2D-POROSITY OF CRUSTED SILTY SOILS: INDICATORS OF SOIL QUALITY IN SEMIARID RANGELANDS?

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ABSTRACT.

Little is known about the morphological characteristics of pores in soil crusts. The objective was to characterize the 2D-porosity (amount, shape, size and area of pores) of soil crusts to ascertain their potential as indicators of soil quality for natural crusted soils. 2D-porosity was described in thin sections and measured by image analysis of polished resin-impregnated soil blocks. Physical soil crust and incipient biological soil crusts appear to be the lowest-quality soils in terms of number of pores (average of 131 to 133 cm⁻¹) and area occupied by pores or meso-macroporosity (3.5 to 4.2%). Their most abundant pore types were small unconnected rounded pores. Soil crust infiltration coefficients (65-75% annual) were among the lowest and their high erosion rates (81 to 204 g m⁻² y⁻¹) and low infiltrability (47 to 61%) were not only due to their lower total porosity, but also to their pore shapes and sizes. Biological soil crusts appear on higher-quality soil, where the higher the organic C content, the more evolved the soil crust is (with lichens and cyanobacteria). Such soil crusts have better developed pore-systems with specific meso- and macropore morphologies, e.g., large, interconnected elongated and irregular pores. Biological soil crusts dominated by lichens have the largest meso-macroporosity (up to 23.65%) due to the predominance of elongated pores. In many cases, infiltration is low (46 to 57%) because the biological crusts are somewhat detached from the soil underneath, but the armouring effect decreases erosion rates (7 to 23 g m⁻² y⁻¹). Soil crust pore numbers, size and shape were useful indicators of soil quality.

Abbreviations: PSC, physical soil crust; BSC, biological soil crust; IBC, incipient biological soil crust; LC, lichen crust; CVS, crusted vegetated surface; ROI, region of interest.

INTRODUCTION

Physical and biological soil crusts (PSC and BSC, respectively) constitute the main types of soil cover in most arid and semiarid areas worldwide. Although they are an almost negligible portion of the soil profile, they play a significant role in ecosystems (Belnap et al., 2001), as they control vertical and horizontal fluxes of nutrients, water, gases and heat to and from the soil (Beymer and Klopatek, 1991; Belnap 1995; Belnap and Gillette 1998). PSCs are transient soil-surface layers (ranging in thickness from less than 1 mm to a few cm) that are structurally different from the material immediately beneath them. BSCs are a complex mosaic of cyanobacteria, green algae, lichens, mosses, microfungi, and other bacteria (Belnap et al., 2001).

Considering that arid and semiarid regions cover about 40% of the Earth's land surface (Reynolds et al., 2007), the mentioned effects on the ecosystems where soil surface crusting appears may play a crucial role in soil quality (NRCS, 1996). At present, soil quality is defined not only in terms of soil production capacity, but also in terms of stability or resilience to environmental perturbation (Hartemink, 1998; Miralles et al., 2009). However, despite the fact that soil quality has been subjected to extensive research (Singh and Tripathy, 1992; Jurgensen et al., 1996; Sahani and Behera, 2001, and references therein), most studies are carried out at humid sites and very few in arid or semiarid zones (Miralles, 2007; Miralles et al., 2009). In such zones, physical and biological crusts are especially fragile to environmental constraints (microtopographical features leading to abrupt changes in slope, orientation and exposure of soils, unpredictable rainfall, etc.) and certain human actions that lead to severe erosion and degradation (Belnap 1995; Miralles, 2007), and in general, alter soil quality. In this sense, the assessment of soil quality in crusted soils is of particular importance to forecasting the resilience of the whole ecosystem. In natural ecosystems soil crusting is a very dynamic suite of processes which can influence soil quality, but unfortunately little is known about them.

It is well known that evaluation of soil surface structure provides valuable information about physical soil quality (Dexter, 2004). Therefore, soil crusts, as a type of soil surface, should also provide such information. Some authors have evaluated soil structure by considering the complete soil profile (Dexter, 2004; Ball et al., 2007; Miralles, 2007). However, Cavalieri et al. (2008) noted that the soil structure of the surface layer can be even more crucial to soil

physical quality than other soil properties, such as texture or bulk density, and the soil just below the surface layer might also play an important role. These authors showed that the surface layers were less porous and had less macroporosity and higher soil bulk density than underlying layers. However, the saturated hydraulic conductivity and intrinsic air permeability were higher at the surface than in deeper layers (Bhattacharyya et al., 2006, Azooz and Arshad, 1996). Hence, the best conditions for gas and water exchange are found in the surface layers, where soil has a higher organic carbon content and biological activity and better structure with well-connected pores. The importance of the surface layer is especially critical in crusted soils as crusts regulate all the processes in the underlying soil. As in natural ecosystems, not all soil surface crusts behave the same in pedological and hydrological terms. It would be attractive to consider some specific properties of soil crusts and the soil immediately underneath it, e.g., porosity and pore characteristics, as indicators of soil quality.

Among the above considerations, it is also well known that soil sealing and crusting causes strong changes in the pore system of the top layer (Panini et al., 1997; Assouline and Mualem, 2000), and that transient surface seals and physical crusts strongly reduce the size and continuity of macropores (Pagliai, 1987; Panini, 1997). However, very few papers on BSCs report that such crusts have larger pore volumes (Malam-Issa, 2009; Verecchia et al., 1995). When studied by Hg intrusion porosimetry, Hg is observed to enter gradually and continuously through pores in contrast to adjacent uncrusted soil or soil with very low BSC cover (Malam-Issa, 2009). The porosity of both the crust and the soil underneath it modulates water transit through the soil, depending on the connectivity and the size of pores. Belnap (2006) showed the need to study soil crust structure and porosity to better understand their role in infiltration and erosion. However, transient surface seals and crusts on agricultural soils have been studied much more (Assouline, 2004; Lee et al., 2008; among many others) than soil crusts in natural areas.

According to Greenland (1977), 0.5 to 50- μm pores (storage pores) are a water reservoir for plants and microorganisms, and 50 to 500- μm pores (transmission pores) are important in soil–water–plant relationships and in maintaining good soil structure conditions. Pores >500 μm (fissures) are particularly useful for water infiltration and drainage in fine-textured soil (Panini et al., 1997). Luxmoore (1981) classifies pore sizes of less than 10 μm as micropores, from 10 to 1000 μm as mesopores and above 1000 μm as macropores with functions similar to those above. However, these pore functions are related not only to their

size but also to their shape and connectivity, as round unconnected pores are less effective in transmitting water than connected, irregular and elongated pores (Panini et al., 1997; Valentin, 1991; Fox et al., 2004). In this sense, the detailed quantification of the size, shape and connectivity of pores could allow precise soil water movement modelling (Bouma, 1981; Germann and Beven, 1981; Douglas, 1986; Pagliai et al., 2004) and would thus provide useful information about soil infiltration processes (Valentin and Bresson, 1992).

Several authors (Casenave and Valentin, 1989 and 1992; Dexter, 2002; Fox et al., 2004) have also shown that soils with poor physical quality characterized by lack of structure or poor structure with less favourable pore types, i.e., small disconnected rounded pores, contribute to low water infiltration capacity, high runoff and poor aeration and rootability.

Even though the important role of the soil surface pore system in water flow, infiltration and erosion is well known, there is still little information about the porosity of soil crusts, especially for BSCs, which have been quantitatively investigated in only a few cases (Edwards et al, 1988; Malam Issa et al., 2009; Papadopoulos et al, 2009; VandenBygaart et al., 2000; Verrecchia et al., 1995). In some of those papers, and in other more general papers on crust formation, crust micromorphology¹ is also described (Arshad and Mermut, 1988; Onofriok and Singer, 1984; Wakindiki and Ben-Hur, 2002). Given that pore size distribution, shape, and continuity have been found to be good indicators of soil physical quality (Pagliai and Vignozzi, 2002; Pagliai et al., 2004; Papadopoulos et al, 2009), assessment of 2D-porosity³ by soil micromorphology¹ and soil micromorphometry² (in the sense given by Ferrari and Pagliai, 1980) has been used for physical soil characterisation (Papadopoulos et al., 2009; Protz and VandenBygaart, 1988; Rossi and Graham, 2009), soil management (Pagliai and Guidi, 1985; Pagliai et al., 2004; Grieve et al., 2005; Mooney and Morris, 2008; among others), characterising soil crusts, and understanding crust formation and its hydrological implications (Arshad and Mermut, 1988; Bresson and Boiffin, 1990; Valentin and Bresson, 1992; Wackindiki and Ben-Hur, 2002).

The use of 2D-porosity to assess the effects of soil crusts on soil quality is a new approach not yet developed. In this paper, the hypothesis tested is that the amount, shape, size and area of pores can be used as indicators of soil quality in natural crusted soils in semiarid areas. Better soil quality should be associated with evolved BSCs with high porosities and well-connected

pores. Worse soil quality should be associated with either physical soil crusts or incipient biological crusts with low porosities and small, unconnected pores. The aims of this research are to describe and quantify the 2D-porosity of soil crusts in a semiarid ecosystem where crusts are the most important soil cover and to ascertain whether the characteristics of 2-D porosity of both soil crusts and the soil immediately beneath can be used as indicators of quality for natural crusted soils.

¹ Micromorphology = suite of methods and techniques for the study of undisturbed soils in thin sections by optical microscopy (Kubiena, 1938). Modern micromorphological techniques also include electron microscopy (SEM, TEM), coupled or not coupled to X-ray diffraction, and many types of microprobes.

² Micromorphometry = with reference to soil is the measurement of microscopic features (particles, aggregates, pores, etc.).

³ 2-D porosity = number, size, area and shape of pores in two dimensions of a material assessed either in thin sections or polished blocks, essentially by image analysis techniques.

MATERIALS AND METHODS

Site description

The study area is the Tabernas Desert, in the Sorbas–Tabernas basin, in the Province of Almería (SE Spain), surrounded by the Gador, Nevada, Filabres and Alhamilla Mountain Ranges in the Betic Chain (Figure 1). The basin fill is mainly soft Miocene, mostly gypsum-calcareous mudstone and calcareous sandstone (Cantón et al., 2001a), which, along with the Quaternary tectonics and the dry climate, have produced an extensive stepped landscape of multiple-age badlands separated by dissected pediment surfaces (Alexander et al., 1994). The climate is semiarid thermo-Mediterranean (Lázaro and Rey, 1990) with long, dry summers. The average annual temperature is 17.9°C, with an absolute maximum of 45°C, absolute minimum of −4.5°C, and a mean annual rainfall of 235 mm, mostly in winter. Annual potential evapotranspiration is around 1500 mm, indicating a considerable annual water deficit (Cantón et al., 2001b). The landscape is formed by asymmetric SE-NW valleys, where NE-facing slopes with gradients of nearly 30° are carpeted by Endoleptic Regosols (FAO, 1998) or Lithic–xeric Torriorthent (Soil Taxonomy, 1999), mainly covered by lichen crusts (essentially *Diploschistes diacapsis*, *Squamarina lentigera* and *Fulgensia fulgida*). At the pediment, on gentle slope gradients, soils are thicker and formed by Haplic Calcisol (FAO,

1998) or Xeric Haplocalcid (Soil Taxonomy, 1999) and covered by scattered perennial plants (with predominance of *Helianthemum almeriense*, *Hammada articulata*, *Artemisia barrelieri*, *Salsola genistoides*) with BSCs in open areas and patches of annual plants (predominated by *Stipa capensis*). SW-facing slopes are steeper (slope gradients up to 70°), with poorly developed soils, Epileptic Regosols (FAO, 1998) or Lithic Torriorthent (Soil Taxonomy, 1999), bare with PSCs or scarcely covered by lichens or annual plants (Cantón et al., 2003).

Soil crust characteristics

Cantón et al. (2004) had previously identified the main ground-cover types in the study site and demonstrated that their spatial distribution is strongly controlled by topography. The main soil crusts taken from those ground-cover types were defined as belonging to three different landforms and to five different soil units. The three landforms are: A) Hillslopes oriented S to W and covered with PSCs or with incipient biological crusts (IBCs), both types covering 38.5% of the total study area, though IBC are less abundant, representing only 5 to 10%; B) Top of N to E-facing slopes covered with well-developed LC interspersed with a few shrubs in a landform representing 19.2% of the total area, and C) Bottom of pediments and other open areas, dominated by scattered dwarf shrubs and/or annual plants interspersed with BSCs, covering 42.5% of the area. Therefore, all together, soil crusts cover more than 75% of the soil surface in the study area.

All the above soil crusts cover five different soil units in different stages of soil development (Cantón et al., 2003), and with different hydrological and erosion behaviour. However, as this paper focuses on crusted soils developed on gypsum-calcareous mudstone, the crusts from one of the soil units, which is developed on a mixed colluvial material (sandstone and mudstone), is not included, because its formation is affected by the sandstone.

The soil crusts in this study are described below, giving type of soil and crust:

1. PSC: physical soil crust. A mostly structural crust (Valentin and Bresson, 1992) covering Epileptic Regosols (Lithic Torriorthents) usually found on slopes with gradients of over 40°, and sometimes on slope gradients of less than 30°. It can also appear on SW pediments as a depositional crust (Valentin and Bresson, 1992) from a few millimetres to over 5-cm thick formed by silty micro-layers.
2. IBC: incipient biological crust, mostly dominated by cyanobacteria and pioneer lichens (*Verrucaris cf. obductilis* and *Psorotichia sp.*). It covers Epileptic Regosols (Lithic Torriorthents) when the soil is sufficiently stable (slope gradients between 30° and 40°).

3. LC: lichen crusts, subdivided in two main types: LC1, formed by *Diploschistes diacapsis*, *Squamarina lentigera*, *Buellia zoharyi* and *Buellia epigaea* as the most abundant species, carpeting about 80% of the surface along with a sparse cover of annual and perennial plants over Endoleptic Regosols (Lithic-xeric Torriorthents) in areas with slope gradients averaging 29°, with little soil development; b) LC2, formed by *Diploschistes diacapsis*, *Squamarina lentigera* and *Fulgensia fulgida*, non-lichen BSCs and scattered annual and perennial plants over Eutric Gypsisols (Lithic Haplogypsisols), essentially in divides, on slope gradients < 20° with a convex curvature, with quite small contributing areas (they receive water only from direct precipitation).

4. CVS: crusted vegetated surface. They cover open areas dominated by scattered dwarf shrubs and/or annual plants on Haplic Calcisols (Xeric Haplocalcid). These crusts are mostly cryptogamic, formed by cyanobacteria, mosses and lichens. They are also subdivided in two types: a) CVS1: thin cryptogamic and/or physical crusts in the spaces between shrubs and scarce annual plants on moderate slope gradients (average 21°), with relatively high infiltration and little erosion. These soil crusts are found over usually thicker and better developed soils than the other soil crusts; b) CVS2: thin cryptogamic crust developed over a physical crust, in areas with annual plants where the average slope gradient is 17°.

Soil surface sampling and physicochemical properties

Though soil surface crusts are *sensus strictus* only the surface layer of the soil, their relationship with the soil underneath is of paramount importance, and therefore, in the following sections, the term *soil crust* will be used in a wider sense to also include the soil immediately underneath (0-3cm).

For physicochemical analysis, four bulk soil samples were collected from 0 to 3-cm in each of the six soil units (PSC, IBC, LC1, LC2, CVS1, CVS2) at the beginning of the dry season.

For both soil micromorphology and micromorphometry, two undisturbed, vertical samples were taken from 0 to 5-cm in every soil unit with Kubiena boxes (10 x 7 x 5 cm) carefully pressing them against the ground with a flat rigid plate kept parallel to the soil surface, assuming that there was no internal disturbance if no cracks appeared on the surface crust during sampling.

Bulk soil samples were air-dried, gently crushed and passed through a 2-mm sieve to remove coarse fragments.

Particle-size distribution was by the French standard (AFNOR NF X 31-107 in Legros, 2007), where 5 grain fractions are considered, coarse sand (2 – 0.2 mm), fine sand (0.2 – 0.05 mm), coarse silt (0.05 – 0.02 mm), fine silt (0.02 to 0.002 mm) and clay (<0.002 mm), determined by sieving (fractions > 0.05 mm) and sedimentation by the pipette method (fractions < 0.05 mm) (Gee and Bauder, 1986). The following pretreatments were applied: a) removal of organic matter with 30% H₂O₂, b) sulphate leaching with distilled water, c) removal of carbonates with 1 M NaOAC at pH5, and d) dispersion by shaking the sample in 10 mL of 40% sodium hexametaphosphate. The total organic C (TOC) content was determined by the Nelson and Sommers (1982) method. Water content (WC), at two different tensions, -33 kPa and -1500 kPa, was calculated using pressure-plates on repacked, sieved fine earth samples (all samples treated the same to homogenize bulk density as much as possible, necessary for valid results according to Elrik & Tanner, 1955). The calcium carbonate equivalent was found by rapid titration (Puri, 1930). Soil pH was measured in the saturation extract, and total gypsum by precipitation with BaCl₂ (Porta, 1998). Soluble Ca²⁺, Mg²⁺, Na⁺, and K⁺ in the saturation extract were measured by atomic absorption spectrophotometry and SO₄²⁻ by ion chromatography.

Micromorphology

Undisturbed soil samples were air dried at room temperature, and then impregnated under vacuum with an unsaturated polyester resin, in which a fluorescent dye (UVITEX-OB) was added, using high-grade acetone as a thinner (Murphy, 1986). After resin polymerization, i.e., hardening, the oriented blocks were cut perpendicular to the soil surface, into 1-cm-thick vertical slices with a diamond disk saw, yielding 5x10-cm sections. All faces were polished by SiC grit paper on a grinding wheel. A thin section was made from one slice of each block. Micromorphological descriptions followed the terminology proposed by Bullock et al (1985). 2-D pores were assessed from high-contrast photographs of vertical polished blocks where only the resin-filled pores appeared when illuminated with UV light (Torrentó and Solé-Benet, 1992). Then the photographs were scanned and analyzed at a resolution of 30.3 µm per pixel in a Leica Quantimet-570 image analysis system following the method of Pagliai et al. (1983). Automatic thresholding was employed as the contrasted photographs satisfactorily separated the soil from the pore phase. Results with this analytical system have been proven comparable to more recent image analysis systems used in other 2-D porosity studies, e.g., Josa et al., 2010. In every photograph, two 15.5-mm x 15.5-mm regions of interest (ROI) near the soil surface and four ROIs per block were analysed and the data averaged. As the pixel

size was 30.3 μm , the minimum visible pore was this size or larger, and consequently only mesopores $> 50 \mu\text{m}$ and macropores (Luxmoore et al, 1990), could be measured.

Meso-macropores were counted and measured in every ROI examined. The following variables were calculated in every ROI, which was always 2.4025 cm^2 : a) number of meso-macropores per cm^2 or NP (number of macropores in every ROI divided by its surface), b) meso-macroporosity or AP (area occupied by meso-macropores divided by the total ROI area, in percentage), c) pore shape in three classes according to the form factor calculated for every pore as $\text{Area}/(\text{Perimeter})^2$. When the form factor was above 0.04, the pores were labelled as *rounded*, between 0.015 and 0.04 *irregular*, and below 0.015 *elongated* (Bouma, 1977). Moreover, each pore shape class was then subdivided into eight size classes ($< 100 \mu\text{m}$, 100-200 μm , 200-300 μm , 300-400 μm , 400-500 μm , 500-1000 μm , 1000-1500 μm , 1500-2000 μm , and $> 2000 \mu\text{m}$) which were grouped in three classes for the statistical analyses ($< 100 \mu\text{m}$, 100 to 1000 μm , $> 1000 \mu\text{m}$). The $< 100\text{-}\mu\text{m}$ class was not included in the shape analysis because the shape of pores containing fewer than 9-10 pixels is uncertain. Total NP and total AP were measured for each sample (slices from blocks) as well as by shape and size class.

Hydrological properties

Soil crust response to natural rainfall was examined using 0.24 m^2 bounded circular runoff plots (with no upslope run-on). The plots were connected to 50-L tanks, where total runoff and sediment yield were sampled after each rainfall event during three complete hydrological years (from October to September of the following year). Three plots were available for each soil crust type, except for CSV2 with only two plots. The plots were adjacent to the soil crusts sampled for this study. Rainfall data were provided by the meteorological station at the experimental field site (Cantón et al., 2001b). The variables available were mean annual infiltration coefficient (ratio of infiltration rate (mm) to rainfall (mm)) and mean annual sediment yield for the 3-year monitoring period. Maximum and minimum infiltration coefficients per event were also available to explain specific infiltration behaviour.

Statistics

Physicochemical parameters, NP and AP from all soil crusts were first processed statistically to find out if there were significant differences among soil crust types. Therefore, after testing for normality and performing a one-way ANOVA, a Fisher's LSD as Multiple Range Test was done to check for significant differences among soil crusts. The various soil crusts were

taken as classification variables and the physicochemical soil properties and pore characteristics (NP and AP, subdivided by their respective shape and size classes) as response variables. A further discriminant analysis allowed reducing all the studied crusts into a small number of crust groups with similar properties. All physicochemical parameter means were also tested for their Pearson's correlation with pore variables (NP and AP) to find any significant relationships between these two groups of variables. All statistical analyses were performed using Statgraphics Plus v.5.1 for Windows (2001) and Statistica v.6.0 (2001).

RESULTS

Physical and chemical properties of soil crusts

For all surfaces tested, silt (coarse plus fine) was the most abundant fraction (Table 1), followed by fine sand and clay.

WC at -33 kPa ranges from 22.2 to 30.5 kg kg⁻¹ and WC at -1500 kPa from 7 to 10.9 kg kg⁻¹, though there are no significant differences among the soil crusts. All soil crusts show a slightly alkaline pH ranging from 7.62 to 7.80, without significant differences.

PSC and IBC had the lowest organic carbon content of all the soil crusts studied (Table 1). In general, these soil crusts have a weak structure. They also have the highest water content (WC) at -1500 kPa, numerically, though not statistically (Table 1), due to their high gypsum content, as described by Eswaran and Zi-Tong (1991). Both soil crusts are also high in calcium carbonate content (242.7 g kg⁻¹ in PSC and 213.3 g kg⁻¹ in IBC). Mg⁺², Na⁺, K⁺ and SO₄⁻² content are also the highest in IBC and PSC, while the Ca⁺² ion is more abundant in CVS1, CVS2 and LC1 (Table 1).

CVS1 and CVS2 have more organic matter content than the rest of the soil surfaces, ranging from 16.1 g kg⁻¹ to 19.0 g kg⁻¹ with well-developed soil structures. LC1 and LC2 both have higher organic carbon content (Table 1) than PSC and IBC, though somewhat higher in LC2, which has better soil structure and development, than LC1. Fine silt and clay are the most abundant particles in LC1 and LC2, and WC at -1500 kPa and -33 kPa, respectively, are also similar in both, (Table 1). Calcium carbonate content is less abundant in LC2 than in the rest of soil surfaces, only 164.9 g kg⁻¹, though statistically similar to CVS1.

Description and quantification of pore characteristics

Thin sections permitted observation of the overall soil microstructure in the different soil crusts (Fig 2). PSC is formed by a structural crust (Valentin and Bresson, 1992) over a very well developed depositional one (Valentin and Bresson, 1992). A dense layer formed by fine mineral particles with some small, unconnected vesicles and some cracks at the top can be observed as well as layering of fine particles and vesicles below the surface. IBC is an incipient biological crust near the bottom of a SW-oriented slope. It is formed by discontinuous biological elements over a physical, structural crust. The crusts itself is quite massive but just below there are many rounded unconnected pores and a few irregular and elongated pores, larger in size and poorly connected. LC1 is from a NE-oriented slope. The lichen is mostly detached from the soil beneath, leaving large elongated pores parallel to the soil surface. Below the crust, the soil fabric is very porous with some large, well-interconnected irregular and elongated pores and rounded unconnected pores. LC2 is a lichen crust from a divide. The lichen is somewhat detached from the soil beneath it but not as much as in LC1. Interconnected irregular and elongated pores can be observed along with many unconnected rounded pores. CVS1, from the middle of NE-oriented slopes (pediment), formed over a well developed soil structure. Its fabric is highly porous with many large, interconnected rounded, elongated and irregular pores. CVS2, a mixed soil-crust type from the lower part of pediments, formed over a medium-grade soil structure. It contains many large, interconnected rounded, elongated and irregular pores (Fig 2).

<Insert Figure 2 here>

IBC and PSC soil crusts have the lowest number of pores per cm² (131 and 133, respectively), while CVS1 has the highest (367) (Table 2). By shape, most pores in all soil crusts are rounded, then irregular and least frequently elongated.

AP also follows a similar trend with PSC and IBC (4.22% and 3.45%, respectively), having the lowest AP of all soil crusts (Table 3). The areas of the different pore shapes are not evenly distributed in these soil crusts. In PSC, most rounded pores are small ($<300\text{ }\mu\text{m}$) as shown in Fig 3a.

LC2 has an intermediate NP (Table 2) though its AP (Table 3) is one of the largest of all soil crust types (23%) along with LC1 (24%). The number of pores with different shapes in these crusts is unevenly distributed following a decreasing sequence: rounded pores $>$ irregular pores $>$ elongated pores. The area from different pore shapes is also unevenly distributed (Fig 3b) but follows an increasing sequence: rounded pores $<$ irregular pores $<$ elongated pores.

AP in CVS1 and CVC2 is quite evenly distributed among the 3 pore shapes (Table 3). All crusts have the most pores in the 100-1000- μm range and very few over 1000 μm . Moreover, AP is quite evenly distributed among the three pore shapes in the 100 to 1000- μm range in the different subranges (Fig 3c) in contrast to LC1 soil crust, where most of the AP is in the 400-1000 μm range and mainly elongated pores (Fig 3b).

The highest number of $> 1000\text{-}\mu\text{m}$ pores is irregular, and found in LC1 and CVS2 soil crusts (2.1 and 1.6 respectively). AP is also dominant in the 100-1000 μm range. Irregular pores with the largest area, $> 1000\text{ }\mu\text{m}$, are found in soil crusts CVS2, LC1, and LC2, but the largest elongated pores are found only in LC1.

<Insert Figure 3 here>

Relationships between physicochemical properties and 2-D porosity

Many significant Pearson's correlations were observed between physicochemical properties and 2-D porosity characteristics (Table 4). Properties positively correlated are TOC and coarse silt (Table 4). In contrast, properties negatively correlated with 2-D porosity are coarse sand, gypsum, Ca^{2+} , K^{+} and SO_4^{2-} , which usually do not favour good soil structure (Table 4). Specific pore shapes and sizes show particular relationships with physicochemical parameters. The number of pores of any size and pore shape is positively correlated with TOC. However, only the largest AP of irregular pores is positively correlated with TOC. AP between 100 and 1000 μm , of any shape, is negatively correlated with coarse sand.

Differences among soil crust types and further grouping

The results of ANOVA and further Multiple Range Tests are presented in Tables 1, 2 and 3.

In general there are few significant differences between PSC and IBC soil crusts (only coarse sand and gypsum content are significantly different). However, these soil crusts show significant differences with the rest of soil crusts (LC1, LC2, CVS1 and CVS2). These differences refer to some physicochemical variables (TOC, CaCO_3 , Ca^{2+} , Na^+ , SO_4^{2-} from Table 1) and to some NP and AP variables (e.g. AP, AEP and AEP 100-1000 μm from Table 3).

Similarly there are few significant differences between LC1 and LC2 (only CaCO_3 and Na^+ show significant differences) but some significant differences between these two soil crusts and PSC, IBC, CVS, and CVS2 (Tables 1, 2, 3).

CVS1 and CVS2 also showed numerical differences with PSC, IBC, LC1 and LC2 in most of the variables (Tables 1, 2 and 3) but they only differ significantly ($P < 0.05$) in AP, AEP and AEP 100-1000 μm (Table 3).

Consequently, it would be possible to gather the six soil crusts into 3 groups, each one with some similar physico-chemical properties and some similar 2-D pore characteristics (NP and AP). Group 1 will gather PSC and IBC; Group 2, LC1 and LC2; and Group 3, CVS1 and CVS2. In order to test the validity of such grouping, a factorial discriminant analysis was performed. The three groups of soil crusts were considered as classification factors and the physicochemical properties showing significant differences among crust groups (Table 1) and AP properties (Table 3) as independent variables. Fig 4 shows the corresponding scatter diagram where the three predefined groups were clearly differentiated with 100% of the cases correctly classified.

Hydrological behaviour of the soil crusts

Average annual infiltration coefficients for the six soil crust types ranged from 63.3% to 78%, though without noticeable differences. This might be because annual averages also included many small rainfall events which did not produce any runoff or yielded negligible volumes. However, the differences among soil crusts became noticeable (Table 5) for rainfall events with intensities over 30 mm/h, when infiltration coefficients ranged from 47.3% to 86% (Table 5, event 1). The highest infiltration was recorded in CSV crusts and the lowest in PSC. Under low rainfall intensities, the behaviour of the different soil crusts tended to be homogeneous, as it was more dependent on soil matrix behaviour than the crust. However, under high rainfall intensities soil crusts and their specific morphologies behave differently. PSC behaved as seals in which unconnected rounded pores, mostly vesicles, drastically reduced infiltration capacity. IBC, as an intermediate type between physical and biological

soil crust, had an intermediate behaviour. LC1 may behave differently depending on how close lichen contact with the substrate is. When close contact is predominant, infiltration can be high as in LC2, whereas, when lichens are mostly detached from the substrate, they act as roofs, preventing infiltration and enhancing runoff. CSV soil crusts are usually found on soils with higher OC content, and consequently soil structure, and thereby infiltration, is better.

DISCUSSION

The statistical analysis based on ANOVA and Multiple Range Tests (Tables 1, 2, 3) showed that three groups of soils crusts were possible based on the physico-chemical and 2-D porosity similarities and differences between pairs of soil crusts. These 3 groups were also confirmed by discriminant analysis (Figure 4) where the three groups of soil crusts were considered as discriminant factors, showing that soil-crusts groups were correctly classified.

These groups of soil crusts could therefore be associated with comparatively distinct soil properties and hydrological behaviour.

In the following section, these three different groups and their 2-D porosity characteristics are explained with their physicochemical properties in order to verify the hypothesis that 2D-pore characteristics (based on amount, shape, size, and area occupied by pores) can be used as indicators of soil quality in crusted, natural soils from semiarid regions.

Group 1, formed by soil crusts PSC and IBC, has the lowest total porosity of the three groups, both in number of pores (NP) and meso-macroporosity (AP). The most abundant are 100 to 1000 μm rounded pores (Table 2). Most of these are vesicles (Fig 2) which are usually formed by splash as reported by other authors (Moore and Singer, 1990; Zhan and Miller, 1996; Bajracharya and Lal, 1998). These soil crusts hardly have any intermediate or large pores, a fact attributed to their breaking up into smaller rounded pores under the compacting effect of raindrops, as suggested by Fox et al (2004). The comparatively high fine silt content and low organic matter of these soil crusts (Table 1) seem to contribute to a massive structure with a denser low-porosity layer. The higher coarse sand content could also contribute to a decrease in aggregate stability due to the larger grain size and the lower reactivity of sand grains (Table 4 shows the negative correlations between coarse sand and the area occupied by pores, especially rounded and elongated pores, mostly between 100 and 1000 μm). The high carbonate and gypsum content, which could act as the key binding agent in these soils, seems to have a negative effect on their porosity, as suggested by the negative correlations between

gypsum, SO_4^{2-} and Ca^{2+} content and several porosity variables (Table 4). Miralles et al. (2009) also found that soils with high calcium carbonate and/or other simple salts, though belonging to another semiarid Mediterranean environment in SE Spain, had lower total porosity.

The Group 1 pore system may explain the low infiltration rate in such soil, especially under rain of moderate to high intensity, and its concurrent high erosion rate (Table 5), as shown in previous papers in the same area (Solé-Benet et al., 1997; Cantón et al., 2001b; Cantón et al., 2002). As explained by Valentin (1991), small rounded pores are less effective in transmitting water than irregular and elongated pores, because by Poiseuille's Law, water flow is extremely sensitive to pore diameter. Therefore, low infiltrability is not only due to the lower total porosity of the soil crusts, but also to a particular distribution of pore shapes and sizes. As shown in Table 5, the differences from the rest of the soil crusts are especially pronounced for intense rainfalls at event scale, although annual differences are smaller due to the effect of frequent small rains that generate negligible runoff regardless of the soil crusts. Cantón et al (2001a) found a rainfall threshold of about 3 mm was required to produce runoff at the plot scale and rainfall of less than 3 mm represents 67% of annual rainfall at this site (Cantón et al., 2001b). When these light rains start to fall after a dry period, the added effect of very frequent vertical cracks contributes significantly to total infiltration (Table 5). However, with heavy rainfall, these cracks are quickly sealed as soil gets wet, decreasing the infiltration rate again, as found by Li et al., (2005) and Solé-Benet et al., (1997) in similar soil crusts at this site.

Group 2, formed by soil crusts LC1 and LC2, has the highest AP (up to 23.65%) of the three groups, though NP (193 to 291) is similar to *Group 3*. The higher AP in these soil crusts is mostly due to the predominance of elongated, interconnected pores (Table 3), a large part of which are between the detached lichen and the substrate underneath it (Fig 2). This pore system, with higher AP than *Groups 1* and *3*, does not connect the surface with the soil underneath and therefore does not favour infiltration. However, in spite of this enhanced runoff, the armouring effect of lichens decreases erosion rates (Table 5). Several studies have shown how trapping and binding by the living filaments of microorganisms forming BSCs, favour soil particle aggregation and provide soil cohesion (Cameron and Devaney, 1970; Belnap and Gardner, 1993; Cantón et al., 2004; Malam Issa et al., 2009). This cohesion stabilizes soil against water erosion.

Group 3 (CVS1-CVS2), shows a 2-D porosity pattern similar to the one in *Group 2* (Figure 2). Their well-developed structure may be attributed to the fact that they have the highest organic matter content from abundant annual plants, shrubs and inter-shrub BSCs, and also the highest fine sand and coarse silt content (Table 1). It also has the highest total number of pores with a large number of rounded pores of various diameters and large interconnected irregular and elongated pores (Figure 2). Rounded pores of all sizes up to 1000- μm diameter are also quite evenly distributed in *Group 3* (Fig 3c), where much larger rounded pores may be observed than in Groups 1 and 2 (Fig 3). In addition to the hypothesis on rounded pore formation (purely mechanical), rounded, irregular and elongated pores might also be due to biological activity linked to biological crusts (lichens, cyanobacteria and other microbiotic organisms), as described elsewhere by other authors like Stanier and Cohen-Bazire (1977), Decho (1990), Kidron et al.(1999). According to Malam Issa et al. (2009), some of these types of pores could be caused by bacterial filaments, hydrophilic polymers (polysaccharides) and hydrophobic (glycoproteins and lipopolysaccharides) molecules in microbiotic crusts. Both hydrophilic and hydrophobic components confer adhesive properties that make filaments able to adhere to and bind soil particles, thereby affecting the soil's spatial organisation. Furthermore, large rounded and elongated pores are also more frequent and occupy larger areas in this group, especially in CVS2, than in the rest of the soil crusts, which may be mainly due to the action of very fine roots from annual plants and even to soil mesofauna (earthworms and arthropods) that build galleries or tunnels.

As in *Group 2*, size, shape and connectivity of pores in *Group 3* may affect water flow through the soil. In fact, CVS1 and CVS2 did show higher infiltration rates than LC1, PSC or IBC (Table 5). Nevertheless, despite the lower infiltration rates in LC1, soil crusts with microbiotic cover play an important role in the conservation and improvement of soil properties. Hence, BSCs have a direct impact on soil erosion reduction and favour soil water retention/transit, and their role is therefore crucial in Mediterranean arid and semiarid regions, where according to the International Union of Soil Scientists (IUSS), Commission VIII "Soil and the Environment", one of the main environmental problems is the threat of progressive desertification due to erosion and water deficit in soils (Sánchez-Marañón et al., 2002; Miralles, 2007). Moreover, keeping in mind that BSCs increase available nutrients in the soil by concentrating essential elements, such as nitrogen and carbon (Harper and Pendleton, 1993), their abundance and distribution could serve as soil quality indicators, especially in the more fragile ecosystems where human or environmental disturbances are common, as in many arid and semiarid zones.

CONCLUSIONS

Soil micromorphology and micromorphometry of meso- and macropores have proven to be reliable methodology suites for differentiating soil crusts in a semiarid rangeland. Soil crusts associated with different physicochemical soil properties in the upper centimetres of soils are related to different degrees of soil development. Infiltration and soil erosion behave differently in the various crust types and the soil underneath them, and therefore the soil quality also differs. The significant statistical relationships among physicochemical properties with 2-D porosity of soil crusts, suggests that 2-D pore properties can be used as soil quality indicators in such environments.

High organic C content are associated to biological soil crusts and pore-systems with large, interconnected, elongated and irregular pores. On the contrary, physical crusts and incipient biological crusts have meso-macropore systems with few small unconnected rounded pores. The low infiltrability of these physical and incipient biological crusts is not only due to the lower total porosity, but also to the particular distribution of pore shapes and sizes.

However, the soil crusts with the highest meso-macroporosity are not always associated to the most developed soils. Such soil crusts, e.g. crustose lichens, are often detached to the soil beneath and, while providing the highest meso-macroporosity, such pore system does not connect the surface with the soil and does not favour infiltration.

Therefore, the number of pores, pore size, shape and area of soil crusts could be considered useful indicators of soil quality. However, to extrapolate this to a wider range of soil crusts, a much larger and more comprehensive range of soil surface crusts should be analyzed.

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Figure captions

Figure 1: Map showing geographic location of the study area with the different crusted soil surfaces in SE-NW-oriented valleys. Legend: PSC = physical soil crust; IBC = incipient biological crust; LC = lichen crust; CVS = mixed crusted surface.

Figure 2: Photographs of thin sections of the crusted soil surfaces in the study area, where the general soil structure can be observed in plain light: **a)** Physical soil crust, PSC, formed by a structural crust over a very well-developed depositional one. Observe a dense layer formed by fine mineral particles (FP) with some small disconnected rounded pores (vesicles V) and cracks (C) at the top, and layered fine particles (LP) and vesicles below the surface. **b)** View of an incipient biological crust (IBC) near the bottom of a SW-oriented slope with many rounded unconnected pores (vesicles V) in the upper part and few irregular (I) pores in the middle part. **c)** Lichen crust, LC1, from a NE-oriented slope. Lichen (LC) is mostly detached from the soil beneath it; large elongated (E) pores quite connected and few rounded pores (V). **d)** Lichen crust, LC2, from a divide; the lichen is somewhat detached from the soil beneath it; as in LC1, interconnected irregular (I) and elongated (E) pores can be observed. **e)** Mixed crusted surface, CVS1, formed by mosses, lichens and cyanobacteria, from the middle of NE-oriented slopes (pediment) over a well-developed soil structure. The fabric is highly porous with many large, interconnected, elongated (E) and irregular pores. **f)** Mixed crusted surface, CVS2, formed by lichens (LC), mosses and cyanobacteria, from the bottom of pediments over a medium-grade soil structure; some large and fine interconnected, elongated (E) pores can be observed and some rounded unconnected pores (R). The black bars are 10 mm in all photographs.

Figure 3: Relative percentages of AP (area of meso-macropores) considering shape and size (between 100 and 1000 μm) for PSC (3a), LC1 (3b) and CSV1 (3c) soil crusts.

Figure 4: Scatter diagram from the discriminant analysis with the 3 groups of soil crusts as classification factors. Independent variables were TOC, coarse sand, gypsum, ARP 100-1000 μm , ARP > 1000 μm , AIP 100-1000 μm , AIP > 1000 μm . 100% cases correctly classified. $P = 0.0000$ for both function 1 and function 2.

Figure 1

Figure 2

a

b

c

d

e

f

Figure 3

Figure 4

Table 1.- Mean and standard error values of physico-chemical soil parameters as indicators for every soil crust ([†]), one way ANOVA (*P* significance) and LSD Fisher test (differences among soil crusts).

Indicators [‡]	<i>P</i>	Mean ± standard error for each soil crust					
		PSC [†]	IBC [†]	LC1 [†]	LC2 [†]	CVS1 [†]	CVS2 [†]
Coarse sand (g kg ⁻¹)	0.001	60.9 ± 8.8a	37.3 ± 14.4b	16.2 ± 6.4c	21.0 ± 9.5bc	12.7 ± 4.4c	18.4 ± 2.1bc
Fine sand (g kg ⁻¹)	0.184	199.0 ± 21.0a	190.6 ± 38.5a	198.7 ± 16.1a	341.9 ± 150.2 a	301.5 ± 21.3a	242.6 ± 33.3a
Coarse silt (g kg ⁻¹)	0.493	168.2 ± 12a	172.2 ± 15a	181.3 ± 6.4a	163.5 ± 37.5a	196.0 ± 11.5a	188.8 ± 22.7a
Fine silt (g kg ⁻¹)	0.140	411.5 ± 21a	411.2 ± 33.9a	408.1 ± 19.6a	315.2 ± 86.3a	340.9 ± 15.7a	379.4 ± 42.1a
Clay (g kg ⁻¹)	0.181	160.4 ± 14a	188.8 ± 23.1a	195.7 ± 3.1a	158.4 ± 37.5a	148.8 ± 14.4a	170.9 ± 15.8a
WC (-33 kPa)	0.184	22.2 ± 1.9a	25.9 ± 2.1a	26.4 ± 0.5a	27.0 ± 5.7a	30.5 ± 2.1a	26.1 ± 1.9a
WC (-1500 kPa)	0.159	10.9 ± 1.3a	8.5 ± 0.6a	7.9 ± 1.2a	7.8 ± 2.4a	7.0 ± 0.6a	8.3 ± 0.7a
TOC (g kg ⁻¹)	0.000	9.5 ± 4bcd	7.1 ± 0.8d	11.5 ± 1.7bc	12.9 ± 1.8b	16.1 ± 1.7ab	19.0 ± 1.6a
CaCO ₃ (g kg ⁻¹)	0.025	242.7 ± 22.1a	213.3 ± 17.5a	232.0 ± 14.3a	164.9 ± 23.2b	202.6 ± 20.6ab	223.4 ± 19.4a
Gypsum (g kg ⁻¹)	0.000	243.5 ± 41a	105.6 ± 14.1b	53.9 ± 30.7bc	64.4 ± 76.5bc	1.9 ± 0.7c	17.0 ± 9c
pH	0.849	7.6 ± 0.9a	7.6 ± 0.1a	7.6 ± 0.2a	7.8 ± 0.1a	7.7 ± 0.1a	7.7 ± 0.4a
Ca ²⁺ (cmol kg ⁻¹)	0.062	0.61 ± 0.1ab	1.07 ± 0.23a	0.54 ± 0.18b	0.52 ± 0.28b	0.60 ± 0.16b	0.27 ± 0.03b
Mg ²⁺ (cmol kg ⁻¹)	0.717	0.17 ± 0.1a	0.29 ± 0.07a	0.22 ± 0.07a	0.08 ± 0.03a	0.61 ± 0.6a	0.09 ± 0.02a
Na ⁺ (cmol kg ⁻¹)	0.038	0.09 ± 0.01a	0.08 ± 0.04ab	0.07 ± 0.02ab	0.03 ± 0.01bc	0.05 ± 0.02b	0.04 ± 0.02b
K ⁺ (cmol kg ⁻¹)	0.248	0.04 ± 0.01a	0.04 ± 0.01a	0.03 ± 0.01a	0.02 ± 0.00a	0.04 ± 0.01a	0.03 ± 0.01a
SO ₄ ²⁻ (cmol kg ⁻¹)	0.070	0.20 ± 0.1a	0.19 ± 0.06a	0.08 ± 0.04ab	0.05 ± 0.05b	0.11 ± 0.07ab	0.05 ± 0.01b

[†]PSC: physical soil crust; IBC: incipient biological crust; LC: lichen crust; CVS: crusted vegetated surface.

[‡]WC: water content (kg kg⁻¹); TOC: total organic carbon; soil separates explained in the methods section.

Significant (*p* < 0.05) differences after Fisher LSD are indicated by different letters within rows.

Table 2.- Mean and standard error values of the number of pores per cm² (rounded, irregular and elongated), as indicators for every soil crust ([†]), one way ANOVA (*P* significance) and LSD Fisher test (differences among soil crusts).

Indicators [‡]	<i>P</i>	Mean ± standard error for each soil crust					
		PSC [†]	IBC [†]	LC1 [†]	LC2 [†]	CVS1 [†]	CVS2 [†]
NP (all pores)	0.037	133.3±7.1b	131.1±22.3bc	291.4±82.3ab	193.0±14.6b	367.1±76.4a	232.4±93.2abc
NRP (all pores)	0.027	90.0±3.5bc	113.6±22.8b	235.4±116.3ab	149.3±16.8b	304.4±116.0a	186.7±69.7abc
NIP (all pores)	0.089	37.1±2.9ab	15.5 ± 6.8b	49.3±23.9a	34.9±6.6ab	56.8±18.6a	40.1±20.8ab
NEP (all pores)	0.216	6.3±0.6a	2.0±2.0a	6.6±3.3a	8.9±3.8a	6.0±4.0a	5.6±3.0a
NRP (100-1000 µm)	0.018	43.8±0.8bc	73.8±17.6b	140.0 ± 60.1ab	88.0±10.6b	172.9±77.1a	112.5±42.6abc
NIP (100-1000 µm)	0.081	33.8±0.8ab	13.9±5.9b	44.4±23.8a	31.4±8.9ab	52.5±21.9a	36.2±18.1ab
NEP (100-1000 µm)	0.036	2.9±0.3b	1.1±1.6bc	5.1±2.7ab	7.5±3.6a	4.5±3.5abc	4.6±1.5ab
NRP (>1000 µm)	0.668	0.0±0.0a	0.0±0.0a	0.2±0.4a	0.1±0.2a	0.3±0.6a	0.3±0.2a
NIP (>1000 µm)	0.142	0.4±0.1a	0.5±0.9a	2.1±2.6a	0.8±0.9a	0.8±0.8a	1.6±0.7a
NEP (>1000 µm)	0.561	0.0±0.0a	0.0±0.0a	0.1±0.2a	0.0±0.0a	0.0±0.0a	0.0±0.0a

[†]PSC: physical soil crust; IBC: incipient biological crust; LC: lichen crust, CVS: crusted vegetated surface.

[‡] NP: total number of pores; NRP: number of rounded pores; NIP: number of irregular pores; NEP: number of elongated pores.

Significant (*p* < 0.05) differences after Fisher LSD are indicated by different letters within rows

Table 3.- Mean and standard error values of 2D porosity (shape and size) as indicators for every soil crust ([†]), one way ANOVA (P significance) and LSD Fisher test (differences among crusts).

Indicators [‡]	P	Mean $\pm$ standard error for each soil surface					
		PSC [†]	IBC [†]	LC1 [†]	LC2 [†]	CVS1 [†]	CVS2 [†]
AP (all pores)	0.006	4.2 $\pm$ 0.3bd	3.5 $\pm$ 1.0bd	23.7 $\pm$ 4.0a	23.0 $\pm$ 8.3a	11.6 $\pm$ 1.5b	13.2 $\pm$ 1.3bc
ARP (all pores)	0.002	0.7 $\pm$ 0.7bcd	1.5 $\pm$ 0.1bc	3.0 $\pm$ 0.9ab	1.8 $\pm$ 0.2b	3.2 $\pm$ 0.9a	2.6 $\pm$ 0.9abc
AIP (all pores)	0.006	1.7 $\pm$ 0.1b	1.3 $\pm$ 0.5bc	4.5 $\pm$ 1.7a	3.5 $\pm$ 1.2ab	3.1 $\pm$ 0.6abc	5.0 $\pm$ 1.3a
AEP (all pores)	0.013	1.8 $\pm$ 0.1b	0.7 $\pm$ 0.7b	16.2 $\pm$ 9.3a	17.7 $\pm$ 9.1a	5.4 $\pm$ 1.6b	5.9 $\pm$ 2.0b
ARP (100-1000 μ m)	0.004	0.5 $\pm$ 0.1bcd	1.4 $\pm$ 0.4bc	2.5 $\pm$ 0.9ab	1.6 $\pm$ 0.3b	2.5 $\pm$ 1.0a	2.1 $\pm$ 0.8abc
AIP (100-1000 μ m)	0.018	1.6 $\pm$ 0.2b	0.9 $\pm$ 0.3bc	2.6 $\pm$ 0.9a	2.0 $\pm$ 0.6ab	2.6 $\pm$ 0.9a	2.0 $\pm$ 1.0ab
AEP (100-1000 μ m)	0.009	1.4 $\pm$ 0.2cb	0.6 $\pm$ 1.1cb	14.1 $\pm$ 10.9ab	17.5 $\pm$ 9.2a	5.3 $\pm$ 5.1cb	5.9 $\pm$ 2.0b
ARP (>1000 μ m)	0.637	0.0 $\pm$ 0.0a	0.0 $\pm$ 0.0a	0.2 $\pm$ 0.4a	0.1 $\pm$ 0.1a	0.3 $\pm$ 0.5a	0.3 $\pm$ 0.2a
AIP (>1000 μ m)	0.020	0.2 $\pm$ 0.0b	0.3 $\pm$ 0.4b	1.8 $\pm$ 0.7ab	1.5 $\pm$ 1.2ab	0.5 $\pm$ 0.1ab	3.0 $\pm$ 1.4a
AEP (>1000 μ m)	0.561	0.0 $\pm$ 0.0a	0.0 $\pm$ 0.0a	2.0 $\pm$ 2.3a	0.0 $\pm$ 0.0a	0.0 $\pm$ 0.0a	0.0 $\pm$ 0.0a

[†]PSC: physical soil crust; IBC: incipient biological crust; LC: lichen crust; CVS: crusted vegetated surface.

[‡]AP: total area occupied by all pores (%); ARP: area (%) occupied by rounded pores; AIP: area (%) occupied by irregular pores; AEP: area (%) occupied by elongated pores.

Significant (P < 0.05) differences after Fisher LSD are indicated by different letters within rows.

Table 4.- Pearson's correlations between physico-chemical and porosity variables. Soil separates follow the French system.

	Crs sand	Crs silt	Total OC	pH	Gypsum	K ⁺	Ca ²⁺	SO ₄ ²⁻
NP	-0.40	0.25	0.71*	0.20	-0.49*	-0.11	-0.56*	-0.34
NRP	-0.42	0.27	0.70*	0.21	-0.51*	-0.12	-0.53*	-0.33
NIP	-0.30	0.18	0.73*	0.13	-0.40	-0.04	-0.62*	-0.37
NEP	-0.22	-0.07	0.70*	0.17	-0.35	-0.13	-0.72*	-0.44
NRP 100-1000	-0.43	0.30	0.69*	0.18	-0.50*	-0.16	-0.48*	-0.30
NRP > 1000	-0.21	0.34	0.65*	0.08	-0.40	-0.10	-0.36	-0.46*
NIP 100-1000	-0.30	0.18	0.73*	0.14	-0.40	-0.04	-0.63*	-0.36
NIP > 1000	-0.32	0.18	0.64*	0.08	-0.39	-0.20	-0.37	-0.31
NEP 100-1000	-0.31	-0.01	0.75*	0.16	-0.45*	-0.16	-0.68*	-0.52*
NEP > 1000	-0.17	-0.06	-0.17	-0.65*	0.06	-0.31	-0.05	-0.20
AP	-0.66*	0.27	0.17	-0.10	-0.23	-0.53*	-0.16	-0.42
ARP	-0.68*	0.50*	0.46*	0.31	-0.68*	-0.08	-0.12	-0.19
AIP	-0.42	-0.11	0.64*	0.32	-0.57*	-0.10	-0.63*	-0.50*
AEP	-0.55*	0.26	0.01	-0.20	-0.06	-0.55*	-0.04	-0.33
ARP 100-1000	-0.73*	0.46*	0.41	0.28	-0.66*	-0.15	-0.07	-0.08
ARP >1000	-0.13	0.44*	0.34	0.10	-0.35	0.08	-0.02	-0.39
AIP 100-1000	-0.51*	0.18	0.50	0.23	-0.52*	0.10	-0.52*	-0.33
AIP > 1000	-0.27	-0.24	0.56*	0.28	-0.45*	-0.18	-0.53*	-0.46*
AEP 100-1000	-0.57*	0.30	0.06	-0.08	-0.09	-0.53*	-0.03	-0.33
AEP > 1000	-0.17	-0.06	-0.17	-0.65*	0.06	-0.31	-0.05	-0.20

* significant at the 0.05 probability level; NP = total number of pores per cm²; NRP = number of rounded pores; NIP = number of irregular pores; NEP = number of elongated pores; AP = area of all pores (%); ARP = area occupied by rounded pores (%); AIP = area occupied by irregular pores (%); AEP = area occupied by elongated pores (%).

Table 5.- Infiltration coefficients and erosion rates for the six soil crusts under annual average conditions and under special rainfall events (event 1: P = 32 mm, I=17 mm h⁻¹, over dry soil; event 2: P = 22 mm, I = 52 mm h⁻¹, over wet soil)

Crust type	Annual Infiltration Coefficient (%) ^{†‡}	Event 1 Infiltration Coefficient (%) [‡]	Event 2 Infiltration Coefficient (%) [‡]	Sediment yield (g m ⁻²)
PSC	65.6 ± 0.9	47.3 ± 5.2	50.1 ± 4.5	203.5 ± 26.1
IBC	71.7 ± 6.2	61.5 ± 5.6	54.4 ± 0.5	80.9 ± 26.5
LC1	63.3 ± 0.5	57.0 ± 4.3	46.5 ± 7.8	23.5 ± 8.7
LC2	74.6 ± 3.0	81.8 ± 3.9	77.1 ± 0.1	7.0 ± 0.2
CSV1	78.0 ± 3.9	86.3 ± 0.8	81.0 ± 11.5	1.0 ± 1.0
CSV2	73.9 ± n.a.	85.0 ± 0.7	75.1 ± 2.9	1.4 ± n.a.

[†] These values correspond to the annual mean values of 3 years of monitoring on 0.24 m² plots (3 replicates on all surface crusts except CSV2 which had 2).

[‡] Infiltration coefficient = ratio between annual infiltration rate (mm) and annual rainfall (mm).

n.a. = not available.