%)
Semivariogram models				
Erythrina RLD (ERLD)	0.620	0.200	3.5	24
Chemical fertility (CF)	0.000	0.416	5.08	100
Acidity (Ac)	0.154	0.388	8.17	72
Residuals of coffee RLD (RC)	0.054	0.067	8.41	55
Cross- semivariogram models				Spatial correlation coefficient
RC vs CF	−0.200	0.173	5.50	0.61
RC vs Ac	0.250	−0.260	5.50	−0.70
RC vs ERLD	0.250	−0.260	4.23	−0.63

The presence of relatively short distance aggregate patterns of fine roots, depending on plot size and sample intervals has been demonstrated in other studies for different species. For example, for fine root mass density of *Larix olgensis*, the scales of spatial heterogeneity (aggregation patterns) have been estimated between 1.8 and 5.6 m (Sun et al. 2006) in 900 m^2 plots (values increasing as plant age increases). In 2 m^2 micro plots, the aggregation patterns of *Populus fastigiata* fine root mass increased temporally from 18.8 to 85 cm during two months of evaluation (Stoyan et al. 2000).

This has been confirmed that high relatively concentrations of Al along low Ca concentrations, negatively affect coffee RLD; they may prevent roots from exploring deeper soil layers (Cardoso et al. 2003). Mou et al. (1995) determined a positive correlation between Loblolly pine fine root density and soil P and K, but not with soil N, as demonstrated in this study suggested that correlations may be nutrient- specific. Assuming that the response of a portion of a plant's root system to its nutritional environment is indicative of whole-plant nutrient status, the greater proliferation of coffee fine roots in soil cores with high P content may indicate P-limitation of this perennial crop. In a heterogeneous and P-limited environment, plants would maximize the amount of P acquired by greater investment in roots that encountered P-enriched microsites (McGrath et al. 2001).

Marschner (1997) reported that greater fine root length increases the capacity of a plant to absorb available soil N. In the present study, "high spots" of the CF factor (exchangeable bases; i.e., Ca, Mg, and K content) were associated with greater coffee RLD. Coffee roots responded to acidity. Even though there was not statistically difference, it was observed that the nutritional status in the conventional plot slightly promoted higher coffee fine RLD than in the organic plots. Conventional management resulted in lower soil pH values and higher Al saturation (Table 2), which apparently lead to the coffee investing more resources in fine roots to overcome these limitations; i.e., if the soil is acid, foraging for resources (root proliferation) increases.

The results of semivariogram modeling established that different nutritional status in soil affects the aggregation patterns (scale of spatial heterogeneity) of *C. arabica* RLD: i.e., the choice of management system affects the ability of coffee roots to explore spatially variable soil resources.

The pruning (partial or total) of Erythrina trees affects the proliferation of fine roots. Partial pruning preserves more fine RLD than when total removal of branches is applied to Erythrina trees (Chesney 2008), as it was observed in this study (Table 2). Besides, it could be suggested that the type of pruning also affects the spatial variability of Erythrina RLD promoting a very short- range of spatial aggregation. The negative spatial relationship found between coffee and

Erythrina RLD suggests that coffee fine roots are not displaced by tree fine roots in depth layer 0–20 cm.

Conclusion

In this study, geostatistics showed that nutrients (e.g., P, Zn, and exchangeable bases) are positively spatially correlated to coffee fine root density but negatively correlated with an acidity soil factor; i.e., pH and exchangeable aluminum. The scale of spatial heterogeneity and the aggregation pattern of coffee RLD were influenced by the spatial changes of the soil nutrients (related to exchangeable bases, P, and Zn contents) and the soil acidity. The fact that coffee RLD had higher scale of spatial variation than Erythrina RLD and a negative spatial correlation indicate that pruned Erythrina trees are not so competitive for acquiring shared nutrients in an agroforestry system. The spatial response of coffee RLD suggests a differential root nutrient uptake strategy for acquiring soil nutrients depending on whether coffee plantations are organically and conventionally managed under *E. poeppigiana* shade trees.

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