



**VERTICAL DISTRIBUTION AND SPATIAL PATTERN OF FINE
ROOT DENSITY IN COFFEE – BASED AGROFORESTRY SYSTEMS
UNDER ORGANIC AND CONVENTIONAL INPUTS †**

**[DISTRIBUCIÓN VERTICAL Y PATRÓN ESPACIAL DE DENSIDAD
DE RAÍCES FINAS EN SISTEMAS AGROFORESTALES BASADOS EN
CAFÉ BAJO MANEJO ORGÁNICO Y CONVENCIONAL]**

Argenis Mora- Garcés

*Edificio Académico 3, Universidad Earth, Mercedes de Guácimo, Provincia de
Limón, Costa Rica. E- mail: armora@earth.ac.cr*

**Corresponding author*

SUMMARY

This research shows results on spatial changes of fine roots ($d < 2.0$ mm) in two *Coffea arabica*- shade tree associations: coffee shaded by a) *Abarema idiopoda* (timber and nitrogen fixing tree), and b) *Terminalia amazonia* (timber tree). These associations were submitted to organic and conventional inputs. In order to identify fine root vertical distribution and using soil cores, coffee and shade tree fine roots were quantified to 50 cm depth. A geostatistical approach was used to quantify the scale of spatial heterogeneity (aggregation patterns) of coffee and shade- tree fine root length density (RLD, cm cm^{-3} ; 0- 20 cm soil depth). Results about vertical distribution demonstrated that in all the associations the coffee fine roots were concentrated in the upper 20 cm of soil. The significant amount of coffee fine roots in the litter layer demonstrated the importance of including this layer for a real estimation of coffee fine roots in shaded coffee systems. The shade tree fine roots showed marked differences in their vertical distribution and affected the fine root density of coffee plants between 0- 50 cm soil depth; being more abundant when coffee is planted with *T. amazonia*. The scale of spatial heterogeneity (aggregation patterns) for coffee RLD was longer in the organic plot than in the conventional plot for all of the coffee- tree associations. In the coffee- *T. amazonia* association, the semivariogram of the coffee RLD under conventional management showed a spatial correlation at a relative short scale (3.5 m); however, in the organic plot, the semivariogram did not show spatial heterogeneity and exhibited a random pattern of coffee RLD at the scale examined. It is concluded that the type of management affects the pattern of spatial aggregation (spatial heterogeneity scale) of *C. arabica* fine roots. Implying that the ability of coffee roots for the water and nutrient intake change spatially, either vertically or horizontally, depending on the accompanying shade- tree. According to the occupation of the fine roots within the layers of the soil to the depth studied, *T. amazonia* seems to be the timber species recommended for the establishment of a coffee-based agroforestry system.

Key words: Vertical distribution; fine root length density; geostatistic; *Coffea arabica*; *Abarema idiopoda*; *Terminalia amazonia*; organic management.

RESUMEN

El artículo presenta resultados sobre los cambios espaciales de raíces finas ($d < 2.0$ mm) en dos asociaciones de *Coffea arabica* y árboles sombras: a) con *Abarema idiopoda* (árbol fijador de nitrógeno y maderable) y b) con *Terminalia amazonia* (árbol maderable). Ambas asociaciones fueron sometidas a manejo orgánico y convencional. Con el objetivo de identificar la distribución vertical de raíces finas tanto de plantas de café como de árboles sombra hasta una profundidad de 50 cm, monolitos de suelos fueron utilizados. Un análisis geoestadístico basado en transformación por rangos ordenados fue usado para cuantificar la escala de la heterogeneidad espacial (patrones de agregación) de la densidad longitudinal de raíces finas de café y árboles sombra (RLD, cm cm^{-3} ; 0- 20 cm). Los resultados obtenidos demostraron que las raíces finas de *C. arabica* estuvieron mayormente concentradas hasta los 20 cm de profundidad del suelo. La cantidad significativa de raíces finas de esta especie encontradas en el mantillo superficial del suelo demuestra la importancia de incluir esta capa para una estimación real de raíces finas en plantas de café en sistemas agroforestales. Raíces finas de árboles sombra mostraron marcadas diferencias en su distribución vertical y afectaron la distribución de la densidad longitudinal de raíces finas del café entre 0- 50 cm de profundidad del suelo; siendo más abundante cuando ésta especie está asociada con *T. amazonia*. En ambas asociaciones, la escala de heterogeneidad espacial estimada para la densidad de raíces del café fue mayor en las parcelas manejadas con insumos orgánicos que en las parcelas bajo manejo convencional. Sin embargo, bajo el asocio con *T. amazonia* y bajo manejo convencional,

† Submitted February 23, 2017 – Accepted March 13, 2018. This work is licensed under a CC-BY 4.0 International License

el semivariograma para la densidad de raíces finas del café mostró tener una correlación espacial a una extensión espacial de hasta 3.5 m (Tamaño de los patrones de agregación estimados). Por otro lado, en el mismo asocio pero con manejo convencional, el semivariograma demostró que las raíces finas del café mostraron un patrón espacial aleatorio sobre la parcela. Se concluye que el tipo de manejo afecta el patrón de agregación espacial (Escala de heterogeneidad espacial) de *C. arabica* implicando que la habilidad de las raíces finas del café para la toma de agua y nutrientes cambia espacialmente tanto vertical como horizontalmente dependiendo de la especie árbol-sombra en asocio, ya que la ocupación de las raíces finas dentro de las capas del suelo a la profundidad estudiada, *T. amazonia* parece ser la especie maderable recomendada para el asocio con plantas de café para el establecimiento de sistemas agroforestales.

Palabras claves: distribución vertical; densidad raíces finas; geo estadística; *Coffea arabica*; *Abarema idiopoda*; *Terminalia amazonia*; manejo orgánico.

INTRODUCTION

Coffee (*Coffea arabica* L.) is the most important commodity in the international agricultural trade, representing a significant source of income to several Latin American, African, and Asian countries. Traditionally, coffee has been one of the most important agricultural export products of Central American countries, including Costa Rica. In this country, coffee agroforestry systems are frequently based on associations with leguminous trees, in particular as *Erythrina* spp. (Redondo, 2005). However, native and introduced timber species are increasingly being tested as coffee shade trees in formal trials and by farmers in their commercial plantations. Amongst the main species tested, native timber trees seem to have better characteristics as coffee shade trees. For example, *Terminalia amazonia* (Gmel.) has been identified as a promising fast growing native species for agroforestry systems due to its high survival, good adaptability to acid soils and high decomposition rates of litter (Kershner and Montagnini, 1998; Piotto *et al.*, 2003). Some leguminous timber species have been recommended for agroforestry projects because of their potential as multipurpose trees, and for reforestation of degraded lands: e.g., *Abarema idiopoda* (S.F. Blake) Barneby and Grimes (Tilki and Fisher, 1998).

When tree and crop overlap in an agro-ecosystem, competition can occur due to one of them (e.g., the tree) reducing one or more resources and affecting the performance of the other (García-Barrios and Ong, 2004); e.g., the tree and its environment modify the nutrient availability around the crop (Anderson and Sinclair, 1993).

Agroforestry system research has emphasized that belowground interaction studies are fundamental to understand better the competition processes between crop and tree. Root density distribution of trees and crops is usually seen as a main indicator of competition between trees and crops. It has been recognized that the quantification of fine root parameters is an essential input for the modeling of ecosystems

productivity (Landsberg and Waring, 1997; Masera *et al.*, 2003).

Some of the most widely applied ecosystem models have been calibrated to assign carbohydrates to roots, because fine and medium (< 5mm) root dynamics affect carbon cycles at both the tree and stand scale (Vogt *et al.*, 1996). From a viewpoint of agroforestry, it has been hypothesized that trees and crops should use different soil layers with their root systems when associated; consequently, complementarity in the use of soil resources may be the main interaction between tree and crop (Schroth, 1995; Brassard *et al.*, 2011). Thus, studies about rooting depth and vertical distribution of root systems are fundamental for agroforestry research.

The tree root systems affect both soils and associated crops. Competition for soil resources can vary with the spatial and temporal distribution of roots, and fine-scale nutrient heterogeneity could have a strong effect on belowground interactions. The biophysical interaction studies in coffee-based agroforestry systems have identified some complementarity and weak competition. The spatial variability of coffee fine roots, probably an indicator of competition, depends on nutrient availability and can be influenced both by the manner of fertilizer application and distance from the shade tree (Schaller *et al.*, 2003; Wilson and Ndafa, 2014).

According to Webster (2001), “variability” means the potential of some properties (characteristic or attribute of interest) to vary. In geostatistics, it is quantified when dispersion measures (e.g., coefficient of variation) and semivariances are computed. Thus, values of a given property or characteristic can vary over space randomly or have a spatial structure. When such variability is spatially structured, it is called heterogeneity or patchiness. Thus, many attributes (e.g., soil properties, presence of a tree, biotic factors, etc.) can exhibit spatial heterogeneity as a spatial arrangement (pattern) of high and low values across the field or plot (Ettema and Wardle, 2002). Although geostatistics have been widely applied on agricultural soils (Utset and Cid, 2001; Lopez-Granados *et al.*

2002) and natural ecosystems at different scales (Robertson *et al.*, 1988; Jackson and Caldwell, 1993; Maestre and Cortina, 2002), publications on geostatistical analysis in agroforestry systems and in special on fine roots are uncommon (Mora and Beer, 2013).

In the present paper, the vertical distribution of fine roots (RLD, $d < 2.0$ mm) of shade- tree and coffee plants was determined in two coffee- shade tree associations (*C. arabica* shaded by *A. idiopoda* and *T. amazonia*) under two types of inputs: conventional and organic. Moreover, the scale of spatial heterogeneity (aggregation pattern) of coffee fine root length density was estimated

MATERIALS AND METHODS

Site description

The study was carried out in a long- term experiment of alternative coffee production systems established in 2000 (Haggar *et al.* 2011). This site represents a low altitude (685 masl), wet zone (3,200 mm annual rainfall) with no marked dry season. Soils were classified as Typic Endoaquepts and Typic Endoaquults, and characterized as mixed alluvial with a poor or medium fertility and a water table ranging between 40 and 120 m (Sanchez- de Leon *et al.*, 2006). Coffee planting holes were spaced 1 x 2 m apart with trees planted at 4 x 6 m. Before the establishment of the trial, the site was used (commercial farm) for sugar cane (*Saccharum officinarum*) production. For the moment of the study, coffee plants and shade- trees were 5 years old.

Three coffee- shade tree associations were studied; coffee shaded by: (1) *Terminalia amazonia* (Gmel.) Excell (timber tree), and (2) *Abarema idiopoda* (S.F. Blake) Barneby and J. W. Grimes (nitrogen fixing- timber tree). Within each coffee- shade tree association, two types of coffee treatments were considered: conventional and organic input.

The conventional input corresponded to standard levels of management used at that time by local farmers; e.g., chemical weed and pest control plus mineral fertilizer (Table 1). The organic system included manual weed control, nutrients supplied in the form of composted manure and foliar applications of botanical and biological composts. In all coffee- tree associations and input systems studied, shade was permanent but regulated by pruning twice a year.

Sampling scheme and soil core processing

Vertical sampling. Preliminary sampling was carried out to determine the vertical distribution of coffee and tree fine roots ($d \leq 2$ mm); soil cores (internal diameter

6 cm) were taken under the coffee canopy, approximately 30 cm from the coffee stem base and at 45 cm from a shade tree, to 50 cm depth in 10 cm increments. The presence of rocks or a water table restricted sampling at greater depth. Fine roots from the litter layer were sampled separately by using a ring (internal diameter 8 cm).

In this phase, 90 soil cores (4 depths + litter layer x 3 shade tree species x 2 management types x 3 samples) were extracted. For comparing litter layer and four depths, fine root density was expressed on surface area basis (cm cm^{-2}).

Spatial sampling. One central plot 16 x 18 m of each coffee- shade tree association and input type was fixed. In each plot, containing 16 shade trees, 32 soil cores were taken. The soil cores were spaced on an irregular grid to account for the potential changes in coffee and tree RLD (at small and large scales) that may occur along and between the coffee rows (a 1 m border was not considered).

All sampling points were identified according to X and Y coordinates in order to apply geostatistical analyses. Soil cores (0-20 cm) close to coffee stems were taken approximately 30 cm apart by hammering an auger into the soil (internal diameter 6 cm). The samples were collected during the principal coffee fruit production period, august 2005. The grand total of soil cores was 192 (taken from six treatment combinations; i.e., 32 x 6).

Samples processing

Soil cores were bagged and transported to the laboratory. Each soil- root sample was weighed and homogenized; stones and other impurities were removed and roots cut to a length < 3 cm with scissors. Later, a sub-sample (on average 50 % or 400 g) was separated for fine root extraction and the remainder for soil analyses. All sub-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 fine roots.

Under a stereoscope (8X), tree and coffee roots were separated based on morphological characteristics. The *C. arabica* roots were brown- reddish and showed smooth branching. *T. amazonia* roots were dark brown to iridescent green under illumination, and notably thinner than the rest of the other species. *A. idiopoda* fine roots were grayish, with nodules in irregular form, and had an easily removable epidermis. Both *A. idiopoda* and *T. amazonia* fine roots presented angular branching.

Table 1. Fertilizer and herbicide applications and other inputs* in the conventional and organic sub- treatments of the coffee -based agroforestry system trial.

Inputs	Organic	Conventional
Soil amendment	20 t ha ⁻¹ yr ⁻¹ coffee pulp 7.5 t ha ⁻¹ yr ⁻¹ chicken manure 200 kg ha ⁻¹ yr ⁻¹ KMAG 200 kg Phosphoric rock ha ⁻¹ yr ⁻¹	400 kg ha ⁻¹ yr ⁻¹ 18-15-6-2 (N, P, K, Mg and B) 45 kg ha ⁻¹ yr ⁻¹ NH ₄ HO ₃ Foliar application: B, Zn (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 ₂ O per block of Atemi or Copper sulfate (once a year)

*Nutrient inputs from decomposition of shade tree biomass were not considered.

The total fine root length from coffee and each tree species 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 to 0.0001 g. Next, the density of fine root length (RLD, cm cm⁻³) was computed for coffee and each tree species.

Geostatistical Analysis

Because fine root data are highly skewed, with a large variation and some extreme values, the procedure of standardized rank transformation was used (Juang *et al.*, 2001). The n data values (x_k) were assigned their rank orders $r(x_k)$ and the standardized ranks $u(x_k)$ of the sample were calculated by:

$$\mathbf{u}(x_k) = \frac{\mathbf{r}(x_k)}{\mathbf{n}};$$

The values of $\mathbf{u}(x_k)$ are between $1/n$ and 1 . According to Juang *et al.* (2001), the n data points of $\mathbf{u}(x_k)$ are considered as a conditional realization on a random sample of size n from the original continuous variable. A semivariogram of standardized ranks built from estimated semivariances was used to quantify the scale of spatial heterogeneity (patch size) and dependence of fine root parameters. The semivariance statistic was estimated using the following expression

$$\hat{\gamma}_u(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{k=1}^{N(\mathbf{h})} [\mathbf{u}(x_k) - \mathbf{u}(x_k + \mathbf{h})]^2$$

where, $N(\mathbf{h})$ is the number of observation pairs separated by distance \mathbf{h} , $\mathbf{u}(x_k)$ is the standardized value

of the fine root variable scored at location x_k , and $\mathbf{u}(x_k + \mathbf{h})$ is its value at a location at distance \mathbf{h} from x_k . Likewise, in order to determine the magnitude of spatial correlations between coffee and shade tree fine root length cross- semivariograms were estimated by

$$\hat{\gamma}_u(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{k=1}^{N(\mathbf{h})} [\mathbf{u}_i(x_k) - \mathbf{u}_i(x_k + \mathbf{h})][\mathbf{u}_j(x_k) - \mathbf{u}_j(x_k + \mathbf{h})]$$

Where, $\mathbf{u}_i(x_k)$ and $\mathbf{u}_j(x_k)$ represent the standardized ranks for coffee and shade tree fine roots, respectively, scored at a location at distance \mathbf{h} from x_k (Isaaks and Srivastava, 1989). Prior to constructing each semivariogram, the data was segregated into distance classes by setting the appropriate number of bins and bin width (lag distance). This procedure permitted finding the maximum resolution of the semivariograms at small sampling distances (Franklin and Mills, 2003). Each of the experimental semivariograms was modeled using the following spatial models:

Gaussian

$$\gamma(\mathbf{h}) = \left\{ C_0 + C_1 \left(1 - \text{Exp} \left(\frac{-\mathbf{h}}{a} \right)^2 \right) \right\}$$

Spherical

$$\gamma(\mathbf{h}) = \left\{ C_0 + C_1 \left(1.5 \frac{\mathbf{h}}{a} + 0.5 \frac{\mathbf{h}^3}{a^3} \right) \right\}$$

Exponential

$$\gamma(\mathbf{h}) = \left\{ C_0 + C_1 \left(1 - \text{Exp} \left(\frac{-\mathbf{h}}{a} \right) \right) \right\}$$

where C_0 is the nugget variance, C_1 is the sill, a is the range, and h is the lagged distance. The selection of spatial models was based on the goodness of fit (highest R^2) and the most reasonable parameter estimates. In the analysis, an index of spatial dependence was employed, the Q value, which indicates the intensity of spatial structure at the sampling scale (Cambardella *et al.*, 1994). It was calculated as $[C_p / (C_0 + C_p)] * 100$, where C_p is the partial sill. Spatial dependence was classified according to Cambardella *et al.* (1994). If Q was greater than 75 %, the variable was considered “strongly spatially dependent” (S), while between 75 and 25 % the classification was “moderate spatial dependence” (M), and lesser than 25 % the spatial dependence was defined as weak (W).

When spatial dependence was determined, the ordinary kriging estimator was used to estimate the standardized ranks at unsampled locations.

Maps were created using a grid specification of 1 x 1 m to characterize local patterns of variation. On the other hand, in order to compare fine roots among shade- tree species and input types, a mixed model was assumed

$$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{(i)j} + \varphi_{ik} + \varepsilon_{ijk}$$

where each main plot (α_i , shade- tree species) was divided into sub- plots (that contain nested input types, $\beta_{(ij)}$). Samples took inside main plot ($\varphi_{ik} \sim N(0, \sigma_\varphi^2)$) and the within-group residuals ($\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon^2)$) denote the random effects, and α_i and β_j the fixed effects. An analysis of variance based on mixed models with Satterthwaite approximation for degrees of freedom was applied (Kuznetsova *et al.*, 2016).

Adjusted means were estimated and compared using Tukey comparison tests (Pinheiro and Bates, 2000; Russell, 2016). All the statistical analyses were carried out under the statistical environment R (R Development Core Team, 2016). Specifically, the libraries “gstat” (Pebesma, 2004) for geostatistical analysis.

RESULTS AND DISCUSSION

Vertical distribution of shade trees and coffee fine roots

Coffee fine roots had an even vertical distribution to 20 cm of soil under *A. idiopoda*-conventional; fine roots were not observed below 30 cm. Besides, the proportion of coffee fine roots found in the litter layer was 39 %, but under organic 65 %. Thus, the proportion of *A. idiopoda* fine roots was higher in conventional plots than in organic.

More than 90 % of the coffee fine roots were concentrated in upper 20 cm of soil plus litter for both systems. *A. idiopoda* fine roots had a similar vertical distribution under conventional and organic input; the highest values were observed for 0- 10 cm depth. *A. idiopoda* had 73 and 65 % of fine roots to 20 cm depth under conventional and organic input, respectively.

In association with *T. amazonia*, under both types of inputs, the proportion of coffee fine roots in the litter layer was lower than in the other tree- coffee associations (14 and 28 % for conventional and organic, respectively). However, the concentration of coffee fine roots was estimated as ≥ 70 % in the upper 20 cm and higher coffee root length density (RLD, cm cm^{-2}) was found in the *A. idiopoda*-coffee association.

Including the litter layer, few fine roots of *T. amazonia* were found in the upper 10 cm of the soil profile (3 % for conventional and 4 % for organic); they increased rapidly below 10 cm with highest values for 30-40 cm. For 40 -50 cm depth, fine roots only were found for *A. idiopoda* in organic plot.

In general, most of the coffee fine roots were concentrated in the upper 20 cm of soil. Between 0- 40 cm, the vertical pattern of coffee fine roots observed close to the shade trees agrees well with Aranguren *et al.* (1983), Schaller *et al.* (2003), Cardoso *et al.* (2003), van Katen *et al.* (2005), and Padovan *et al.* (2015); they demonstrated that more than 70 % of the coffee fine root total ($d < 2$ mm) can be found in the first 30 cm of the soil profile in agroforestry coffee systems.

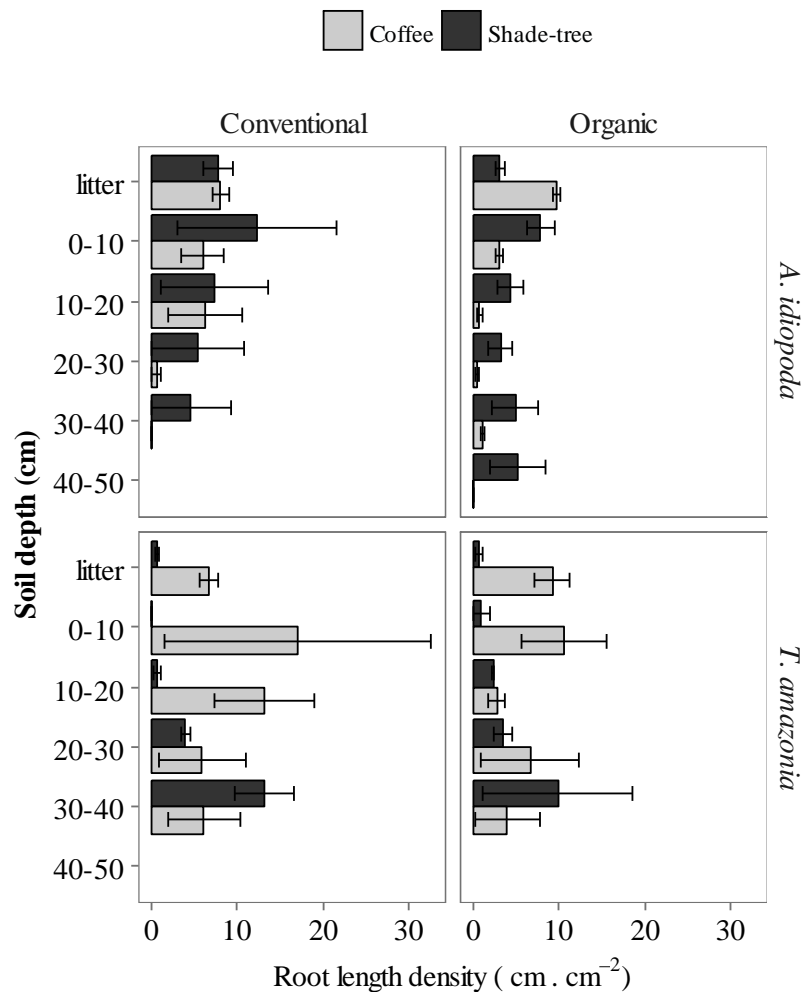


Figure 1. Vertical distribution of fine root length density ($d \leq 2$ mm; RLD, cm cm^{-2}) for *Coffea arabica* and shade trees (*Abarema idiopoda* and *Terminalia amazonia*) under organic and conventional inputs.

According to soil chemical attributes, under conventional management, soils had lower pH's (≤ 5.2) compared to soils organically managed (pH's > 5.2) (Table 2). Aluminum saturation under organic management was lower than under conventional management and values under *A. idiopoda* trees were lower than under *T. amazonia*. In conventional management plots, soils were saturated up to 41 % by exchangeable Al (coffee- *T. amazonia* association). The effective cation exchange capacity (E.C.E.C) was consistently higher under organic management and especially in the associations with *A. idiopoda*.

Likewise, available P contents differed markedly among management types and associations; in conventional plots, P contents were between 6.9 and 12.5 mg kg^{-1} while in the organic plots P values were between 6.9 and 44.0 mg kg^{-1} ; once again the highest values were observed under legume tree shade in organic plots. Soil C and N contents were relatively low and similar among associations.

In the humid tropics, root systems might be expected to be shallower and smaller than they are under drier conditions since sufficient moisture may be obtained from a smaller volume of soil, thus satisfying the transpiration requirements of the plants (Hutching and John, 2003). This superficial distribution pattern of coffee fine roots could also be a consequence of more favorable chemical conditions in the topsoil (e.g., 0- 20 cm soil depth). The distribution of crop and tree roots depends on factors such as species genotypic characteristics, and soil properties, among other factors (Akinifesi *et al.*, 2004).

This study showed that the vertical pattern of coffee fine roots also might change when it is planted or associated with different shade tree species. The abundance of coffee fine roots below 20 cm was higher in the *T. amazonia*- coffee association, the shade tree which had few fine roots between 0- 20 cm but increasing values with depth. This suggests that *T.*

amazonia has the ability to develop deeper root systems in these soils where a hard pan, high water table and acid sub-soil may restrict the development of roots; however higher biomass of fine roots at greater soil depth indicates higher construction and maintenance costs due to penetration resistance.

In contrast, *A. idiopoda* fine root biomass declined linearly with depth and they were more abundant than coffee fine roots. It has been theorized that coffee plants with shallow fine root systems (rapid decline in root density with increasing soil depth) may be more competitive in the top soil than those that have a substantial proportion of roots in deeper soil layers (Defrenet *et al.*, 2016). Coffee fine roots exploit more soil layers when associated with *T. amazonia* compared to other associations; it is feasible that the coffee is able to explore a larger total soil volume due to the rooting characteristics of the other component.

Hence, the vertical distribution of *T. amazonia* fine roots is one desirable characteristic for agroforestry practices in this suboptimal region. This pattern reduces competition in top soil for nutrients. It is likely that *T. amazonia* rooting depth determines to which extent it can use subsoil water and nutrients; making it less dependent from the supply in the topsoil and possibly giving to associated coffee plants complementary nutrients by pumping (Schroth, 1995).

Very few reports have included coffee fine roots in the litter layer (Aranguren *et al.*, 1982; Cuenca *et al.*, 1983; Schaller *et al.*, 2003). In this study, fine roots in the litter layer were abundant. Coffee fine roots dominated completely in the litter layer; indicative that coffee fine roots proliferate more than shade tree roots in areas where nutrients are available. It has been demonstrated that in relatively fertile soil, fine roots respond rapidly to increments of surface litter inputs, because this creates a persistent organic layer and sufficient moisture (Sayer *et al.*, 2006).

In this trial, fertilizers have been applied on the coffee row. This rooting characteristic suggests that coffee plants intercropped with shade trees have an advantage; i.e. developing and absorbing the mineralized nutrients very efficiently from the litter layer. It has been demonstrated that the decomposition of litter containing coffee fine roots is faster than for litter without coffee roots (Cuenca *et al.*, 1983). In coffee- based agroforestry systems, coffee fine root proliferation in the litter layer may improve the N capture when N additions (e.g., tree leaf litter) are released slowly (Gill and Jackson, 2000).

Coffee and shade tree fine roots in top soil

The box- plots show a high variation existing in the data of fine roots; i.e., highly skewed and many outliers

(Figure 2). The mean values of coffee RLD not were statistically different among shade- tree species ($p = 0.1292$; Table 3). Besides, there were not significant differences between organic and conventional for Coffee RLD, independently of the coffee- tree association.

On the other hand, for both input types, *A. idiopoda* RLD was notoriously higher than *T. amazonia*. Moreover, fine roots of *A. idiopoda* provided a much higher proportion of the total compared to the contribution of the shade tree in the other system; i.e., the proportion of coffee fine roots in the *A. idiopoda* system was only 40 % compared to 80% in the other system.

Spatial variability of coffee and shade tree fine roots

The spherical, exponential and Gaussian models fit very well to this coffee root data. Semivariograms revealed that the scale of spatial heterogeneity (range parameter) for coffee fine roots associated with *A. idiopoda* was longer in the organic plot than conventional plot (9.0 vs. 7.5 m, respectively; Table 3). According to the index of spatial dependence (Q), coffee RLD (standardized ranks) exhibited a moderate spatial correlation structure in the organic and conventional plots (40 and 46 %).

In the coffee- *T. amazonia* association, the semivariogram of coffee RLD under conventional input showed a scale of aggregation relatively shorter (3.5 m). However, in the organic plot, the semivariogram for coffee RLD did not exhibit any spatial heterogeneity within the sampled area, indicating a random pattern of coffee fine root density in this association at the scale examined.

Spatial correlation of *A. idiopoda* fine roots among sample locations occurred in both conventional and organic plots; aggregation sizes were estimated at 5.3 and 8.0 m for conventional and organic input, respectively (Table 3). This spatial behavior was similar to that observed for coffee RLD in the same plots. In the organic plot, the aggregation size for *A. idiopoda* fine roots was similar to that observed for coffee fine roots (8.0 and 9.0 m, respectively). However, in the conventional plot, *A. idiopoda* fine root values were correlated up to 5.3 m whereas for coffee up to 7.5 m.

In the conventional plot, *A. idiopoda* fine roots formed aggregation patterns with hot spots (Figure 3; the lightest areas on the maps) smaller than the coffee fine roots. In fact, the spatial pattern followed by the coffee roots showed a displacement from north-west (less presence of fine roots) to southeast of the plot (more fine roots). On the other hand, in the organic plots

concentrations of coffee RLD occurred in areas adjacent to spots where *A. idiopoda* fine roots were highly concentrated.

This fact reflects the spatial correlation detected between coffee and *A. idiopoda* roots at a spatial range of 3.6 m. Moreover, the concentration of coffee and *A. idiopoda* fine roots were potentially high next to the trees, but decrease gradually with distance from the tree.

Input type did not affect the spatial cross- correlation between coffee and *A. idiopoda* fine roots. For

Conventional plot the value was 0.58 up to 5 m separation (beyond that distance the magnitude of spatial correlation decreases or it is not significant) while in the organic plot, the value was 0.43 up to 3.6 m. On the other hand, the cross-correlation between coffee and *T. amazonia* (Conventional plot) was estimated in -0.67 with an extent of spatial cross-correlation of 4.5 m; This result is in according to vertical distribution found for this association, less abundance of *T. amazonia* fine roots than coffee plants at 0- 20 cm.

Table 2. Means and standard errors of soil chemical attributes in mineral soil (0 - 20 cm) of two coffee- tree associations (*Coffea arabica* shaded by *Abarema idiopoda*, and *Terminalia amazonia*) under organic and conventional managements in Turrialba, Costa Rica.

Soil attributes	Unit	Coffee shaded by			
		<i>A. idiopoda</i>		<i>T. amazonia</i>	
		Conventional	Organic	Conventional	Organic
pH (water)		5.1 (0.1)	6.1 (0.1)	4.9 (0.1)	5.3 (0.1)
E.C.E.C	cmol(+) l ⁻¹	5.7 (0.1)	9.7 (0.5)	6.5 (0.3)	7.5 (0.2)
Al-saturation	%	24 (2.0)	3 (1.5)	41 (2.7)	9 (2.5)
Available P	mg l ⁻¹	6.9 (0.4)	44.0 (6.9)	12.5 (7.0)	6.9 (0.6)
Total N	%	0.25 (0.01)	0.30 (0.01)	0.24 (0.01)	0.23 (0.01)
Organic C	%	2.53 (0.05)	2.97 (0.05)	2.53 (0.06)	2.37 (0.06)

Table 3. Anova with Satterthwaite approximation for degrees of freedom and Tukey mean comparison tests for square least means of coffee and tree fine root length density (RLD, cm cm⁻³) estimated in three coffee- tree associations (shaded by *Abarema idiopoda* and *Terminalia amazonia*) under organic and conventional input.

Source of Variation	Root fine length density (cm.cm ⁻³)	
	<i>Coffea arabica</i>	Tree species
	<i>p-value</i>	<i>p-value</i>
Tree species, <i>A</i>	0.1292	< 0.0001
Input types, <i>B</i>	0.5455	0.3140
Interaction <i>A:B</i>	0.4508	0.4725
Among tree species	<i>Ls mean</i>	<i>Ls mean</i> [¥]
<i>T. amazonia</i>	0.901 a	0.691 b
<i>A. idiopoda</i>	1.006 a	1.022 a
Comparisons between inputs within tree species		
<i>T. Amazonia</i>		
Conventional	1.018 a	0.738 a
Organic	0.995 a	0.643 a
<i>A. idiopoda</i>		
Conventional	0.930 a	1.030 a
Organic	0.872 a	1.014 a

¥: least square mean; *Ls means* with the same letter are statistically equals ($p < 0.05$)

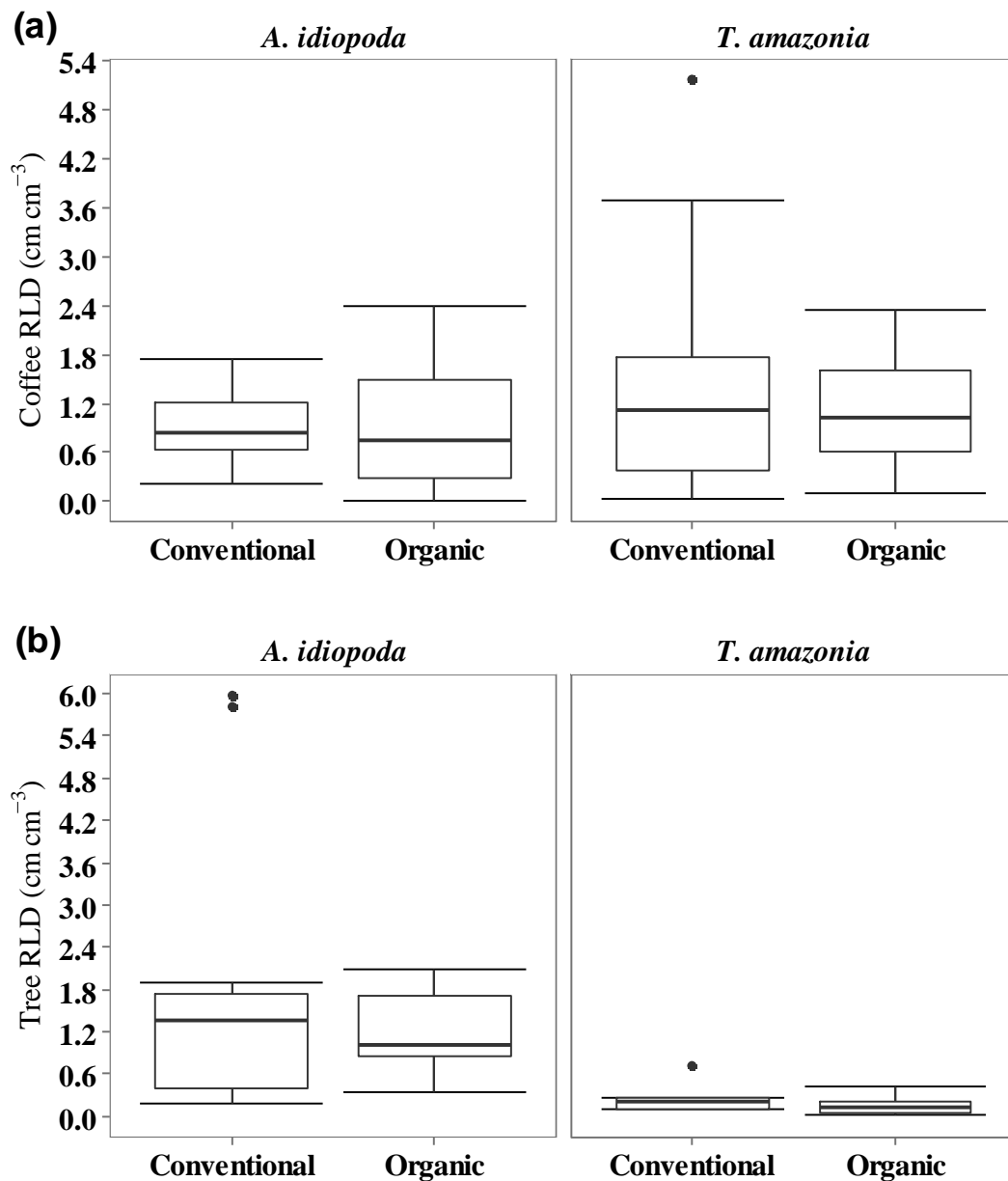


Figure 2. Box-plots of (a) coffee and (b) tree fine root length density (RLD, cm cm⁻³) estimated in three coffee- tree associations (shaded by *Abarema idiopoda* and *Terminalia amazonia*) under organic and conventional input.

This information confirms that there was a spatial correlation distance-dependent between the coffee and *A. idiopoda* fine roots at the plot scale studied.

Geostatistical methods have been used to map the distribution of fine roots at cm scales and above. The presence of relatively short aggregate patterns of fine roots has been demonstrated in a reduced number of

studies for different species; results depend on the plot size and sample intervals. For example, for fine root mass density of *Larix olgensis* in 900 m² plots, the scales of spatial heterogeneity (aggregation patterns) have been estimated between 1.8 and 5.6 m (Sun Zhi-Hu *et al.*, 2006), rising as plant age increases.

Table 4. Summary of results from geostatistical analyses of standardized ranks for fine root length density (RLD, cm cm⁻³) in the coffee- tree associations (*Coffea arabica* shaded by *Abarema idiopoda*, and *Terminalia amazonia*) under the organic and conventional (Conv.) inputs.

Coffee under	Coffee RLD		Tree RLD	
	Organic	Conv.	Organic	Conv.
<i>Abarema idiopoda</i>				
Model	Spherical	Gaussian	Exponential	Spherical
Nugget	0.060	0.061	0.010	0.042
Sill	0.100	0.112	0.135	0.097
Range	9.0	7.5	8.0	5.3
Q%	40 M	46 M	93 S	57 M
<i>Terminalia Amazonia</i>				
Model	Random	Spherical	Random	Spherical
Nugget	0.085	0.040	0.085	0.000
Sill	-	0.050	-	0.079
Range	-	3.5	-	3.3
Q%	-	58 M	-	100 S

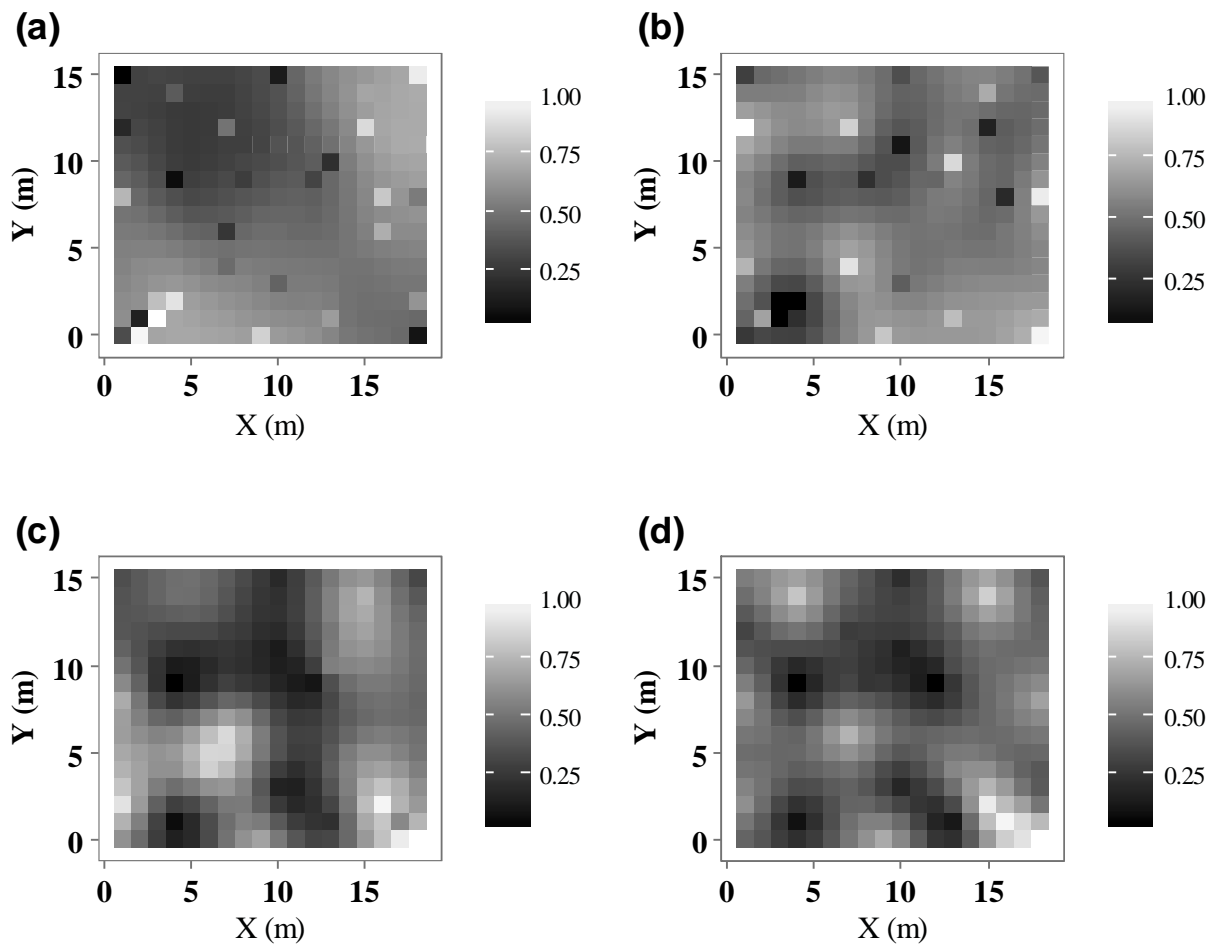


Figure 3. Kriged maps of standardized ranks of coffee and *Abarema idiopoda* fine root length density (RLD, cm cm⁻³) under conventional (“a” and “b”) and organic (“c” and “d”) input. Value 1 indicates the rank highest of fine root length density according to standardized rank order (lightest areas).

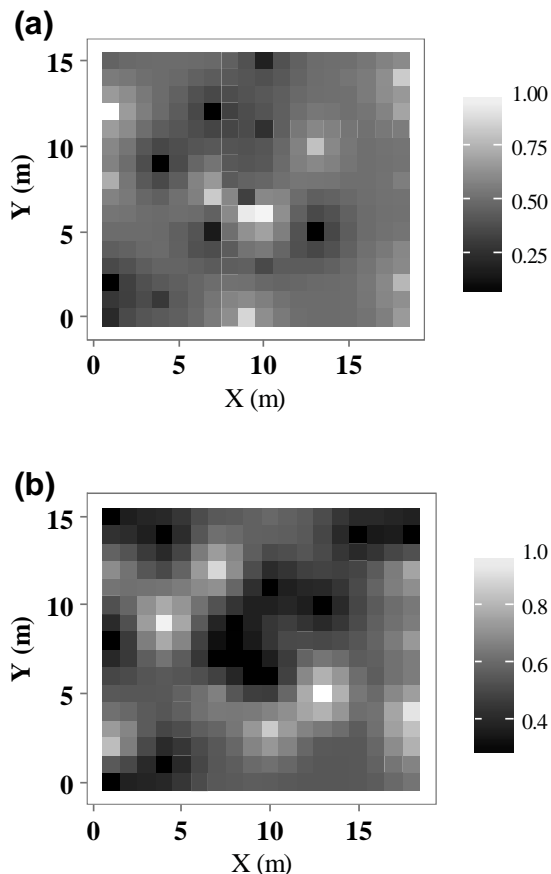


Figure 4. Kriged maps of standardized ranks of (a) coffee and (b) *Terminalia amazonia* fine root length density (RLD, cm cm^{-3}) under conventional input. Value 1 indicates the rank highest of fine root length density according to standardized rank order (lightest areas).

In 2 m^2 microplots, the aggregation patterns of *Populus fastigiata* fine root mass increased from 18.8 to 85 cm during two months of evaluation (Stoyan *et al.*, 2000). In the present study, the scale of spatial heterogeneity of coffee RLD shaded by *A. idiopoda* in conventional plots was less than in organic plots (288 m^2 plots). A root system will never experience exactly the same solute concentrations, water potentials and penetration resistances simultaneously over its entire extension. The resulting non-uniformity can cause roots to proliferate in confined soil volumes affecting rates of water and nutrient capture by the plants (Robinson *et al.*, 2003).

When crop and tree are in competition for organic patches containing a finite supply of nutrients

(especially N) and these nutrients are released slowly, root proliferation is a strategy for soil foraging (Hodge, 2006). Spatial heterogeneity in the supply of nutrients occurs at scales relevant to plant roots; roots must respond rapidly to acquire temporally available peaks of nutrients in the soil solution. Aluminum is widely regarded as the most common limitation to growth in many acid soils because as pH falls to less than about 5.0- 5.5, Al containing minerals become soluble causing phytotoxicity (Juo and Franzluebbers, 2003).

Changes in the spatial heterogeneity of coffee RLD suggest changes in the morphological features of coffee fine roots. It is likely that coffee plants renew their fine roots more frequently to maintain the resource exploiting function (Godbold *et al.*, 2003). Given the potential for competition between coffee and shade trees for nutrients, it is suggested that root morphological plasticity will be expressed in nutrient patches. Inputs from shade-tree leaf litter and fine root turn over (especially legume trees) could have significant effects on spatial heterogeneity of nutrient dynamics and hence on coffee RLD; for example, creating patches of nutrients around the shade-trees as well as improving nutrient availability (increased microbial activity resulting in higher mineralization and denitrification rates).

CONCLUSIONS

In the two associations (*C. arabica* with *T. amazonia*, and *A. idiopoda*), coffee fine roots were concentrated in the upper 20 cm of the soil. The significant amount of coffee fine roots found in the litter layer demonstrated the importance of including this layer for a true estimation of coffee fine roots in coffee-based agroforestry systems.

Vertical distribution of shade tree fine roots (0 - 50 cm) differed markedly between species. Shade trees affected the abundance of coffee fine roots; abundant coffee fine roots were found when it is planted with *T. amazonia* (and at greater depths). The vertical rooting pattern of the timber tree, *T. amazonia*, was completely inverse to that of coffee; coffee fine roots decreased to 50 cm depth while *T. amazonia* fine roots increased with depth. As a consequence, sampling to only 20 cm depth is insufficient for evaluations of *T. amazonia* fine roots because this species has few fine roots in top soil.

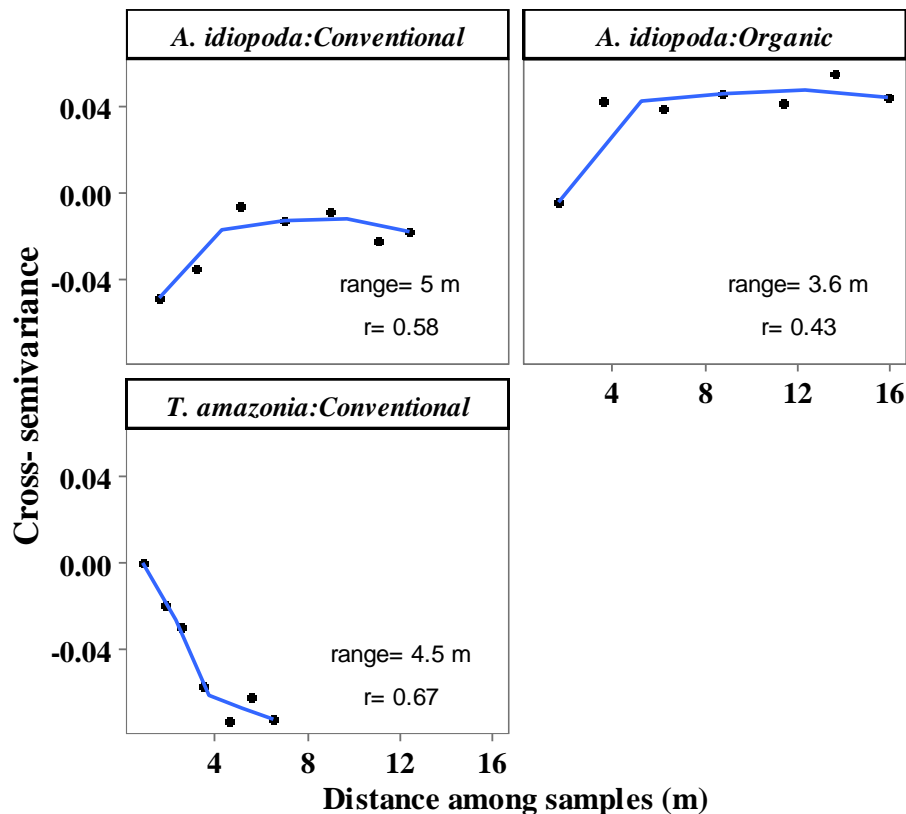


Figure 5. Cross- semivariogram between Coffee and *Shade tree* fine root density (standardized ranks): i) Coffee-*Abarema idiopoda* (Conventional), ii) Coffee- *Abarema idiopoda* (Organic), and iii) Coffee- *Terminalia amazonia* (Conventional).

T. amazonia has desirable root characteristics for agroforestry practices; their fine roots occupy profound soil strata when grown in association with coffee, leading to a degree of complementarity in their use of soil resources. For this reason, rooting depth and the vertical distribution of root systems are of particular interest for agroforestry.

A. idiopoda fine roots declined linearly with depth and were much more abundant than coffee roots between 20 and 50 cm soil depth. This could be due to coffee roots are more competitive, displacing *A. idiopoda* to greater depth and/or because *A. idiopoda* roots compete strongly below 20 cm displacing coffee roots to the surface layers.

The type of management affects the aggregation patterns (scale of spatial heterogeneity) of *C. arabica* RLD, especially under *A. idiopoda*, implying that the coffee roots show differential ability to forage for soil nutrients under the different systems of management. Estimating scales of spatial heterogeneity of plant fine roots using geostatistics provides insights into the belowground plant-soil and plant-plant interactions in agroforestry systems.

REFERENCES

- Akinnifesi, F. K., B. T. Kang, and D. O. Ladipo. 1999. Structural root form and fine root distribution of some woody species evaluated for agroforestry systems. *Agroforestry Systems* 42: 121- 138.
- Anderson, L. S. and F. L. Sinclair. 1993. Ecological interactions in agroforestry systems. *Agroforestry Abstracts* 6(2): 57-91.
- Aranguren, J., G. Escalante, and R. Herrera. 1982. Nitrogen cycle of tropical perennial crops under shade trees I. Coffee. *Plant and Soil* 67: 247- 258.
- Brassard B.W., Chen H.Y.H., Bergeron, Y., and Paré, D. 2011. Differences in fine root productivity between mixed- and single- species satnds. *Functional Ecology* 25: 238- 246.
- Cambardella, C.A., T.B. Moorman, J.M. Noval, T.B. Parkin, D.L. Karlen, R.F. Turco, and A.E. Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. *Soil Sci. Soc. Am. J.* 58: 1501–1511.

- Cardoso, I. M., Boddington, C., Janssen, B. H., Oenema, O., and Kuyper, T. W. 2003. Distribution of mycorrhizal fungal spores in soils under agroforestry and monocultural coffee systems in Brazil. *Agroforestry Systems* 58: 33- 43.
- Cuenca G., J. Aranguren, and R. Herrera. 1983. Root growth and litter decomposition in a coffee plantation under shade trees. *Plant and Soil* 71: 477- 486.
- Defrenet E., Roupsard O., Van den Meersche K., Charbonnier F., Pastor Pérez-Molina J., Khac E., Prieto I., Stokes A., Roumet C., Rapidel B., Virginio Filho E., Vargas V., Robelo D., Barquero A., Jourdan Ch. 2016. Root biomass, turnover and net primary productivity of a coffee agroforestry system in Costa Rica: effects of soil depth, shade trees, distance to row and coffee age. *Annals of Botany* 118: 833- 851.
- Ettema, C. H. and Wardle, D. A. 2002. Spatial soil ecology. *Trends in Ecology and Evolution* 17: 177- 183.
- Franklin, R. B. and A. L. Mills. 2003. Multi-scale variation in spatial heterogeneity for microbial community structure in an eastern Virginia agricultural field. *FEMS Microbiology Ecology* 44: 35- 346.
- García-Barríos, L. and C. K. Ong. 2004. Ecological interactions, management lessons and design tools in tropical agroforestry systems, *Agroforestry Systems* 61: 221-236.
- Gill, R. A., and R. B. Jackson. 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytologist* 147: 13-31.
- Godbold, D. L., H. W. Fritz, G. Jentschke, H. Meessenburg, and P. Rademacher. 2003. Root turnover and root necromass accumulation of Norway spruce (*Picea abies*) are affected by soil acidity. *Tree Physiology* 23:915 – 921.
- Haggar, J. Barrios M. Bolaños M. Merlo M. Moraga, P. Munguia M. Ponce A. Romero S. Soto G. Staver C. Virginio E. 2011. Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. *Agroforestry Systems* 82: 285-301
- Hauggaard-Nielsen, H. and E. S. Jensen. 2005. Facilitative root interactions in intercrops. *Plant and Soil* 274: 237- 250.
- Hodge, A. 2006. Plastic plants and patchy soils. *Journal of Experimental Botany* 57: 401- 411.
- Hutching, M. J and E. A. John. 2003. “Distribution of Roots in Soil, and Root Foraging Activity”. Pp.33- 56 In *Root Ecology*. Edited by Hans de Kroon, and Eric J. W. Visser. Springer-Verlag. Germany.
- Isaaks, E.H., and R.M. Srivastava. 1989. *An Introduction to Applied Geostatistics*. USA: Oxford University Press, New York.
- Jackson, R B and M M Caldwell. 1993. The scale of heterogeneity around individual plants and its quantification with geostatistics. *Ecology* 74: 612- 614.
- Jentschke G., M. Drexhage, H. W. Fritz, E., B. Schella, and D. H. Lee. 2001. Does soil acidity reduce subsoil rooting in Norway spruce (*Picea abies*)? *Plant and Soil* 237:91 – 108.
- Juang, K, D. Lee and T. Ellsworth. 2001. Using rank-order geostatistics for spatial interpolation of highly skewed data in heavy- metal contaminated site. *Journal of Environmental Quality* 30: 384- 903.
- Juo, A.S.R. and K. Franzluebbers. 2003. *Tropical soils: properties and management for sustainable agriculture*. Oxford University Press, Inc.
- Kershner, R. and F. Montagnini. 1998. Leaf litter decomposition, litterfall and effects of leaf mulches from mixed and monospecific plantations in Costa Rica. *Journal of Sustainable Forestry* 7(3/4): 95-118.
- Kuznetsova, A.; Brockhoff, P. B, and Haubo R. 2016. lmerTest: Tests in Linear Mixed Effects Models. R package version 2.0-32. <https://CRAN.R-project.org/package=lmerTest>.
- Landsberg, J.J. and Waring, R.H. (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* 95: 209-228.
- Lopez-Granados, F., M. Jurado- Exposito, S. Atencio, A. Garcia-Ferrer, M. Sanchez and L. Garcia-Torres. 2002. Spatial variability of agricultural soil parameters in southern Spain. *Plant and Soil* 246: 97–105.
- Maestre, F. and J. Cortina. 2002. Spatial patterns of surface soil properties and vegetation in a Mediterranean semi-arid steppe. *Plant and Soil* 241: 279- 291.
- Masera, O.R., J. F. Garza-Caligaris, M. Kanninen, T. Karjalainen, J. Liski, G. J. Nabuurs, A. Pssinen, B. H. J. de Jong, and G. M. J. Mohren. 2003. Modeling carbon sequestration

- in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modeling* 164: 177-199.
- Mora A. and Beer J. 2013. Geostatistical modeling of the spatial variability of coffee fine roots under *Erythrina* shade trees and contrasting soil management. *Agroforestry systems* 87: 365- 376.
- Pebesma, E.J., 2004. Multivariable geostatistics in S: the gstat package. *Computers & Geosciences*, 30: 683-691.
- Pinheiro, J.C. and D. M. Bates. 2000. Mixed-effects models in S and S-plus. Springer-Verlag, New York.
- Piotto, D., F. Montagnini, L. Ugalde and M. Kanninen. 2003. Growth and effects of thinning of mixed and pure plantations with native trees in humid tropical Costa Rica. *Forest Ecology and Management* 177: 427-439.
- Padovan, M.P., Cortez, V.J., Navarrete, L.F. et al. 2015. Root distribution and water use in coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal environmental conditions. *Agroforestry Systems* 89: 857–868.
- R Development Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org>.
- Redondo, A. 2005. A review of the agroforestry systems of Costa Rica. *Journal of Sustainable Forestry* 21: 97- 119.
- Robertson, G. P., M. A. Huston, F. C. Evans, and J M Tiedje. 1988. Spatial variability in a successional plant community: patterns of nitrogen availability. *Ecology* 69: 1517-1524.
- Robinson, D., A. Hodge, and A. Fitter. 2003. Constraints on the form and function of root systems. In *Root Ecology*. Editors Hans de Kroon, and Eric J. W. Visser. Springer-Verlag, Germany. pp
- Russell V. L. 2016. Least-Squares Means: The R Package lsmeans. *Journal of Statistical Software*, 69(1), 1-33.
- Sánchez- de León, Y., E. De Melo, G. Soto, J. Johnson-Maynard, and J. Lugo Perez. 2006. Earthworm Populations, Microbial Biomass and Coffee Production in Different Experimental Agroforestry Management Systems in Costa Rica. *Caribbean Journal of Science* 42 (3): 397- 409.
- Sayer EJ, EVJ Tanner and AW Cheesman. 2006. Increased litterfall changes fine root distribution in a moist tropical forest. *Plant Soil* 281: 5–13.
- Schaller J., G. Schroth, Beer, and F. Jimenez. 2003. Species and site characteristics that permit the association of fast-growing trees with crops: the case of *Eucalyptus deglupta* as coffee shade in Costa Rica. *Forest Ecology and Management* 175: 205-215.
- Schroth G. 1995. Tree root characteristics as criteria for species selection and systems design in agroforestry. *Agroforestry Systems* 30: 125-143.
- Stoyan H., H. De-Polli, S. Böhm, G.P. Robertson and E.A. Paul. 2000. Spatial heterogeneity of soil respiration and related properties at the plant scale. *Plant and Soil* 222: 203-214.
- Sun Z., Mu C., and Sun L. 2006. The estimate of fine root biomass in upper soil layer of *Larix olgensis* plantation by geostatistics method. *Chinese Journal of Plant Ecology* 30: 771-779.
- Tilki F.; Fisher R.F. 1998. Tropical leguminous species for acid soils: studies on plant form and growth in Costa Rica. *Forest Ecology and Management*, 108: 175-192.
- Utset, A. and G. Cid. 2001. Soil penetrometer resistance spatial variability in a Ferralsol at several soil moisture conditions. *Soil & Tillage Research* 61: 192- 202.
- Van Katen R., G. Schroth, J. Beer, and F. Jimenez 2005. Fine-root dynamics of coffee in association with two shade trees in Costa Rica. *Agroforestry Systems*, 63: 247- 261.
- Vogt KA, Vogt DJ, Palmiotto PA, Boon P, O'Hara J, Abjorsen H. 1996. Review of root dynamics in forest ecosystems grouped by climatic forest type and species. *Plant and Soil* 187:159–219
- Webster, R. 2001. Statistics to support soil research and their presentation. *European Journal of Soil Science* 52: 331- 340.
- Wilson, J. and Ndufa, J. 2014. Soil moisture. In: de Leeuw, J., Njenga, M., Wagner, B., Iiyama, M. (eds.) *Treesilience: an Assessment of the Resilience provided by Trees in the Drylands of Eastern Africa*. World Agroforestry Centre (ICRAF), Nairobi, Kenya, pp. 74-77.