

Root-aggregation in a pumiceous sandy soil

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Abstract

Short-term effects of amaranth, maize and sunflower (*Amaranthus hypochondriacus*, *Zea mays* and *Helianthus annuus*, respectively) roots on soil aggregation of a pumiceous sandy soil (79% of sand) are reported. Thin sections were obtained from root-centered and lateral positions at four soil depths (0–28 cm) of undisturbed field samples. The three crops had the same effects on soil porosity and soil structural development, although pore types, and dry and water-stable aggregates presented differences by crops. The fine (<1 mm) and intermediate (1–5 mm) roots reduced the soil porosity and formed aggregates strongly developed. Soil adhesion by roots and high root density were the main mechanisms affecting soil porosity and aggregation. Three degrees of aggregation were distinguished: (a) strongly developed with 12% porosity; (b) moderately developed with 18% porosity, (c) weakly developed with 25% porosity. Root-adhering soil in amaranth had a drastic decay six months after harvest, while maize and sunflower kept the amount of soil adhered by roots. Results showed that roots are the main factor contributing to aggregate formation of the pumiceous sandy soil and they are also the main factor influencing structural differences at 1 cm² scale.

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1. Introduction

Information about soil process and plant–soil interaction for volcanic soils is necessary to counterattack the negative effects of soil erosion. These soils are open to wind erosion and constitute the most important source of the aeolian dust during the dry season (Dubroeuq et al., 1998). Management practices is crucial to control wind and water erosion. Reduced tillage before seeding helps to conserve the improvements in soil structural stability due to roots of precedent crop (Bronick and Lal, 2005). In order to assess the crop species effect on soil adhered by roots, we focused on the interaction between sandy soil structure and roots, when crops have been harvested. The main idea of this approach is that crops with high capacity to maintain soil attached by roots could be integrated in farming systems planned with conservation purposes. Previously, it was reported that maize roots retained a higher mass of soil than

those of amaranth and common bean (De León et al., 2006). Knowledge about how roots facilitate soil adhesion requires evidence on soil–roots interplay, at vertical and horizontal positions (van Noordwijk et al., 1992). Although the interplay between roots and soil structure has been intensely studied (Guidi et al., 1985; Dexter, 1987; Materechera et al., 1992; Kooistra et al., 1992; Amato and Ritchie, 2002; Pierret et al., 2005; Whalley et al., 2005), few research related to soil adhesion by roots have been performed under volcanic soils (Dahlgren et al., 2004).

Micromorphology technique based on soil thin sections permits to obtain evidences about pore system, microstructure and roots–soil interactions (van Noordwijk et al., 1992; Kooistra et al., 1992). By micromorphology and high-resolution X-ray imaging techniques, these authors established that fine roots explore mainly inter-aggregate pores created by actual or previous root growth. However, there is little information about the interaction between the roots of different species and the structural development of pumiceous sandy soils. The objectives of this study were: (a) to analyze the influence of crop-

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roots on structural development and soil porosity in a pumiceous sandy soil, (b) to determine the effect of root size on soil porosity and aggregation, and c) to measure changes in root-adhering soil in two sampling dates after crop harvest.

2. Materials and methods

2.1. Soil and climate

The experimental site is located in the Southern part of the Valley of Mexico (19°15'22.42" N 99°01'05.66" W, at 2280 m, altitude). The soil is loamy sand with 79% sand, 14% silt and 7% clay, weakly alkaline, low degree of alteration and 1.5% of soil organic carbon (De León et al., 2006). The area consists of Quaternary sediments from the Teuhtli volcano (De Cserna et al., 1988). The sands are mainly composed by pumice and feldesphatic pyroclasts particles. The soil is classified as *Udic Ustifluent* pumiceous, sandy over coarse-loamy, no calcareous, isothermic (Soil Survey Staff, 2003), or as *Eutri-Tephric Fluvisol* (WRB, 1998; Segura et al., 2005). The climate is temperate, with an average annual precipitation of 537 mm and a temperature of 17.3 °C (De León et al., 2006).

2.2. Experimental field

The experiment consisted of 9 plots (3 for each crop species; 4 × 3 m). The genotypes were amaranth cv “Froncosa”; maize cv “CMT939011” (by CIMMYT) and sunflower cv “Negra”. Plant heights averaged 170, 150 and 200 cm for the three crops, respectively. Crops were grown under dry land farming. Soil was ploughed (20 cm, depth) and rowed (animal traction) one week before seeding (7 July 2003). Fertilization (80-40-0, NPK) and weed control were manually done. Harvest of three crops was done on 15 December 2003. Amaranth, maize and common bean were grown the previous year (2002) on the experimental field. The experimental site received applications of plant residues (amaranth and maize; approx. 3 ton ha⁻¹) during the last 10 years.

2.3. Texture and organic matter

Four bulk soil samples taken each 7 cm depth were air-dried and the fine fraction (<2 mm) was separated from the gravel (>2 mm) by sieving. Particle size distribution of the <2 mm fraction was determined by pipette method, and organic matter content by the Walkey and Black method, procedures reported in the manual edited by van Reewijk (2002).

2.4. Micromorphological analysis

2.4.1. Sample collection and preparation

Eight undisturbed soil samples (2 column positions × 4 soil depths), for each crop species, were field collected on 6 January 2004 (Fig. 1a). Once the amaranth, maize and sunflower plants were harvested, stalks were cut at ground level. One soil column (0–28 cm, depth) was taken from the area of the main root-stalks (centre), and a second one 11.5 cm separated (laterally) at the same depth. In each soil column, 4 soil layers were sampled (each 7 cm).

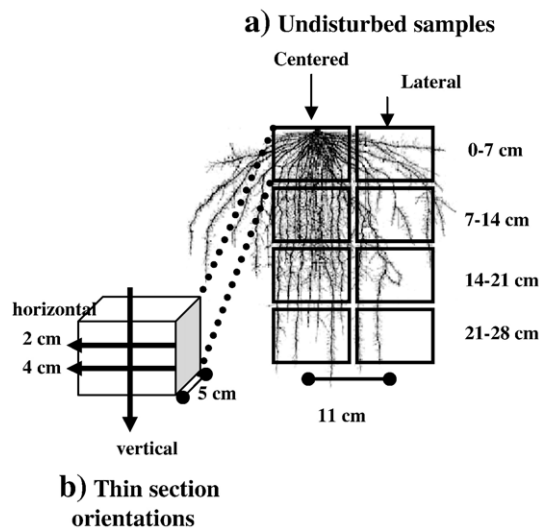


Fig. 1. Spatial distribution of undisturbed root-soil samples (a) root-centered and lateral soil sampling, and (b) orientation cuts of thin sections: horizontal (2 and 4 cm for 0–7 and 7–14 depths, at root-centered position; three species; $n=12$), and vertical for root-centered and lateral, three species and four soil depth ($n=24$).

In the laboratory, samples were air-dried and then impregnated with un-saturated polyester resin (HU-543) and monostyrene (7:1 ratio). Once the resin hardened, root-centered blocks were horizontally and vertically sectioned, while lateral blocks were just vertically sectioned (Fig. 1b). This procedure permitted to know the density of roots growing in vertical and lateral directions. Thin sections (30 μm thickness, 7.5 × 5 cm) were prepared and mounted on glass according to Murphy (1986). They were described using the concepts and terminology of Bullock et al. (1985) and Stoops (2003).

2.4.2. Spatial distribution of roots and aggregates

Three root sizes were distinguished: fine (<1 mm), intermediate (1–5 mm) and large (>5 mm). Large roots were easily seen by the naked eye but intermediate and fine roots were identified only under a microscope, because of their small size and transparency (Costa et al., 2001). Alive roots were identified by their complete birefringence and dead roots by their opacity (partial or total). Soil thin sections were scanned, magnified and printed on paper (22 × 16.5 cm).

On this printed material, equivalent squares 1 × 1 cm from thin section were drawn (35 squares in total). In order to assess the presence of roots and aggregates, thin sections were systematically observed under a petrographic microscope (Olympus® BX51) using a transparent grid (0.5 × 0.5 cm, 2×). Each feature observed on the thin sections was drawn on the printed image and a map was prepared. This method permitted to establish the distribution of root (different sizes) and its relation with soil structure. The three sizes of roots were counted and their density was expressed as the number of roots in 100 cm².

2.4.3. Criteria to assess the aggregates structural development

The degree of pedality of soils with regular or high clay content is determined by the separation of peds and surrounding voids

(Bullock et al., 1985). However, for the sandy soil under study, peds were not clearly separated by pores due to the presence of fine and very fine sand particles. Therefore, peds were recognized by their compaction (intra-porosity), and contrast and sharpness of their boundaries (Bullock et al., 1985). Three structural development degrees of aggregates were recognized: strong (high compaction; prominent and sharp boundaries), moderate (moderate compaction; distinct and medium boundaries) and weak (non-compacted; faint and diffuse boundaries). Finally, pumice grains were identified by their light brown color and vesicular porosity in PPL, and by their isotropy in XPL.

2.5. Soil porosity

Once the map of aggregates and roots was obtained, soil porosity was determined on 2-D images processed with the program Image-Pro[®] (5.1 version). The segmentation function of the program was used following the next procedure: black and white transformation of color images, contrast improvement, three color segmentation (the first two colors for soil particles, and the last one for soil pores) and area corresponding to soil pores (%).

In order to compare the changes introduced by the roots on soil structure, soil porosity was measured on either root sizes (< 1 mm, 1–5 mm, > 5 mm) or without root zones. The number of images for each zone was in function of their density on each thin section.

Soil porosity was also measured inside the aggregates with different degrees of pedality cited above. Eight microscopic images were analyzed for each development degree (0.5 × 0.5 cm).

2.6. Root-adhering soil

Soil was sampled at two post-harvest dates (13 February 13th, and June 1st 2004) in the rhizosphere of three crop species. Eight plants of each species were cut at 3 cm from soil surface. A metallic frame (0.20 × 0.20 × 0.30 m) was placed on the ground surface leaving the plant stalks in the center. A metal spade was vertically introduced in the four sides of the frame. Once the monolith was loosen, the mass of roots plus the adhering soil were manually lifted (pulling from the stalks) and the sample placed into a plastic bag. The number of stalks per sample was counted. The soil water content at two sampling dates was determined. The soil samples were air-dried in the laboratory during 30 days. The soil was manually detached from roots, using a dissection needle. Root-adhering soil and root mass were weighed.

2.7. Dry and water aggregate stability

The mass of root-adhering soil was separated in seven aggregates fractions (<0.04, 0.25, 0.5, 1, 5, 30 and >30 mm; Kemper and Rosenau, 1986). A stalk of sieves was manually

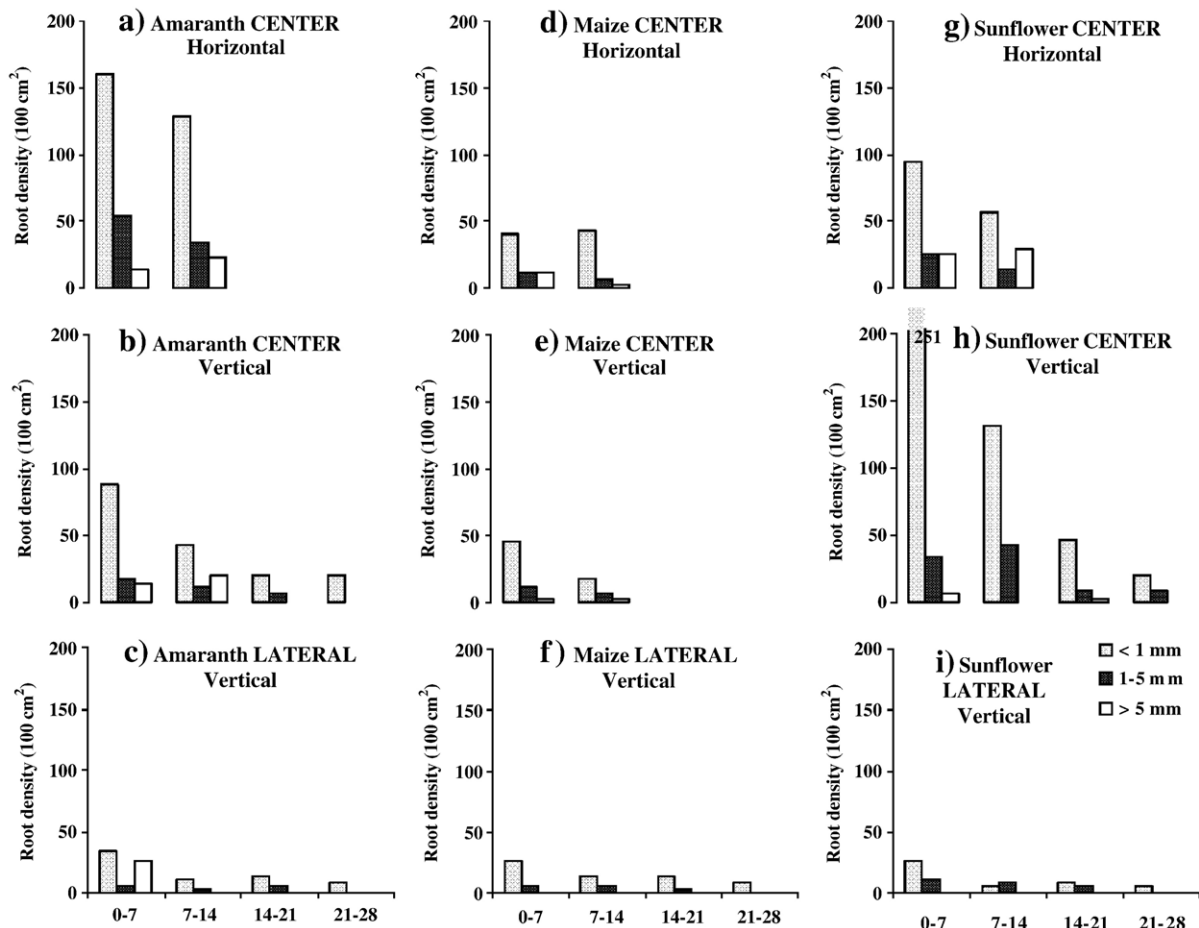


Fig. 2. Density of roots (3 different sizes) for each crop species in root-centered and lateral positions, and horizontal and vertical orientation of thin sections.

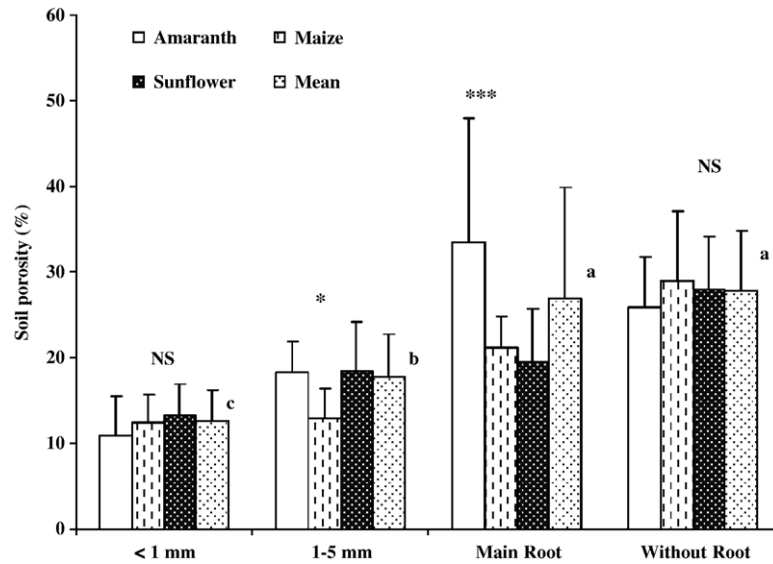


Fig. 3. Porosity (means and standard deviations) in zones colonized by roots of different sizes. Statistical comparisons were made among crop species and root sizes. In the case of crop species, * = significant ($P < 0.05$), ** = highly significant ($P < 0.001$). Different letters indicate different mean group, in the case of root sizes comparisons.

agitated for 3 min to separate the aggregates fractions. The soil mass of each fraction was expressed as a proportion of the root-adhering soil.

The aggregate stability was done with 5 g of 2–5 mm aggregate fraction which was pre-wetted for 30 min under -3 kPa (Le Bissonais, 1996). Aggregates were put in a 250 mL Erlenmeyer flask and 50 mL of ethanol were added; 10 min after the ethanol was eliminated, 250 mL of distilled water were added. Aggregates were manually shaken (20 spins). The water was removed and the soil aggregates mass was dried for 48 h at laboratory temperature (22 °C). Water-stable aggregate mass was determined from the dry weight retained on a 2 mm sieve.

2.8. Statistical analysis

Linear models and analysis of variance were used to test for the experimental factor effects on the studied variables (with SAS® software, version 9.1. SAS Institute Inc., Cary, NC., USA). For thin section variables, the experimental factors were crop species (amaranth, maize and sunflower), soil column position (central and lateral), orientation (horizontal and vertical) and soil depth (7, 14, 21 and 28 cm). For root biomass, root-adhering soil and aggregate stability the experimental factors were crop species and sampling date (February and June 2004). Soil porosity data were transformed to square-root arcsinus, and root density to square-root to fulfill the normal distribution assumption required by the analysis used. Because of the limited number of samples, in the case of thin section variables, only the main effect factors were analyzed.

3. Results

3.1. Soil texture and organic matter

The texture analysis (< 2 mm) indicated 0.5, 0.97, 9.1, 12.5 and 39.9 g 100 g $^{-1}$ for the size classes of very coarse, coarse,

medium, fine and very fine sand, respectively. The soil is dominated by < 200 μ m particles (52.3% of soil mass). Pumiceous grains reached 30% in the gravel fraction (> 2 mm). The organic matter content in 0–7, 7–14 cm for amaranth, maize and sunflower ($n = 3$) was 1.04 and 0.66; 0.89 and 0.81, and 0.42 and 1.42%.

3.2. Root density

Fig. 2 shows the root density data by crop, soil position, thin section orientation and soil depth. For 1–5 cm roots the differences by crop were significant (amaranth $>$ maize $>$ sunflower; $P < 0.04$). Fine roots were more abundant in main root-centered than in lateral position ($P < 0.001$), as occurred with total roots (data not graphed; $P < 0.002$). On horizontal thin sections were found more > 5 cm roots than in vertical ones (17.6 and 3.1 cm^{-2} , respectively; $P < 0.03$). In root-centered position, amaranth and maize had more roots in the horizontal thin sections (Fig. 2a and d) than in vertical ones (Fig. 2b and e). Sunflower duplicated the number of roots in vertical thin section (Fig. 2h) in contrast with the horizontal one (Fig. 2g). The sunflower root abundance (Fig. 3h) is related to the robust size of plants.

Table 1

Effect of different experimental factors on soil porosity of (a) zones colonized by roots of different sizes, and (b) aggregates with different structural development

Source	Soil colonized by roots (size)				Aggregate development		
	$(P > F)$				$(P > F)$		
	> 5 mm	1–5 mm	< 1 mm	No-root	Strong	Moderate	Weak
Crop	0.0001	0.02	0.40	0.32	0.01	0.02	0.08
Soil position	0.33	0.75	0.81	0.61	0.54	0.01	0.005
Thin section cut	0.01	0.48	0.53	0.03	0.59	0.96	0.21
Soil depth	0.17	0.17	0.39	0.0001	0.0006	0.29	0.01

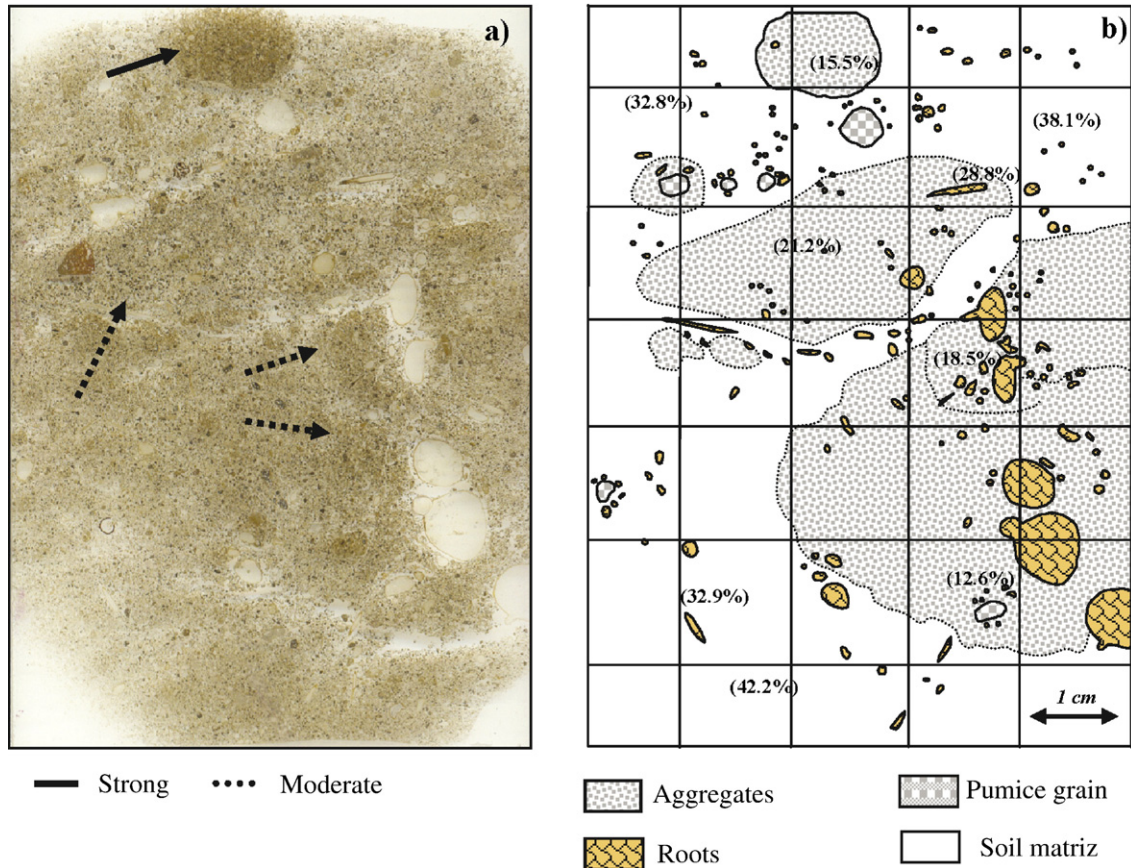


Fig. 4. Spatial distribution of roots and aggregates with different degrees of pedality: a) vertical thin section (sunflower; 0–7 cm; root-centered), and b) map of roots and aggregates and its relation with soil porosity (in parenthesis).

The soil depth had a significant effect on total (data not graphed; $P < 0.001$) and 1–5 cm roots (Fig. 3; $P < 0.0009$). We observed that roots were concentrated in 0–14 cm layer, comparing with deeper rooting zone reported by Gregory (2006) for crops growing under sandy soils.

Crop affected density of decomposed roots (30.6, 1.4 and 5.4 cm^{-2} , for amaranth, maize and sunflower, respectively). These results are consistent with the higher organic matter content in soil sampled from amaranth rhizosphere.

3.3. Soil porosity

Crops did not affect the soil porosity of zones with $< 1 \text{ mm}$ roots (Table 1). In contrast, the crop effect was significant for the soil zone colonized by 1–5 mm roots; under the maize, this zone showed a lower soil porosity (12%) than that observed under amaranth or sunflower. It was as similar as that of $< 1 \text{ mm}$ roots zone (Fig. 3). Differences by crop were also highly significant in the case of main roots (Table 1). For amaranth, the

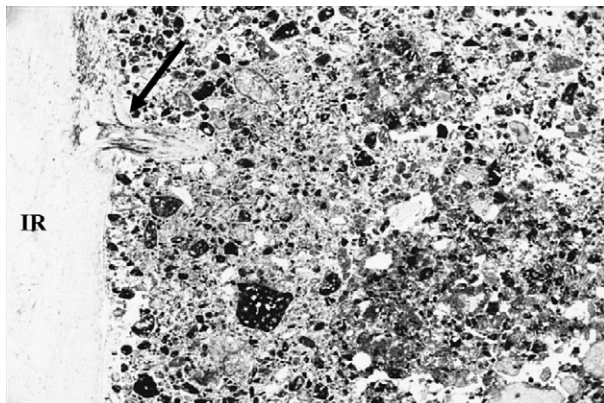


Fig. 5. Association between a fine root (sunflower) and a moderately developed aggregate. IR=Intermediate root, arrow shows fine root. PPL. Horizontal frame length, 5 mm.

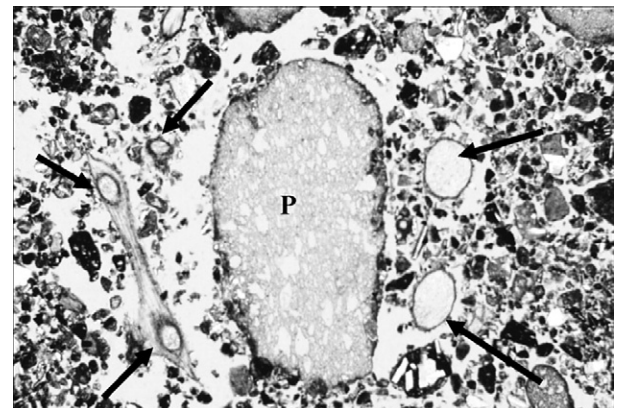


Fig. 6. Roots of sunflower (arrows) around a pumice grain (P). PPL. Horizontal Frame length, 5 mm.

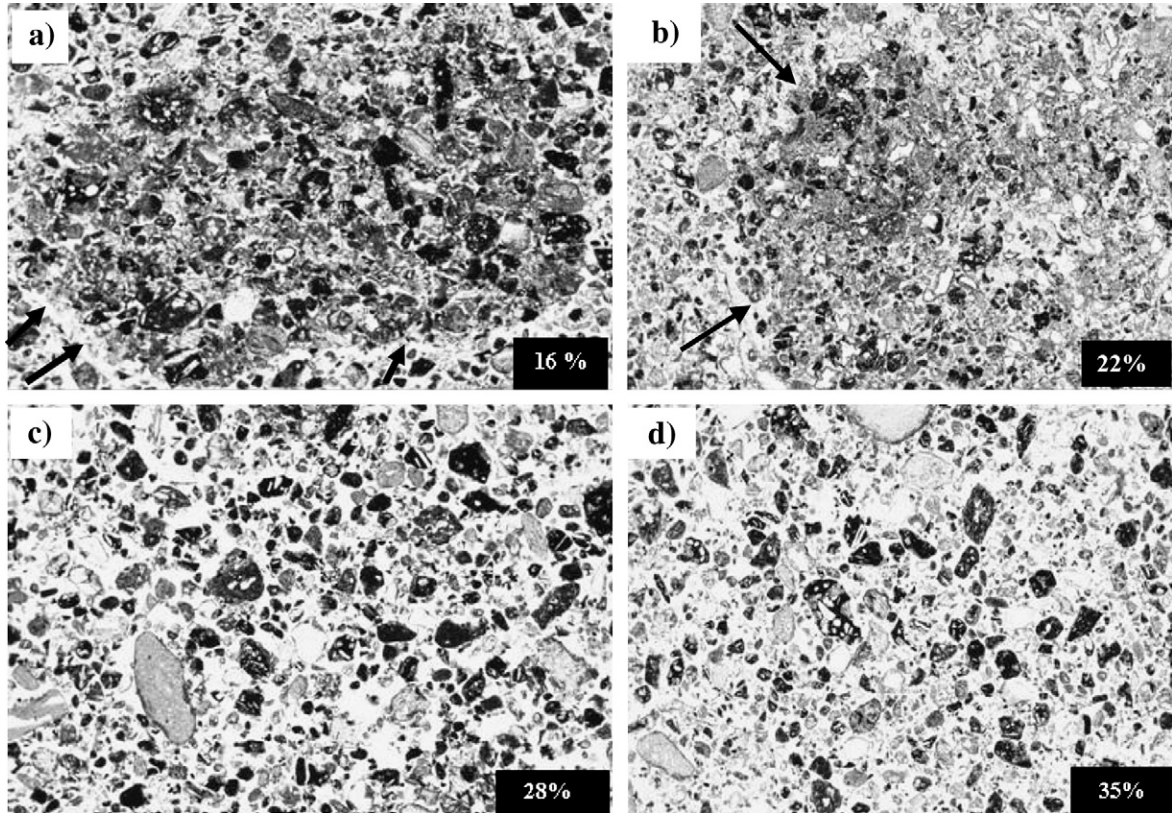


Fig. 7. Degree of structural development of aggregates (contrast and sharpness of their boundaries): a) strong (prominent and sharp), b) moderate (distinct and medium), c) weak (faint and diffuse), d) no aggregation. Numeric values correspond to soil porosities. Arrows in 7a and b indicate the separation between the aggregate and surrounding voids. Non statistical difference was found between soil porosity in c) and d). PPL. Horizontal frame length, 5 mm.

average of soil porosity was 34% in main roots zone (0–7 cm depth), similar to that of the zone without roots (21–28 cm depth); however, qualitative differences (pore types) were observed between both zones. For soil-main roots zone, porosity (range between 23 to 75%) was associated to compound

packing voids (macroaggregate zone), while in soil without roots to simple packing voids (without macroaggregates). These differences seem to be due to the root growth and organic matter content (1.4 vs. 0.24%, for main roots and without roots zones, respectively). For all soil depths, there were no

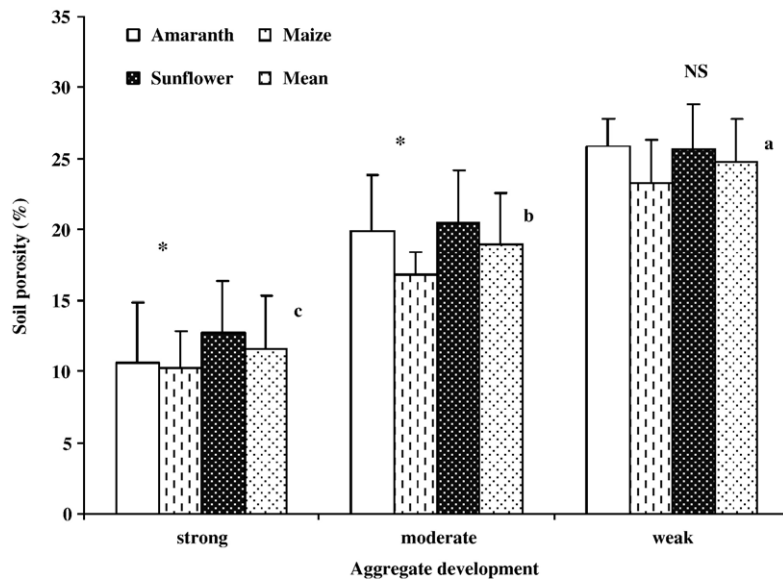


Fig. 8. Soil porosity corresponding to aggregates with different degrees of pedality: strong ($n=46$), moderate ($n=39$) and weak ($n=43$). Statistical comparisons were made among crop species and pedality degree. In the case of crop species, * = significant ($P < 0.05$), NS = no significance ($P > 0.05$). Different letters indicate different mean groups.

Table 2
Mean root biomass and soil adhesion variables by crop and sampling date

Variable	Sampling date	Amaranth	Maize	Sunflower
Plants per monolith (stalk diameter > 1 cm)	1 ^a	4.8 ± 2.4a	1.6 ± 1.7c	3.0 ± 1.1b
	2 ^b	3.5 ± 1.7a	4.0 ± 0.9a	3.0 ± 0.5a
Root biomass (g m ⁻²)	1	68.7 ± 28.3a	25.1 ± 10.4b	68.1 ± 30.9a
	2	21.5 ± 10.8b	42.8 ± 10.2a	58.3 ± 30.8a
Root-adhering soil (kg m ⁻²)	1	5.8 ± 2.6a	5.4 ± 1.2a	5.6 ± 1.4a
	2	0.4 ± 0.6c	5.9 ± 2.1a	4.0 ± 1.6b
RAS/RB	1	95 ± 56b	239 ± 90a	102.1 ± 57.5b
	2	14 ± 23c	147 ± 71a	78 ± 36b

Means with different letters indicate different least square mean groups ($P < 0.05$).

^a Sampling date No. 1: February 2004.

^b Sampling date No. 2: June 2004.

differences in porosity ($P > 0.05$) among the three crop species (28%; Fig. 3).

Soil position (root-centered or lateral) did not affect soil porosity of soil–roots zones (Table 1). Horizontal and vertical thin sections had a significant effect ($P < 0.05$) on porosity of the zone colonized by main roots (Table 1). In the horizontal positions soil porosity averaged 28.5%, while in vertical ones it was 22.6%. In zones without roots, soil porosity was 28.6% vs. 27.7%, for horizontal and vertical positions, respectively.

Soil depth did not affect the soil porosity of different soil–roots zones but a significant effect was found in soil zones without roots (Table 1); the deeper was the soil, the lower was the soil porosity: 30, 32, 26, 23% for 0–7, 7–14, 14–21 and 21–28 cm, respectively.

3.4. Root aggregate zones

Fig. 4a shows an image of thin section corresponding to sunflower (0–7 cm) and Fig. 4b present the map with the distribution of roots: fine (<1 mm) and intermediate (1–5 mm),

and degree of pedality. The thin section shows a high concentration of intermediate (1–5 mm) and fine (<1 mm) roots associated to a large zone with compacted sand particles, represented in the map (Fig. 4b) as a patch. It can be observed that porosity of these compacted particles was 15.5% (average) against 38.1% of the soil matrix (Fig. 4b). Similarly, porosity measured in the aggregate patches was lower than porosity measured in its exterior vicinity (Fig. 4b). The association between a sunflower root and a moderately developed aggregate is shown in Fig. 5.

The 34% of observed fine roots under the sunflower were related to pumice grains (>2 mm; Figs. 4b and 6). This behavior was not observed under the amaranth and maize rhizospheres.

3.5. Porosity of aggregates with different degrees of pedality

Fig. 7 shows aggregates with different degrees of pedality. The comparison of porosity for each developed aggregate type resulted in significant differences ($P < 0.05$, Fig. 8). The lowest soil porosity corresponded to strong aggregates; in contrast, the highest porosity to weakly developed aggregates (25%; Fig. 8). Analysis of variance indicated that the crop had a significant effect on soil porosity in strong and moderate developed aggregates (Table 1). Root-aggregates under maize always presented lower porosity than under amaranth or sunflower (Fig. 8).

3.6. Root-adhering soil

Means of root-adhering soil and root biomass are shown in Table 2. For the first sampling date (February 2004), the three species showed similar amounts of root-adhering soil; however, in the second date (June 2004) the differences by crop species were significant (Table 2). The crop species factor had a highly significant effect ($P < 0.01$) on root biomass. Amaranth root biomass had a drastic fall in the second date (Table 2), probably due to the lower C:N ratio observed for amaranth roots (28) as

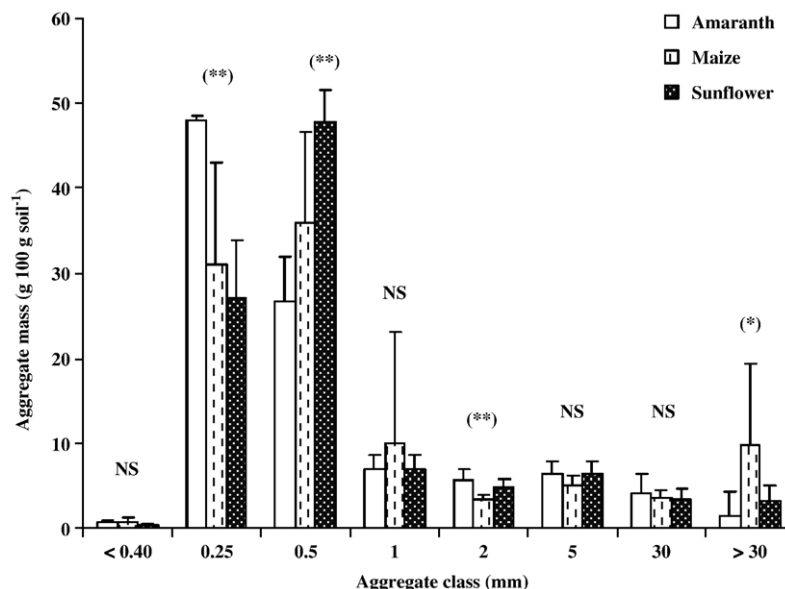


Fig. 9. Mass of air-dried aggregates according to their sizes. Crop species effect: * = significant ($P < 0.05$), ** = highly significant ($P < 0.001$), NS = no significance ($P > 0.05$).

compared to those of maize (48) (De León et al., 2006). The higher organic matter reported for soil samples under amaranth, and its higher density of decomposed roots is an indicator of a faster rate of root decomposition of amaranth than the other two crops. The ratio RAS/RB serves as a parameter of root efficiency to adhere soil (Czarnes et al., 2000a). This ratio was affected ($P < 0.01$) by crop species and sampling date (Table 2). Maize had the highest RAS/RB ratio in both dates. Sampling date affected ($P < 0.05$) the soil water content (8.0 for the first date, and 5.9 g 100 g⁻¹ in the second one), but crop species did not.

3.7. Aggregates stability

Crop species had a significant effect on the four air-dried aggregates fractions (0.25, 0.5, 2 and >30 mm; Fig. 9). For maize, a significant mass of soil (near to 10 g 100 g⁻¹) corresponded to large aggregates (>30 mm diameter). The proportion of water-stable aggregates (2–5 mm) diminished ($P < 0.01$) in the second sampling date (69 and 55 g 100 g⁻¹ for the first and second date, respectively). The crop species had a significant effect on this variable ($P < 0.05$); aggregates from the maize monoliths had the highest stability (67 against 61 and 58 g 100 g⁻¹ for amaranth and sunflower, respectively).

4. Discussion

Results reported here offer new information about the structure of a volcanic soil dominated by pumice and feldspathic minerals, under the influence of crop-roots. The main findings were: a) the introduction of large pores in the soil surface (0–7 cm) by the main roots; b) the growth of sunflower and amaranth fine roots, in the vertical and horizontal direction, and their concentration in the first 0–14 cm soil depth; c) high association between fine and intermediate roots with moderate and strong developed aggregates (2–15 mm); d) the lowest soil porosity in strong developed aggregates; e) the prevalence of non-aggregated zones, and aggregates weakly developed below the first 14 cm; and f) the highest efficiency of maize roots to adhere soil mass. Taken together, these results confirm that roots are responsible for the structural heterogeneity of this sandy soil.

In the present study, fine roots represented the main component of root systems in the three crops, which is consistent with reports from Bengough (2006) and Pallant et al. (1993). Kooistra et al. (1992) found that fine roots (<0.3) may represent between 40 to 80% of the length of root systems in annual plants. In all these studies, no references to compacted aggregates have been cited; in contrast, in the present research, the fine roots were frequently associated to compacted and discrete aggregates, and compacted soil patches. The dark color of aggregates and patches is mainly due to the high concentration of sand particles resulting in a low light transmission, although it is not discarded as the complementary effect of organic exudates from roots or bacteria associated to them.

The map of roots distribution permitted to observe (for the three crop species) the inclusion of fine roots in strong and moderate developed aggregates (>60% of cases). This result contrast with the observations of the preponderant pattern of

external aggregate colonization of roots, reported for clay soils (Pierret et al., 2005; Hinsinger et al., 2005). Stewart et al. (1999) showed in a structured soil that 80% of the roots penetrated in the aggregates less than 1 mm.

Some thin sections (mainly in the 0–7 cm soil layer) showed high root density associated to a larger area (patches) than discrete aggregates having higher sand particles concentration than the soil zone without roots. This result also confirms that roots were participating in the aggregation of the volcanic soil. Individual aggregates and soil compacted patches presented a lower porosity than soil without roots (Fig. 4a and b).

The mechanisms that may be involved in the formation of root-aggregates and compacted soil zones are: 1) soil adhesion by root hairs (rhizosheaths), 2) soil compaction effect caused by high root density. It is well known that root hairs form rhizosheaths when soil is dominated by sand particles (Watt et al., 1994). Grass species have abundant root hairs which grow in a tortuous way producing enmeshment of sand particles (Goodchild and Myers, 1987). Moreno-Espindola et al. (2007) found under the same pumice sandy soil that amaranth, maize and sunflower formed rhizosheaths, which can be the mechanism responsible of forming the 1–2 mm root-aggregates observed on thin sections. Due to the high strength of root hairs and the enmeshment of sand particles, rhizosheaths are a stable form of root-aggregation (Czarnes et al., 2000a).

The evidence of the second mechanism is presented in Fig. 4. In this thin section was observed a very high density (near to 160), resulting in a soil porosity reduction from 28 to 12%. Previous studies have reported that the root growth is a compaction factor on the root vicinity (Dexter, 1987; Bruand et al., 1996) or a generator of large pores (Whalley et al., 2005). In the case of the sandy soil under study, high root density as that reported in Fig. 4b, at the vicinity of 1–5 mm roots, macro-aggregates with low porosity were found, forming a large zone (3 × 3 cm) of compacted soil. These patches may correspond to compacted soil networked by roots. Direct stereomicroscope observations (Fig. 10) of clods (3–5 cm) obtained from the rhizosphere showed that roots networked a soil volume that disrupted easily under hand pressure, suggesting that the root

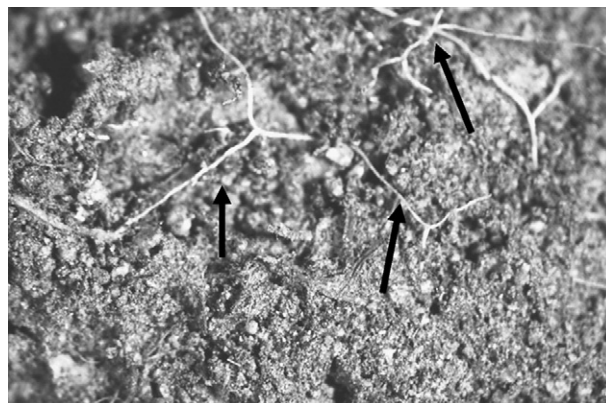


Fig. 10. Example of root network in a clod (3 cm) sampled from the sunflower rhizosphere. Fine roots diameter between 0.04 and 0.07 mm. Optical microscope. Horizontal frame length, 8.8 mm.

network gave only a weak stability to clods. As cementing clay is absent, the union between sand grains and roots did not create stable clods. That is why we conclude that the soil forms clods under the influence of root networks and their stability depend on root-decomposition rate.

Sunflower was the crop species that formed aggregation patches in a more clear way. We conclude that in addition to high root density, the high roots suction capacity helps to form aggregate zones by desiccation effect at the root surface. Driessen and Konijn (1992) reported that sunflower present a high capacity to extract residual soil water.

It was also found that sunflower fine roots (33%) were associated to large pumice grains (Fig. 6). Vesicular structure of pumice grains and their capacity to retain water in their internal pores, make this material able to attract dense root colonization. In a study in Central Mexico, Segura et al. (2005) reported that either large (2–3 mm) or intermediate (0.3–1 mm) pumice grains have a strong holding water capacity (70 and 50%, respectively). Moreover, moisture of the soil studied by Segura et al. (2005) is kept for five months after rainfalls. For the soil under study, abundant fine roots of sunflower may use the water stored by these particles. However, new studies are needed in order to probe this hypothesis.

Although maize cultivar used in the present study had a very short height, thin stalk diameter (1 cm) and low root biomass (Table 2), it produced the highest proportion of water-stable aggregates and RAS/RB ratio. This may result from a low root-decomposition rate (evidenced by the low density of decomposed roots on thin sections), and also from a root exudation of polysaccharides which is a stabilization factor of sand particles, in interaction with drying cycles, as has been reported by Czarnes et al. (2000b).

Little root colonization, structure without macroaggregates and low soil porosity was found in soil layers below 14 cm, which may be related to soil compaction and plant root architecture. For maize, the lack of roots at the soil bottom may be related to the short plant height and small root biomass as was mentioned above. For sunflower and amaranth, the reduction in root density at the bottom of the soil profile seems to be a root response to soil compaction (23% of soil porosity at 21–28 cm depth; against 31% at 0–7 cm; average of zones without roots).

5. Conclusions

Roots are the main factor contributing to aggregate formation of the pumiceous sandy soil and also the main factor influencing strong porosity differences at 1 cm² scale. Main roots of crops introduced macropores only in the surface soil (0–7 cm). Compacted aggregates were associated to fine and intermediate roots; in the majority of the cases, roots were found within the aggregates. Under high density of roots, large compacted soil zones (3.5 × 2 cm²) were formed. For the three crop rhizospheres, three degrees of aggregation, according to aggregate intra-porosity and boundaries were distinguished: (a) strongly developed with 12% porosity; (b) moderately developed with 18% porosity, (c) weakly developed with 25% porosity. The

fine and intermediate roots were responsible for the reduction of soil porosity and for the formation of aggregates strongly developed. The two suggested mechanisms of root-aggregation were soil adhesion by roots, and high density of roots with different sizes effecting soil porosity. Root-adhering soil in amaranth had a drastic decay six months after harvest, while maize and sunflower kept the amount of soil adhered by roots to that showed at two months after harvest.

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