ISSN impreso: 0258-5936
ISSN digital: 1819-4087

Ministerio de Educación Superior. Cuba
Instituto Nacional de Ciencias Agrícolas
http://ediciones.inca.edu.cu

ROOT DEVELOPMENT AS AN INDICATOR OF SOIL SUSTAINABILITY OF CROPPING SYSTEMS IN THE ATLANTIC FOREST BIOME

Desarrollo de las raíces como indicador de la sustentabilidad del suelo de los sistemas de cultivo en el Bioma de la Mata Atlántica

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ABSTRACT. Agricultural sustainability depends on the soil functionality in mechanisms that support plant and animal productivity, water and nutrient cycling, and contamination buffering. Therefore, roots and soil samples from two typical agricultural systems in the Atlantic Forest biome were collected, to evaluate their sustainability through the relationship between roots and soil functionality. The agricultural systems were annual fields as, maize (*Zea mays* L.) and perennial, palm (*Bactris gasipaes* K.). The roots were collected from monoliths (48 x 30 x 5 cm) and after, they were gently washed. The root profiles with the IDRISI and SAFIRA softwares were scanned and then analyzed. Soil samples were submitted to evaluations of microbial-C biomass and physical and chemical attributes. The palm field produced more dry matter roots and had greater root area and volume than the maize field (cf. 1.37 versus 0.14 t ha^{-1}). Considering the 0-5 cm layer, the palm field sustained larger mean weight diameter of soil aggregates (4.2 versus 3.4 mm) and held higher saturation of bases (65 versus 47 %) than the maize. Although the palm field did not have larger total organic C content (20 versus 24 g kg^{-1}), it stimulated microbial biomass (MB-C; 942 versus 428 mg MB-C kg^{-1} soil) and decreased metabolic quotient (0.023 versus 0.034 mg C-CO_2 g^{-1} MB-C h^{-1}) in relation to maize field. This clear relationship between root and soil attributes indicates that better root development contributes to improve soil functionality and for consequence the sustainability of agricultural systems. Therefore, crop systems and soil managements that privilege root growth are better choice to reach the agricultural sustainability.

Key words: biological activity in soil, soil aggregates, soil organic matter

RESUMEN. La sustentabilidad agrícola depende de la funcionalidad del suelo en mecanismos que suporten la productividad vegetal y animal, el ciclo del agua y de los nutrientes y el tamponamiento de contaminación. Para tanto, las muestras de raíces del suelo de dos sistemas agrícolas típicos en el bioma de la Mata Atlántica fueron colectadas para evaluar su sustentabilidad a través de la relación entre raíces y funcionalidad del suelo. Los sistemas agrícolas eran cultivo anuales, maíz (*Zea mays* L.) y perennes palmeras, (*Bactris gasipaes* K.). Las raíces fueron colectadas de monolitos (48 x 30 x 5 cm) y lavadas suavemente. Los perfiles de raíz fueron digitalizados y después analizados con los softwares IDRISI y SAFIRA. Las muestras del suelo fueron sometidas a evaluaciones de biomasa microbiana-C y atributos físicos y químicos. El cultivo de palmeras produjo más materia seca de raíces y tuvo mayor área y volumen de raíz que el campo de maíz (cf. 1,37 contra 0,14 t ha^{-1}). Considerando la camada de 0 a 5 cm, el campo de palmeras sostuvo mayor peso medio de diámetro de los agregados del suelo (4,2 contra 3,4 mm) y mantuvo mayor saturación de bases (65 contra 47 %) que el maíz. Aunque el cultivo de palmeras no tenga una cantidad total de C orgánico total (20 contra 24 g kg^{-1}), estimuló la biomasa microbiana (MB-C; 942 versus 428 mg MB-C kg^{-1}) y disminuyó el cociente metabólico (0,023 contra 0,034 mg C-CO_2 g^{-1} MB-C h^{-1}) en relación al cultivo de maíz. Esta relación clara entre los atributos de la raíz y del suelo indica que un mejor desarrollo de raíces contribuyó para mejorar la funcionalidad del suelo y, consecuentemente, la sustentabilidad de los sistemas agrícolas. Por tanto, los sistemas de culturas y manejo del suelo que privilegian el crecimiento de las raíces son mejores opciones para alcanzar la sustentabilidad agrícola.

Palabras clave: actividad biológica en el suelo, agregados del suelo, materia orgánica del suelo

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INTRODUCTION

The sustainability of the agricultural systems depends on soil functionality that supports plant and animal productivity, water and nutrient cycling, contamination buffering. The soil functionality is result of the interaction of minerals, soil organisms and plants (1) and these interaction is driven by roots (2). The roots add carbon to the soil by discharging exudates and root detachment (3). Thus, the carbon added stimulate the organisms that play crucial roles in processes such as soil organic matter decomposition, nutrient cycling, pesticides degradation and biological control aggregation formation and stabilization (4–7).

In this study, we tested the hypothesis that the ecological soil sustainability of agricultural systems is a function of root attributes (abundance and composition). Roots provide a more lasting source of substrates for microbial growth as they have more lignin and cellulose than shoots (7). Root exudation and byproducts stimulate microbial growth in the rhizosphere, affecting soil nutrient availability and organic matter composition (5). Furthermore, through organomineral interactions, root exudation contributes to the formation of microaggregates (< 0,25 mm), which are bound into macroaggregates (> 0,250 mm) by mycelia and root segments (6,7). The interactions of plant, soil organisms, particularly microorganisms, and soil organomineral particles cooperate to improve soil functionality (1) and consequently, contribute to the sustainability of agricultural systems.

Brazil´s Atlantic Forest Biome covers 1,110,182 km^2 and it is considered a hotspot for biodiversity conservation; however, about 90 % of its extent has been shattered by urbanization, agriculture and mining activities (8) and major efforts are necessary to establish strategies that improve soil sustainability and productivity in already antropogenized areas, allowing the remaining forests to be entirely preserved. With the confirmation that root attributes are governing ecological soil functions, agronomists could design better strategies to improve soil functionality and sustainability of agricultural systems, for example, by choosing plant species, planting densities and arrangements.

Our aim was to evaluate the relationship between root development of annual and perennial cropping systems and soil biological, physical and chemical attributes in the light of sustainability improvement to indicate management directions to agricultural systems of the region.

MATERIALS Y METHODS

Field site and sampling

The study was performed on a farm at the coordinates of 25º16’S and 48º42’W on the North Coast of the State of Paraná, in the Southern Atlantic Forest Biome, Brazil. Climate is subtropical Cfa according to Koppen´s classification, with average annual temperature of 22 ºC and variation of 10 to 18 ºC in cooler months (9). The annual average precipitation is 2,587 mm per year, with an average of 208 rainy days per year. The farm is on a Cambisol according to FAO (10), consisting of 49 % clay, 46 % silt and 5 % sand. Soil chemical characteristics of the field sites are presented in Table 1.

Four composite samples were taken from two experimental fields, 180 m apart and oriented towards each other, chosen to represent varying agricultural roots composition and abundance of the Atlantic Forest biome. The experimental fields are described as follows: 1) perennial cropping of palm trees (*Bactris gasipaes* K.) grown under no-tillage for 16-months, row spacing of 1,40 m, plant spacing of 0.80 m, comprising 7,142 plants ha^{-1}; hereafter referred as *palm*; 2) annual cropping with maize (*Zea mays* L.), row spacing of 1,40 m, plant spacing of 0,55 m, comprising 17,647 plants ha^{-1}, under conventional tillage (ploughing and weekly rotary harrowing at 15 cm depth) for two growing seasons; hereafter referred as *maize*. Fertilizers were applied following official recommendations for each crop (11) being for maize 40 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}; and for the palm 80 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}. Weeds were controlled by rotary hoe (annual cropping) and mowing (perennial cropping). Plant disease did not identify during the period of study and the crops were not irrigated. Samples were collected in each experimental field during the months of March of 2014, when maize was at grain filling stage and palm trees were 16-months-old.

Table 1. Soil chemical characteristics with depth in palm and maize fields

Field	pH + $CaCl_2$	Al + H	Al^{+3}	Ca^{+2}	Mg^{+2}	CEC	K^+	$P_{Mehlich}$	Saturation of bases
				mmol kg^{-1}			- mg dm^{-3} -		%
0-5 cm depth									
Palm	5,3	43*	0,5	52	24*	120	220*	26	65*
Maize	4,7	64	6	41	14	120	90	31	47
5-15 cm depth									
Palm	5,1	45	1	47	22*	120	106*	17	61
Maize	4,7	63	5	43	14	120	64	29	48
15-30 cm depth									
Palm	4,9	48	2	36	19*	100	54	8	54
Maize	4,6	68	14	36	07	110	34	6	35
Average (0-30 cm depth)									
Palm	5,1	5	1	45	22	110	11	17	60
Maize	4,7	4	8	40	12	120	8	22	43
CV(%)	11	12	112	45	24	11	30	65	28

CEC – Cation Exchange Capacity; CV – Coefficient of variation
*Significant at the 0.05 probability level between the fields within the layer by the *t*-test

Root abundance and composition

Four root samples were obtained by digging monoliths with dimensions of 48×30×5 cm (length × height × width) (12). Monoliths were gently washed with a stream of water until soil was removed and root profiles were photographed with a digital camera (Nikon Coolpix P90). Later, profile images were analyzed with the software IDRISI Selva 17.0 (Clark Labs). Sampled roots were also separated according to their original depth layers (0-5, 5-15 and 15-30 cm) and scanned with a portable scanner (Lexmark 1200 Series) at 200 dpi. Images were analyzed with the software SAFIRA for the calculation of length, density, area, volume and diameter of roots. Root length density was obtained by dividing root length per soil volume in each depth. Carbon and nitrogen contents in root dry matter were determined by dry combustion using a CN analyzer (Vario El III – Elementar®). Lignin was determined with the methodology described by Morais *et al*. (13). No statistics are provided for lignin measurements because too little root material was left over and its determination could only be achieved by compositing all replicates.

Soil chemical and physical analyses

Soil samples were taken with a stainless steel knife at layers 0-5, 5-15 and 15-30 cm depths, near each of the four root sampling sites. Soil chemical and physical analyses followed standard procedures as follows: chemistry (pH in $CaCl_2$, Al+H, Ca^{2+}, Mg^{2+}, K^+, $P_{Mehlich}$, total organic carbon and total nitrogen) with the methodology described by Marques and Motta (14); total soil polysaccharides (15); and wet aggregate size distribution in classes of diameter and the Mean Weight Diameter (16) modified using not previously humidified aggregate samples (slaking process).

Soil microbial indicators

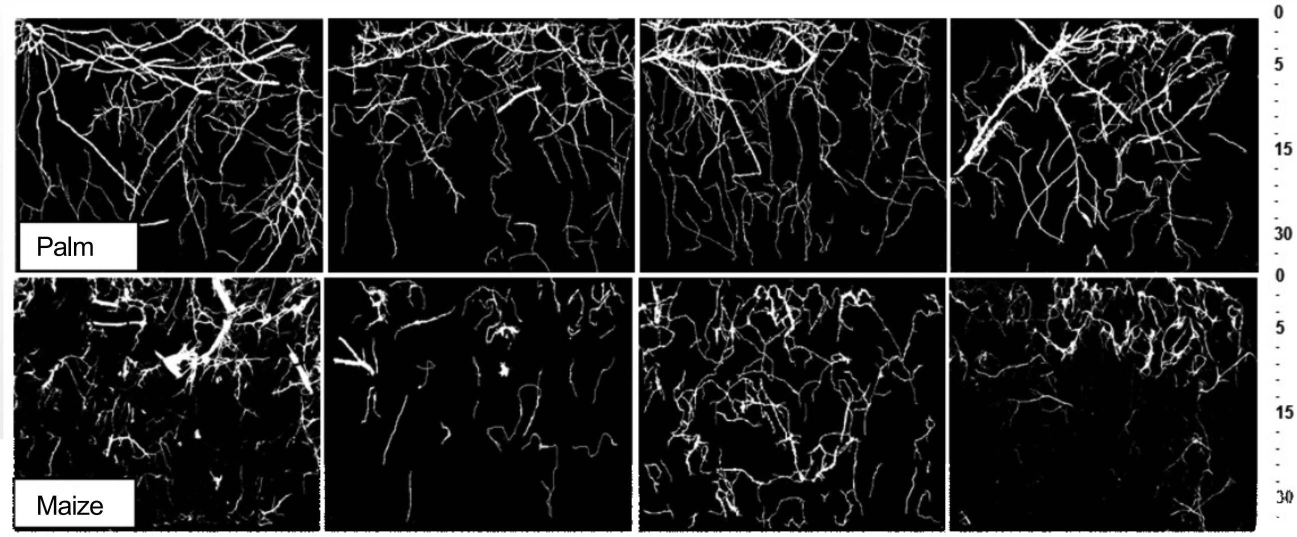
Soil microbial respiration was measured (17) and soil microbial biomass (MB-C) was determined (18). The microbial quotient (*q*Mic) was estimated as the ratio between MB-C and total organic C and, metabolic quotient (qCO_2) as ratio between soil microbial respiration and MB-C.

Statistical analysis

Data was first checked for normality and homogeneity with the Shapiro-Wilk and Bartlett tests. One-way ANOVA was applied considering samples from a completely randomized design comparing each parameter within its layer. In cases where statistical significance was detected, means were compared with the Tukey test at $p < 0,05$.

RESULTS AND DISCUSSION

The palm field had denser root arrangements and its root profile contained fragments more evenly distributed through lateral and vertical directions in comparison to maize (Figure 1). Along with Figure 1, Table 2 shows that the palm field had greater root area and volume than the maize field. In both fields, the largest proportion of roots was formed by very fine roots, comprising fragments with diameters smaller than 0,5 mm.



Ruler on the right-hand side indicates the profile depth measured in cm (0-30 cm)

Figure 1. Root distribution into the profile in palm and maize fields

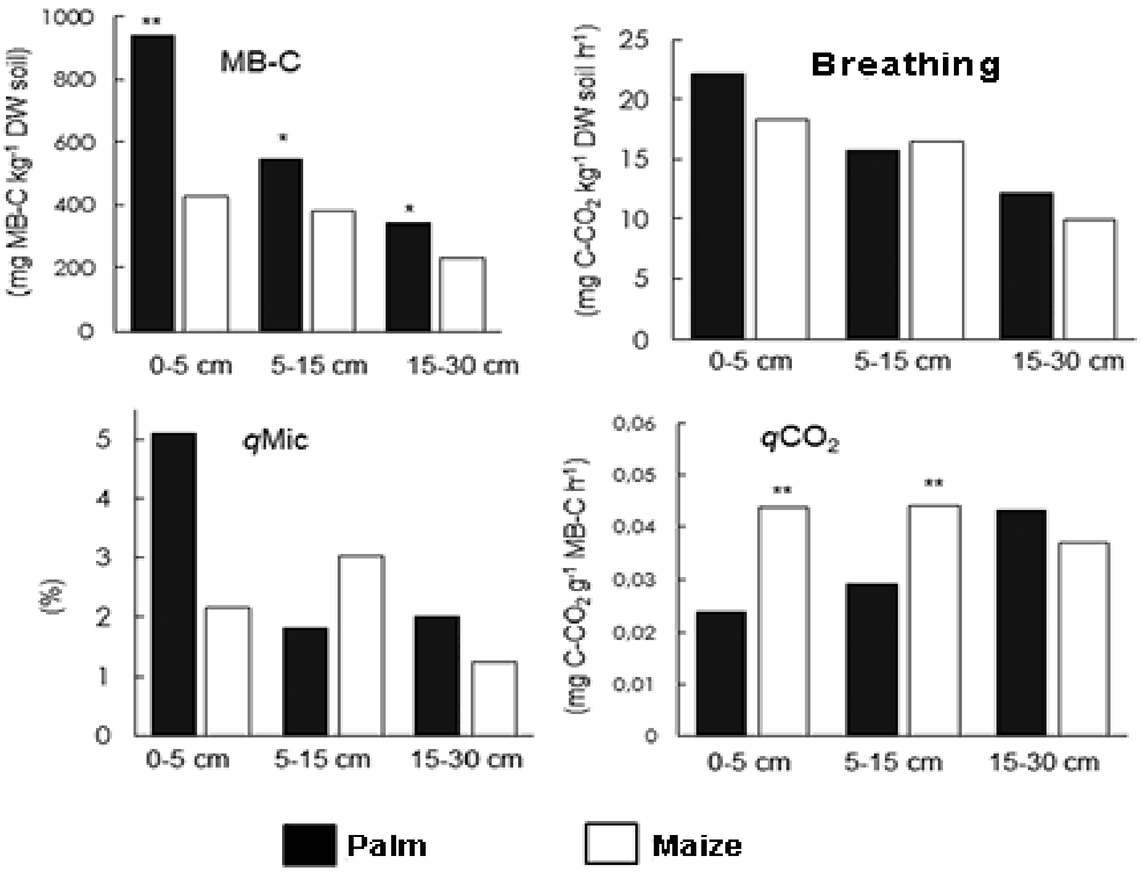
Table 2. Root attributes with depth in palm and maize fields

Field	RDL	RA	RV	Diameter classes (mm)#			C	N	Root C:N
				<0,5	0,5-2,0	2,0-5,0			
	cm cm^{-3}	mm^2 cm^{-3}	mm^3 cm^{-3}	Number of fragments			g kg^{-1}		
0-5 cm depth									
Palm	2,0	36,9*	9,8*	433	12*	ND	376	10*	37*
Maize	1,4	14,4	1,6	1179	7	ND	388	12	31
5-15 cm depth									
Palm	0,9	20,1*	6,3*	300	41*	2	385*	10*	38
Maize	0,7	9,4	1,3	408	16	ND	407	12	36
15-30 cm depth									
Palm	0,3	6,8	1,9*	158	40	ND	382*	9*	42
Maize	0,2	2,5	0,5	268	12	ND	410	12	36
Average (0-30 cm depth)									
Palm	0,9	18	5	400	36	0,5	383	10	39
Maize	0,9	12	2	740	16	ND	399	12	34
CV(%)	46	46	55	48	42	ND	3	16	16

RDL – root density length; RA – root area; RV – root volume; C – root carbon content; N –root nitrogen content; ND – not determined for absence of material; CV – Coefficient of variation. # Roots were classified according to Böhm (1979) in three diameter classes: very fine (< 0,5 mm), fine (0,5 a 2 mm) and thick roots (2 a 5 mm). *Significant at the 0.05 probability level between the fields within the layer by the *t*-test.

When considering the fraction of fine roots (0,5-2,0 mm), palm had significant more root segments than maize (Table 2). Larger proportions of fine roots favor soil functionality because fine roots allow plants to exploit nutrients in larger soil volumes (6,7). Fine roots are important for nutrient cycling because they have a faster decomposition rate than other organic debris (19).

By assembling all material (across all depths from 0-30 cm), we calculated that palm field formed 1,37 t ha^{-1} of dry matter roots whereas maize field formed approximately10-fold less (0,14 t ha^{-1}). The lower amount of dry matter roots is consequence of the wide row lines and low plant density in the maize field, which is typical of the kind of agricultural systems in the region studied. The palm had the shoot:root ratio smaller (9,9) than maize field (13,6), and the higher roots dry matter from palm field especially in top layers (Table 2) promoted soil microbial biomass carbon (Figure 2). Interestingly, the metabolic quotient in the 0-5 and 5-15 cm depth was significantly lower in the palm field when compared with maize. There was a trend that soil microbial respiration decreased with depth, but there were no significant differences in respiration and microbial quotient between fields.



*Significant at the 0,05 probability level and **Significant at the 0,01 probability level between the fields within the specific layer by the *t*-test.

Figure 2. Soil carbon microbial biomass (MB-C), microbial respiration, microbial quotient (qMic) and metabolic quotient (qCO_2) of palm and maize fields

More roots and microbial biomass carbon were associated with a higher proportion of larger aggregate diameter classes in the upper layer in palm field (i.e., the Mean Weight Diameter was 4.2 mm in the palm field and 3.4 mm in the maize field in the 0-5 cm depth layer; Table 3). These results support our hypothesis that roots play an important role in governing microbiological and physical soil attributes that determine soil functionality and sustainability of agricultural system. Tisdall & Oades (3) explained that soil macroaggregates (> 0,250 mm) are formed during the growth and exudation of roots and microbes (particularly fungi).

Although there were no differences in soil total nitrogen, the total organic C in the palm field was significantly lower than the maize field (Table 3). Indicated that lignin content is one of the most important factors to stabilize rhizodeposited carbon in the soil (20). Considering that roots harvested in the palm field contained only 140 mg lignin g^{-1} of roots whereas roots from the maize fields contained 300 mg g^{-1}, we may surmise that root composition (lignin content) contributed to prevent total organic carbon from microbial decomposition in the maize field. Interestingly, results of total organic carbon (Table 3) could be contradicting the fact that, better root development results in soil total organic carbon increases (21). However, although perennial palm field did not hold larger total organic carbon content (Table 3), it supported greater carbon microbial biomass and lower metabolic quotient than annual maize fields (Figure 2). That is a strong indication that the maize field might be losing C_{tot} over time, due to higher metabolic quotient (Figure 2), which is often associated with conventional tillage (22), typical in the agricultural systems in the region.

The total organic carbon and total nitrogen carbon ratio (C_{tot}:N_{tot}) of root debris (potential microbial substrates) from the palm field was slightly higher that of maize field (Table 2), although it was only significant in the upper layer (0-5 cm depth), but the soil C_{tot}:N_{tot} ratios were lower (Table 3). Similarly to what has been observed (23), we found that the metabolic quotient was positively related with soil C_{tot}:N_{tot} ratios (Table 3, Figure 2).

Table 3. Soil aggregation characteristics and soil total carbon (C_{tot}), N (N_{tot}), and soluble polysaccharides (TSP) with depth in palm and maize fields

Field	Aggregate diameter classes (mm)				MWD	C_{tot}	N_{tot}	TSP	Soil C_{tot}:N_{tot}
	8,0-2,0	2,0-0,25	0,25-0,053	<0,053					
	%				mm	g kg^{-1}			
0-5 cm depth									
Palm	73*	20*	3,9	3,1	4,2*	20*	2	23	9*
Maize	59	34	3,7	3,3	3,4	24	2	25	10
5-15 cm depth									
Palm	62	28	6,1*	3,9	3,5	18*	2	19	9*
Maize	57	38	3,4	1,6	3,2	22	2	21	10
15-30 cm depth									
Palm	44*	45*	6,6	4,4*	2,5*	16	2	18	9
Maize	68	27	3,1	1,9	3,9	15	2	18	9
Average (0-30 cm depth)									
Palm	60	31	5,5	4,1	3,4	18	2	19	9
Maize	61	33	3,4	2,1	3,5	21	2	21	10
CV (%)	20	32	20	20	19	18	15	20	5

MWD= mean weight diameter of soil aggregates; CV= Coefficient of variation
*Significant at the 0,05 probability level between the fields within the layer by the *t*-test.

Several studies have shown that increasing organic carbon diversity (as provided by crop rotation compared to monoculture) and long-term carbon accumulation stimulates development of microbial communities that are much more efficient in utilizing carbon, resulting in higher microbial quotient and smaller metabolic quotient (4,24). In our study it appears that perennial palm management leads to changes in soil functionality by diversifying root systems (palm and weed roots), changing soil C_{tot}:N_{tot} ratios and stimulating more efficient use of carbon resources, which could lead to the sustainability system. In a similar way (25), concluded in their study that the perennial cereal cultivation is a way to achieve the agricultural sustainability.

There were nutrient savings (for example, more Mg and K; Table 1) in the soil of the palm field. The saturation of bases was 65 % in the palm field and 47 % in the maize field. Systems that have a continuum carbon addition by shoots and roots dry matter are likely to preserve more nutrients in soil microbial biomass. Soil microbial biomass plays an important role as a source and sink of nutrients (24) and increasing carbon microbial biomass results in positive effects on soil fertility and soil functionality (1,26).

As roots deposit exudates and dead tissues, they stimulate soil biological activity and building of carbon microbial biomass, which in turn, promotes aggregation of soil particles and improves soil chemical characteristics with the final result being better soil functionality. Then, soil functionality and sustainability system may be improved by stimulating root growth. This could be achieved by rotating or intercropping plants with different roots types or by choosing soil managements that do not injure root growth.

CONCLUSION

- The perennial cropping (palm) produced more dry matter roots and had greater root area and volume than the annual cropping (maize). At the soil surface layer, the perennial cropping built the better soil physical and chemical structure and promoted soil biological attributes than annual cropping.
- This clear relationship between root and soil attributes indicates that better root development contributes to improve soil functionality and for consequence the sustainability of agricultural systems.

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Received: 9 de mayo de 2017
Accepted: 12 de febrero de 2018