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Root distribution and water use in coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal environmental conditions.

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Introduction

Roots are the connection between shoot requirements and soil resources in terrestrial plants. While structural roots form the anchorage for the plant and storage of carbohydrates, fine roots perform the function of resource acquisition. Water and nutrients uptake are related to the root system distribution pattern which is in turn influenced by genotype, environmental interactions and management (Nair 1984; Fitter 1996).

In agroforestry systems where crop and tree growth occur simultaneously the root system distribution pattern of the different components is a determinant of complementarity or competition in resource use. An ideotype of a shade tree would be that it should possess a deep root system in order to take up water and nutrients that are not available for crops (Sanchez 1995; Cannell *et al.* 1996). In reality most tree species have dense root systems in the topsoil where nutrients are concentrated (Schroth 1995). A global study of tropical tree rooting distributions showed that on average 26% of roots are in the upper 10 cm of the soil profile, 60% down to 30 cm and 78% in the top 50 cm (Jackson *et al.* 1996).

Comparison between pure tree stands and agroforestry showed that in the monocrop stands of hybrid walnut (*Juglans nigra* x *regia*) and poplar (*Populus euramericana*) fine root density decreased with depth while in the intercropped stand tree fine root density was displaced to deep soil layers (Mulia and Dupraz 2006). Other study demonstrated that maize confined the root system of apple tree (*Malus domesticus*) laterally and induced a greater vertical root development in intercropping compared to monoculture apple tree growth in Nebrasca (Yocum 1937).

Below-ground competition may be avoided by both selection of shade trees with appropriate rooting architecture and tree root management. Root pruning of trees provides a powerful management tool for manipulating competition although the interruption of bi-directional flow of water from deep soil horizons to lateral roots at the top layer and vice-versa may be a disadvantage (Ong *et al.* 2007). Root bi-directional flow may benefit shallow-rooted crops growing in drying soils if adjacent trees can provide water from depth by accessing groundwater and therefore, the coexistence between tree and crops may be facilitated (Roupsard *et al.* 1999; Smith *et al.* 2004).

Although coffee root system is characterized by its concentration in the upper soil layers (Nutman 1934; Bull 1963; Huxley *et al.* 1974), coffee root extension and distribution are also highly influenced by environmental and soil conditions. In dry sites coffee root distribution is skewed towards deeper soil layers, and this distribution is related to higher drought tolerance (Ramos and Carvalho 1997; Da Matta and Ramalho 2006).

In optimal conditions for coffee cultivation in Costa Rica no competition for water was found when shaded with *Eucalyptus deglupta* (Schaller *et al.* 2003) or *Inga densiflora* (Siles *et al.* 2009). However reports on coffee and tropical timber tree interactions in sub-optimal environmental conditions are few. This paper discusses soil exploration by coffee and shade tree roots in a mature agroforestry experiment comparing unshaded monoculture coffee (FS, “full sun”) with adjacent agroforestry (AFS) plots, comprising coffee cultivated under mixed shade of two tree species.

The research described in this paper took place in a coffee agroforestry system in a location with a compacted soil horizon. Other work has demonstrated that compacted soil layers may limit water movement, root penetration and therefore, plant water uptake (Bennie 1996; Bengough *et al.* 2011). In such soil conditions tree roots play an important role in facilitating water flow and crop root penetration (Nair 1984; Van Noordwijk *et al.* 1996). Voids left by partially decomposed tree roots may be utilized by crops to acquire water from deeper soil layers (Van Noordwijk *et al.* 1991). Moreover, root channels with live or decaying roots can increase saturated hydraulic conductivity by serving as conduits for preferential flow (Johnson-Maynard *et al.* 2002; Benegas *et al.* 2014).

For this study the hypotheses tested were that under soil conditions characterized by a compact layer, trees roots penetrate through the hard-pan and so facilitate coffee water uptake throughout the soil profile; that coffee and tree roots explore different spatial niches; and that evergreen and deciduous tropical timber tree species exhibit different root system distributions.

The study was conducted in sub-optimal conditions for arabica coffee cultivation, typified by a dry season with six months with rainfall < 50 mm, the presence of a compacted soil layer at intermediate and variable depth, and root exploration ultimately limited by a mineral compact layer at approximately 2 m depth. This experiment site is representative of the whole Carazo coffee growing region in Nicaragua. Location of such studies in agriculturally difficult environments is important, as these are the conditions under which many farmers have to operate.

Materials and methods

Site description This study was carried out from November 2011 to May 2014 in an experiment located at Jardin Botánico, Masatepe, Department of Masaya, southern Nicaragua (11^0 53’ 54’’ N, 86^0 08’ 56’’ W) at a long term research site managed by the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), jointly with the Universidad Nacional Agraria (UNA), Federación Cooperativas de Ahorro y Crédito (CENECOOP-FEDECARUNA) and Instituto Nicaraguense de Tecnologia Agropecuaria (INTA). The experiment was established in 2000 and was described by Haggar *et al.* (2011).

The site is located at 455 m.a.s.l. which is considered to be rather low for arabica coffee cultivation. The mean annual temperature is 27^0C with only slight seasonal variation and mean annual rainfall is 1470 mm. From 85% to 97% of the total annual precipitation falls over the wet season (May-November) while a pronounced seasonal drought occurs from late November to mid-May (Vogel and Acuña Espinales 1995). Annual rainfall recorded was 968 mm and 1312 mm in 2012 and 2013 respectively.

Soils in the area are predominantly characterized as andisols, which are derived from volcanic ejecta. These soils are typically deep, well drained and have high organic matter content, low bulk density, high allophane content and consequently a high phosphorus fixation capacity, high amorphous mineral content and high water retention capacity (FAO, 2001).

On this particular study site, however, soils are characterized by the presence of a hardened layer locally known as talpetate (Fig. 1). Such layers occur in about 15% of the Nicaragua Pacific region. Its properties reflect both geologic and soil-forming processes and can be extremely variable. It ranges from soft, weathered material containing some harder rock fragments to a fairly continuous hard layer with rock-like properties. The texture varies from fine to sandy, with the latter often appearing stratified (Vogel and Acuña Espinales 1995).

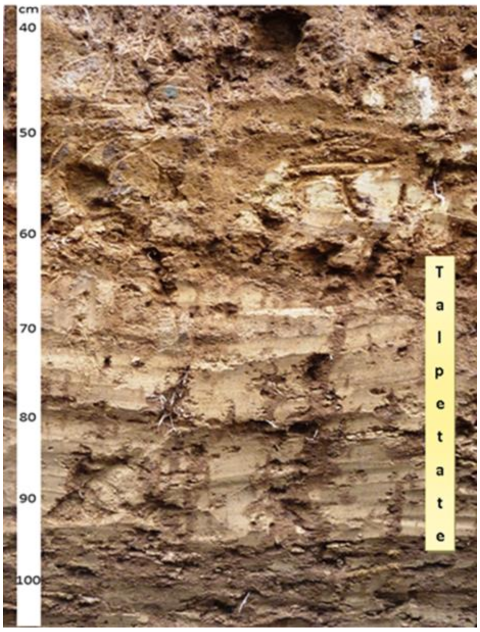


Fig. 1 Talpetate layer in the soil profile with roots inside the fractures

At Masatepe, the talpetate layer is characterized by high aluminium and silicon contents which are retained in allophones after irreversible dehydrating to become a cemented material. This is usually associated with limitations to water movement and root growth. However, weaknesses or fractures that occur in the talpetate layer allow roots to access the deeper soil horizons (Vogel and Acuña Espinales 1995).

Besides the talpetate, in Masatepe, the soil profile consists of three other main layers distinguished by color: brown (uppermost layer), reddish (usually above the talpetate) and a yellowish, granular layer, under the talpetate. At 1.60 - 2.0 m depth, there is a dark granular compact layer, without organic content, where neither roots nor breaks were observed, so we did not explore below 2.10 m.

The bulk density varied from 0.62 g cm^{-3} (S.E.= 0.026) to 0.65 g cm^{-3} (S.E.= 0.039) on average in the shade and full sun plots, respectively, while in the talpetate layer it reached 0.72 g cm^{-3} in both systems. The mean organic matter content of the soil profile was 3.38% (S.E.=1.05) and 3.82% (S.E.=2.0) in the shade and full sun plots respectively. In the uppermost, brown layer organic matter content was found to be 8.75% (S.E.=0.10) in the shade system and 8.22% (S.E.=0.25) in the full sun, and decreased with depth. The pH (in H_2O) did not differ in both systems and ranged between 5.70 and 5.80 which is considered adequate for coffee cultivation. Management includes fertilization with 37.3 kg ha^{-1} of N, 48.8 kg ha^{-1} of P and 27.6 kg ha^{-1} of K as NPK per year. In addition 34.4 kg ha^{-1} of N as urea and 12 kg ha^{-1} of K as KCl are applied each year.

The experimental design consists of a full sun monocrop coffee (FS) plot (50.5 m x 28.5 m) as a pseudo replication and two adjacents coffee agroforestry system (AFS) plots (80.0 m x 40.0 m and 60.0 m x 23.7 m) in which data were collected in 2011 and 2013. For the current study, pseudo-replication occurred within the full sun treatment plot due to the poor set of coffee plants and problems with small floods in the real replication. However, it was considered appropriate for a process-based study such as this one. The *Coffea arabica*, variety “Pacas” was planted in 2000, at a density of 4000 plants ha^{-1}. Coffee spacing was 2 m between rows and 1.25 m between plants. Coffee plants are pruned periodically in accordance with standard agronomic practice. In the coffee agroforestry system plot *Coffea arabica* is associated with *Simarouba glauca* DC. (Simaroubaceae) and *Tabebuia rosea* (Bertol.) DC. (Bignoniaceae) planted as shade trees. The initial density of the mixed tree covered was 667 trees per ha with alternating rows of both species, but tree density was reduced over time in order to achieve an agronomically appropriate shade level. The mean density of *Tabebuia rosea* was 113 trees ha^{-1} and that of *Simarouba glauca* was 75 trees ha^{-1} over the period of the study (Fig. 2). The experimental design was based on three hypothesized levels of competition for water in AFS compared to full sun coffee. The split-split plot design consisted of five incomplete blocks (whole plot) with four split plots (treatments): coffee monoculture, and in the coffee agroforestry system, coffee near *Simarouba glauca* trees, coffee near *Tabebuia rosea* trees and shaded coffee as far as possible from both tree species (around 4 m); and two split-split plots (soil profiles) for each treatment.

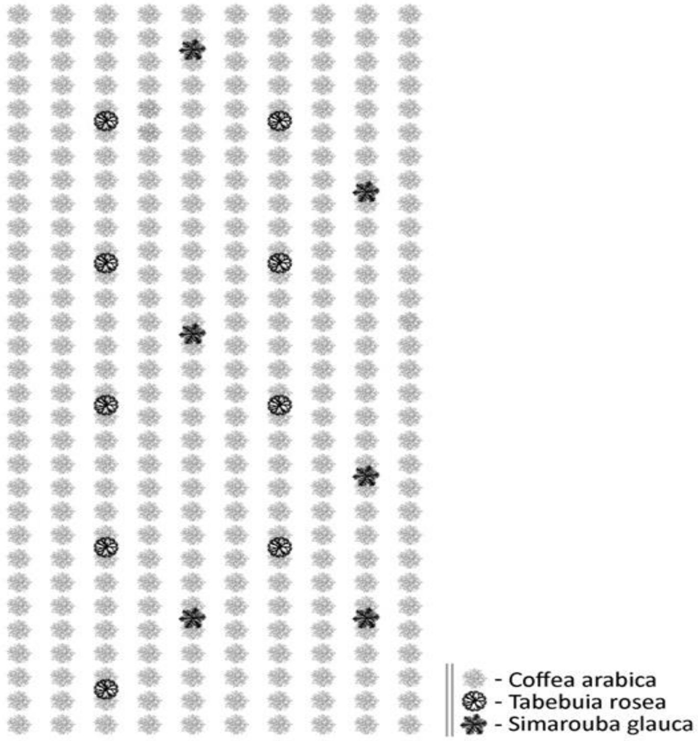


Fig. 2 Schematic representation of the experimental design of (one quarter of) the shade plot with coffee, *Simarouba glauca* and *Tabebuia rosea* spatial distribution pattern

Tree species studied

Simarouba glauca DC. is native to tropical and sub-tropical regions of Central America, Mexico and the Caribbean. It is an evergreen timber tree that grow successfully over a range of soil types and their deep root system enables efficient access to water year round (Brodribb *et al.* 2003). In the study area *Simarouba glauca* trees reached in the average 17 m height with 25.5 cm DBH.

Tabebuia rosea Bertol. is native to Mexico, Central America, Venezuela and coastal Ecuador. Trees grow in a great variety of habitats, but prefer regions with high annual rainfall (between 1200 and 2500 mm). It has a deep root system and tolerates occasional waterlogging. It is a deciduous tree that sheds its leaves in the late dry season (CABI, 2013). In the study area *Tabebuia rosea* trees stood bare for about two months (April and May) in 2012 and for four months (from the end of February to the end of June) in the more severe dry season of 2013. Trees reached 15.5 m height and 28.7 cm DBH on average in the experimental area.

Fine root distribution

Fine root distribution of trees and coffee plants was recorded by the root impact counting method (Tardieu 1988; Van Noordwijk *et al.* 2000). This method is based on the traditional profile wall method proposed by Thiel in 1892 that has been used with modifications by several authors (Bohm 1979). A root impact was considered to be any intersection of a root with the exposed vertical soil profile under study (Laclau *et al.* 2001). Fine roots were defined as root with diameters ≤ 2 mm. Three and six trenches were dug in the full sun and shade coffee respectively in November 2011while another two and six trenches were dug in unshaded and shaded coffee in November 2013. Both trench faces were used for recording. No significant effects of time of recording were found on root distribution ($p>0.05$), so a mature, stable root system was assumed for analytical purposes. Ten profiles were analyzed in the full sun coffee plot and twenty four profiles in coffee agroforestry plots: eight profiles were 150 cm distant from *Tabebuia rosea* stems; eight profiles 150 cm distant from *Simarouba glauca* stems and the other eight as far as possible from any tree, but within the agroforestry plots. Trenches were located between the coffee rows and about 50 cm away from the coffee stems. Each trench was 200 cm deep and 60 cm wide. The soil profile was divided into 10 x 10 cm grid cells and the number of roots in each grid cell was counted. We used a small knife to gently remove the surrounding soil and expose the root ends. Roots of *Coffea arabica*, *Tabebuia rosea* and *Simarouba glauca* were distinguished from each other on the basis of color, smell and rigidity characteristics.

Soil water content

We measured the changes in the soil water content during the two and a half years of our experiment: when the first trenches were dug, we inserted time domain reflectometers (Campbell Scientific Inc. CS616, subsequently called TDR probes) into the soil of one of the trench walls, horizontally in the middle of each of the four soil layers reported above; thus, depths of insertion were variable. Horizontal location of each TDR soil profile was established so that it was representative of a reproducible cell (mid distance from the center of the coffee row and the center of the interrow). TDR probes were connected to dataloggers (CR 1000 with multiplexer, Campbell Scientific Inc.), scanned every minute and data were stored every 30 minutes during the whole experiment. Undisturbed soil samples of sufficient dimensions to insert a TDR probe were also extracted from each soil layer (two samples per layer). Progressive drying was measured simultaneously by TDR and by weighing, so that a calibration equation was available for each soil layer, following a protocol adapted from Udawatta *et al.* (2011). The volumetric soil water contents were then multiplied by the thickness of the soil layers in which each TDR probe was inserted to calculate the soil water content of each layer. All soil layer water contents were added to get the soil water content of the whole profile at each time step.

We then calculated water uptake for each trench per period of time. As a first step, the deepest TDR in each trench was examined. For the purposes of this paper we only selected periods when these deep TDR showed a consistent decrease or a stable signal throughout the period, indicating that water was not diffusing down from upper layers. We were thus able to discard periods when drainage out of the observed soil profile could have occurred. All periods with heavy rains had thus to be discarded (whole wet season in 2013, and almost all wet season in 2012, with the exception of a one month period in July-August when rainfall events were very low). The data retained covered 53% of the two-year experiment, in nine continuous periods ranging 25-60 days. Soil surface run-off and run-on was also discounted since no run-off was observed in the study area because the soil surface was horizontal. Moreover, andisols are renowned for their high infiltration rates.

We could then estimate evapotranspiration from the coffee systems from soil water content change: providing the assumptions of lack of drainage were accepted the water balance equation could be simplified to:

$$S1 - S2 + R = Et$$

Where: $S1$ is the soil water stock in the soil profile at the beginning of the period (mm); $S2$ is the soil water stock in the soil profile at the end of the period (mm); R is the accumulated rainfall during the period (mm); Et is the evapotranspiration by the soil-plant system accumulated during the period (mm). Final data were expressed in mm.day^{-1}, calculated as the ratio between total evapotranspiration and the total number of days of the period.

Data analysis

General and mixed linear models were performed taking into account the hierarchical model in the split-split plot design (Pinheiro and Bates 2009). Roots were analyzed by variance analysis to compare root impacts between both data collection periods. Root spatial distribution was analyzed by co-variance analysis regarding the depth as co-variable. As residuals did not conform to a normal distribution, data were transformed into natural log (1+root impact). The model was also applied to analyze the effect of the talpetate on coffee root distribution by contrast analysis. The model took into account the logarithm of coffee root impacts in the treatments and the presence or absence of talpetate in replications by depth. Differences in soil water content between both the full sun and agroforestry system in the three dry periods studied were tested. The temporal series for both treatments were assumed in the model as a first order autoregressive function. Model assumptions were evaluated by residuals and predictors plots. Heterogeneous variances were modelled for treatments and years. All analyses were performed by using InfoStat software 2014 (Di Rienzo *et al.* 2014).

Results and Discussion

Coffee and tree fine root distribution

Coffee root growth in deep layers was not significantly enhanced in the presence of tree roots (p>0.05), fine root growth being similar in full sun and in shaded coffee systems. Coffee roots reached 150 cm and 170 cm depths in the full sun and in agroforestry system respectively which suggest only a weak influence of tree roots on coffee root depth penetration (Fig. 3). Most roots were concentrated in the upper 30 cm of the soil profile where 56.9% coffee fine root impacts in the full sun and 50.6% in the shade occurred. However, coffee root distribution did differ between shade tree species. There were more coffee root impacts on average in the soil profile near *Simarouba glauca* than near *Tabebuia rosea* trees (p=0.001) (Fig. 4). In the uppermost 30 cm, coffee root counts were approximately an order of magnitude greater than maximum tree root counts. In contrast to the coffee, shade tree root density was greater in deep soil layers than close to the soil surface, exhibiting niche differentiation between them and the shallower coffee roots (Fig. 5). Roots of both tree species reached the dark, granular compacted layer at around 200 cm depth but penetrated no further. Tree root distribution pattern varied with species. In the deeper layers although both tree species showed higher root density below 110 cm depth, the *Simarouba glauca* root system was denser and more concentrated while *Tabebuia rosea* roots did not display such a distinct zonation in the soil profile ($p<0.0001$). Maximum fine root density of *Simarouba glauca* occurred at 165 cm depth and *Tabebuia rosea* exhibited a less distinct peak at 115 cm depth (Fig. 6).

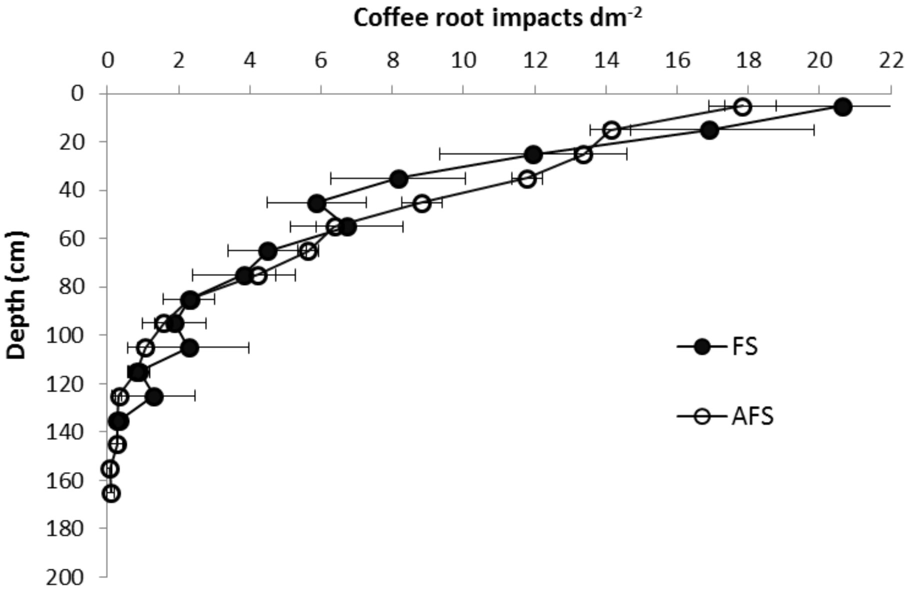


Fig. 3 Coffee root impacts dm^{-2} in the soil profile in full sun coffee (FS) and coffee agroforestry (AFS) from the mean of ten soil profiles in FS plot and 24 in AFS. Errors bars represent the standard error of the mean

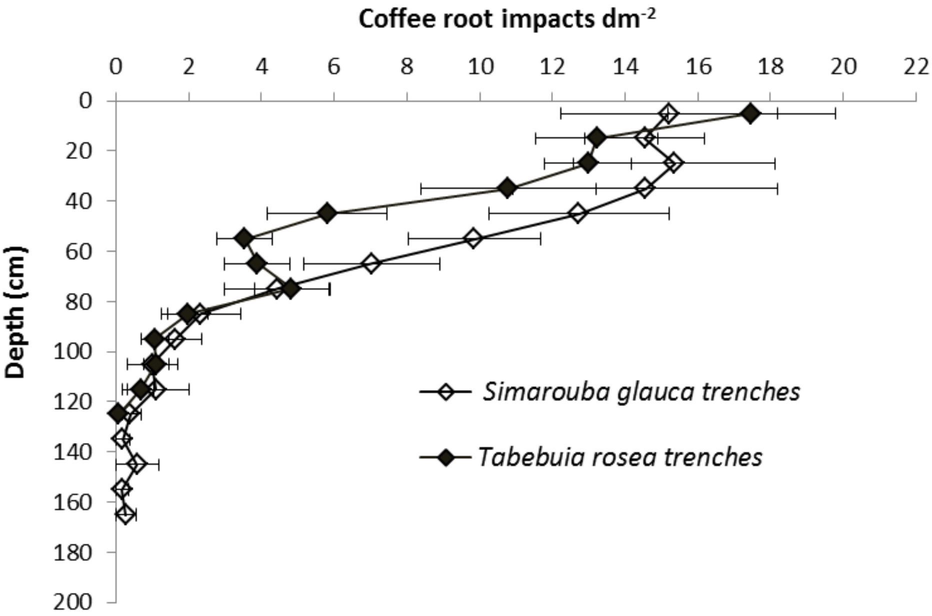


Fig. 4 Coffee root impacts dm^{-2} in soil profiles near *Tabebuia rosea* and *Simarouba glauca* trees from the mean of eight soil profiles near each tree. Errors bars represent the standard error of the mean

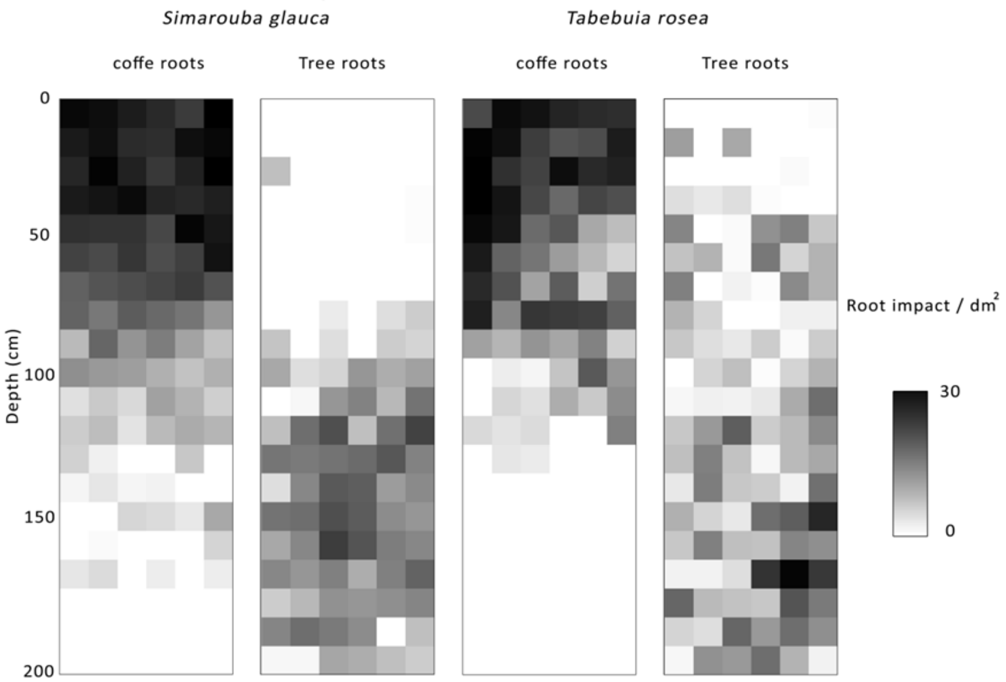


Fig. 5 Niche differentiation of fine coffee roots and fine tree roots in the agroforestry system from the mean of 24 soil profiles in shade plots. Pictures represent the whole grids where roots were counted in 10cm x 10cm cells

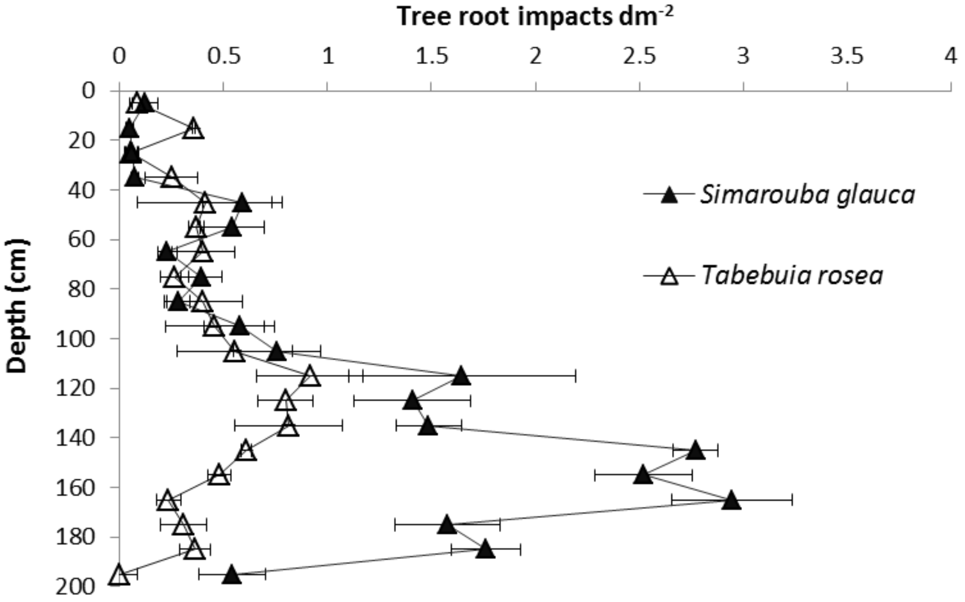


Fig. 6 *Simarouba glauca* and *Tabebuia rosea* fine root distribution from the mean of 24 soil profiles in shade plots. Errors bars represent the standard error of the mean

The effect of talpetate on coffee roots distribution

Field observations demonstrated that the depth of the talpetate layer varied between 20-170 cm and 20-150 cm in the full sun and in the shade plots respectively. The talpetate layer width was also highly variable ranging from 20 to 120 cm in the full sun and 30 to 80 cm in the shaded plots, although these differences were not significant between both systems. Also, there were sites where the tapetate layer was dense and compact and others where it was fractured at different levels regardless of the treatment. The bulk density and the organic matter content of the talpetate layer were not significantly different between the full sun and agroforestry systems or between the treatments ($p>0.05$). The bulk density ranged from 0.54 g cm^{-3} to 0.85 g cm^{-3} while the organic matter varied from 0.5 % to 1.66 %. The presence of the talpetate layer had a significant effect ($F=6.32$; $p=0.02$) on coffee root growth.The contrast analysis of presence and absence of talpete on coffee root distribution by depth showed that coffee root impacts diminished in the presence of talpetate (0.55; S.E=0.03) compared to in the absence of talpetate (0.67; S.E.=0.04) regardless of the treatment. Vogel and Acuña Espinales (1995) also found limitations on root growth and agriculture development in soils with talpetate in comparison to soils without talpetate layer in Nicaragua.

Soil water content

Soil water content was a consequence of the rainfall inputs and its interactions with water uptake by plants and movement within the soil. Rainfall in 2011 was normal for the region, with relatively late rains in November (data not recorded locally). Total rainfall in the 2012 dry season was 57.2 mm with a maximum daily rainfall event of 16.8 mm. In 2012 (Fig. 7), the rainfall in September to November was low, and the following dry season lasted almost six months, with only 10 mm rainfall overall.

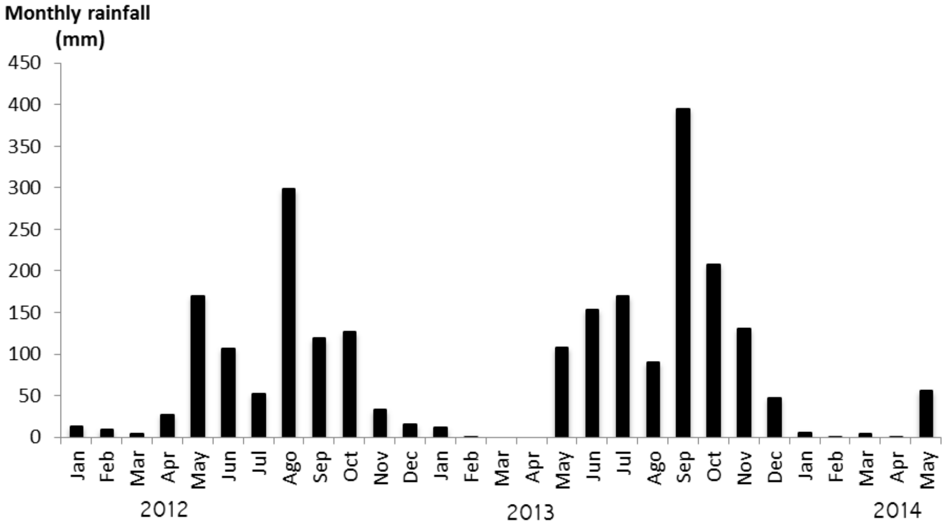
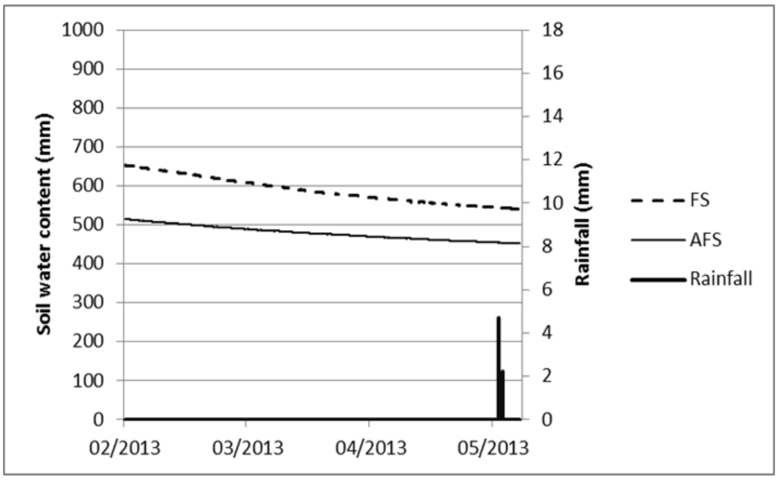


Fig. 7 Monthly rainfall distribution from climate station, Masatepe, Nicaragua; February 2012 to May 2014

The corresponding rainfall in late 2013 was much more abundant. Comparison between soil water content of both systems showed significant differences (F = 5.98; p = 0.0148) on the soil water content in the three periods studied (Fig. 8). The full sun coffee showed greater mean water content (561 mm; S.E.=20.2) over the whole soil profile than the agroforestry system (484 mm; S.E.=26.3) in the period of study. Comparison of temporal differences in soil water content of both systems showed that in 2012 soil water content was greater (584 mm; S.E.= 27.1) compared to 2013 (468 mm; S.E.=23.2). In 2014 slopes were similar to 2012 (516 mm; S.E.=33.9) indicating the same rates of water uptake (Fig. 8a and 8c). However, in 2013 in AFS the slope was close to zero due to lower available water. The lowest values of water content during the observation period were registered at the end of the 2013 dry season in AFS when it reached 453 mm while in 2012 it was 572 mm and in 2014 506 mm (Fig. 8b).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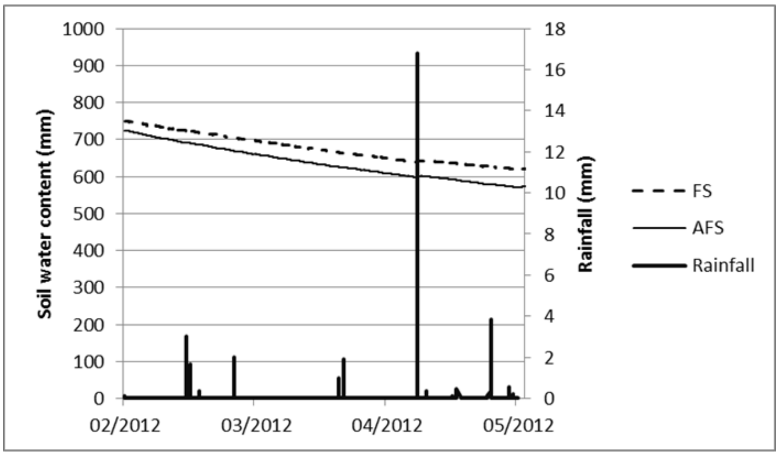
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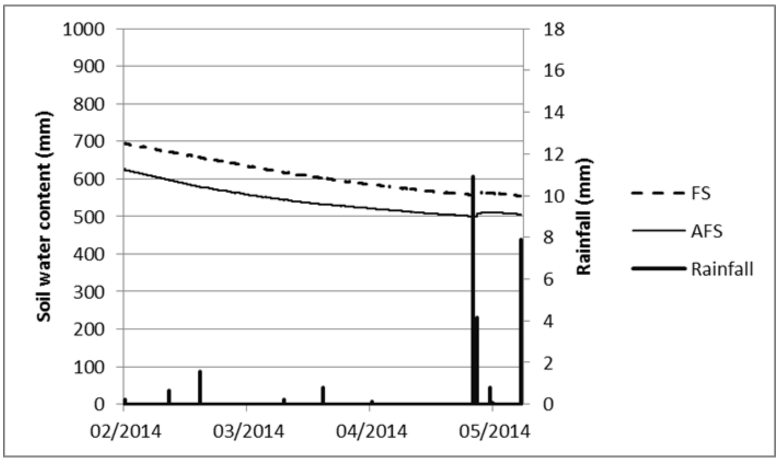

Fig. 8 A comparison of soil water content in the whole soil profile (2000 mm) from the mean of three trenches in the full sun and six trenches in agroforestry in the (a) 2012, (b) 2013 and (c) 2014 dry periods

Soil water uptake

The comparison of daily water uptakes by both coffee systems from the soil profile is presented in Fig. 9. We used only periods when drainage could be discounted. Soil water content data came from a total of nine soil profiles: three in the full sun coffee and six in the coffee agroforestry system. In the agroforestry system we found greater water consumption than in full sun coffee for most of the periods presented. However, at the end of the severe 2013 dry season (p=0.07) this condition seemed to be reversed. Both systems showed a very low rate of water uptake at the end, but data indicated that the coffee agroforestry system had lower soil available water than the full sun coffee (Fig. 9). This indicates that in 'normal' dry seasons, water extraction rate in AFS was similar to FS and due to deeper tree root exploration, water content was lower. However, in the 2013 dry period, roots in AFS had extracted water to the point that soil water content was approaching a steady state, while there was still enough water in the FS soil to permit water uptake, albeit at reduced rate, to continue. Thus, only in very dry periods did the presence of tree roots exert competition to the point where coffee was no longer able to extract water.

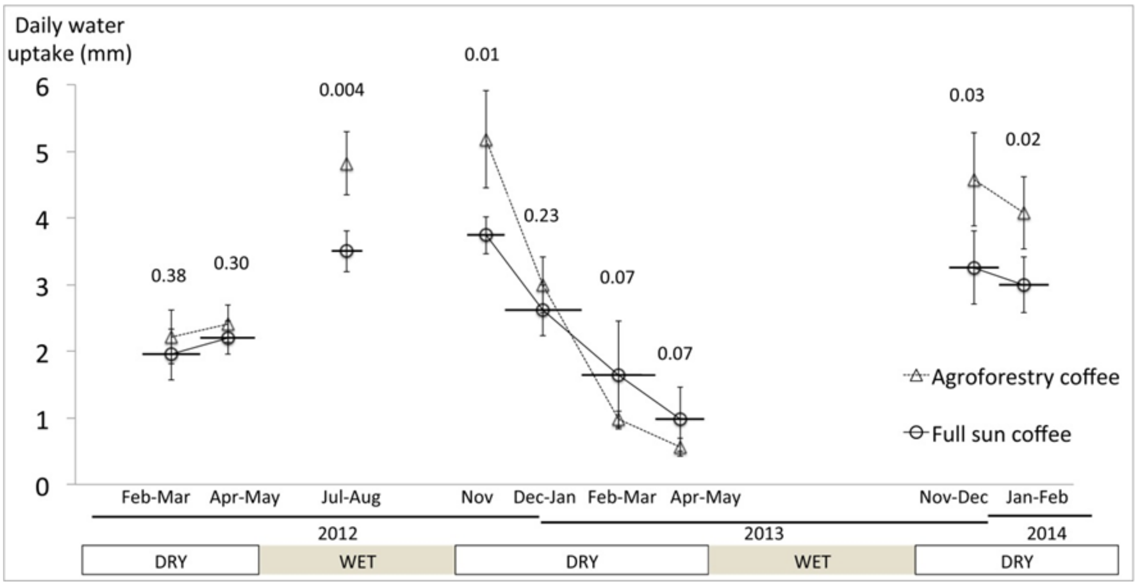

Fig. 9 Comparison of soil water uptake by the two coffee cropping systems from the whole soil profile 2012 to early 2014. Horizontal bars represent the period lengths under consideration. Errors bars represent standard error of the mean. Probabilities for identical values figure above each comparison (T-test)

Conclusions

Root distribution may define competition or complementarity in resources use in agroforestry systems. In this investigation shallower coffee roots and deeper tree root distribution patterns suggest complementarity in soil water use throughout the soil profile. This root niche differentiation is desirable in agroforestry but is not often demonstrated.

However, coffee and tree root system distribution varied with tree species. *Simarouba glauca* presented denser root system in deep soil layers compared to *Tabebuia rosea* suggesting a facilitative relationship upon coffee root growth. Coffee and *Simarouba glauca* exhibited a clear niche differentiation whereby soil water and nutrients are likely to be extracted from different strata. The results reinforced the ecological hypothesis (Cannell *et al.* 1996) in which tree deep root system may improve soil resources use that are not available for crops.

We demonstrated that although coffee roots crossed the talpetate zone, there was some influence of this hard layer on restricting coffee root growth regardless of the treatment.

Soil water content was higher in the full sun coffee rather than the agroforestry in the whole soil profile in the dry seasons of the investigation period. At the beginning of both 2013 and 2014 dry seasons, the agroforestry coffee system was able to take up water at a greater rate from the soil profile, explained by a greater requirement by trees and a better exploration of the whole profile by roots.

But by the end of a severe dry season, as observed in 2013, the advantage of the better soil exploration was cancelled: it seems that soil water became almost exhausted during the dry season. By comparison, full sun coffee, which used less water at the beginning of the 2013 dry season, still had soil water left in the deeper layer when the dry season extended. This deep soil water was progressively used by the system, allowing a greater water use when compared to the agroforestry coffee.

Although more data would be required to distinguish the water uptake from coffee, both species of trees or the soil evaporation, we can hypothesize that there was a competition between trees and coffee for soil water uptake in atypically dry periods.

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