

**Characterization of the spatial variability of soil properties and  
Coffee fine roots in shade tree- coffee associations under organic and  
conventional management practices**

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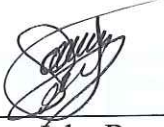
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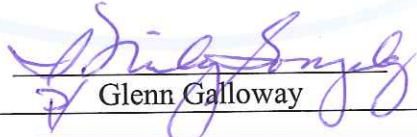
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## **Dedication**

To the memory of my Mom

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## **Biography**

Argenis Mora Garcés is a citizen of Venezuela, born on September, 17th 1965. He concluded his elementary and high school education in Punto Fijo, Estado Falcon and obtained his Agronomical Engineering degree with honor by degree work on emphasis in experimental design at Universidad Nacional Experimental Francisco de Miranda (Coro, Estado Falcon, Venezuela) in 1990. A Master Science degree in Applied Statistics was awarded at Universidad Central de Venezuela in 1996. Since 1996 he has been working as Professor and researcher at Faculty of Forestry and Environmental Sciences, Universidad de Los Andes, Venezuela. At present, he is Associate Professor and Head of Forest Management Department. His research interests are Experimental design, Data analysis and modeling applied to Agroforestry Systems, and Forestry Plantations.

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## Summary

Agroforestry system research has highlighted that belowground interaction studies are fundamental to understand the development and distribution of crop and tree fine roots. The spatial variability of coffee fine roots, as a potential indicator of competition, depends on nutrient availability and how these fine roots are distributed in space. As consequence, crops could respond by selectively proliferating their fine roots within nutrient-rich patches. Studies on spatial heterogeneity of coffee fine roots by using geostatistics are not known. This thesis characterized spatial changes of fine root attributes ( $d < 2.0$  mm) and soil properties in three *Coffea arabica*- shade tree associations: coffee shaded by a) *Abarema idiopoda* (Timber and nitrogen fixer tree), b) *Erythrina poeppigiana* (nitrogen fixer tree), and c) *Terminalia amazonia* (Timber tree). These associations were submitted to organic and conventional management. Also, it was quantified by geostatistic the scale of spatial heterogeneity (aggregation patterns) of the coffee fine root length density (RLD,  $d < 2.0$  mm), and, finally, the spatial relationships between the length density of coffee fine roots and soil nutrient- related factors at plot scale was analyzed in a coffee- *Erythrina poeppigiana* association under the conventional and organic managements. The main results were the followings: significant amount of coffee fine roots in litter layer demonstrates the importance to include 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 fine roots at 40 cm soil depth; being coffee fine roots more abundant when coffee plants is grown with *T. amazonia*. Coffee fine roots explored more soil under the conventional management during the fruit formation; however, at harvest peak when coffee plants become exhausted, coffee root length density was not affected by management type. Competition and alterations in soil environment originated by the presence of shade trees modified the thickness (diameter) of coffee roots. Coffee- shade tree associations organically managed showed substantial increments in the soil nutritional status and decrease of exchangeable Aluminum. Vertical distribution of *T. amazonia* fine roots promise to have a desirable characteristic for agroforestry practices in this suboptimal region for coffee production. In addition, results demonstrated that the type of management affects the aggregation patterns (scale of spatial heterogeneity) of *C. arabica* RLD for all of the coffee- tree associations.

Nutrients linked to P, Zn, and exchangeable bases were positively and spatially correlated to coffee fine root density; but, negatively correlated with the acidity soil factor (i.e., pH and exchangeable aluminum). The spatial response of coffee RLD showed in my study suggests a differential foraging strategy for acquiring soil nutrients induced by the quality of organic and inorganic fertilizer inputs and explained by the morphological plasticity of coffee fine roots. For example, if soil is less acid the foraging pattern for resources and the mechanism of root proliferation tend to increase. In Addition, estimating scales of spatial heterogeneity of plant fine roots by geostatistics analysis may provide insights into the studies about belowground plant-soil and crop-tree interactions in agroforestry systems

## Resumen

Investigaciones en sistemas agroforestales han enfatizado que estudios sobre interacciones bajo el suelo son importantes para el entender el desarrollo y la distribución de raíces finas de cultivos y arboles asociados. La variabilidad espacial de raíces finas de *Coffea arabica* L. depende sobre la disponibilidad de nutrientes y cómo dichas raíces finas están distribuidos espacialmente; a su vez, estas raíces finas suelen ser consideradas como un indicador potencial de competencia bajo el suelo entre la planta cultivo y árbol. Como resultado, Los cultivos podrían responder a través de la proliferación selectiva de sus raíces finas dentro de parches ricos de nutrientes. Estudios sobre heterogeneidad espacial de raíces finas de café usando geo-estadística no se conocen hasta ahora. Esta tesis caracterizó los cambios espaciales de raíces finas de café ( $d < 2.0$  mm) y propiedades de suelos en tres asociaciones árbol- café: a) *Abarema idiopoda* (maderable y fijador de N), b) *Erythrina poeppigiana* (fijador de N), and c) *Terminalia amazonia* (Maderable) todas sometidas a manejos convencional y orgánico. También, se cuantifico a través de geoestadística, la escala de la heterogeneidad espacial de las raíces finas de café. Finalmente, la relación espacial entre la densidad longitudinal de raíces (DLR) de café y algunos factores nutricionales del suelo fueron analizadas en la asociación café- *Erythrina poeppigiana* bajo los manejos convencional y orgánico. Los principales resultados fueron los siguientes: una cantidad significativa de raíces finas de café encontrado en la capa de hojarasca o mantilla demuestra la importancia de incluir esta capa para una correcta estimación de raíces finas en sistemas agroforestales con café. Los árboles sombra mostraron marcada diferencia en la distribución vertical de sus raíces finas y afectaron la densidad longitudinal de raíces finas del café a una profundidad de 40 cm. Siendo las raíces finas de café más abundante bajo la sombra de *T. amazonia*. Raíces finas de café exploraron mayor volumen de suelo bajo el manejo convencional durante la época de formación de frutos, sin embargo, al momento del pico de cosecha la DLR de café no se vio afectada por los tipos de manejo. Competencia y alteraciones en el suelo originado por la presencia de los árboles sombra modificó el grosor (diámetro) de las raíces finas del café. En las asociaciones árbol- café con manejo orgánico mostraron incrementos importantes en el estado nutricional del suelo y una disminución en la concentración del Al intercambiable. La distribución vertical de raíces finas de *T. amazonia* promete tener la característica deseable para la práctica agroforestal en las

regiones sub óptima para la producción de café. Además, los resultados demostraron que el tipo de manejo afecta el patrón de agregación (Escala de heterogeneidad espacial) de la DLR de café en todas las asociaciones. Nutrientes ligados al P, Zn y bases cambiables estuvieron correlacionadas espacialmente con la DLR de café; pero negativamente con el factor acidez de suelo (pH y Al cambiante). Esta respuesta especial de las raíces del café sugiere un tipo de estrategia de exploración diferencial para la adquisición de nutrientes inducida por la calidad de las entradas de fertilizantes tanto orgánicos como químicos; y explicada por la plasticidad morfológica de las raíces finas de café. Es decir, si el suelo es menos ácido el patrón de exploración por recursos y los mecanismos de proliferación de raíces tienden a aumentar. Además, determinaciones de escalas de variación espacial en raíces finas pueden ofrecer nuevos hallazgos en los estudios de las interacciones planta-suelo y cultivo- árbol en los sistemas agroforestales.

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## Chapter 1. Introduction

Traditionally, coffee (*Coffea arabica*) has been one of the most important agricultural export products of Central American countries, including Costa Rica. Many small to medium farms in Central America are dedicated to coffee production, which generates profits and employment for 20 to 25 million people (Aguilar and Klocker, 2002; Redondo, 2005). In Costa Rica, leader in un-shaded coffee production in this region, some coffee plantations have been diversified with timber trees since the 1990's. Amongst the main species recommended, native timber trees seem to have better potential characteristics to be used in shaded coffee systems in humid lowlands of Costa Rica (Redondo, 2005). For example, *Terminalia amazonia* (Gmel.) Exell has been characterized as a promising fast growing native species for agroforestry systems due to its good adaptability to acid and low fertility soils (Nichols, 1994; Haggard et al., 1998). Some leguminous timber species, such as *Abarema idiopoda* (S.F. Blake) Barneby & J. W. Grimes, have been recommended for agroforestry projects because of their good potential as multipurpose trees, and for reforestation of degraded lands (Tilki and Fisher, 1998). In the sub-optimal conditions for coffee cropping (e.g., Turrialba, Costa Rica) there is a need to study basic processes of soil-plant interactions in coffee-tree associations; the sustainability and performance of these agroforestry systems is affected by how these processes vary spatially in the soil environment. Spatial distribution of tree and coffee root density is usually seen as a main indicator of competition between trees and crops (Schroth, 1995). Fine-scale nutrient heterogeneity could have a strong effect on the proliferation of fine roots and, presumably, increases nutrient capture, especially when plants compete for nutrients with other plants (Robinson et al., 2003, Hodge, 2006).

In the humid tropics, it has been recognized that soils in a third of the total land area are mainly poor in nutrients and strongly acid (Juo and Franzluebbers, 2003). Aluminum toxicity together with low calcium concentrations are the most limiting for plant fine root growth and foraging in deeper soil layers (Rodrigues et al., 2001). Large differences in spatial variability of chemical, physical and biological properties may occur at different scales and be determined by various processes (e.g., management practices). Ecologists did not explicitly study nutrient spatial heterogeneity in soils until the application of geostatistics began to clarify spatial patterns of nutrients in ecosystems (e.g., Robertson et al., 1988; Rossi et al. 1992). Fine-scale nutrient heterogeneity could have a strong effect on belowground interactions in coffee- shade tree associations. The spatial variability of coffee fine roots depends on nutrient availability and can be influenced according to both manner of fertilizer application and distance from the shade tree (Schaller et al., 2003). Higher concentration of coffee fine root length in shaded plantations has been found in nutrient rich- fertilized areas (Schaller et al., 2003; van Kanten et al., 2005). In response to this spatial variation of nutrients, many plants selectively increase fine root biomass within enriched patches in order to forage efficiently for nutrients (Hodge, 2006). A literature search did not identify any publication describing the use of geostatistics to study spatial heterogeneity of coffee fine roots in agroforestry systems. In the following chapters, the effects of three shade tree species (*T. amazonia*, *A. idiopoda* and *Erythrina poeppigiana*) and contrasting management (organic and conventional) on the spatial variability of coffee fine root density is discussed. In chapter 2, the following aspects are covered: how coffee fine roots respond to micro site changes at varying distances from the nearest shade tree under the two contrasting management systems; and whether the spatial changes of top soil

nutrient availability depend on the proximity of the shade tree that reflects the influence and the type of management. In chapter 3, geostatistic is used to show how organic and conventional management affect the scale and aggregation pattern of coffee and *A. idiopoda* fine roots. In chapter 4, the spatial heterogeneity of both coffee fine roots and factors related to soil nutrient availability are quantified to determine whether coffee fine root density was spatially correlated with those nutrient factors at a plot scale in the coffee-*E. poeppigiana* association under soil conditions managed organically and conventionally. Previous studies suggest that spatial changes of coffee fine root density can be influenced by soil acidity, nutrient availability and the rooting pattern of the shade trees; as a consequence, it was hypothesized that these changes are possible due to the morphological plasticity of the fine roots of coffee depending on whether plantations are managed organically or conventionally.

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## **Chapter 2. Spatial changes of *Coffea arabica* and shade tree fine roots and soil attributes under organic and conventional coffee agroforestry management systems**

### **Abstract**

This paper presents data on spatial changes of fine root attributes ( $d < 2.0$  mm) and soil properties in three *Coffea arabica*- shade tree associations: coffee shaded by a) *Abarema idiopoda* (timber and nitrogen fixing tree), b) *Erythrina poeppigiana* (nitrogen fixing tree), and c) *Terminalia amazonia* (timber tree). These associations were submitted to organic and conventional management. Using soil cores, coffee and shade tree fine root distributions were quantified to 40 cm depth, in order to identify fine root vertical distribution; and to a 20 cm, at three sampling distances from a shade tree, during two sampling periods (litter layer was included). 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 demonstrates 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 fine roots between 0- 40 cm soil depth; being more abundant when coffee is planted with *T. amazonia*. At 0- 20 cm depth, the decreasing (*A. idiopoda*) or increasing (*E. poeppigiana*) tree fine root density with increasing distances from tree base did not affect the concentration of coffee fine roots. While coffee root concentration was lower in alley positions, greater coffee fine root density was found close to the coffee rows not only beside shade tree but also distant to it. Coffee fine roots explored more soil under the conventional management during the fruit formation; however, at harvest peak, when coffee plants become exhausted, coffee root length density was not affected by management type. Competition and alterations in soil environment, due to the presence of shade trees, modified the thickness (diameter) of coffee roots. Coffee- shade tree associations organically managed showed substantial increments in the soil nutritional status and decrease of exchangeable Al. A decrease of the C concentration with increasing distance from the *A. idiopoda* and *E. poeppigiana* trees suggests that processes associated with these individual trees spatially modifies the C stock in the soil beneath their influence

zone. Finally, the vertical distribution of *T. amazonia* fine roots appears to be a desirable characteristic for agroforestry practices in this suboptimal region for coffee production.

Key words: Fine root length density, specific fine root length, *Abarema idiopoda*, *Terminalia amazonia*, *Erythrina poeppigiana*, root distribution.

## Introduction

Coffee (*Coffea arabica* L.) is the most important commodity in international agricultural trade representing a significant source of income to several Latin American, African and Asian countries. Coffee has been fundamental for the economical, social and political development of Central America countries for over 100 years (Aguilar and Klocker, 2000). Millions of people are involved in its production and preparation; many more in consumption. During the years 2000 and 2001, coffee plantations occupied some 6.6 million ha worldwide, of which 63 % were planted with *C. arabica* and the remainder with *Coffea canephora* Pierre (robusta coffee) (DaMatta, 2004). Traditionally, coffee has been one of the most important agricultural export products of Central American countries, including Costa Rica. In these regions, *C. arabica* has been grown under “service” shade trees such as *Gliricidia sepium* (Jacq.) Kunth ex Walp, *Inga* spp. or *Erythrina* spp., which are managed principally for the benefit of the coffee and some secondary products such as firewood (Galloway and Beer, 1997).

Costa Rican coffee plantations have been increasingly diversified with timber trees since 1990's. The native timber tree species used include *Cordia alliodora* (Ruiz and Pav.) Oken, and *Terminalia amazonia* (Gmel.) Exell, as well as the exotic *Terminalia ivorensis* A. Chev. Recently, *Eucalyptus saligna* J.E. Sm. and *Eucalyptus deglupta* Blume (exotics) have been planted as shade trees for coffee in the Southern region and the Central Valley of Costa Rica. (Ugalde, 1997; Tavares et al., 1999). However, amongst the main species tested, native timber trees seem to have better characteristics to be used in shaded coffee systems. For example, *T. amazonia* has been characterized as a promising fast growing native species for agroforestry systems due to its high survival, good adaptability to low intensity site preparation, and high decomposition rates of litter (Kershner and Montagnini,

1998; Piotto et al., 2003). 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 & J. W. Grimes (Tilki and Fisher, 1998).

There is a need to study basic processes of soil –plant interactions in agroforestry systems, and how these processes vary spatially in the soil, because sustainability and performance of these systems are affected by such soil-plant interactions. When tree and crop overlap in an agroforestry ecosystem, competition can occur due to one of them (e.g., tree) reducing one or more resources and affecting the performance of the other (Garcia- Barrios and Ong, 2004); e.g., the tree and its environment modify the nutrient availability around the crop plants (Anderson and Sinclair, 1993). Agroforestry system research has emphasized that belowground interaction studies are fundamental to understand the competition processes between crop and tree; and how these influence soil properties and dynamics. Root density distribution of trees and crops is usually seen as a main indicator of competition between trees and crops (Schroth, 1995), assuming that at equal available growth resources in the soil, the resource uptake is related to the amount of root length per unit soil volume irrespective of species. Competition for soil resources can vary with the spatial and temporal distribution of roots, especially if crop-tree roots overlap; fine-scale nutrient heterogeneity could have a strong effect on belowground interactions. In this respect, biophysical interaction studies in coffee-based agroforestry systems have shown some sort of complementarily or weak competition. The distribution of tree-coffee roots depends on spatial variations in nutrient availability and can be influenced by the manner of fertilizer application and distance from the shade trees (Schaller et al., 2003).

It has been recognized that the quantification of fine root parameters are 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 view point 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). Thus, studies about rooting depth and vertical distribution of root systems are fundamental for agroforestry research.

About a third of the soils in the total land area of the tropics (about 1.5 billion ha) are strongly acidic; in this area, exchangeable  $Al^{+3}$  occupies more than 60 % of the cation exchange sites of the 0- 50 cm soil layer. In the humid tropics, the poor chemical properties of the soils are a major problem for crop production; for instance, exchangeable base contents, nutrient reservoirs, and phosphorus availability are low. Poor drainage, and low effective cation exchange capacity (ECEC) are also important soil constraints in the humid tropics and all of these restrict growth and performance of tropical crops (Szott et al., 1991). Large changes in spatial variability of chemical, physical, and biological properties may occur at different scales and be determined by various processes (e.g., soil macro fauna or management practices).

This study addressed the questions: i) how do coffee fine roots respond to micro site changes at varying distances from shade trees under two contrasting management systems; i.e. organic and conventional?, ii) do the spatial changes of top soil nutrients depend on the

proximity of the nearest shade tree and the type of management of the coffee- based agroforestry systems?.

## **Materials and Methods**

### ***Site description***

The study was carried out in the experimental coffee fields of the “Centro Agronómico Tropical de Investigación y Enseñanza” (CATIE), Turrialba, Costa Rica (9°53'44'' N; 83°40'7'' W; 602 m). Annual precipitation is 2700 mm yr<sup>-1</sup> (1948- 2005), mean annual temperature is 21.8 °C, and relative humidity 88% (<http://catie.ac.cr/> [verified march 2006]). Soils were classified as Typic Endoaquepts and Typic Endoaquults (Sanchez- de Leon et al., 2006), and characterized as mixed alluvial with a poor or medium fertility and a water table ranging between 40 and 120 m (Aguirre, 1971). The study site is relatively flat (slope of < 1 %) and a main limitation was impeded drainage, which has been resolved by establishing deep principal drainage channels (> 1.0 m). *C. arabica* cv. “Caturra” and shade trees were planted during August and October 2000. Coffee planting holes are spaced 1 x 2 m apart with trees planted at 4 x 6 m. In November 2000, coffee replanting had to be done because of mortality due to the initial impeded drainage problem on some plots. Prior to the establishment of the trial, the site was used (commercial farm) for sugar cane (*Saccharum officinarum*) production. During the study period, registered rainfalls of 141.2 (May- June, 2005) and 255.1 cm (October- November, 2005) were below historical records.

### ***Design of Experiment***

For the purposes of the present study, a factorial treatment arrangement, in a split- plot design with three blocks was used. Three coffee- shade tree associations were studied;

coffee shaded by: (1) *T. amazonia* (timber tree), (2) *A. idiopoda* (nitrogen fixing- timber tree), and (3) *Erythrina poeppigiana* (Walp.) O. F. Cook (nitrogen fixing “service” tree). The total area of shaded plots with *Erythrina*, *Abarema*, and *Terminalia* treatments was 4000, 4088, and 3200 m<sup>2</sup>, respectively. Within each coffee- shade tree association, two types of coffee management treatments (sub-treatments) were considered: conventional and organic. Fertilizer, herbicide and fungicide application rates within each sub-treatment are shown in Table 1. 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. 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. In all coffee- tree associations and management systems studied, shade was permanent but regulated by pruning twice a year. When present, *Erythrina* pruning residues (leaves/branch) were not homogeneously distributed on the plot.

### ***Spatial sampling scheme and samples processing***

Preliminary sampling was carried out in May 2005 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 40 cm depth in 10 cm increments. The presence of rocks 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<sup>-2</sup>).

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

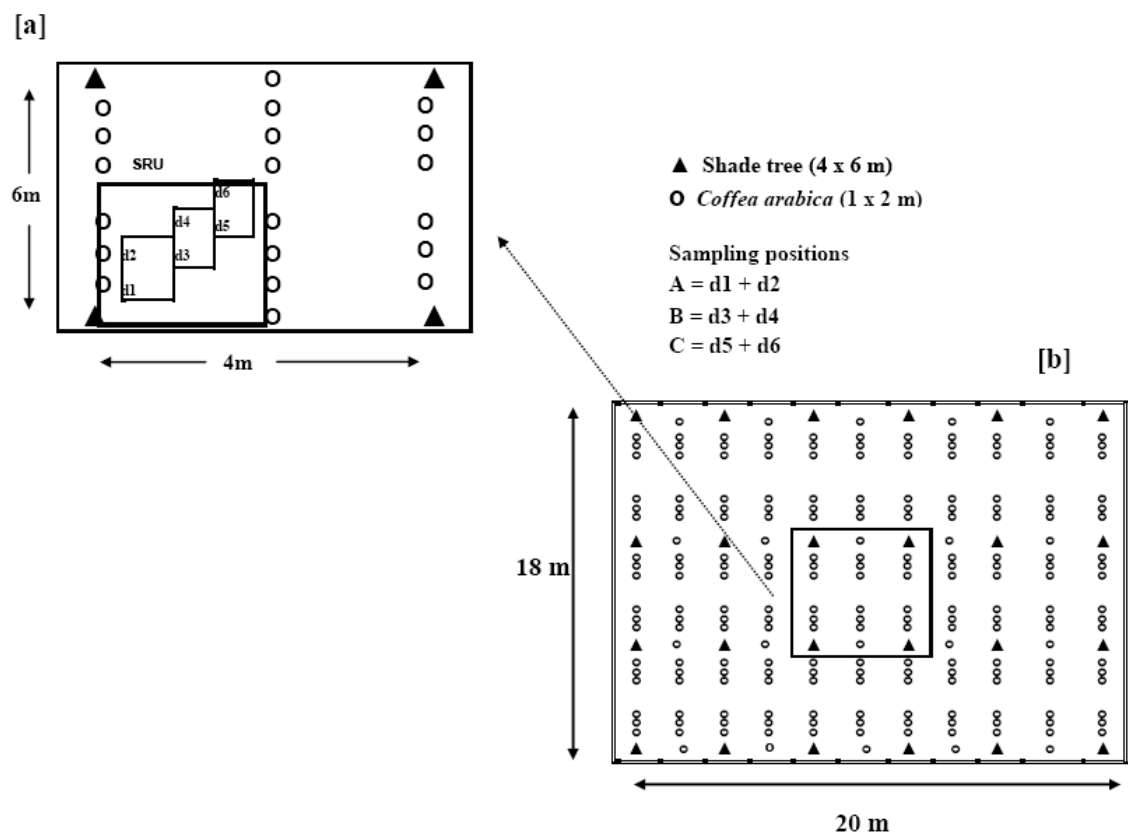
Inputs	Organic	Conventional
Soil amendment	20 tons ha <sup>-1</sup> yr <sup>-1</sup> coffee pulp 7.5 tons ha <sup>-1</sup> yr <sup>-1</sup> chicken manure 200 kg ha <sup>-1</sup> yr <sup>-1</sup> KMAG 200 kg ha <sup>-1</sup> yr <sup>-1</sup> Phosphoric rock	400 kg ha <sup>-1</sup> yr <sup>-1</sup> 18-15-6-2 (N, P, K, Mg and B) 45 kg ha <sup>-1</sup> yr <sup>-1</sup> NH <sub>4</sub> HO <sub>3</sub> 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 <sup>-1</sup> Roundup to eliminate herbaceous species among coffee plants within a row
Pest control	No application of fungicides	fungicides: 2.5 g l <sup>-1</sup> H <sub>2</sub> O per block of Atemi or Copper sulfate (once a year)

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

Subsequently, to determine the effect of shade trees on coffee fine roots and soil attributes, two principal periods of sampling were carried out. The first set of samples was collected during May and June 2005, just after the driest period of the year and at the conclusion of coffee flowering and onset of coffee fruiting. A second sampling was carried out during October and November 2005 (during the wettest period of the year and during the second main harvest). In each experimental plot, a shade tree was randomly selected and the smallest representative unit (SRU, 3x2 m) was identified (Figure 1a). This sampling scheme represents the smallest spatial element contained in a plot with a shade-tree in one corner (Coe et al., 2003, chap.3). Two sampling points were placed according to sectors or



strata: (A) on the coffee row close to the shade-tree, (B) on inter-coffee row, and (C) on the coffee row far from trees. These strata form a diagonal in each SRU and from the shade tree base; six distances were set, two in each strata (distances to shade trees, denominated “d” in Figure 1a). This sampling strategy gave samples such that it was possible to analyze the spatial effect of the shade tree comparing distances of 53- 146 and 309- 392 cm (strata denominated B not included for this particular analysis). Soil cores were taken at 0-20 cm soil depth by hammering an auger into the soil (internal diameter 6 cm) after removing litter layer. Sampling positions were approximately 30 cm (perpendicular to row) from the coffee bushes.



**Figure 1. Distribution of fine root sampling positions in the experimental (a) and central (b) plot of the *Coffea arabica*- shade tree associations / management type trial, Turrialba, Costa Rica.**

All of collected samples 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. Later, a sub-sample (on average 50 % or 405 g) was separated for fine root extraction and the remainder for soil analyses. All sub-samples for root analysis 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. A total of 108 soil cores were collected per each principal sampling period: i.e., 6 sampling positions x 3 shade tree species x 2 types of management (organic or conventional) x 3 SRU.

Additionally, during the second period (October and November), fine roots in the litter layer were collected from the first millimeters of the topsoil by using the same 8 cm internal diameter ring utilized for the vertical distribution study. Again, the SRU's were selected randomly in each plot.

Under a stereoscope (8X), tree and coffee roots were separated based on morphological characteristics. *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. Finally, *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 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 0.001 g (RDW). Next, the fine root length density (RLD cm per cm<sup>3</sup> soil) and the specific root length (SRL, fine root length to dry weight ratio; cm per mg) were computed for coffee and each tree species. However, density of fine roots from the litter layer was expressed by cm cm<sup>-2</sup>.

From the first sample set processed during May- June, the unused sub-samples for extraction of fine roots were sent for soil analyses. Effective cation exchange capacity (Ecec) was obtained as the sum of exchangeable “bases” (Ca, Mg, K); exchangeable acidity determined in 1.0 N KCl; saturation of exchangeable aluminum was calculated as a percentage from Ecec. Organic carbon was determined by the combustion method using auto- analyzer equipment; available P, K and micronutrients (Cu, Zn, Mn, Fe) were extracted by modified Olsen method (pH 8.5) and pH was determined in H<sub>2</sub>O.

### ***Statistical Analysis***

Coffee and tree species root length from the vertical distribution study were analyzed with analysis of repeated measures to compare types of management, tree species, depth and their respective interactions. To test the effect of shade tree species, managements, sampling positions and interactions on coffee fine root length density, tree fine root length density, coffee specific root length, tree specific root length and the eight soil parameters the following mixed effects model (Pinheiro and Bates, 2000) was applied:

$$y_{ijkl} = \mu + \alpha_{i(l)} + \beta_{j(i)} + \delta_{k(j)} + \alpha\beta_{(ij)} + \alpha\delta_{(ik)} + \beta\delta_{(jk)} + \alpha\beta\delta_{(ijk)} + b_l + b_{i(l)} + b_{j(i)} + \varepsilon_{ijkl},$$

where  $\mu$  was the overall mean,  $\alpha_{i(l)}$  was the shade tree effect,  $\beta_{j(i)}$  was the effect of management (i.e., organic or conventional),  $\delta_{k(j)}$  was the effect of stratum or sampling position, and its respective interactions ( $\alpha\beta$ ,  $\alpha\delta$ ,  $\beta\delta$ , and  $\alpha\beta\delta$ ). The  $b$  components represent

the random effects (i.e., SRU, SRU in managements and managements in specie tree, respectively). Data were analyzed by each sampling period to avoid complicated model estimations and interpretations. Posteriori mean comparisons and graphics were used. By means of residuals, normal distribution and non-constant variances were checked. The variance heterogeneity structure of residuals was the structure most fitted for estimating repeated measures and mixed models. All the statistical analyses were carried out with the software package R (R Development Core Team, 2008).

## **Results**

### **Vertical distribution of shade trees and coffee fine roots**

In the preliminary sampling, under *E. poeppigiana*, the proportion of coffee fine roots in the litter layer was 47 and 62 % for conventional and organic management, respectively (Fig 2). Including the litter layer, more than 75 % of coffee fine roots were concentrated in the upper 20 cm of soil of the 0-40 cm sampled under *E. poeppigiana*-conventional (EC); but under *E. poeppigiana*-organic (EO), 94 % of coffee fine roots were found in these strata. On the other hand, the percentage of *E. poeppigiana* fine roots in the litter layer differed markedly under conventional and organic systems (17 and 68 % for EC and EO, respectively). Not including the litter layer, under conventional management, *E. poeppigiana* fine roots had a homogeneous vertical distribution and more roots than that found under organic management (6.4 vs. 4.5 cm cm<sup>-2</sup>). Coffee fine roots had an even vertical distribution to 20 cm of soil under *A. idiopoda*-conventional (AC); fine roots were not observed below 30 cm. The proportion of coffee fine roots found in the litter layer in AC was 39 %, and under AO 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 management; 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 management, respectively. In association with *T. amazonia*, under both kinds of management, 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  $\geq 70$  % in the upper 20 cm and higher coffee RLD was found than in the *E. poeppigiana*-coffee and *A. idiopoda*-coffee associations. Including the litter layer, few fine roots of *T. amazonia* were found in the upper 10 cm of the soil profile (3 % for conventional management and 4 % for organic); they increased rapidly below 10 cm with highest values for 30-40 cm.

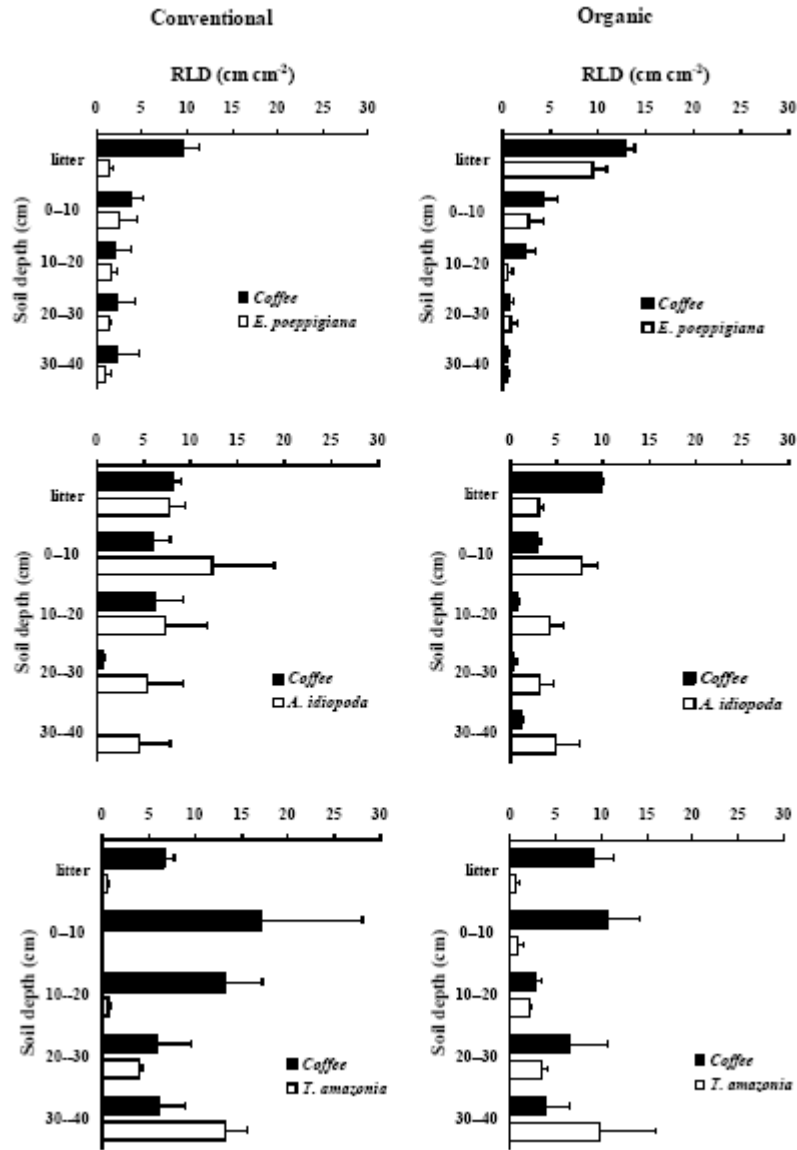


Figure 2. Vertical distribution of fine root length density ( $d \leq 2$  mm; RLD,  $\text{cm cm}^{-2}$   $n = 4$  for each association and depth) for *Coffea arabica* and shade trees (*Abarema idiopoda*, *Erythrina poeppigiana*, and *Terminalia amazonia*) under organic and conventional management in Turrialba, Costa Rica.

Averaging RLD for all combinations in the litter layer, coffee RLD varied significantly ( $p = 0.041$ ) between conventional and organic management ( $8.1 \pm 1.2$  and  $10.6 \pm 1.1 \text{ cm cm}^{-2}$ , respectively). Tree RLD in the litter layer was consistently lower but differed among the shade tree species and the type of management. For example, *E. poeppigiana* had RLD of  $1.3 \pm 0.5 \text{ cm cm}^{-2}$  for EC vs.  $9.4 \pm 1.4 \text{ cm cm}^{-2}$  for EO. The comparable RLD's for *A. idiopoda* were  $7.7 \pm 1.7$  and  $3.1 \pm 0.6 \text{ cm cm}^{-2}$  for AO and AC, respectively, while *T. amazonia* RLD was not higher than  $0.7 \text{ cm cm}^{-2}$  in the litter layer. Comparing the total values accumulated to 40 cm depth (average of AO and AC), the RLD of *A. idiopoda* was higher than *E. poeppigiana* or *T. amazonia* (Table 2;  $p = 0.008$ ). There was, however, no significant difference between organic and conventional management (averaging all shade tree associations) and no interaction between associations and managements for tree RLD means (Table 2). Under conventional management, *A. idiopoda* amassed more fine roots than *T. amazonia* or *E. poeppigiana*; but in organic systems, the total values of shade tree RLD to 40 cm depth did not vary significantly between associations. Conversely, the accumulated RLD for coffee to 40 cm was consistently higher in the coffee- *T. amazonia* association, under either conventional or organic management (Table 2); additionally, in conventional management coffee fine roots gathered significantly higher length density than in the organic (Table 2).

**Table 2. Total accumulated values of fine root length density ( $d \leq 2$  mm; RLD, cm cm<sup>2</sup>; mean  $\pm$  SE; 0-40 cm, includes litter layer) of *Coffea arabica* and associated shade trees (*Abarema idiopoda*, *Erythrina poeppigiana* or *Terminalia amazonia*) under organic and conventional management in Turrialba, Costa Rica (Preliminary sampling, May 2005).**

Coffee shaded by	Conventional	Organic	Mean
	<i>Coffee</i> -RLD		
<i>E. poeppigiana</i>	20.2 (5.3) <b>b</b>	20.7 (6.5) <b>b</b>	<b>20.4 (4.2)<b>b</b></b>
<i>A. idiopoda</i>	20.8 (5.9) <b>b</b>	14.9 (4.8) <b>b</b>	<b>17.8 (3.8)<b>b</b></b>
<i>T. amazonia</i>	48.9 (12.7) <b>a</b>	33.0 (7.4) <b>a</b>	<b>40.7 (7.4)<b>a</b></b>
<b>Mean</b>	<b>30.0 (4.9)<b>a</b></b>	<b>22.9 (3.7)<b>b</b></b>	
	<i>Tree</i> -RLD		Mean
<i>E. poeppigiana</i>	7.7 (1.9) <b>b</b>	13.9 (5.0) <b>a</b>	<b>10.8 (2.8)<b>b</b></b>
<i>A. idiopoda</i>	37.5 (9.2) <b>a</b>	23.2 (3.7) <b>a</b>	<b>30.3 (4.6)<b>a</b></b>
<i>T. amazonia</i>	18.3 (7.3) <b>b</b>	17.1 (7.2) <b>a</b>	<b>17.7 (5.1)<b>b</b></b>
<b>Mean</b>	<b>21.1 (4.1)<b>a</b></b>	<b>18.1 (3.0)<b>a</b></b>	

Significant differences are indicated by different letters ( $p < 0.005$ ; LSD with Bonferroni corrections) for RLD means from within and between management (conventional and organic).



## **Fine root abundance and sampling positions**

### ***The mineral topsoil***

More coffee fine root biomass (RDW) was found close to coffee rows with and without shade trees (sampling positions A and C, respectively, Fig. 3a). The analysis of variance produced by fitting the mixed effect models showed significant differences of coffee RDW means; higher RDW was found under conventional than organic management ( $p = 0.004$ ). Under conventional management, in all shade tree- coffee associations, coffee RDW means close to the shade trees (position A) were significantly higher than RDW for the more distant position (C); under organic management this occurred only in the coffee- *A. idiopoda* and coffee- *T. amazonia* associations. For the second set of samples, taken in October-November 2005, the relative spatial behavior of the coffee fine roots was identical to that found during the first set taken during May-June 2005 (data not shown). However, no significant differences between either management types or associations were found in October-November. In general, for the first period, coffee fine roots were more abundant under the conventional than organic management.

*A. idiopoda* had higher RDW than the coffee only under the organic treatment in the inter-row but, in the proximity of the coffee rows, *A. idiopoda* RDW was always much lower than the coffee RDW. There were significant interactions between tree species and type of management and the RDW of each tree species varied among sampling positions ( $p < 0.05$ ). The *A. idiopoda* RDW declines with distance from shade trees and was the same under both management systems (Fig. 3b). In contrast, *E. poeppigiana* RDW under organic management was markedly higher than under the conventional management (where *E. poeppigiana* roots were very scarce). Moreover, the *E. poeppigiana* RDW increased with distance from the shade tree. *T. amazonia* fine roots not only were scarce under

conventional but also under organic management (0-20 cm) this was in agreement with the results obtained in the preliminary study in which more *T. amazonia* fine roots were found in the deeper layers (Fig. 2).

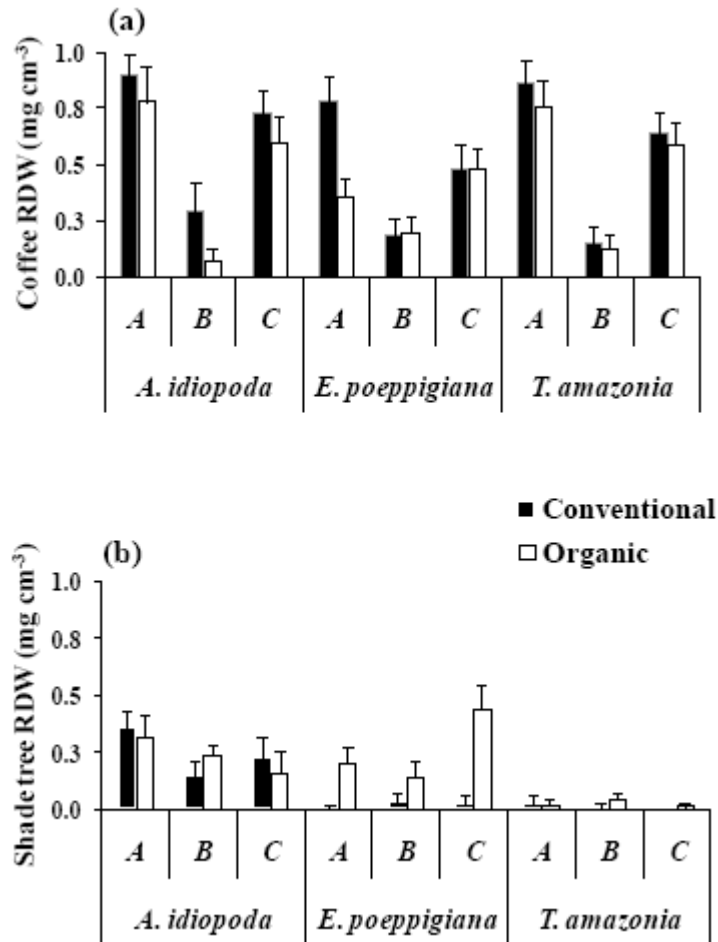


Figure 3. Effect of three shade tree species (*Abarema idiopoda*, *Erythrina poeppigiana*, and *Terminalia amazonia*) and sampling positions (A, B, and C; distance from shade tree) on dry weight density (RDW, mg cm<sup>-3</sup>; means and standard error bars) of (a) *Coffea arabica* and (b) shade tree fine roots ( $d \leq 2$  mm) in mineral soil (0 - 20 cm) under organic and conventional management in Turrialba, Costa Rica. Samples collected during May and June 2005.

### ***The litter layer***

The coffee fine roots (RDW) completely dominated shade tree roots in the litter layer (Fig. 4a and 4b; root biomass above soil surface; note different scales). Coffee fine roots in the *E. poeppigiana* association were more abundant under conventional than organic management. On the contrary, the coffee RDW in the *T. amazonia*- coffee association was higher under organic than conventional treatment. However, coffee RDW was not significantly different for both managements in *A. idiopoda*. The shade tree fine roots in the litter layer were relatively scarce: RDW values differed between tree species (more under *E. poeppigiana*) and management types ( $p = 0.002$ , Fig. 4b).

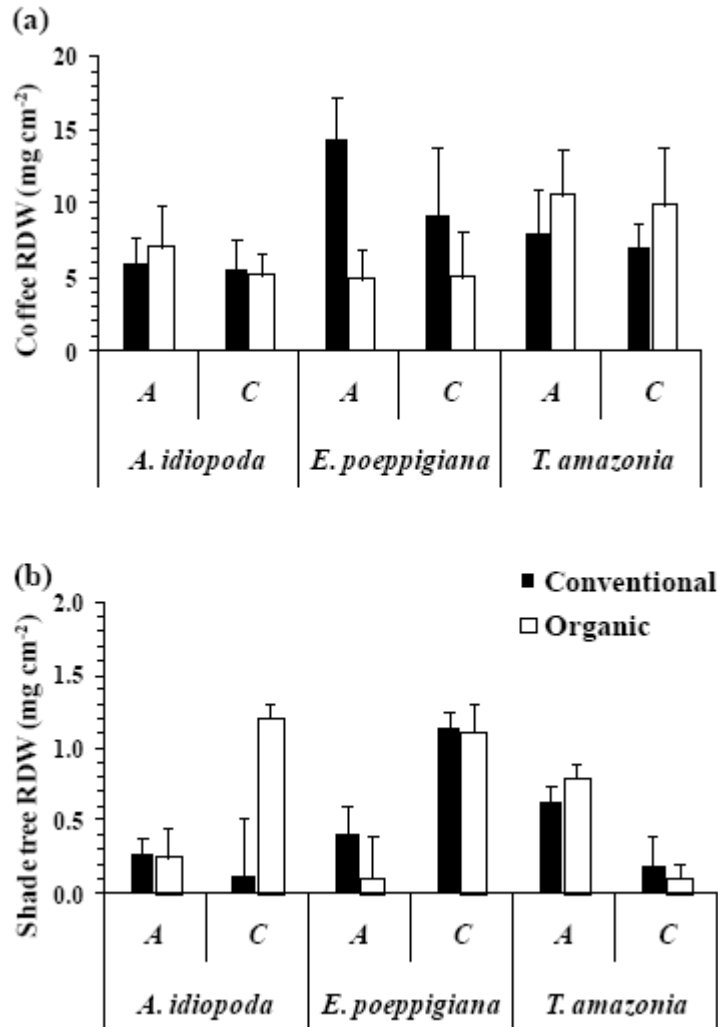


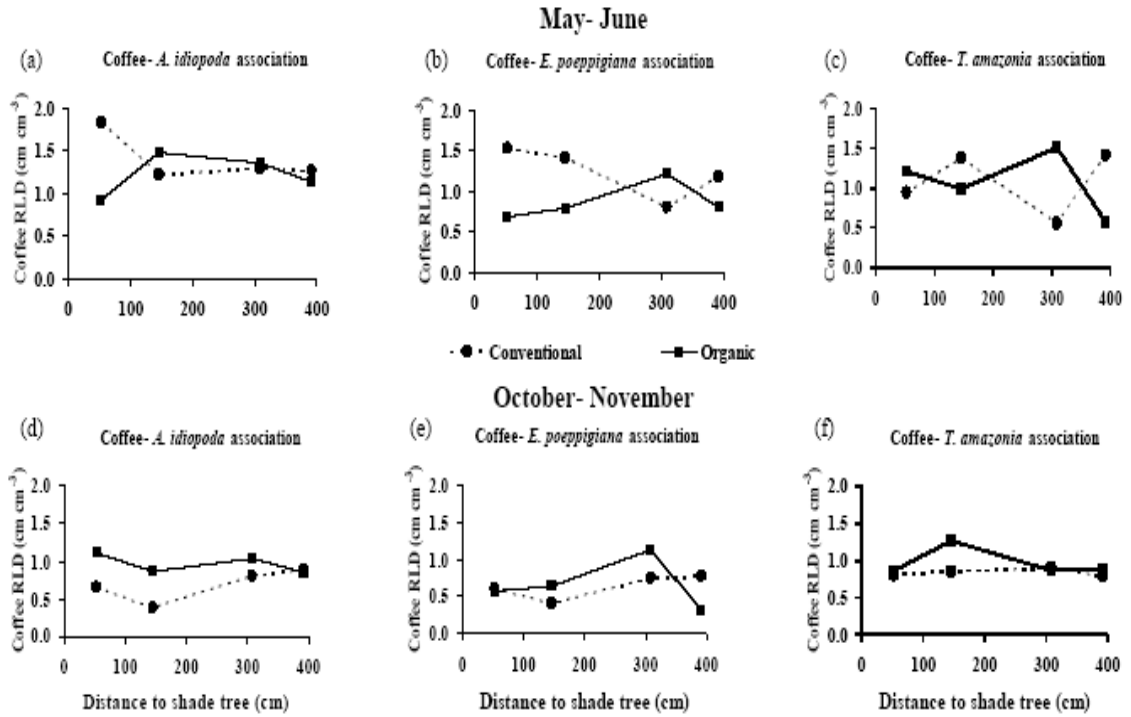
Figure 4. Effect of three shade trees species (*Abarema idiopoda*, *Erythrina poeppigiana*, and *Terminalia amazonia*) and sampling positions (A and C; distance from tree base) on dry weight density (RDW, mg cm<sup>-2</sup>; means and standard error bars) of (a) *Coffea arabica* and (b) shade tree fine roots ( $d \leq 2$  mm) in litter layer under organic and conventional management, in Turrialba, Costa Rica. Samples collected during October and November 2005.

### Spatial patterns of coffee and tree fine roots at varying distances from shade trees

#### *Root length density (RLD)*

In order to evaluate the spatial effect of the shade tree distances of 53- 146 (strata A) and 309- 392 cm (strata C) were used; strata denominated B was not included. Coffee RLD

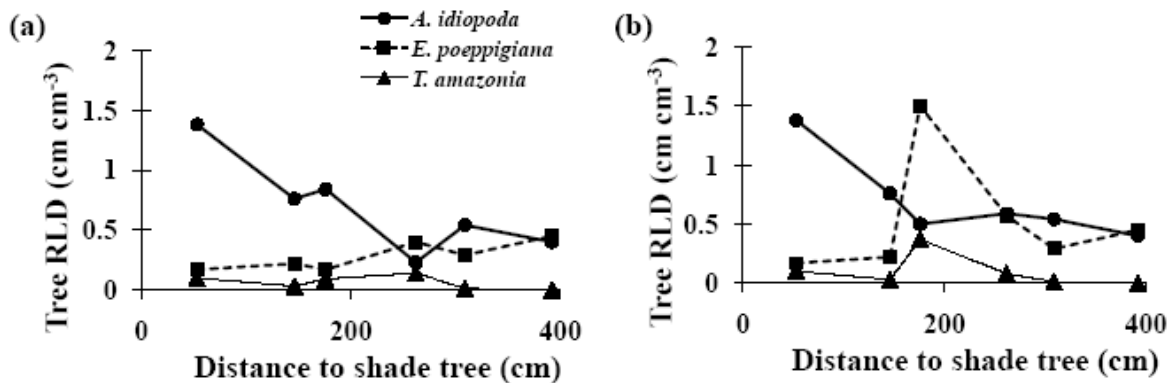
from the first sampling period showed a significant interaction between type of management and shade tree distance ( $p = 0.041$ ; Fig. 5a, 5b, and 5c); i.e., coffee RLD tendencies with distance from the shade tree differed under organic vs. conventional management. Close to the shade tree, coffee RLD was higher under conventional than organic management in the *A. idiopoda* and *E. poeppigiana* associations, although there was no difference for the *T. amazonia* association at the same distance from the tree. Under conventional management the coffee RLD estimated close to shade tree (at 53 cm; on coffee row) was higher than the comparable value on the coffee row without trees (309 and 392 cm) for the *A. idiopoda* and *E. poeppigiana* associations. In contrast, under the organic management, coffee RLD tended to increase with distance from the shade tree base in these two associations; e.g., under *E. poeppigiana*, the coffee RLD estimated at 392 cm was  $0.80 \text{ cm cm}^{-3}$  vs.  $0.56 \text{ cm cm}^{-3}$  at 53 cm distance, respectively. Coffee RLD in the *T. amazonia* association did not show any clear tendency when distance to shade tree increases, independently of the type of management.



**Figure 5.** Spatial pattern of *Coffea arabica* root length density (RLD,  $\text{cm cm}^{-3} \text{ cm}^{-3}$ ,  $d \leq 2 \text{ mm}$ ; 0- 20 depth cm) shaded by *Abarema idiopoda* (a and d), *Erythrina poeppigiana* (b and e), or *Terminalia amazonia* (c and f) under organic or conventional management, in Turrialba, Costa Rica. Samples collected during May- June (a, b and c) and October and November (d, e and f) 2005.

In the samples collected in October- November (Fig. 5d, 5e, and 5f), coffee RLD had a propensity to be higher under organic than under conventional management but did not

differ between management and associations. There were no significant spatial changes of the coffee RLD in any of the association. Considering the results from both sampling periods, the soil exploration by coffee fine roots was higher under *A. idiopoda* than *T. amazonia* or *E. poeppigiana*; however, during the second sampling period coffee RLD was similar among the three associations.



**Figure 6. Spatial pattern of root length density (RLD,  $\text{cm cm}^{-3}$   $d \leq 2$  mm) of three shade tree species (*Abarema idiopoda*, *Erythrina poeppigiana* and *Terminalia amazonia*) in mineral soil (0 - 20 cm) under organic and conventional management in *Coffea arabica* plantations in Turrialba, Costa Rica.**

For both sampling periods, the spatial changes of tree RLD differed among shade tree species (Fig 6a and 6b;  $p < 0.002$  for both study periods). *A. idiopoda* RLD declined with increasing distance to the tree. On the contrary, *E. poeppigiana* RLD showed a slight increase with increasing distance from the tree during both sampling periods and a large (possibly anomalous) value during the second period at 176 distance cm ( $1.5 \pm 0.4 \text{ cm cm}^{-3}$ ; Fig. 6b). As reported above, *T. amazonia* fine roots were scarce in the 0- 20 cm soil layer, and it did not seem to vary with distance from tree.

### ***Specific root length (SRL)***

In May- June, coffee SRL varied significantly between tree species and management types ( $p = 0.002$ ), but significant changes with distance from shade trees was not detected. Coffee fine roots close to the *E. poeppigiana* were thinner than coffee fine roots close to *A.*

*idiopoda* or *T. amazonia*. Coffee SRL was consistently higher (thinner roots) under organic than conventional management. When coffee was associated with *E. poeppigiana* or *A. idiopoda*, less biomass was invested per unit coffee root length (2 and 1.8 cm mg<sup>-1</sup>, respectively) than when grown beneath *T. amazonia* (1.5 cm mg<sup>-1</sup>).

Coffee roots tended to be thicker (lower SRL; approximately 0.5 cm mg<sup>-1</sup> less) in October-November than in May- June (Fig. 7a, b and c vs. 7d, e and f). Shade tree species-management interaction was significant ( $p = 0.002$ ). With the exception of the coffee- *T. amazonia* system (no difference), the coffee SRL continued to be higher under organic management than conventional. In the coffee- *A. idiopoda* and coffee- *E. poeppigiana* associations under organic management, the coffee SRL means were the highest (1.4 ± 0.5 and 1.6 ± 0.5 cm mg<sup>-1</sup>, respectively), while for the coffee- *T. amazonia* system the coffee SRL averaged 1.0 ± 0.4 cm mg<sup>-1</sup> for both types of managements. Again, coffee fine roots did not exhibit a clear spatial pattern at varying distances from shade trees ( $p = 0.953$ ).

In May- June, the tree SRL varied significantly between shade tree species ( $p = 0.008$ ). The spatial pattern of the tree SRL was different for all of the shade tree species ( $p = 0.029$ ).

The tree fine roots were thinner (Fig. 8a) at 176 and 262 cm from the tree's base (inter row position) than in the coffee rows (at 53, 146, 302, and 392 cm) suggesting a lower investment of biomass per unit root length in the inter-row position. Apart from this observation, management did not appear to affect shade tree SRL. On average, tree SRL was twice that of coffee SRL, suggesting that shade trees allocated half the biomass for the



production of the same root length as coffee. In October- November, the tree SRL in inter-rows was lower than observed in May- June. Since *T. amazonia* fine roots showed very low density at 20 cm soil depth for all of sampling periods, their SRL values are showed only as reference.

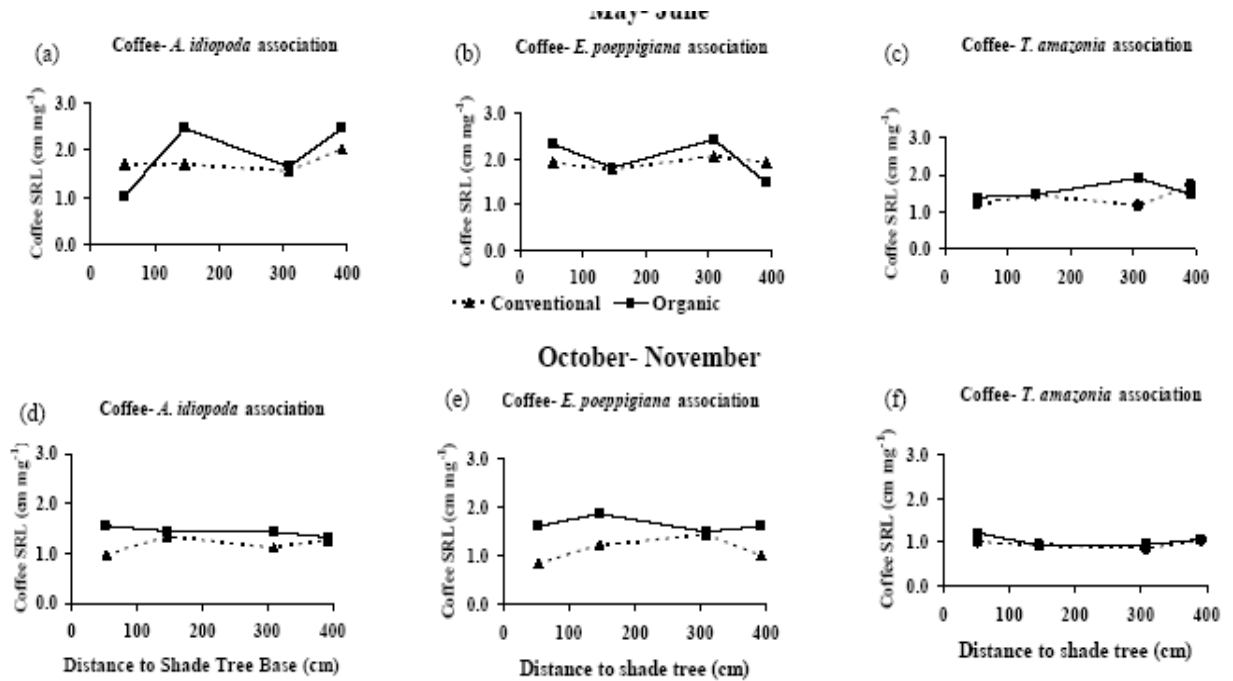


Figure 7. Spatial pattern of *Coffea arabica* specific root length (SRL, cm mg<sup>-1</sup>,  $d \leq 2$  mm; 0- 20 depth cm) shaded by *Abarema idiopoda* (a and d), *Erythrina poeppigiana* (b and e) or *Terminalia amazonia* (c and f) under organic and conventional management, in Turrialba, Costa Rica.

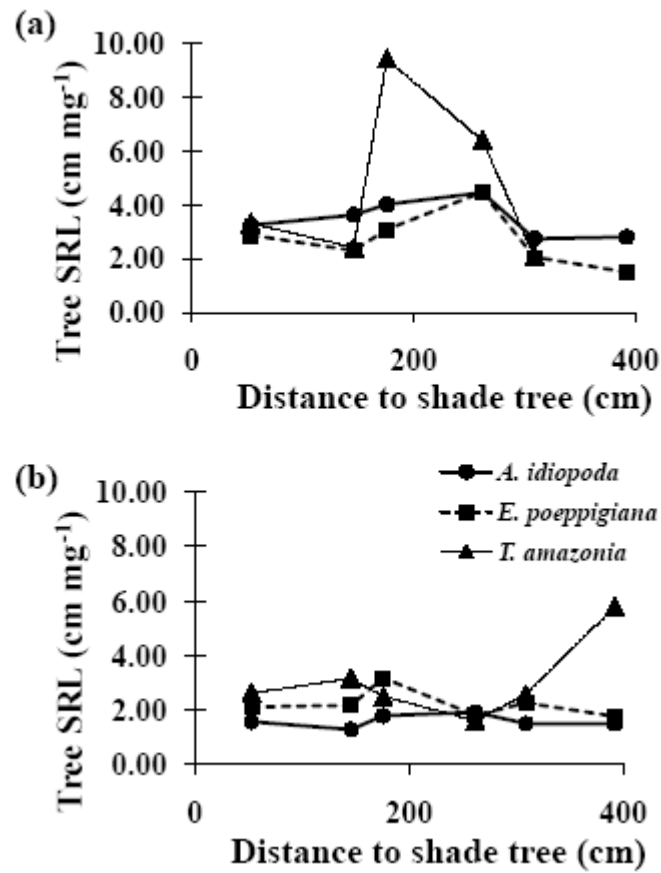


Figure 8. Spatial pattern of specific root length (SRL, cm mg<sup>-1</sup>  $d \leq 2$  mm) for three shade tree species (*Abarema idiopoda*, *Erythrina poeppigiana* and *Terminalia amazonia*), in mineral soil (0 - 20 cm) under organic (a) and conventional (b) management in Turrialba, Costa Rica.

### Soil nutritional status and sampling positions

The organic management regime dramatically reduced the acidity of soils in all associations. Under the conventional management, soils had lower pH's (< 5.5) compared to soils organically managed (pH's > 5.5). Aluminum saturation varied significantly between management treatments ( $p = 0.016$ ); values under legume shade trees were consistently lower than under *T. amazonia*. The exchangeable bases not only differed significantly between type of management ( $p < 0.001$ ) but also between associations and sampling positions ( $p = 0.032$ ). The concentration of bases under organic was 100 % higher than conventional management; under conventional management exchangeable bases were higher close to shade trees while under organic there was no difference. Under conventional management, soils had low to medium soil base status (4.6- 5.8 cmol (+)  $\text{l}^{-1}$ ) and were saturated by exchangeable Al (up to 32 %; Table 3). The effective cationic exchange capacity (Ecec), varied significantly between management type and among the tree- coffee associations (significant tree- management interaction,  $p = 0.011$ ). As was observed for base status, Ecec had consistently higher values under the organic management and, only under organic, in the associations with legume shade trees (i.e., *A. idiopoda* and *E. poeppigiana*). Ca contents were approximately double in the organic plots ( $p < 0.001$ ). Under organic management, soils under *E. poeppigiana* and *A. idiopoda* showed the highest Ca contents compared to soils under *T. amazonia*. Besides, under the organic management, Ca values were noticeably and significantly superior close to *T. amazonia* than distant to it (7.1 to 5.8 cmol (+)  $\text{l}^{-1}$ , respectively). Available P contents differed markedly among management and sampling positions ( $p < 0.001$ ). Under conventional, P contents were between 9.1 and 15.8 mg  $\text{kg}^{-1}$  while under the organic, P values were between 23 and 124 mg  $\text{kg}^{-1}$ , being much higher in the *A. idiopoda*- coffee association

(108- 124 mg kg<sup>-1</sup>). Also under organic management, P values observed close to the *T.*

*amazonia* were higher than distant to the tree.

**Table 3. Effect of three shade trees species (*Abarema idiopoda*, *Erythrina poeppigiana* or *Terminalia amazonia*) and distance from tree (A\* and C) on soil nutrients in mineral soil (means and standard errors, 0 - 20 cm) under organic and conventionally managed coffee in Turrialba, Costa Rica.**

	<i>A. idiopoda</i>				<i>E. poeppigiana</i>				<i>T. amazonia</i>			
	Conventional		Organic		Conventional		Organic		Conventional		Organic	
	A	C	A	C	A	C	A	C	A	C	A	C
pH-H <sub>2</sub> O	5.3(0.1)	5.0(0.1)	6.4 (0.2)	6.4 (0.3)	5.1 (0.1)	5.0 (0.2)	6.1 (0.2)	6.4(0.1)	5.2 (0.1)	4.9 (0.1)	5.9 (0.3)	5.6 (0.1)
S-Al (%)	11.6(3.3)	23.9(8.4)	1.1 (0.3)	3.1 (2.5)	16.1(6.6)	18.4(4.9)	1.2(0.5)	0.9(0.4)	22.4(8.9)	31.9 (8.9)	2.8 (1.3)	3.9 (1.0)
	----- cmol(+) l <sup>-1</sup> -----											
<b>Bases</b>	5.8 (0.3)	4.9 (0.6)	10.7(1.1)	11.2(1.5)	5.6 (0.6)	5.3 (0.5)	10.6(0.8)	11.0(0.9)	5.1 (0.7)	4.6 (0.7)	9.5 (0.9)	7.8(0.7)
<b>Ecec</b>	6.5 (0.2)	6.4 (0.1)	10.8(1.1)	11.4 (1.4)	6.6 (0.2)	6.5 (0.2)	10.7(0.8)	11.1(0.9)	6.6 (0.2)	6.7 (0.3)	9.8 (0.8)	8.0 (0.7)
<b>Ca</b>	4.4 (0.3)	3.6 (0.5)	7.7 (0.6)	8.9 (1.3)	4.2 (0.5)	4.1 (0.4)	8.1 (0.7)	8.4(0.9)	3.7 (0.6)	3.2 (0.6)	7.1 (0.7)	5.8 (0.7)
	----- mg kg <sup>-1</sup> -----											
<b>Fe</b>	353(96)	332(61)	157 (15)	219(81)	300 (38)	260 (57)	262 (68)	221(38)	334 (34)	340 (38)	259 (23)	327 (29)
<b>P</b>	13.7(2.5)	12.1(1.4)	108(25)	124(39)	15.8(1.5)	12.9(1.1)	70 (14)	83(14)	9.1 (1.0)	12.0 (1.5)	78 (33)	23 (4.0)
<b>C (g kg<sup>-1</sup>)</b>	26.5(3.0)	22.2(1.4)	24.6(1.1)	22.1(1.4)	29.1(1.3)	30.6(3.0)	32.1(2.4)	30.4(2.9)	28.6(2.8)	27.5(3.8)	30.4(3.2)	29.2(1.7)

\*A: sampling position on the coffee row close to the shade-tree, and C: on the coffee row far from trees.

Fe contents were very high under both organic and conventional management. Fe varied significantly between management treatments being consistently lower in the organic plots ( $p = 0.005$ ). On the other hand, organic carbon only varied between sampling positions ( $p=0.002$ ). Carbon content in the soils of this study is relatively low. However, when inter-row sampling is included, soil under *E. poeppigiana* showed slightly higher C contents than in the other association. Carbon contents decrease with distance from leguminous shade trees (*A. idiopoda* and *E. poeppigiana*) (Fig 9a-c).

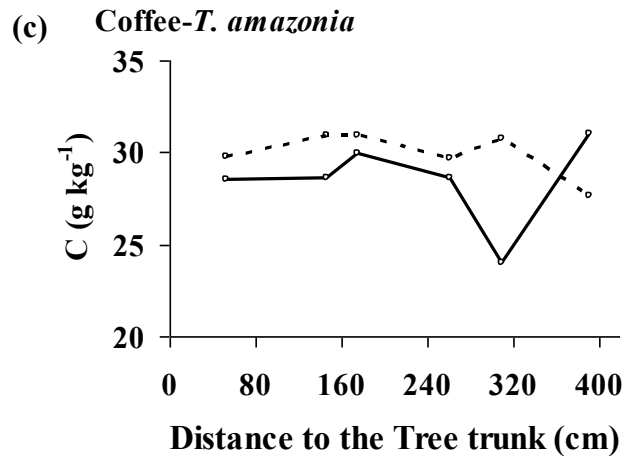
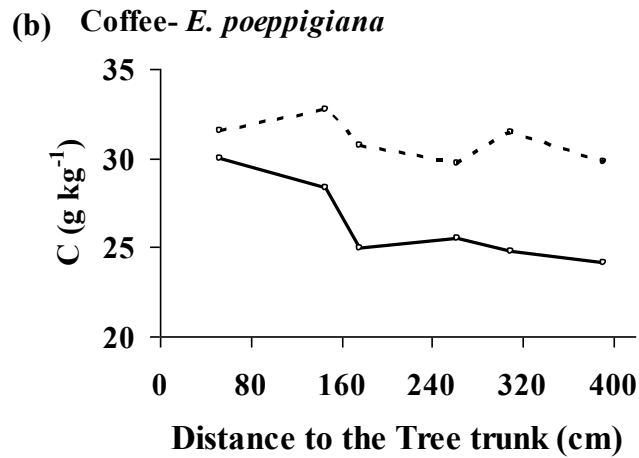
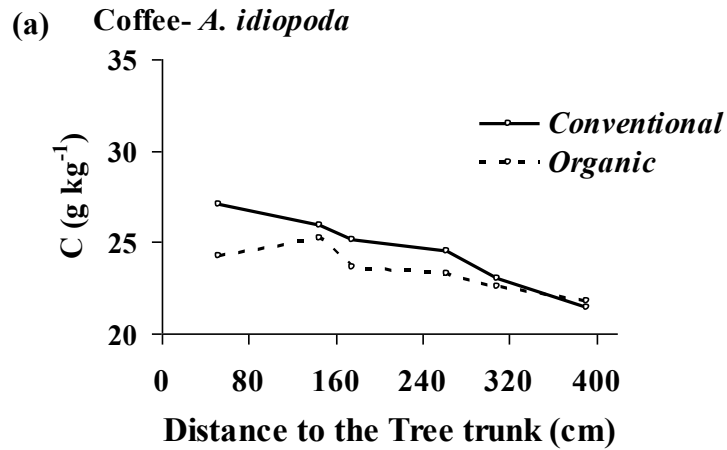


Figure 9. Organic Carbon ( $\text{g kg}^{-1}$ ) in the mineral soil (0 - 20 cm) at different distances to *Abarema idiopoda* (a), *Erythrina poeppigiana* (b) or *Terminalia amazonia* (c) shade trees under organic and conventional management in Turrialba, Costa Rica.

## Discussion

### *Vertical distribution of coffee and shade tree fine roots*

In this study, 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 that reported by Bermudez (1954) for the Turrialba region (Costa Rica) in coffee plantations (30 year- old) under *E. poeppigiana* and *Inga* spp. He determined that coffee fine root density declined sharply with soil depth; after 30 cm, roots were scarce. It has been 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; as reported for Ultisols (Aranguren et al., 1983), Andisols (Schaller et al., 2003), Oxisols (Cardoso et al., 2003a), and Alfisols (van Katen et al., 2005). For this study, a high water table, the existence of a hard pan, and the presence of stones and rocks near the surface could cause superficial coffee rooting. 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 (Akinnifesi 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 plants with shallow fine root systems (rapid decline in root density with increasing soil depth) may be more competitive than those that have a substantial proportion of roots in deeper soil layers (Akinnifesi et al., 1999). Decreasing fine root length density of *E. poeppigiana* at greater soil depth was reported for a partial pruning regime (Chesney, 2000). In the current trial, *E. poeppigiana* trees are partially pruned twice per year. According to Schroth (1995), one way to minimize belowground crop- tree competition is by aboveground pruning of the trees; i.e., foliage pruning has important effects on the belowground dynamics of tree fine roots. Partially pruned trees could be more efficient at exploiting nutrients at greater soil depth than completely pruned trees since the proliferation of fine roots of partially pruned trees is higher than for completely pruned trees (Nygren and Ramirez, 1995). 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 (Hauggaraard-Nielsen and Jensen, 2005). 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).



### ***The litter layer***

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, *E. poeppigiana* under organic management gave a higher contribution of litter- fall ( $3634 \text{ kg ha}^{-1}$ ) than the rest of the agroforestry treatments whose litter- fall inputs were lesser than  $3000 \text{ kg ha}^{-1}$  (Romero, 2006) coinciding this fact with the highest density of coffee fine roots found in this study. The proliferation of coffee fine roots in the litter layer has been found to be higher on the fertilized side as compared to the unfertilized side of coffee rows (Schaller et al., 2003). In this experiment, 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).

### ***Spatial patterns of coffee and tree fine roots at varying distances from shade trees***

At 0- 20 cm soil depth, the abundance of coffee fine roots was higher under conventional management. The concentration of coffee fine roots was higher close to shade trees and lower in the inter row position. Van Katen et al. (2005) found that coffee and *E. deglupta*

fine root length density tended to be higher in positions close to coffee plants under shade trees. When nutrients are plentiful, it seems that fast growing shade timber trees do not restrain coffee root proliferation irrespective of proximity to shade trees. *A. idiopoda* had the highest abundance of fine roots but declines with distance from the tree (Fig. 6a and 6b). In contrast, *E. poeppigiana* fine root concentration increased in the coffee row without shade trees. Chesney (2000) reported a similar pattern for *E. poeppigiana* grown in an alley crop on the same soil and environmental conditions. Previous studies in different environments have shown that coffee fine roots are concentrated close to the coffee rows, while shade tree fine roots are preponderant in the inter row positions; decreasing tree fine root density with increasing distance from the tree does not affect the concentration of coffee fine roots. As a result, fast-growing tree fine roots with increasing age of the system do not displace coffee fine roots (Morales and Beer, 1998; Schaller et al., 2003; Van Katen et al., 2005).

The spatial pattern of coffee RLD was affected by the type of management during the May-June period. RLD was higher at 53 cm from *A. idiopoda* and *E. poeppigiana* under conventional management but decreased with distance from the shade trees. Under *T. amazonia*, the coffee RLD did not show any clear tendency independently of the management applied. No statistical differences between management types and the tree-coffee systems were found in October- November when coffee RLD diminished. This could be explained by: a) the phenological cycle of the coffee (in May- June, coffee fruits are forming while October- November is close to harvest peak when plants are becoming exhausted; e.g. die back can be observed); and b) an uncommonly dry period occurred before the first sampling period. Coffee fine root biomass and RLD is high during fruit

formation; high fine root length increases the capacity of a plant to absorb available soil water and nutrients.

The spatial pattern of tree RLD (0- 20 cm soil depth) varied among shade tree species but was not influenced by the use of organic vs. conventional management. *A. idiopoda* RLD showed a decline with distance from the tree; *E. poeppigiana* RLD slightly increased with increasing distance from the tree; and *T. amazonia* RLD was very low (vertical rooting pattern completely inverse to coffee RLD). At an individual scale, trees create islands of fertility by proximal litter deposition, thus increasing soil resource heterogeneity (Zinke, 1962; Schlesinger et al., 1996); in this trial, field workers tended to concentrate tree-pruning residues around the trees contributing to increased carbon inputs close to the trees. Small-scale fine root spatial variety can also contribute to heterogeneity. At this level, morphological plasticity is a key behavior; i.e., root system structures respond to changing micro- environmental conditions (Zobel, 2003).

In this study, coffee fine root length to dry weight ratio (specific root length, SRL) was higher under organic management during all sampling periods (Fig. 7a- f). This could be a consequence of improved soil conditions (physical, biological and chemical) under organic management; creating a more favorable environment for root growth that enables the coffee to explore a greater soil volume for the same investment of photosynthate. Coffee fine roots under *T. amazonia* invested more biomass per unit root length compared to coffee roots under *A. idiopoda* and *E. poeppigiana*. This suggests that competition and/ or modification in soil conditions due to the presence of other species also can modify the coffee root growth strategy.

On average, shade tree roots were thinner than coffee roots. *A. idiopoda* RLD decreased and *E. poeppigiana* RLD increased with distance from the tree, but the SRL of

both was higher than the coffee in the inter row position. This implies that these legume shade trees allocated less biomass per unit length of root than coffee. This tree root behavior could be attributed to the fact that in the inter- row position coffee fine roots are scarce both in the litter layer and in the mineral soil (0- 20 cm); tree fine roots may be displaced to alley positions avoiding the highest concentrations of coffee fine roots along coffee rows (Schaller et al., 2003). High SRL in inter-rows suggests increased soil exploration by fine tree roots for equal biomass investments. In October- November, tree SRL was lower and did not show any apparent spatial pattern. SRL may be used as an indicator for average fine root diameters but SRL could also vary due to changes in tissue density (Eissenstat and Caldwell, 1988). A high proportion of fine roots in small diameter classes signify a successful tactic of increasing root surface area and soil resource capture for a minimal carbon investment (O'Grady et al., 2005). The investment in elongation of fine roots for resource acquisition may lead to an increase in SRL; on the other hand, a decrease in SRL implies an adverse environment for root growth (e.g. chemical and mechanical impedance into soil profile). SRL has been proposed as an indicator of agro- ecosystem sustainability (Bakker, 1999) since it can serve to detect temporal changes at the micro site level and is linked to soil resources.

***Soil nutrients as affected by distance to shade trees under Organic and Conventional management.***

In general, soil nutrient status under organic management was markedly improved compared to the soils under conventional management. In Brazil, substantial alterations in soil chemical properties of organic coffee plantations (unshaded) have been shown when compared to conventional systems and during conversion to organic systems (Theodoro et al., 2003); e.g., a decrease in the exchangeable Al as well as important increments in pH,

Ecec, bases status and P. The reduced Al saturation under the organic management, detected in the present study, can be attributed to the increase of pH values, thus, reducing the solubility of the Al (Juo and Franzluebbers, 2003). In addition, it is likely that Al reacted with the organic compost that was provided in high quantities for soils under organic management. In contrast, under conventional management, decreased pH could be associated with the application of nitrogen- based fertilizers, mainly as Urea (Theodoro et al., 2003).

Aluminum toxicity and low calcium (Ca) concentrations affect coffee root growth, preventing roots from exploring deeper soil layers (Cardoso et al., 2003b). In Costa Rica, 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 and have shown a decrease of root dry weight and root length percent in the lower soil horizons (Rodrigues et al., 2001). however, this may be compensated by higher root values in the mineral top soil or in the litter layer as was found in the present study. Likewise, high percentages of Al saturation promote thicker and shorter roots of sensitive varieties (Rodrigues et al., 2001). In this study, coffee roots responded to soil acidity: e.g., coffee fine root biomass was greater under conventional management but there was no difference in RLD, suggesting that in organic systems coffee could explore the same soil volume for a lower biomass investment. In this case, lower pH values and higher Al saturation (Table 3) were the main soil characteristics that apparently lead to the coffee investing more resources in fine roots under conventional management. Phosphorus is an important nutrient in relatively short supply in most natural ecosystems and the primary limiting nutrient for crop production in tropical soils (Juo and

Franzluebbers, 2003). This limitation is mainly caused by strong adsorption of  $\text{H}_2\text{PO}_4^-$  to Al and Iron (hydr) oxides, which transform proportions of total P into a form that is unavailable to plants (Juo and Franzluebbers, 2003). According to Young (1997), trees can increase P supply by retrieving nutrients from lower soil layers; accelerating P cycling; improving the chemical and physical quality of soils; and / or enhancing microbial activity. Cardoso et al (2003b) reported that, in Oxisols under coffee- based agroforestry systems, organic P decreased less with depth and was higher than under conventional coffee monocultures, suggesting that shade trees influence the dynamics and rate of cycling of organic P, favoring the conversion of inorganic P into organic P; as a result, larger fractions of the P were available to the coffee plants. Transformations and availability of soil P not only depend on soil characteristics, but also on interactions with plants and associations of plants with microorganisms. In coffee- based agroforestry systems, correlations between spore production of vesicular arbuscular micorrhiza (VAM) and the abundance of coffee fine roots have been found (Cuenca et al., 1983; Cardoso et al., 2003a).

Variations in soil properties are affected by the spatial distribution or arrangement of trees and coffee in agroforestry systems. For example, Schaller et al. (2003) reported that exchangeable bases concentration (e.g. Ca and Mg) were higher at 1.5 m distance than 5.5 m from *E. deglupta* stems. Payan et al. (2002) also found that C and N concentrations were lower 2 m away from *E. poeppigiana* stems than close to the shade tree in high input conventional shaded coffee systems (4.03 vs. 5.04 % for C and 0.35 vs. 0.44 % for N, respectively). On a tropudalf soil in Brazil, total soil N was found to be higher up to 4.5 m distance from *Erythrina* shade trees compared to surrounding cacao; it was argued that these shade trees locally improved subsoil aeration with their roots (Schroth et al., 2001). Bayala et al. (2002) reported that nutrient concentrations were higher in the proximity to the

stem of *Parkia biglobosa* and *Vitellaria paradoxa* in an agroforestry parkland system (West Africa) and concluded that indicators of soil fertility were higher close to the tree stems than outside the tree crowns.

The decrease of soil carbon with distance from legume shade trees suggests that areas close to these shade trees received greater organic matter inputs *via* leaf litter and pruning residues. These spatial trends were greater under conventional management (Fig. 9) probably because other biomass inputs under organic management mask the effect of the shade tree inputs. In forests, spatial distributions reflect the zone of influence and positioning of single trees; patch size has been estimated at different scales. Riha et al. (1986) demonstrated that processes associated with individual trees could affect soil properties (e.g., litter accumulation and decomposition) and hence spatial variability of soil pH and organic matter concentrations around tree species (*Pinus resinosa*, *Acer saccharum*, and *Picea abis*). In a *Pinus sylvestris* forest, Liski (1995) found that C density was higher and generally varied more under the tree canopies than in the open. Differences between open and shaded areas were most likely due to differences in litter deposition and decomposition rates over decades; tree effects could extend from 1 to 3 m from the base. Soil respiration is also more concentrated around tree stems, because of higher moisture close to the stem because of stem-flow (Stoyan et al., 2000).

Responses to N application are accumulative during various pruning cycles because some of the N will be taken up by the shade trees and then recycled to the coffee (Szott and Kass, 1993).

Organically managed soils, that routinely receive imported organic inputs, differ greatly in their fertility, as well as a number of other soil quality properties, when compared to conventionally managed soils. It has been reported that, even though organic coffee mean

yield under multi strata systems is lower when compared to conventional farming system (Lyngbaek et al., 2001),

organic fertilizers appear to have longer residual effects on nutrient availability than inorganic. However, the main disadvantage of organic fertilizers is the difficulty to determine the nutrient requirements and timing; when inorganic fertilizers are used, it is much easier to manage rates, sources and timing (Szott and Kass, 1993).

### **Conclusion**

In all the associations (*C. arabica* with *T. amazonia*, *E. poeppigiana* or *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 demonstrates 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 - 40 cm) differed markedly between species. Shade trees affected the abundance of coffee fine roots; more were found when coffee 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 40 cm depth while *T. amazonia* fine roots increased with depth. These results indicate that *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. Besides, sampling to only 20 cm depth is inadequate for evaluations of *T. amazonia* fine roots because this species has few fine roots in top soil. . Legume tree fine roots (*A. idiopoda* and *E. poeppigiana*) declined linearly with depth; *A. idiopoda* fine roots were much more abundant than coffee roots between 20 and 40 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 fine root density of shade trees for 0- 40 cm depth did not differ between organic and conventional management. At 0- 20 cm soil depth, the decreasing (observed for *A. idiopoda*) or increasing (*E. poeppigiana*) tree fine root density, with increasing distances from the trees, did not affect the concentration of coffee fine roots. Larger proliferation of coffee fine roots was found close to the coffee rows both beside shade trees as well as distant to the trees. Although coffee root concentration was much lower in alley positions, more coffee roots were found in alleys than tree roots with the exception of the organically managed *A. idiopoda* plots. Coffee roots used more biomass to explore the soil under conventional management during fruit formation; at harvest peak, when coffee plants become exhausted, the coffee root length density was not affected by management type. Competition and alteration of the soil environment, due to the presence of shade trees, modified the thickness (diameter) of coffee roots. Morphological plasticity of the coffee fine root system structure permits a response to changing soil micro- environmental conditions. The spatial pattern of root length density differed among shade tree species and apparently was not influenced by the organic and conventional management. Legume trees (*A. idiopoda* and *E. poeppigiana*) increased the exploration of their fine roots per root biomass in the alley positions. Organically managed coffee- shade tree associations improve the soil condition compared to conventional systems. In this trial, in organic plots, the maintenance of organic inputs in the surface soil could block the fixation sites on Fe and Al oxides. Or else, the placement of organic fertilizers near coffee roots, for example band applications, is likely that the contact volume between soluble P and soil particles was reduced; consequently, an increasing the availability of P to coffee roots could be improved

more than in conventional plots. A decrease of soil C with increasing distance from the *A. idiopoda* and *E. poeppigiana* trees demonstrates how processes associated with these individual trees can spatially modify the soil carbon stock.

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### **Chapter 3. Effects of shade- trees and contrasting management on the spatial heterogeneity of *Coffea arabica* fine roots at plot scale**

#### **Abstract**

A geostatistical approach was used to quantify the scale of spatial heterogeneity (aggregation patterns) of coffee fine root length density (RLD,  $\text{cm cm}^{-3}$ ;  $d < 2.0$  mm; 0- 20 cm soil depth). *Coffee* shaded by *Abarema idiopoda*, *Erythrina poeppigiana* and *Terminalia amazonia*, under two types of managements (conventional and organic), were evaluated. Results demonstrated that coffee grown under *E. poeppigiana* had RLD clearly higher than coffee grown under *A. idiopoda* or *T. amazonia*. Coffee RLD was slightly superior under the conventional management in the coffee- *A. idiopoda* and coffee- *E. poeppigiana* associations. The scale of spatial heterogeneity (aggregation patterns) for coffee RLD was much 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 association 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 aggregation patterns (scale of spatial heterogeneity) of *C. arabica* RLD implying that the ability of the coffee roots to forage for soil nutrients changes. For example, if soil is less acid, the foraging pattern for resources and the mechanism of root proliferation tend to increase. In addition, estimating scales of spatial heterogeneity of plant fine roots by geostatistical analysis may provide insights into belowground plant-soil and crop-tree interactions in agroforestry systems

**Key words:** *Abarema idiopoda*, acid soils, *Erythrina poeppigiana*, fine root length density, geostatistic, *Terminalia amazonia*, organic management.

## 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 *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* 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; Piotta 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 & J. W. 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 (Garcia- 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, assuming, at equal supply of growth resources in the soil, that the resource uptake is related to the amount of root length per unit soil volume (fine root length density; RLD) irrespective of species (Schroth, 1995). 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 complementarily 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).

According to Webster (2001), “variability” means the potential of a variable (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 variable, characteristic or property 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 spatial analysis in agroforestry systems are rare. In particular, no studies on spatial heterogeneity of coffee fine roots by geostatistics in

agroforestry systems were found. In the present paper, the scale of spatial heterogeneity (aggregation pattern) of coffee fine root length density (RLD,  $d < 2.0$  mm) was determined in three coffee- shade tree associations (*C. arabica* shaded by *A. idiopoda*, *Erythrina poeppigiana*, and *T. amazonia*) under two types of managements: conventional and organic. It was hypothesized that (i) the spatial pattern of coffee RLD is affected by both the types and distribution of fertilizer inputs and the species of associated shade tree; and (ii) the scale of spatial heterogeneity (i.e. aggregation patterns) of RLD estimated by geostatistics can be used as indicator of the ability of the component species to explore soil resources in agroforestry systems.

## **Materials and Methods**

### ***Site description***

The study was carried out in the experimental coffee fields of the “Centro Agronómico Tropical de Investigación y Enseñanza” (CATIE), Turrialba, Costa Rica (9°53'44'' N; 83°40'7'' W; 602 m). Annual precipitation is 2700 mm yr<sup>-1</sup> (1948-2005), mean annual temperature is 21.8 °C, and relative humidity 88% (<http://catie.ac.cr/> [verified march 2006]). Soils were classified as Typic Endoaquepts and Typic Endoaquults (Sanchez- de Leon et al., 2006), and characterized as mixed alluvial with a poor or medium fertility and a water table ranging between 40 and 120 m (Aguirre, 1971). The study site is relatively flat (slope of < 1 %) and a main limitation was impeded drainage, which has been resolved by establishing deep principal drainage channels (> 1.0 m). *C. arabica* cv. “Caturra” and shade trees were planted during August and October 2000. Coffee planting holes are spaced 1 x 2 m apart with trees planted at 4 x 6 m. In November 2000, coffee replanting had to be

done because of mortality due to the initial impeded drainage problem on some plots. Prior to the establishment of the trial, the site was used (commercial farm) for sugar cane (*Saccharum officinarum*) production.

### ***Spatial sampling scheme and samples processing***

For the purposes of the present study, three coffee- shade tree associations were studied; coffee shaded by: (1) *T. amazonia* (timber tree), (2) *A. idiopoda* (nitrogen fixing- timber tree), and (3) *E. poeppigiana* (Walp.) O. F. Cook (nitrogen fixing tree). Within each coffee- shade tree association, two types of coffee management treatments (sub-treatments) were considered: conventional and organic management. 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 organic system included manual weed control and nutrients were supplied in the form of composted manure and foliar applications of botanical and biological composts. In all coffee- tree associations and management systems studied, shade was permanent but regulated by pruning twice a year. When present, *Erythrina* pruning residues (leaves/branch) were not homogeneously distributed in both organic and conventional systems.

In order to study the spatial variability of coffee RLD, one 16 x 18 m central plot (a 1 m border was not considered) of each coffee- shade tree association and management type was used. In each plot, containing 16 shade trees, 32 soil cores were taken. In practice, geostatistical sampling designs are often selected informally (Diggle and Ribeiro, 2007). In this study, 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. All sampling points were identified

according to  $X$  and  $Y$  coordinates in order to apply geostatistical analyses. After litter layer was carefully removed, 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 July and August 2005 during the principal coffee fruit production period. The grand total of soil cores was 192 (taken from six treatment combinations; i.e., 32 x 6).

**Table 1. Fertilizer and herbicide applications and other inputs\* 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 <sup>-1</sup> yr <sup>-1</sup> coffee pulp 7.5 tons ha <sup>-1</sup> yr <sup>-1</sup> chicken manure 200 kg ha <sup>-1</sup> yr <sup>-1</sup> KMAG 200 kg ha <sup>-1</sup> yr <sup>-1</sup> Phosphoric rock	400 kg ha <sup>-1</sup> yr <sup>-1</sup> 18-15-6-2 (N, P, K, Mg and B) 45 kg ha <sup>-1</sup> yr <sup>-1</sup> NH <sub>4</sub> HO <sub>3</sub> 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 <sup>-1</sup> Roundup to eliminate herbaceous species among coffee plants within a row
Pest control	No application of fungicides	fungicides: 2.5 g l <sup>-1</sup> H <sub>2</sub> O per block of Atemi or Copper sulfate (once a year)

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

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. 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. Finally, *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 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<sup>-3</sup>) and weight (RDW) were computed for coffee and each tree species. Additionally, the proportion of coffee fine (P<sub>RLD</sub>) roots relative to the total RLD (e.g., tree and coffee) was calculated using the expression

$$P_{RLD} = \frac{RLD_{coffee}}{RLD_{coffee} + RLD_{tree}}, \quad (1)$$

Where,  $RLD_{coffee}$  and  $RLD_{tree}$  represent the values of coffee and shade tree fine root length, respectively. A regression through origin was applied to estimate slopes between coffee RLD (as dependent) and RDW (as an independent) in order to be used as estimate of the specific root length (SRL, cm per mg) in the three coffee- tree associations and managements (Jourdan et al., 2008).

### ***Geostatistical Analysis***

Because fine root data were found to be 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 ( $\mathbf{x}_k$ ) were assigned their rank orders  $\mathbf{r}(\mathbf{x}_k)$  and the standardized ranks  $\mathbf{u}(\mathbf{x}_k)$  of the sample were calculated by:

$$\mathbf{u}(\mathbf{x}_k) = \frac{\mathbf{r}(\mathbf{x}_k)}{n}; \quad (2)$$

The values of  $\mathbf{u}(\mathbf{x}_k)$  are between  $1/n$  and  $1$ . According to Juang et al (2001), the  $n$  data points of  $\mathbf{u}(\mathbf{x}_k)$  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,  $\gamma_u(\mathbf{h})$ , 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

$$\hat{\gamma}_u(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{k=1}^{N(\mathbf{h})} [\mathbf{u}(\mathbf{x}_k) - \mathbf{u}(\mathbf{x}_k + \mathbf{h})]^2, \quad (3)$$

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

$$\hat{\gamma}_u(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{k=1}^{N(\mathbf{h})} [\mathbf{u}_i(\mathbf{x}_k) - \mathbf{u}_i(\mathbf{x}_k + \mathbf{h})][\mathbf{u}_j(\mathbf{x}_k) - \mathbf{u}_j(\mathbf{x}_k + \mathbf{h})], \quad (4)$$

Where,  $\mathbf{u}_i(\mathbf{x}_k)$  and  $\mathbf{u}_j(\mathbf{x}_k)$  represent the standardized ranks for coffee and shade tree fine roots, respectively, scored at a location at distance  $\mathbf{h}$  from  $\mathbf{x}_k$  (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). 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:

5) Gaussian

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

6) Spherical

$$\gamma(h) = \left\{ C_0 + C_1 \left( 1.5 \frac{h}{a} + 0.5 \frac{h^3}{a^3} \right) \right\}; \quad \text{If } h < a$$

7) Exponential

$$\gamma(h) = \left\{ C_0 + C_1 \left( 1 - \text{Exp}\left(\frac{-h}{a}\right) \right) \right\}; \quad \text{If } h > 0$$

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 detected, the ordinary kriging estimator was used to estimate the standardized ranks at unsampled locations. Visual maps were created using a grid specification of 1 x 1 m to evaluate 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, 2007).

## Results

### *Summary statistics of coffee and shade tree fine roots*

The mean values of coffee RLD differed among coffee- tree associations ( $p < 0.0116$ ). Fine root densities of coffee grown under *E. poeppigiana* were higher than of coffee under *A. idiopoda* and *T. amazonia* (Figure 1). On the other hand, for both management types, *A. idiopoda* RLD was notoriously higher than *E. poeppigiana* and *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 two systems; i.e., the proportion of coffee fine roots in the *A. idiopoda* system was only 40 % compared to 80% in the other systems (Figure 1). *A. idiopoda* fine roots were included in the geostatistical analysis because they were abundant. The box- plots show a high variation existing in the data of fine roots; i.e., highly skewed and many outliers. The morphology of coffee fine roots appeared to respond differently in the three associations and managements. Specific root length (SRL) varied among coffee- tree associations and management combinations at 10 % of significance ( $p = 0.0554$ , Figure 2). Even through these results must be interpreted with caution, SRL ( $\text{cm mg}^{-1}$ ) of coffee fine roots was relatively higher for conventional than organic plots, yielding  $0.94 \text{ cm mg}^{-1} (\pm 0.06)$  vs.  $0.89 \text{ cm mg}^{-1} (\pm 0.05)$ , respectively. In addition, comparing among tree species, it was estimated to be highest for the coffee fine roots under *A. idiopoda* ( $0.99 \text{ cm mg}^{-1} \pm 0.03$ ) and lowest in the coffee- *E. poeppigiana* systems ( $0.86 \text{ cm mg}^{-1} \pm 0.04$ ). Coffee fine roots seem to be thicker (greater diameter) in the coffee- *E. poeppigiana* association, irrespective of management.

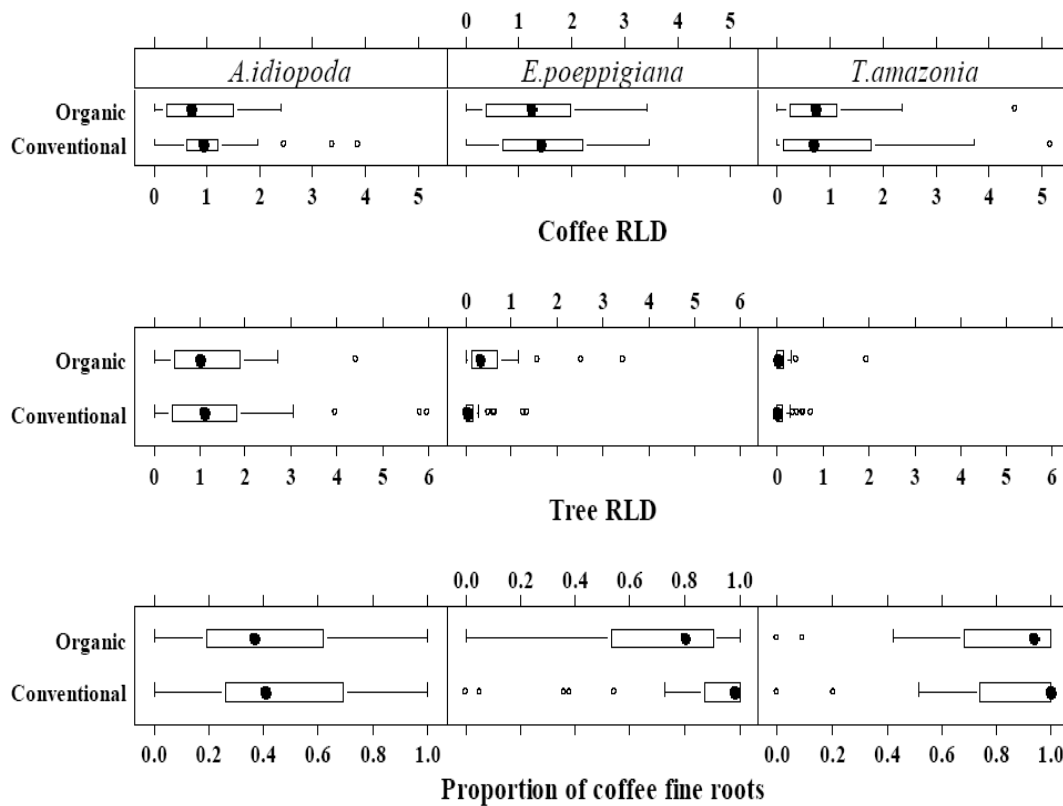


Figure 1. Box-plots of coffee and tree fine root length density (RLD,  $\text{cm cm}^{-3}$ ) and proportion of coffee fine roots in three coffee- tree associations (shaded by *Abarema idiopoda*, *Erythrina poeppigiana* or *Terminalia amazonia*) under organic or conventional management in Turrialba, Costa Rica.

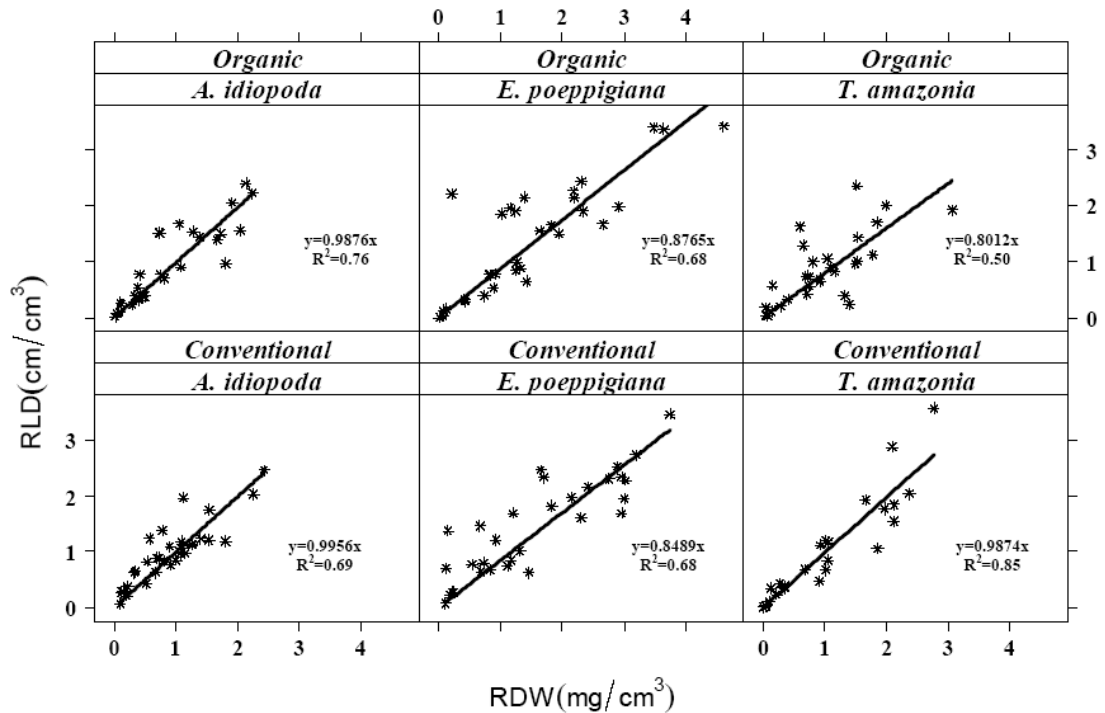


Figure 2. Specific root length (regression slopes,  $\text{cm mg}^{-1}$ ) of *Coffea arabica* estimated in three coffee- tree associations (shaded by *Abarema idiopoda*, *Erythrina poeppigiana* or *Terminalia amazonia*) under organic or conventional management in Turrialba, Costa Rica.

### *Semivariogram analysis*

#### *Spatial variability of coffee 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 significantly ( $p < 0.05$ ) longer in the organic plot than conventional plot (9.0 vs. 7.5 m, respectively; Fig. 3 and Table 2).

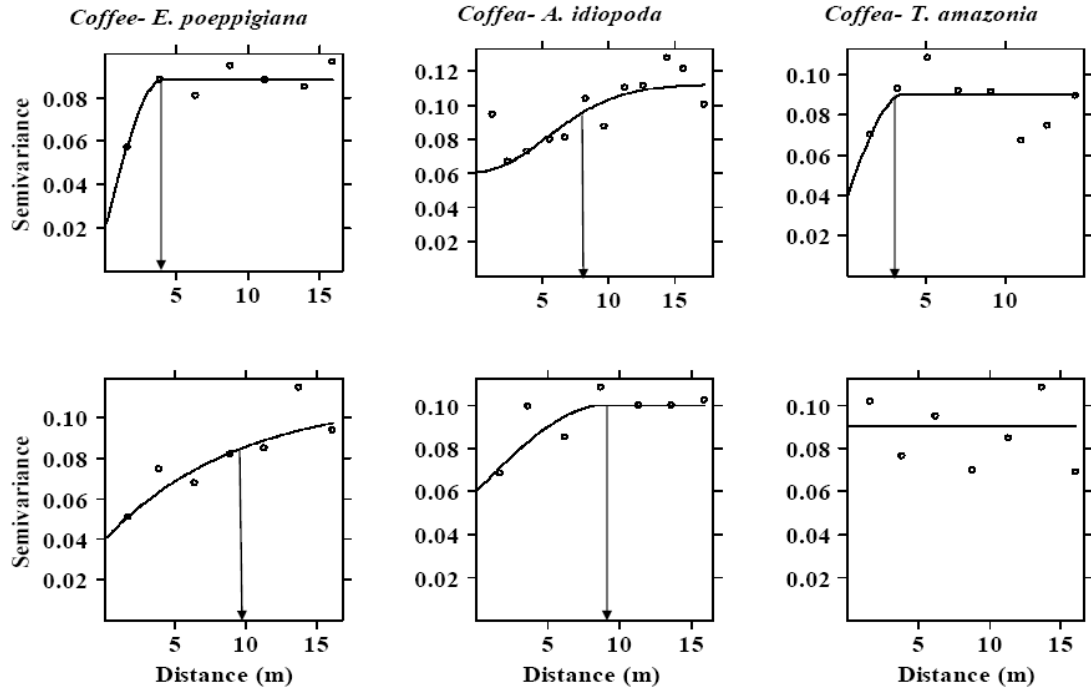


Figure 3. Semivariograms for standardized ranks of coffee fine root length density (RLD,  $\text{cm cm}^{-3}$ ) in coffee- tree associations (*Coffea arabica* shaded by *Abarema idiopoda*, *Erythrina poeppigiana* or *Terminalia amazonia*) under conventional (top) or organic (bottom) management. Arrows indicate the estimated scale (m) of spatial heterogeneity at which fine root length density are aggregated in space.

**Table 2. Summary of results from geostatistical analyses of standardized ranks for fine root length density (RLD, cm cm<sup>-3</sup>) in the coffee- tree associations (*Coffea arabica* shaded by *Abarema idiopoda*, *Erythrina poeppigiana*, and *Terminalia amazonia*) under the organic and conventional management. If *Q* was greater than 75 %, the variable was considered “strongly spatially dependent” (S), between 75 and 25 % the classification was “moderate spatial dependence” (M), and lesser than 25 % the spatial dependence was defined as weak (W).**

Shade tree/ Management	Variable	Model type	Nugget variance	Sill variance	Range (m)	<i>Q</i> %
<i>A. idiopoda</i> / Organic	Coffee <i>RLD</i>	Spherical	0.060	0.100	9.0	40 <i>M</i>
	Tree <i>RLD</i>	Exponential	0.010	0.135	8.0	93 <i>S</i>
<i>A. idiopoda</i> / Conventional	Coffee <i>RLD</i>	Gaussian	0.061	0.112	7.5	46 <i>M</i>
	Tree <i>RLD</i>	Spherical	0.042	0.097	5.3	57 <i>M</i>
<i>E. poeppigiana</i> / Organic	Coffee <i>RLD</i>	Exponential	0.040	0.110	9.5	64 <i>M</i>
<i>E. poeppigiana</i> / Conventional	Coffee <i>RLD</i>	Spherical	0.020	0.088	4	77 <i>S</i>
<i>T. amazonia</i> / Organic	Coffee <i>RLD</i>	Random	0.085	-	-	-
<i>T. amazonia</i> / Conventional	Coffee <i>RLD</i>	Spherical	0.040	0.090	3.5	56 <i>M</i>



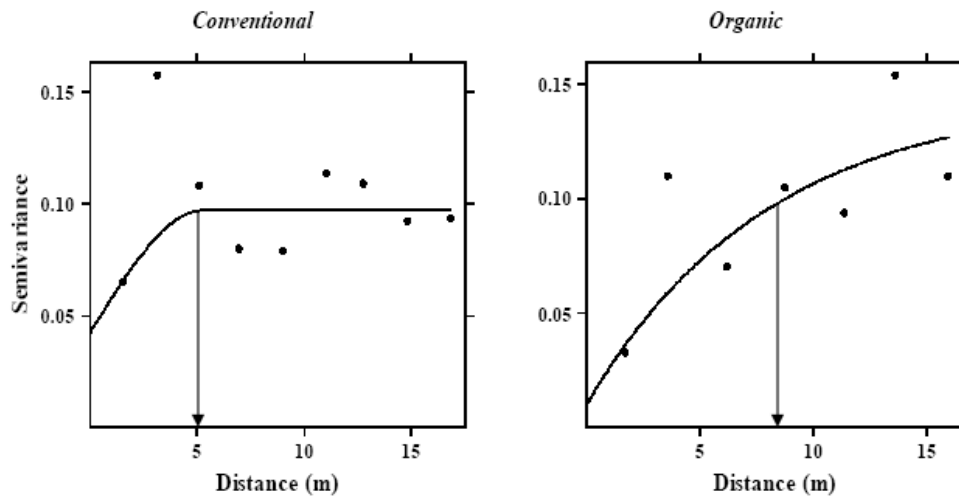
According to the index of spatial dependence ( $Q$ ), coffee RLD (standardized ranks) exhibited a moderate spatial correlation structure in the organic and conventional plots (40 and 46 %). Similarly, semivariogram analyses in the coffee- *E. poeppigiana* association revealed that the aggregation scale was higher ( $p < 0.01$ ) under the organic management than in the conventional plot (9.5 vs. 4 m). For the same coffee-tree association, the spatial structure ( $Q$ ) of coffee fine roots in the conventional plot was stronger than for the organic plot (77 and 64 %, respectively). In the coffee- *T. amazonia* association, the semivariogram of coffee RLD under conventional management shows a scale of aggregation relatively much more shorter (3.5 m). Nevertheless, in the organic plot, the semivariogram for coffee RLD does 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 variability of A. idiopoda fine roots***

Spatial correlation of *A. idiopoda* roots among sample locations occurred in both conventional and organic plots; spatial heterogeneity (aggregation size) was estimated at 5.3 and 8.0 m for conventional and organic management, respectively (Figure 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.

Management did not affect the spatial cross- correlation between coffee and *A. idiopoda* fine roots: under conventional management, the value was 0.58 ( $p < 0.05$ ) up to 5 m separation (beyond that distance the magnitude of spatial correlation decreases

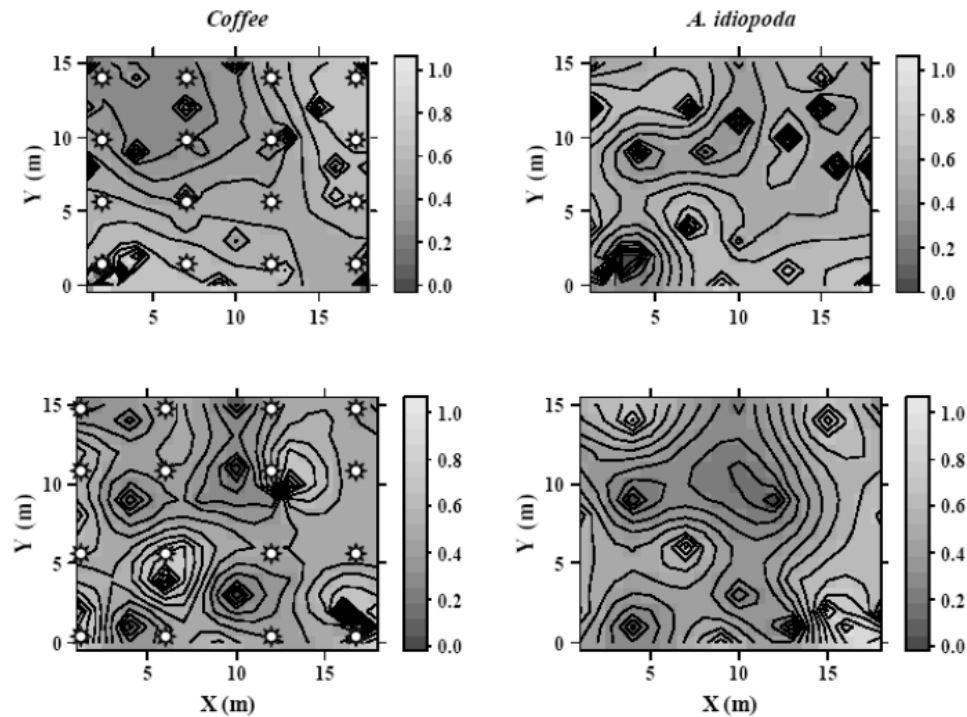
or it is not significant) while in the organic plot, the value was 0.43 ( $p < 0.05$ ) up to 3.6 m. This information confirms that there was a spatial correlation, distance-dependent between the coffee and *A. idiopoda* fine roots at the plot scale studied.



**Figure 4. Semivariograms for standardized ranks of *Abarema idiopoda* fine root length density (RLD,  $\text{cm cm}^{-3}$ ) in the coffee- *A. idiopoda* association under conventional or organic management. Arrows indicate the estimated scale (m) of spatial heterogeneity at which fine root length density are aggregated in space.**

In the conventional plot, *A. idiopoda* fine roots formed aggregation patterns with hot spots (Figure 5; the lightest areas on the maps) smaller than the coffee fine roots. In fact, the spatial pattern followed by the coffee roots shows 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.

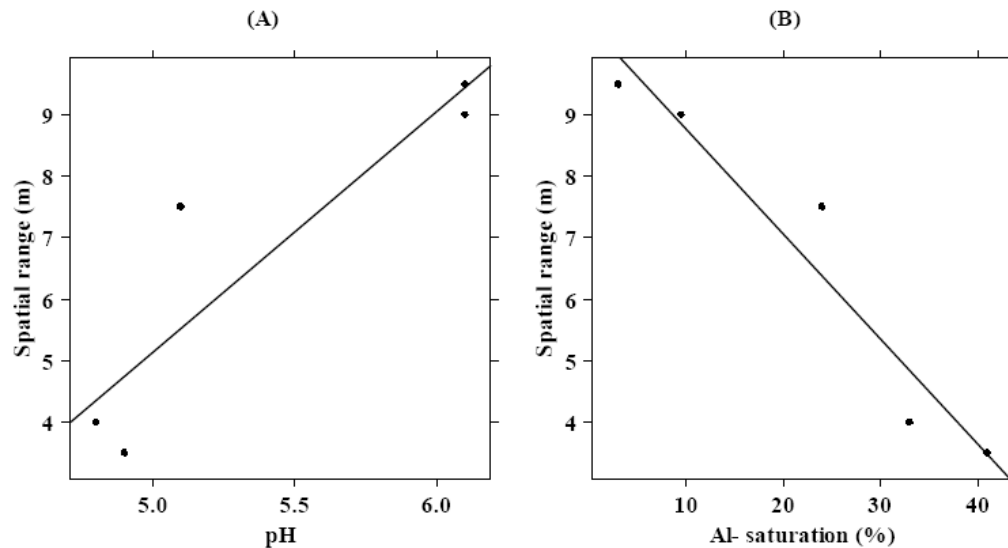


**Figure 5. Kriged maps of standardized ranks of coffee and *Abarema idiopoda* fine root length density (RLD,  $\text{cm cm}^{-3}$ ) in the coffee- *A. idiopoda* association under conventional (top) or organic (bottom) management. Value 1 indicates the highest fine root length density according to standardized rank order (lightest areas). White spots represent the relative position of shade trees on the plot.**

***Soil nutritional status and relationship between coffee RLD spatial heterogeneity (patch size) and soil chemical properties***

Under conventional management, soils had lower pH's ( $\leq 5.2$ ) compared to soils organically managed (pH's  $> 5.2$ ) (Table 3). Aluminum saturation under organic management was lower than under conventional management and values under

legume shade trees were lower than under *T. amazonia*. Under conventional management, 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 legume shade trees; i.e., *A. idiopoda* and *E. poeppigiana*.



**Figure 6. Relationship between the spatial heterogeneity range (patchiness, m) of coffee RLD and pH values (A) and aluminum saturation (B) in the coffee- tree associations (*Coffea arabica* shaded by *Abarema idiopoda*, *Erythrina poeppigiana* or *Terminalia amazonia*) under the conventional or organic management.**

Likewise, Ca and Mg contents were higher in the organic plots, especially under *E. poeppigiana* and *A. idiopoda*. K contents were also higher under organic management except in the coffee- *T. amazonia* plot. Available P contents differed markedly among management types and associations; in conventional plots, P contents were between 6.9 and 12.5 mg kg<sup>-1</sup> while in the organic plots P values were between 6.9 and 76.2 mg kg<sup>-1</sup>; 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. The scales of aggregation of coffee fine roots (3.5 – 9.5 m) were linearly correlated with pH ( $r = 0.90$ ,  $p = 0.036$ ) and Al saturation values ( $r = -0.96$ ,  $p = 0.008$ ); i.e., increasing Al saturation (or decreasing pH) reduces the range of aggregation of coffee fine roots (Figure 6). It was found that pH values less than 5.0 (or Al saturation more than 30%) reduced the aggregation size of coffee fine roots to 4 m, approximately.

**Table 3. Means and standard errors of soil chemical attributes in mineral soil (0 - 20 cm) of three coffee- tree associations (*Coffea arabica* shaded by *Abarema idiopoda*, *Erythrina poeppigiana*, and *Terminalia amazonia*) under organic and conventional managements in Turrialba, Costa Rica.**

Soil Variable	Unit	Coffee shaded by					
		<i>A. idiopoda</i>		<i>E. poeppigiana</i>		<i>T. amazonia</i>	
		Conventional	Organic	Conventional	Organic	Conventional	Organic
<i>pH</i> (water)		5.1 (0.1) <sup>†</sup>	6.1 (0.1)	4.8 (0.1)	6.1 (0.1)	4.9 (0.1)	5.3 (0.1)
Exch- <i>Al</i>	cmol(+) l <sup>-1</sup>	1.4 (0.1)	0.3 (0.1)	2.1 (0.2)	0.4 (0.1)	2.6 (0.2)	0.7 (0.2)
Exch- <i>Ca</i>	cmol(+) l <sup>-1</sup>	3.1 (0.1)	6.9 (0.4)	2.8 (0.2)	7.7 (0.5)	2.4 (0.3)	5.0 (0.2)
Exch- <i>Mg</i>	cmol(+) l <sup>-1</sup>	1.0 (0.1)	1.8 (0.1)	1.2 (0.1)	2.1 (0.1)	1.1 (0.1)	1.6 (0.1)
Exch- <i>K</i>	cmol(+) l <sup>-1</sup>	0.2 (0.03)	0.8 (0.1)	0.4 (0.03)	0.7 (0.04)	0.4 (0.05)	0.3 (0.02)
E.C.E.C	cmol(+) l <sup>-1</sup>	5.7 (0.1)	9.7 (0.5)	6.5 (0.1)	10.8 (0.7)	6.5 (0.3)	7.5 (0.2)
<i>Al</i> -Saturation	%	24 (2.0)	3 (1.5)	33 (2.4)	4 (1.5)	41 (2.7)	9 (2.5)
Available <i>P</i>	mg l <sup>-1</sup>	6.9 (0.4)	44.0 (6.9)	8.2 (0.6)	76.2 (12.6)	12.5 (7.0)	6.9 (0.6)
Total <i>N</i>	%	0.25 (0.01)	0.30 (0.01)	0.25 (0.01)	0.27 (0.01)	0.24 (0.01)	0.23 (0.01)
Organic <i>C</i>	%	2.53 (0.05)	2.97 (0.05)	2.52 (0.04)	2.64 (0.06)	2.53 (0.06)	2.37 (0.06)

## **Discussion and conclusions**

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 m<sup>2</sup> 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. In 2 m<sup>2</sup> 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 in conventional plots was less than in organic plots (288 m<sup>2</sup> 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 has been suggested that SRL is an indicator of the root- nutrient uptake efficiency (Ostonen et al., 2007). In this work, differences among the coffee root SRL values under several shade tree species and management were showed. Thus, lower SRL suggests a decreasing nutrient uptake per root length for coffee fine roots under *E. poeppigiana* (irrespective of management) and in soils with high pH and low exchangeable Aluminum (at least observed for the coffee shaded by *A. idiopoda* and *T. amazonia*). Enhanced nutrient availability under those conditions described reduces the need for explorative fine root length growth and thus account for a decrease in SRL. In contrast, under soil acidity, fine roots are affected in their production, morphology, and turnover (Jentschke et al., 2001). As a result, it is likely that coffee plants renew their fine roots more frequently to maintain the resource exploiting function (Godbold, 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).

The results found in this work demonstrated that 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 in the different systems. If soil is less acid (as observed in the organic

plot), foraging for resources and root proliferation decreases. 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.

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## **Chapter 4. Spatial relationship between the heterogeneous distribution of coffee fine roots and soil nutrient-factors when managed conventionally and organically under *Erythrina poeppigiana* (Walp.) O. F. Cook shade trees.**

### **Abstract**

The spatial relationships between the length density of *Coffea arabica* fine roots (RLD,  $d < 2.0$  mm) and soil nutrient-related factors were studied at plot scale in a coffee- *Erythrina poeppigiana* association under the conventional and organic managements in Turrialba, Costa Rica. In a 24- x 29-m plot, divided by two adjacent sub-plots (one with organic management and the other conventional), coffee fine roots and soil chemical properties were sampled on an irregular grid in the topsoil (0-20 cm) using an auger (internal diameter 6 cm). A four-factor model (Multivariate analysis) was applied. It explained about 83% of the total variation of the soil attributes. Factors were designated as the chemical fertility (CF), micronutrients (M), organic matter (OM), and acidity factors (Ac). Multiple regression analysis demonstrated that the CF and Ac factors significantly explained most of the coffee RLD variation. Semivariogram analysis based on the regression residuals belonging to coffee RLD and soil factors was performed to examine their respective spatial heterogeneity. Based on the spherical model fitted, all the variables presented a strong spatial dependence. The scale of spatial correlation for chemical fertility factor (CF) was lesser than for the acidity factor (Ac), but similar to the coffee RLD range. Patchy areas of high spots of coffee RLD were somewhat greater in organic than conventional plots. Cross-semivariogram analysis demonstrated that the spatial relationship between soil factors and coffee RLD was over a spatial scale of 5.50 m. The spatial correlation estimated between coffee RLD and the CF factor was 0.61 and -0.71 between coffee RLD and the Ac factor. It was also determined that nutrients linked to P, Zn, and exchangeable bases were positively and spatially correlated to coffee fine root density; but, negatively correlated with the acidity soil factor (i.e., pH and exchangeable aluminum), affecting the scale of spatial heterogeneity and aggregation pattern of coffee RLD. The spatial response of coffee RLD suggests a differential foraging strategy for acquiring soil nutrients induced by the quality

of organic and inorganic fertilizer inputs and explained by the morphological plasticity of coffee fine roots

**Key words:** *Coffea arabica*, fine root length density, spatial correlation, acid soils, organic management.

## **Introduction**

Agroforestry system research has highlighted that belowground interaction studies are fundamental to understand the development and distribution of crop and tree fine roots. 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). Fine-scale nutrient heterogeneity could have a strong effect on belowground interactions. The spatial variability of 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 heterogeneity 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. 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). 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). Although geostatistics have been widely applied at different scales on agricultural soils (Utset and Cid, 2001; Paz- Gonzalez et al., 2000) and natural ecosystems (Roberson et al., 1988; Jackson and Caldwell, 1993; Maestre and Cortina, 2002), the approach is still new in studies of the spatial relationships between fine roots and spatial heterogeneity of available nutrients in agroforestry systems. 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 of soil nutrients in experimental plots of a coffee- shade tree association (*Coffea arabica* shaded by *Erythrina poeppigiana*) with contrasting management. 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 the experimental coffee fields of the “Centro Agronómico Tropical de Investigación y Enseñanza” (CATIE), Turrialba, Costa Rica (9°53′44″ N; 83°40′7″ W; 602 m). Annual precipitation is 2700 mm yr<sup>-1</sup> (1948- 2005), mean annual temperature is 21.8 °C, and relative humidity 88% (<http://catie.ac.cr/> [verified march 2006]). Soils were classified as Typic Endoaquepts and Typic Endoaquults (Sanchez- de Leon 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 %) and a main limitation was impeded drainage, which has been resolved by establishing deep principal drainage channels (> 1.0 m). *C. arabica* cv. “Caturra” and shade trees (*E. poeppigiana*) were planted during August and October 2000. Coffee planting holes are spaced 1 x 2 m apart with trees planted at 4 x 6 m. In November 2000, coffee replanting had to be done because of mortality due to the initial impeded drainage



problem on some plots. Prior to the establishment of the trial, the site was used (commercial farm) for sugar cane (*Saccharum officinarum*) production.

**Table 1. Fertilizer and herbicide applications and other inputs\* 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 <sup>-1</sup> yr <sup>-1</sup> coffee pulp 7.5 tons ha <sup>-1</sup> yr <sup>-1</sup> chicken manure 200 kg ha <sup>-1</sup> yr <sup>-1</sup> KMAG 200 kg ha <sup>-1</sup> yr <sup>-1</sup> Phosphoric rock	400 kg ha <sup>-1</sup> yr <sup>-1</sup> 18-15-6-2 (N, P, K, Mg and B) 45 kg ha <sup>-1</sup> yr <sup>-1</sup> NH <sub>4</sub> HO <sub>3</sub> 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 <sup>-1</sup> Roundup to eliminate herbaceous species among coffee plants within a row
Pest control	No application of fungicides	fungicides: 2.5 g l <sup>-1</sup> H <sub>2</sub> O per block of Atemi or Copper sulfate (once a year)

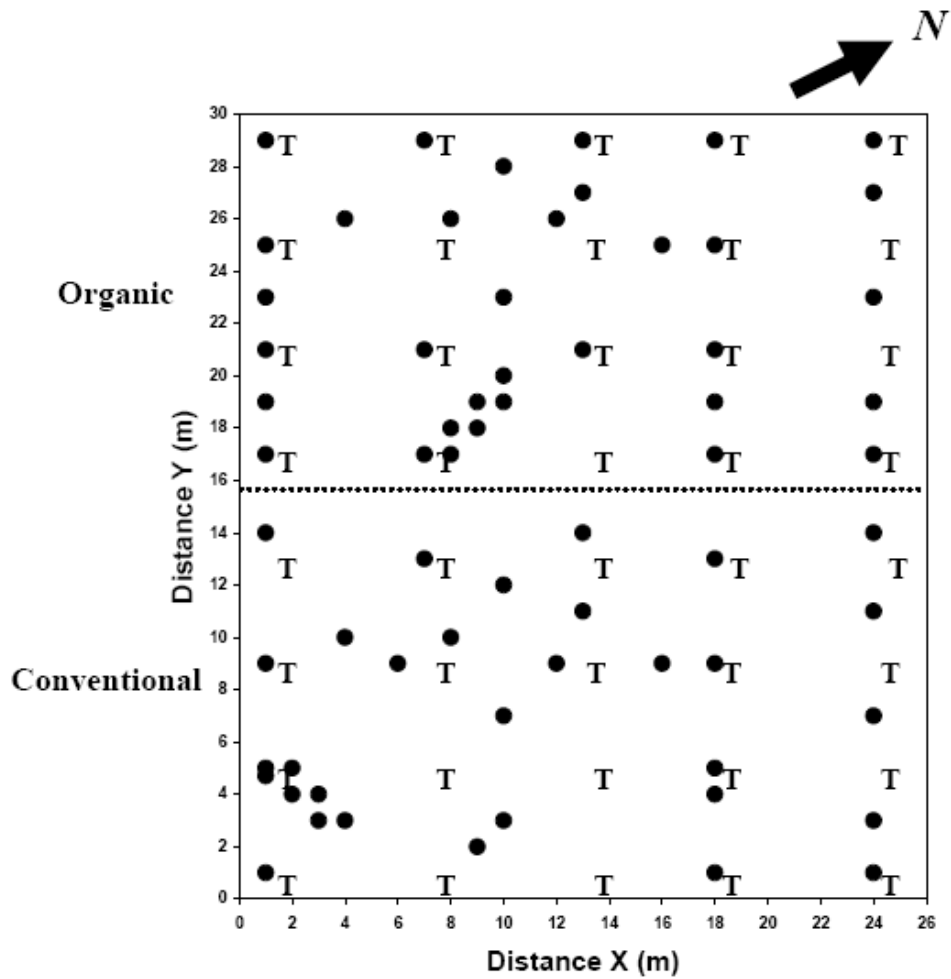
\*Nutrient inputs from decomposition of shade tree biomass were not considered.

For the purposes of the present study two types of coffee management 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 organic system included manual weed control and nutrients were supplied in the form of composted manure and foliar applications of botanical and biological composts. Shade was regulated by pruning twice a

year. *E. poeppigiana* pruning residues (leaves/branch) were not homogeneously distributed in both organic and conventional systems. However, total pruning is applied to *E. poeppigiana* trees managed conventionally, while under organic management the *E. poeppigiana* are partially pruned.

### ***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 two adjacent plots (Figure 1, total area 24 x 29 m): one with organic and the other with conventional management. This grid permitted sampling 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 for geostatistical analyses. After litter layer was carefully removed, soil cores (0-20 cm) were taken at approximately 30 cm from coffee stems 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. 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. Later, a sub-sample (on average 50 % or approximately 400 g) was separated for fine root extraction and the remainder used for soil analyses.



**Figure 1. Sampling scheme in organic and conventional plots of the *Coffea arabica*-*Erythrinapoeppigiana* association. Black dots denote sample cores and “T” the location of *E. poeppigiana* trees.**

All root 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. *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 to 0.0001 g. Next, the density of fine root length (RLD, cm cm<sup>-3</sup>) was computed for coffee. Sub-samples not used to determine RLD were sent for soil analyses: pH in H<sub>2</sub>O; 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).

### ***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 “essential” 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 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. A model-based geostatistic analysis was used to describe and quantify the pattern of spatial variability for coffee RLD and soil factors (extracted by FA), as well as the potential spatial relationships between them. 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 soil factors that were significantly correlated with coffee RLD and management types (potential covariates). 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),  $\beta$ '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

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

where  $N(h)$  is the number of observation pairs separated by distance  $h$ ,  $Z_{(x_k)}$  is the value of the variable  $x$  observed at location  $x_k$ , and  $Z_{(x_k+h)}$  is its value at a location at distance  $h$  from  $x_k$ . Likewise, in order to determine the magnitude of spatial correlations between coffee RLD and soil factors, cross-semivariograms were estimated by

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

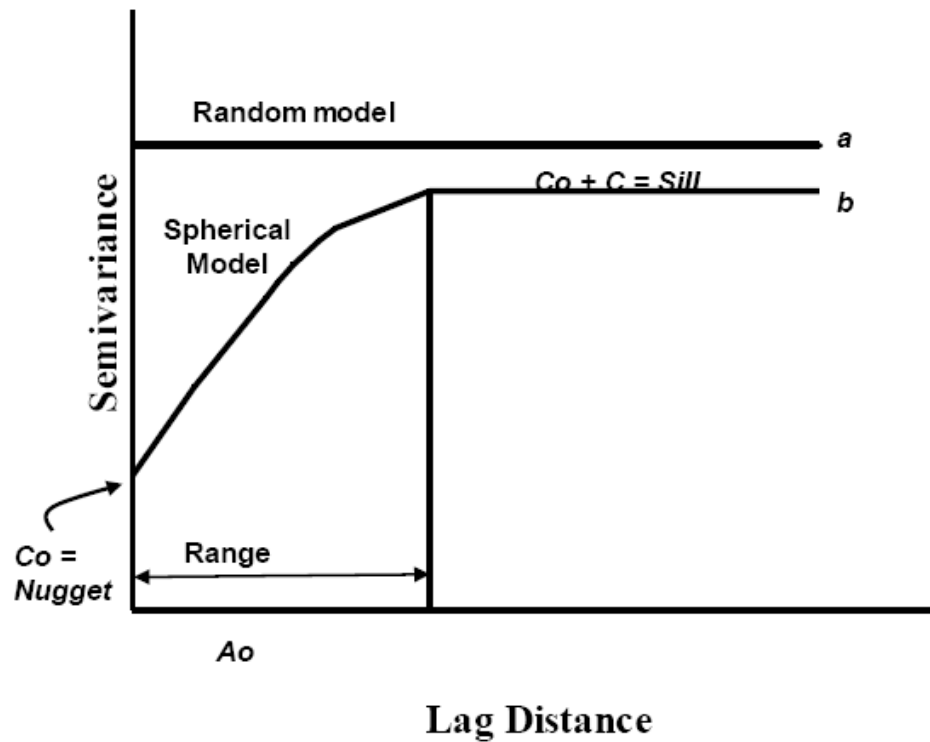
Where,  $Z_{i(x_k)}$  and  $Z_{j(x_k)}$  represent the value of the residuals of the coffee RLD and soil factors scored at a location at distance  $h$  from  $x_k$  (Isaaks and Srivastava, 1989).

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:

$$\gamma(h) = \begin{cases} C_0 + C \left( 1.5 \frac{h}{A_0} + 0.5 \frac{h^3}{A_0^3} \right); & \text{If } h < A_0 \end{cases} \quad (4)$$

Where,  $C_0$  is the nugget variance,  $C$  is the sill,  $A_0$  is the range, and  $h$  is the lagged distance.

For randomly distributed data, one would expect little change in the semivariances estimated with increasing distance (i.e., the total sample variance is found at all scales of sampling) and the semivariogram would be essentially flat (Figure 2, curve *a*). For patterned data, the semivariogram 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 (Figure 2, curve *b*).



**Figure 2.** Hypothetical interpretations of semivariograms, showing the proportion of variance (semivariance) found at increasing distances for paired sample cores (lag distances). Curve *a* is expected when the soil attribute or fine root characteristics are randomly distributed. Curve *b* is expected when soil attributes or fine root characteristics show spatial correlation over a limited range ( $A_o$ ) and independence beyond that distance. Semivariogram that is found at a scale finer than the field sampling is a nugget variance ( $C_o$ ).

A spherical model is often used to fit this form of semivariogram. Statistics from the spherical model indicate the range over which samples show spatial correlation ( $A_o$ , Figure 2), an index of the scale of spatial pattern in the studied plot. Semivariance that exists at scale finer than the field sampling is found at 0 lag distance and is known as the nugget effect ( $C_o$ ). A high nugget value means that most variation occurs over short distances. 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 x 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, 2008).

## **Results and discussion**

### ***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 vs. 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 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 Franzluebbbers, 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). Available P contents differed markedly between management systems ( $p < 0.001$ ). Phosphorus is a limiting nutrient for crop production in tropical soils (Juo and Franzluebbbers, 2003). This limitation is mainly caused by strong adsorption of  $\text{H}_2\text{PO}_4^-$  to Aluminum and Iron (hydr) oxides, which transform large proportions of total P into a form that is unavailable to plants (Juo and Franzluebbbers, 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 micorrhiza (VAM) and the abundance of coffee fine roots have been found in coffee-based agroforestry systems (Cuenca et al., 1983; Cardoso et al., 2003).



**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 in Turrialba, Costa Rica. SE: Standard error; C.V: coefficient of variation (%).**

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

Fe contents were very high in both organic and conventional management but was lower in the organic plots ( $p = 0.005$ ). Organic C and total N values observed in the soils of this study are considered relatively low (approximately 2.5%) with no difference between

management systems. However, it is likely that long-term improvement of soil organic matter (i.e. C and N content) requires maintaining organic management over the long term.

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<sup>-3</sup>, respectively (Table 2). This was comparable with previously reported values (0-20 cm) under different shade- tree species in Costa Rica (Bermudez, 1954; Morales and Beer, 1998; Schaller et al., 2003; van Kanten et al., 2005).

### ***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 less explained by a four factor model and hence was excluded from the subsequent analyses.

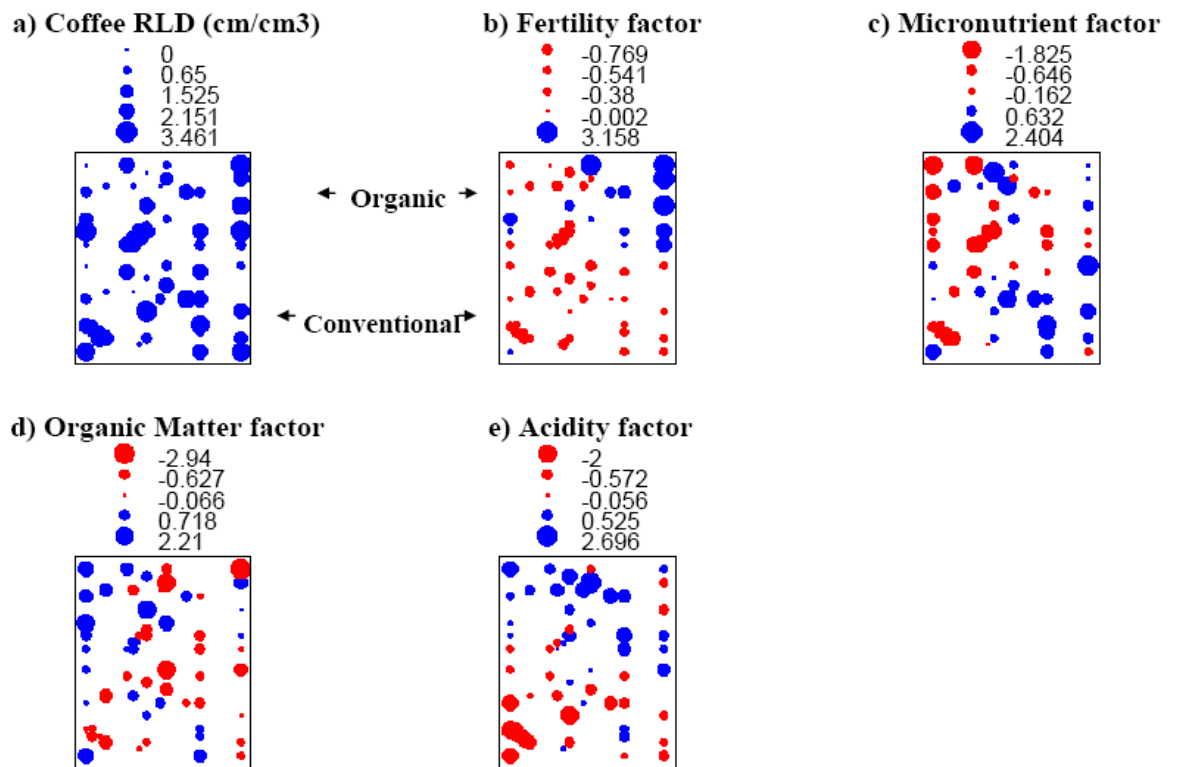
The model using the four factors explained 83.4 % of the total variance (Table 3). Based on the factor loadings after varimax rotation, which was used to increase the interpretability of the factors, factor 1 was called “exchangeable bases or chemical fertility factor” and comprised the exchangeable bases; P, Zn and K loadings > 0.60. The high and positive scores for this factor mean enhanced availability of exchangeable bases and high P, Zn and K concentrations. 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.

**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	Factor1: Fertility	Factor2: Micronutrient	Factor3: OM	Factor4: Acidity	Communality
<i>Exch-Al</i>	-0.422	0.527	-0.175	-0.554	0.794
<i>Exch-Ca</i>	0.645	-0.48	0.248	0.508	0.966
<i>Carbon</i>	0.000	-0.103	0.989	0.000	0.995
<i>Cu</i>	0.000	0.799	-0.194	0.000	0.678
<i>Fe</i>	-0.367	0.909	0.000	-0.182	0.995
<i>Exch-K</i>	0.716	0.000	0.000	0.000	0.525
<i>Exch-Mg</i>	0.696	-0.283	0.000	0.499	0.818
<i>Mn</i>	-0.286	0.000	0.168	-0.544	0.407
<i>N</i>	0.119	-0.123	0.951	0.000	0.933
<i>P</i>	0.955	0.119	0.000	0.231	0.979
<i>pH</i>	0.718	-0.408	0.000	0.527	0.969
<i>Zn</i>	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	

In order to display the spatial distribution of the soil factors 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 RLD for each position sampled (Figure 3); spatial aggregation of high density RLD values can be seen (Figure 3a). 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 North – Eastern corner of the

plot; bigger blue circles, Figure 3b). This factor includes available P, which is a relatively immobile element in the soil. This irregular pattern of nutrient distribution in the organic plot is probably related to the high residuality of different organic compounds that were applied (Mallarino, 1996).



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

In addition, this pattern seems to be inversely related to average available Cu and Fe contents (Figure 3c), which appear to be negatively correlated to the chemical fertility factor including relatively high values in the conventional plot ( $p = 0.0129$ ). It is possible that Cu emerged as an important element in this 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).

The organic matter factor seems to be higher in the organic plot (Figure 3d) 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 blue 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 on the coffee RLD. In this analysis, the best fit ( $F$ - statistic = 3.10;  $p = 0.0227$ ;  $R^2 = 0.20$ ) was obtained using the chemical fertility (CF) and acidity (Ac) factors:

$$\text{Coffee RLD} = 1.41 + 0.324(\text{CF}) - 0.272(\text{Ac}) \quad (5)$$

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 was related to high exchangeable bases and amounts of available P and Zn. On the other hand, the contribution of the acidity factor implies that high acidity or low pH and low Ca content were associated with lower coffee RLD. This confirms that Al toxicity, together and low Ca concentrations, negatively affect coffee RLD; they may prevent roots from exploring deeper soil layers (Cardoso et al., 2003).

In Costa Rica, 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 root values in the mineral top soil layer or in litter layer as was reported in an early study (Chapter 2).

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

Based on the fact that most of the variation of coffee RLD was due to the chemical fertility and acidity factors, and contextual information on contrasting soil managements (i.e., organic and conventional), semivariograms were estimated using residuals from coffee RLD and soil factors from model (1) in order to determine the scale of spatial heterogeneity. For the chemical fertility (CF) and acidity (Ac) factors, semivariograms were estimated using only management types as covariates. All the variables presented a strong spatial dependence and were well modeled with spherical semivariograms (Figure 4). The range (scale of spatial heterogeneity) over which there was a strong spatial dependence was similar between coffee RLD and CF (between 5 and 6 m) but was less than the range for the Ac factor (approximately 8 m; Table 4).

For coffee RLD, the structural variance or partial sill ( $C_p$ ) represents 80 % of the total spatial variance implying a strong spatial correlation among samples separated by 5.6 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 organic than conventional plots (Figure 4a, right side). 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 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 Zhi- Hu et al., 2006) in 900 m<sup>2</sup> plots (values increasing as plant age increases). In 2 m<sup>2</sup> 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).

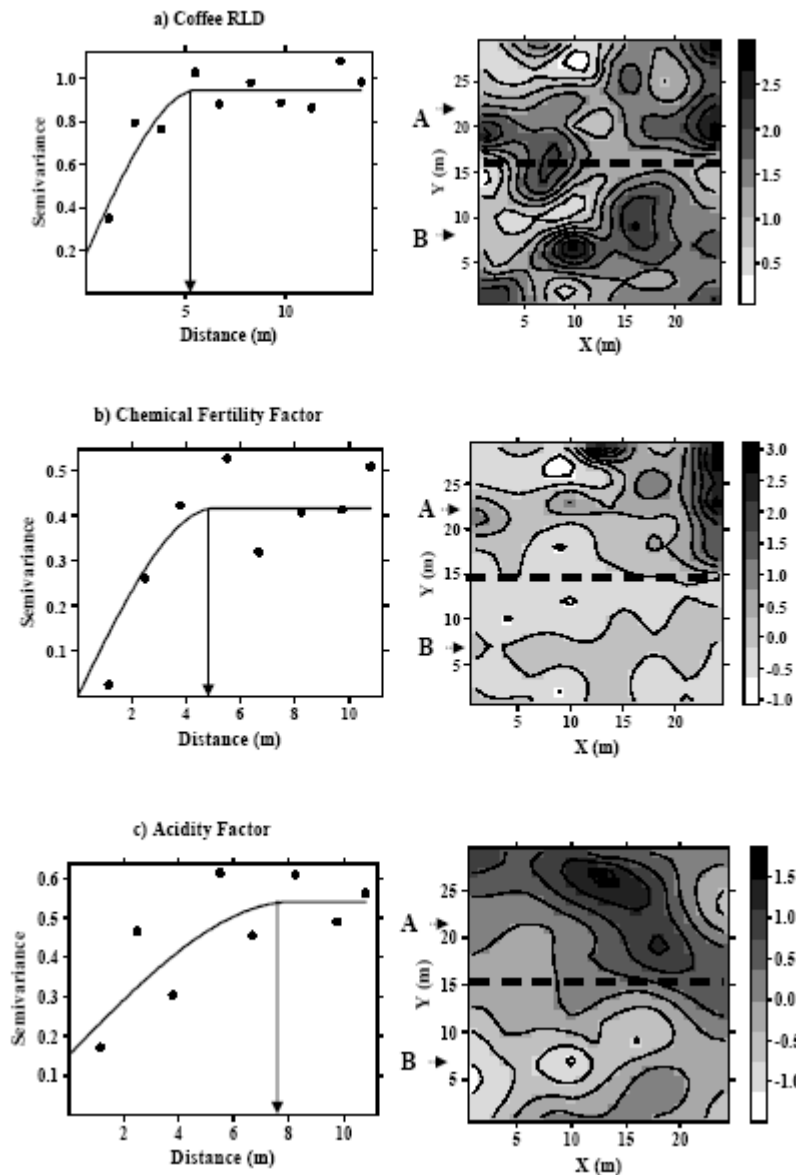


Figure 4. Semivariograms of residuals from the linear model of density of coffee fine root length (RLD, cm cm<sup>-3</sup>) on soil factors extracted by Factorial analysis (left). Kriged maps for coffee RLD and soil factor scores estimated across the organic (A) and conventional (B) plots (right) under the *Erythrina poeppigiana* association. Arrows indicate the estimated scale (m) of spatial heterogeneity at which fine root length density are aggregated in space.

**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 in Turrialba, Costa Rica.**

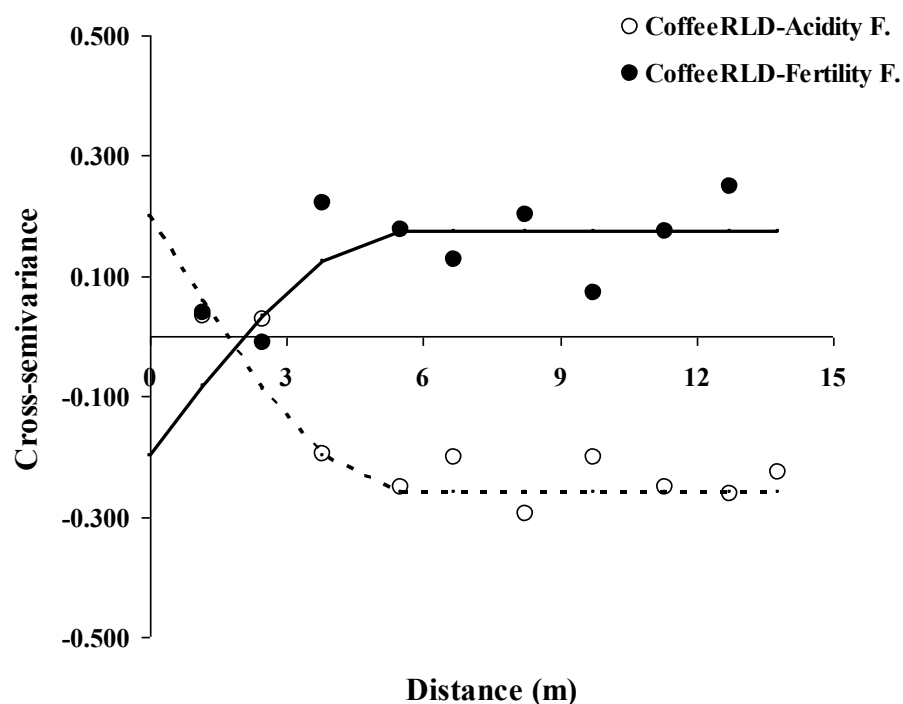
<b>Variables</b>	<b>Nugget (<math>C_0</math>)</b>	<b>Partial sill (<math>C_p</math>)</b>	<b>Range (<math>A_0</math>, m)</b>	<b>Spatial correlation Structure (%)</b>
<b>a) Semivariogram models</b>				
<b>Chemical Fertility (CF)</b>	<b>0.000</b>	<b>0.416</b>	<b>5.08</b>	<b>100</b>
<b>Acidity (Ac)</b>	<b>0.154</b>	<b>0.388</b>	<b>8.17</b>	<b>72</b>
<b>Residuals of Coffee RLD (RC)</b>	<b>0.182</b>	<b>0.763</b>	<b>5.63</b>	<b>80</b>
<b>b) Cross- semivariogram models</b>				<b>Spatial correlation coefficient</b>
<b>RC vs CF</b>	<b>-0.200</b>	<b>0.173</b>	<b>5.50</b>	<b>0.61</b>
<b>RC vs Ac</b>	<b>0.250</b>	<b>-0.260</b>	<b>5.50</b>	<b>-0.70</b>

The geostatistical analysis suggests that type of management 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 spatial heterogeneity scale of the soil factors differed. The range of spatial correlation for the chemical fertility factor (CF) was less than that for the acidity factor (Ac), but similar to the coffee RLD range. As a result, the spatial pattern of the CF factor showed patches smaller and more numerous than for the Ac factor (Figure 4b and c).



Patches with the highest scores (i.e., high exchangeable bases and P content) were found in the organic plot. 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).



**Figure 5. Cross- semivariograms between coffee (*Coffea arabica*) fine root length (RLD) and soil factors. The dotted line corresponds to the fit of coffee RLD on the acidity factor using a spherical model. The continuous line corresponds to the fit of coffee RLD on the chemical fertility factor using a spherical model.**

Cross-semivariograms fitted (Figure 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). This type of association could not be detected using the Pearson correlation coefficient (0.31 and -0.24, respectively) because the Pearson statistic does not take into account the spatial locations of the soil cores. Mou et al. (1995) suggested that correlations may be nutrient-specific. For example, they 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. 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). 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. It also can be inferred that limestone application, resulting in a decrease in Al saturation and improved pH, could lead to a decrease in coffee RLD.

In this study, coffee roots responded to acidity. For example, it was observed that coffee fine roots explored more soil in the conventional 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. Changes in the spatial heterogeneity of coffee RLD due to the type of soil management indicate morphological plasticity (Hodge, 2006) of coffee fine roots to acquire nutrients; e.g., thinner fine roots may develop in conventionally managed plots (Chapter 3). Inputs from shade-tree leaf litter and fine root turn-over (especially from legume trees) can have

significant simultaneous effects on spatial heterogeneity of coffee fine roots and nutrient dynamics creating patches of nutrients around the shade- trees and improving nutrient availability; e.g., increased microbial activity resulting in higher mineralization and denitrification rates.

## **Conclusions**

While the application of geostatistics to study variations of soil properties at different scales is relatively common in croplands, it is a new field of study for the high- resolution analyses of the spatial dependence of coffee fine roots on soil nutrient availability in agroforestry systems.

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 which, at the same time, were affected by the type of management (organic and conventional).

I speculate that the spatial response of coffee RLD suggests a differential root foraging strategy for acquiring soil nutrients depending on whether coffee plantations are organically and conventionally managed under *E. poeppigiana* shade trees. Changes in the spatial heterogeneity of coffee fine root length induced by soil acidity conditions suggest possible changes in the morphological plasticity of coffee fine roots to acquire nutrients; i.e., thinner fine roots in conventionally managed plots.

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## Chapter 5. Concluding remarks

In the chapter 2, the vertical distribution of coffee (*Coffea arabica*) and shade tree fine root length density (RLD) under organic and conventional management, in three coffee-tree associations, was discussed. Shade trees affected the abundance of coffee fine roots; for example, coffee fine roots were more abundant when coffee was planted under *Terminalia amazonia* than under the leguminous trees (*Abarema idiopoda* or *Erythrina poeppigiana*). In addition to, the timber tree, *T. amazonia*, developed more fine roots in deeper soil layers and very few fine roots in the top soil. This result suggests that at the same time as minimizing competition with coffee, which usually has superficial rooting, deep tree root systems provide environmental benefits: 1) a 'safety-net' service by capturing nutrients leached from the top soil; and 2) potential capture of nutrients from deep soil layers, often referred to as 'nutrient-pumping'. Besides, sampling to only 20 cm depth is insufficient for studies on *T. amazonia* fine roots.

Legume tree RLD (*A. idiopoda* and *E. poeppigiana*) had a linear decline with depth. However, *A. idiopoda* fine roots were more abundant than coffee roots at 40 cm soil depth; hence, fine roots of this tree species may be more competitive with coffee plants. The significant amount of coffee fine roots found in the litter layer demonstrates the importance of including this layer for a real estimation of coffee RLD in agroforestry systems. Coffee fine root proliferation in the litter layer may help capture nutrients when they are released slowly from tree leaf litter. Soil nutrient status under organic management was markedly improved compared to the soils under conventional management.

Following this first study, the spatial distribution of fine roots ( $d < 2.0$  mm) and soil properties at varying distances from shade trees in the same associations and management



conditions was studied during two seasons. At 0- 20 cm depth, the type of management affected the spatial pattern of coffee RLD during the May- June period (coffee fruit forming period). Coffee RLD was higher at 53 cm from *A. idiopoda* and *E. poeppigiana* trees under conventional management but decreased with distance from the shade trees. Under *T. amazonia*, the coffee RLD did not show any clear tendency independently of the management applied (but very few *T. amazonia* fine roots were found in top soil). The RLD of coffee had diminished by October- November, the peak harvest period when plants were exhausted.

Coffee specific root length (SRL) was higher under organic management and lower when associated with *T. amazonia*, during all sampling periods. This suggests that competition and/ or modification in soil conditions due to the presence of other species can modify the thickness (diameter) of coffee fine roots. On the other hand, the legume shade trees allocated less biomass per unit length of root than coffee does overall in the inter- row position where coffee fine roots were scarce. It appears that tree fine roots tend to be displaced to alley positions avoiding the highest concentration of coffee fine roots near to coffee rows.

Acidity and P content were the most variable top soil attributes observed for all associations when organic and conventional management was compared. A substantial improvement in the chemical fertility of the soil was observed in organically managed coffee- shade tree associations. A decrease of the C contents with increasing distance from the *A. idiopoda* and *E. poeppigiana* trees demonstrates that processes associated with individual trees spatially modifies the soil carbon stock beneath their influence zone.

In the chapter 3, differences among the coffee root SRL values under several shade tree species and management were tested significantly. Under *E. poeppigiana* (irrespective of

management), coffee SRL values were inferior suggesting a decreasing nutrient uptake per root length for coffee plants. On the other hand, lower coffee SRL also occurred in soils with high pH and low exchangeable Aluminum under *A. idiopoda* and *T. amazonia* (organic plots). As a result, under those conditions described, probably improved nutrient availability reduces the need for explorative fine root length growth of coffee and thus explains a decrease in SRL. Furthermore, rank- order geostatistics was used to evaluate the variations in the scale of spatial heterogeneity and aggregation patterns of coffee RLD as affected by three shade tree species under contrasting management. The RLD of coffee and *A. idiopoda* in conventional plots had a smaller scale of spatial heterogeneity than in the organic plots. A spatial correlation between coffee and *A. idiopoda* fine roots, detected in this study, suggests that these species have similar nutrient foraging strategies. For coffee, it was confirmed that the increased acidity affects the scale and aggregation pattern of the RLD. Higher pH values (or lower Al saturation) were associated with increased aggregation size of coffee RLD suggesting that changes in top soil acidity affected the distribution of coffee fine root systems. In the Chapter 4, it was demonstrated that nutrient availability is spatially correlated to coffee RLD at scale equal to or less than 5.5 m. A fertility variable (integrates information respect P, Zn, and exchangeable bases) was positively- spatially correlated to coffee RLD; but coffee RLD was spatially negatively correlated with soil acidity attributes (i.e., pH and exchangeable Al). The spatial response of coffee RLD to enriched patches of available nutrients and/or different soil acidity conditions, demonstrates the morphological plasticity of coffee fine roots: e.g., their distribution depends on whether coffee plantations are organically or conventionally managed.