Structure and Structure-Related Characteristics of Dryland and Long-Term Irrigated Xerochrept Soils

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Typical soils from the Ebro Valley (NE Spain) under different land use regimes (flood irrigation for more than 100 years and dryland) were studied from various analytical data, including classical physicochemical and mineralogical parameters, and submicroscopic and porosimetric properties, in order to assess potential changes in soil quality (particularly soil structure). The submicroscopic study revealed marked differences in structural characteristics between the dry (uniform, complex granular structure) and the irrigated (weakly developed subangular blocky structure) soils, which may be explained in several ways. When dry soil is flooded, soil aggregates are stressed by swelling of the clay present and entrapped air causing immediate break-up and slaking of aggregates. Another source of soil structure changes is the ploughing and traffic of agricultural machinery under moist conditions in the irrigated soil; these practices create mechanical stress in the top soil (Ap horizons) and lead to the disappearance of packing voids and the formation of a very dense fabric. The B horizons in the irrigated soil show clear signs of degradation typically associated with saline-sodic soils irrigated with low-salinity water (mainly structure collapse and reorganization of fine materials). The use of submicroscopic and porosimetric techniques proved very powerful for assessing soil structure degradation: It allowed detection of some processes that cannot be properly evaluated with conventional analyses. Based on the results, improved water management practices are required to avoid land degradation in semiarid irrigated areas similar to the ones studied.

Keywords degradation, mineralogy, porosity, SEM, soil quality

Sustainable irrigated agriculture requires the absence of adverse effects (mainly soil salinity and soil structure deterioration) on the soil environment. Salinity imposes a stress

Received 2 July 1996; accepted 14 October 1996.

The authors are grateful to Dr. Benayas for a helpful discussion. J. W. also thanks the provision of a fellowship from the Ministerio de Educación y Ciencia (Spain). This research was supported by DGICYT (Spain) under Project PB90/90.

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Arid Soil Research and Rehabilitation, 11:127–138, 1997

0890-3069/97 $12.00 + .00

on crops that can lead to decreased yields. Soil structure deterioration can take place through several processes that are largely associated with the presence of sodium in the exchange complex and the traffic of heavy equipment.

The effects of long-term irrigation with saline water on date-palm orchards (Heakal & Al-Awajy, 1989; Khalifa et al., 1989) reflect changes in several characteristics of the soils after irrigation. When low-salinity water (usually ealled ''high-quality water'') is applied to soil, even at a low exchangeahle-sodium-percentage (ESP), some irreversible alteration of the physical properties of the soil may oeeur (McIntyre, 1979; Oster & Schroer, 1979; Agassi et al., 1981). Mathieu (1978) also reported a morphological transformation of a soil irrigated for 10 years with good-quality water.

Profitable agriculture in the Ebro Valley (Spain), of semiarid climate, is entirely dependent on irrigation with low-saline water. Determining the effects of such water on occasionally saline-sodic soils is therefore important for maintaining prodnction and avoiding potential land degradation. The assessment of such long-term effects may also provide insight into new pathways of soil genesis when arid conditions are replaeed with a moister regime.

In many cases, changes in soil characteristics (soil quality) related to land use are described in terms of classical physicochemical analyses or from standard measurements of soil physical properties (e.g., hydraulic conductivity). This article demonstrates that submicroscopic and porosimetrie teehniques can better deseribe changes in soil quality upon long-term irrigation and provide better understanding of the processes involved, especially when soil structure is concerned. There are many physieal methods for evaluating soil structure, the results of which are strongly dependent on the methodology used (Letey, 1991). However, it has been pointed out that the evaluation of soil structure by use of submieroscopic methods also provides nseful information for the interpretation of soil formation (Smart, 1975; Chen et al., 1976; Bisdom & Thiel, 1980; Tovey et al., 1992; Wierzchos et al., 1995).

Two soil profiles from similar environmental areas and of similar genesis (strueture development, removal and accumulation of calcium carbonates) were studied in this work. One had been under flood irrigation for more than 100 years, and the other had been permanently under dryland conditions.

Materials and Methods

Two soil profiles (QV and ALB) from the province of Lleida in the Ebro Valley (NE Spain) were studied. The climate of the area is dry, with an average rainfall of 380 mm per year and a potential evapotranspiration (Penman, 1948) of 1200 mm; the average annual temperature is 14°C. Irrigation is only possible with river water, so most of the province has traditionally been nnder dryland conditions.

The QV profile was obtained from the Urgell area, which was brought to irrigation in 1857 when a major canal was huilt from the Segre River. Sinee then, water belonging to Cl salinity class (U.S. Salinity Laboratory Staff, 1954) (Table 1) has been applied to a typical crop rotation (alfalfa-wheat-maize) every 15–20 days from Mareh to Septemher in amounts large enough to moisten the profile and leach salts. Heavy agricultural equipment allows fully mechanized agriculture; in many eases, traffic on the land takes place under wet conditions. Many places in the Urgell area became saline upon irrigation (Zulueta, 1907), and a few years later drainage works started, first with the build-up of the main ditches. Around 1960 it was completed with the installatiou of a drainage network

Table 1
Typical characteristics of irrigation water from the Urgell canal

	EC		Ionic composition (mM)								
pH	(S m^{-1})	SAR	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	NO_3^-
7.70	0.03	0.31	0.28	0.02	1.90	0.48	0.20	0.67	tr[a]	1.88	tr[a]

[a]tr, traces.

throughout the irrigation district in order to reclaim the saline areas and drain the other parts.

The ALB profile was collected from a neighboring area (Algerri, about 15 km from QV) under dryland conditions. The whole area has always been under dryland agriculture because no irrigation water is available; it is extensively cropped in a fully mechanized manner, with barley.

Both areas were recently surveyed at the 1:25,000 scale (Boixadera et al., 1989; Olarieta et al., 1991). The QV and ALB soil profiles were described according to C.B.D.S.A. (1983) and classified as Fluventic Xerochrept, fine silty, mixed, mesic (Soil Survey Staff, 1994). Physicochemical analyses were carried out by using methods of MAPA (1986).

Mineralogical identification was performed using X-ray diffraction (XRD) with a Philips PW 1130 diffractometer (graphite monochromated CuK_α radiation). Semi-quantitative estimations of quartz, feldspars, and calcite were obtained from XRD random powder patterns and those of phyllosilicates from oriented aggregate patterns.

Several undisturbed samples from each horizon were collected, equilibrated (–0.05 MPa soil water potential) in a filtration cell (Tessier & Barrier, 1979); the water was gradually replaced by acetone exchange (Murphy, 1985), and, after embedding in polyester resin, small blocks were cut off and finely polished. The polished surface was coated with a 50 nm layer of carbon and observed under a Zeiss DSM 960 scanning electron microscope (SEM) equipped with a backscattered electron detector (Bisdom & Thiel, 1980; Chrétien & Bisdom, 1983). Backscattered electron scanning images (BESI) have a higher resolution than petrographic micrographs (Bisdom & Thiel, 1980), which permits one to study the arrangement of soil constituents in the submicroscopic range. Several BESIs at variable magnification were recorded as microphotographs. In addition, 20 BESIs from each sample at a magnification of 50× were analyzed by using an MIP Microm España image analysis instrument. The smallest pores resolved by image analysis of BESI were 7.5 μm in radius. This length was selected as the cut-off in scale for the purposes of this study. Macroporosity for pores of radius >7.5 μm was calculated from the ratio of the number of pixels representing the polyester resin phase (pores) to the total number of pixels (Fiés & Bruand, 1990). Additional portions of dehydrated soil were carefully dried to preserve the initial organization of soil constituents using the Peldri II method for drying soft clay materials (Wierzchos et al., 1992). Dry samples were mounted on aluminium stubs, sputter-coated with gold, and examined on a Zeiss DSM 960 SEM.

Parts of the soil samples dried with Peldri II were examined by the mercury intrusion porosimetry method as described by Diamond (1970), using a Carlo Erba 2000 porosimeter. This technique was used for the determination of changes in the cumulative pore volume (CV, range 0.0037 to 7.5 μm of equivalent pore radius), the pore size distribution (PSD), and the volume of pores capable of retaining water available to plants (AWV, radius from 0.1 to 4.8 μm) of the irrigated and dryland soils.

Table 2
Physicochemical characteristics of the soils

Profile	Horizon	Depth (cm)	pH[a]	OM[b] (g kg^{-1})	Size distribution[c] (g kg^{-1}) Sand[d]	Silt[e]	Clay[f]	EC[g] (S m^{-1})	ESP[h]	SAR[i]	$CaCO_3$[j] (%)
ALB	Ap	(0–30)	8.30	11.5	356	417	227	0.06	0.33	0.69	19
	Bwkn1	(30–60)	8.13	4.4	332	430	238	0.10	0.26	0.55	35
	Bwkn2	(60–90)	8.27	2.4	250	460	290	0.34	0.55	2.37	39
QV	Ap1	(0–19)	8.12	21.8	244	500	256	0.18	0.40	1.13	13
	Ap2	(19–36)	8.10	16.0	223	517	260	0.26	0.51	1.85	13
	Bw	(36–82)	8.30	7.8	202	461	337	0.35	5.31	5.39	12

[a]pH (1:2.5 H_2O).
[b]OM, organic matter (Walkley & Black, 1934).
[c]Particle size distribution as determiued by the pipette method without removing $CaCO_3$.
[d]Sand 2–0.02 mm.
[e]Silt 0.02–0.002 mm.
[f]Clay <0.002 mm.
[g]EC, electrical conductivity (in saturated paste extract).
[h]ESP, exchangeable sodium perceutage as measured in the ammonium acetate (pH 7) extract.
[i]SAR, sodium adsorption ratio.
[j]$CaCO_3$ equivalent (Williams, 1948).

Results

Physicochemical Study

Both profiles were calcareous throughout (12–35%), with a moderately alkaline reaction (8.1–8.3) (Table 2). They were medium textured and with a similar clay content, the silt fraction being the dominant one. The irrigated profile was richer in organic matter.

Both soils were slightly saline, with a higher SAR in the QV profile. Althongh the SAR value for QV (5.39) is typical of a non-sodic soil (U.S. Salinity Laboratory Staff, 1954), its higher sodium content may account for some of its observed characteristics.

Mineralogical Study

The semiquantitative mineralogical results (Table 3) revealed few differenees between the QV and ALB profiles. The calcite content determined by XRD was consistent with the one obtained from the chemical analysis for carbonates. The $CaCO_3$ contents in the QV soil (clay and total soil fractions) were low and highly uniform (10–15%); those in the ALB profile were higher (20–42%). Despite the difference, the overall chemical behavior of both soils was dictated in many respects by the dominance of ealcium carbonate. It should be noted that the total phyllosilicate content was greater in the QV profile than in the ALB one. The relative distribution of the different clay minerals identified (Table 3) was very similar for both soils; the smectite eontent was very low in both.

Submicromorphological Study

Based on the classification of Bulloek et al. (1985), submicromorphological observation of polished surfaces of ALB profile indicates that the soil has a complex granular structure (Figures 1a, b, and e). No differences were observed with profile depth. Aggregate granules and single grains of quartz, feldspar, and carbonates of various diameters were separated by complex, highly interconnected packing voids. In some areas of the observed samples, a subangular blocky structure with strong pedality was observed (Figure 1b, upper right-hand corner). Locally, a single-grain structure with loosely arranged quartz grains was identified. The BESI (Figures 1d and e) and SE micrographs (Figure 1f) showed the arrangement of structural elements inside the aggregates, as well as clay particles that were closely grouped in microaggregates of variable size with dominant face-to-face contacts. Microaggregates in the form of stepped clusters or chains created a loose interconnecting framework with oblique edge-to-face flocculation contacts. Sand and silt particles were scattered throughout the sample and were out of direct contact with one another (Figure 1d). The pore space (Figure 1e) was made up mainly of isometric intermicroaggregate pores of the cellular type. Some biopores with a diameter of about 10 µm were distinguished in the Ap horizon (Figure 1d, lower right-hand corner). The SE micrograph (Figure 1f) confirmed the BESI results: It showed an open microstructure with common intermicroaggregate pores. This type of organization of soil constituents is related to a honeycomb microstructure and is typical of flocculated clays (Sergeyev et al., 1980). The same type of microstructure was observed inside the granular aggregates in the three horizons of the ALB profile.

The Ap1 and Ap2 horizons of the QV profile (Figure 2) exhibited quite a different structure from that of the ALB soil, of the weakly developed subangular blocky type (Figures 2a and b), with peds separated by planar pores and with vughs (irregular, not

Table 3
Semiquantitative mineralogical composition (relative wt% between samples)

Profile	Fraction	Horizon	Q[a]	F[b]	C[c]	Ph[d]	I[e]	Ch[f]	S[g]
ALB	≤2 mm	Ap	38	10	20	32	nd	nd	nd
		Bwkn1	22	2	42	34	nd	nd	nd
		Bwkn2	28	1	41	30	nd	nd	nd
	≤2 µm	Ap	10	2	21	67	49	13	5
		Bwkn1	8	—	41	51	37	11	3
		Bwkn2	7	2	35	56	41	14	1
QV	≤2 mm	Ap1	30	4	14	52	nd	nd	nd
		Ap2	35	4	15	46	nd	nd	nd
		Bw	32	3	11	54	nd	nd	nd
	≤2 µm	Ap1	12	2	10	76	52	21	3
		Ap2	10	2	10	78	52	20	6
		Bw	10	2	12	76	56	15	5

nd, not determined.
[a]Q, quartz.
[b]F, feldspars.
[c]C, calcite.
[d]Ph, total content of phyllosilicates. When possible, in some samples, it has also been split into their main species (I+Ch+S).
[e]I, illite.
[f]Ch, chlorite.
[g]S, smectite.

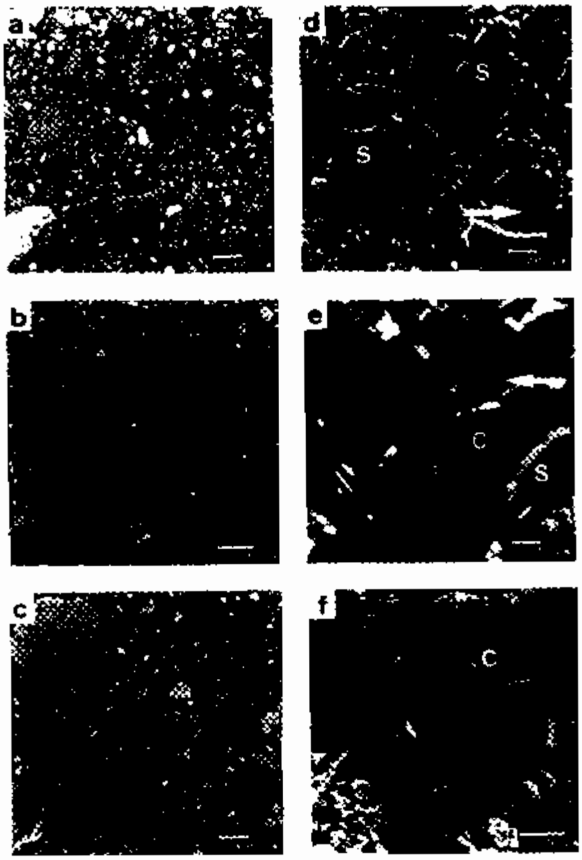

Figure 1. Scanning electron micrographs of ALB profile: (a) and (d), BESI of Ap horizon; (b) and (e), BESI of Bwkn1 horizon; (c) BESI of Bwkn2 horizon; and (f) SEI of Bwkn2 horizon. C, clay; S, sand. Arrows: biopore (d) and cellular pore (e).

interconnected voids). The vughs in the Ap2 horizon were smaller in diameter than those in the Ap1 horizon. Aggregate faces largely accommodated each other. Some channels formed by roots surrounded by s-matrix were observed in the Ap1 horizon (Figure 2a, upper right-hand corner). Some differences in the structure of the Bw horizon were found (Figure 2c) in relation to the Ap1 and Ap2 horizons. The larger subangular blocks were separated by irregular, interconnected vughs. Moderately to locally strong pedality was observed.

At higher magnifications (Figures 2d, e, and f), the inside of the subangular aggregates of all the horizons appeared to have a turbulent microstructure (Sergeyev et al., 1980). Note that clay particles were grouped in microaggregates, where all or most particles lie in approximately the same direction. The interaction of clay microaggregates with one another was of the face-to-face type, and transitional or phase contacts were established in most cases. The microaggregates tended to be curved and molded together, with no distinct inter-domain voids. Some biopores of about 10 μm diameter were observed (Figure 2d, left side). Sand and silt grains were closely "enveloped", thus creating local "turbulence" (see arrow in Figure 2e). These clay particles (Figure 2f) appeared to be arranged in strongly oriented layers.

Porosity Study

The greatest differences between the two profiles were in macropore volume (Table 4), the Ap2 horizon (QV soil) having the lowest (0.027 $cm^3\ g^{-1}$) and that of the Ap1 horizon (QV soil) being roughly one half the value for Ap (ALB soil). A comparison of CV and AWV for the ALB and QV samples revealed no such large differences, except for the lowest horizons considered. The histograms (Figure 3) were consistent with significant differences in pore-size distribution (PSD). Most of the porosity in the irrigated soil corresponded to the smallest pore-size range. The PSD in the available-water range also exhibited substantial differences (black bars in Figure 3). The dryland profile showed much more evenly distributed porosity over the available water range.

Discussion

Physicochemical analyses (Table 2) revealed some differences between the soils, differences that were not large enough to explain some of the structural characteristics observed. The larger content of clay in the Bw horizon may account for the higher pedality of profile QV; this, however, does not hold for the upper horizons.

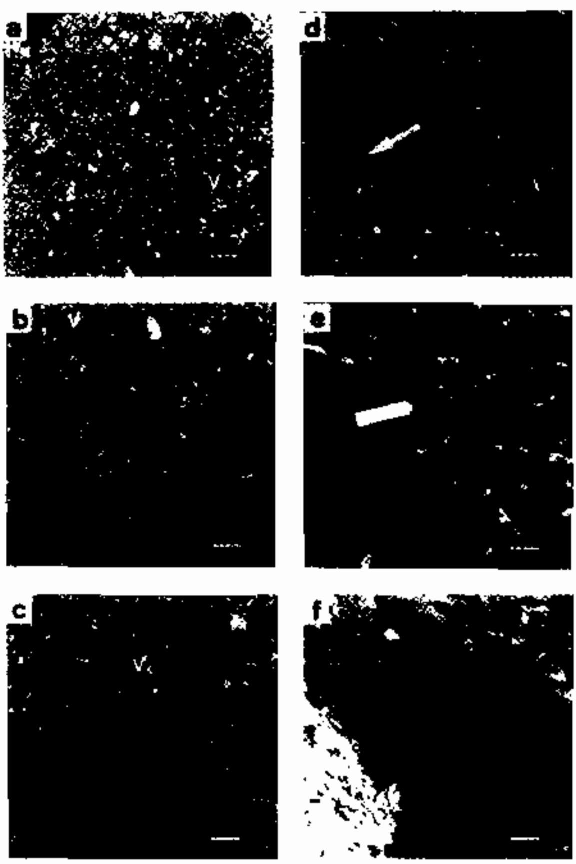

Figure 2. Scanning electron micrographs of QV profile: (a) and (d), BESI of Ap1 horizon; (b) and (e), BESI of Ap2 horizon; (c) BESI of Bw horizon; (f) SEI of Bw horizon. P, planar pores; V, vughs. Arrows: root channel (a), biopore (d), and local "turbulence" (e).

Table 4
Porosimetric data

Profile	Horizon	CV[a]	MV[b]	AWV[c]
ALB	Ap	0.159 (0.008)	0.141 (0.009)	0.115 (0.007)
	Bwkn1	0.154 (0.005)	0.114 (0.007)	0.106 (0.009)
	Bwkn2	0.132 (0.007)	0.134 (0.009)	0.089 (0.007)
QV	Ap1	0.158 (0.007)	0.079 (0.008)	0.102 (0.008)
	Ap2	0.151 (0.002)	0.027 (0.004)	0.092 (0.006)
	Bw	0.097 (0.004)	0.085 (0.008)	0.041 (0.006)

Values are given in $cm^3 g^{-1}$ and represent the mean of 15 measurements. Standard deviations are shown in parentheses.
[a]CV, cumulative pore volume (range 0.0037–7.5 μm) as obtained by mercury porosimetry.
[b]MV, macropore volume (range ≥7.5 μm) as obtained by image analysis.
[c]AWV, pore volume (range 0.1–4.8 μm) as obtained by mercury porosimetry.

The higher $CaCO_3$ content of the Bwkn horizon could also have some influence on the structural characteristics of profile ALB; however, it should be borne in mind that the $CaCO_3$ contents in the Ap horizons were similar for both profiles.

Salinity was also different, even thongh the measured levels were low for semiarid soils; the only striking finding in this respect was the SAR of the Bw horizon. According to some authors (Keren & Shainberg, 1984), such SAR values in combination with the low-salinity irrigation water used may be responsible for the dispersive behavior of illite clays of QV soil. Thus, the lower $CaCO_3$ content can be partly ascribed to the tendency of water to dissolve calcium according to the Langelier index and consistent with previous findings of other authors (Amundson & Smith, 1988).

The mineralogical results (Table 3) contributed no additional information. The mineralogical composition of the clay fraction was markedly similar for both profiles and all the horizons.

The submicroscopic study revealed marked differences in structural characteristics between both profiles. The differences between the uniform, complex granular structure (profile ALB) and the weakly developed subangular blocky structure (profile QV) may be explained in several ways.

Irrigation changes the initial hydrological regime of soil and acts upon its structure via extreme variations of humidity. When dry soil is flooded, soil aggregates are stressed by swelling of the clay present and by entrapped air. The stress may cause immediate break-up and slaking of aggregates on a macroscopic scale (Emerson, 1984). Another source of soil structure change is the ploughing and traffic of agricultural machinery under moist conditions in the irrigated soil; these intensive cultivation practices create mechanical stress in the top soil (Ap horizons) and lead to the disappearance of packing voids and the formation of a very dense fabric. Similar results were reported by Bresson and Zambaux (1988).

The reduction in macropore volume was especially noticeable in the Ap2 horizon of profile QV and could have been the result of intensive cultivation.

Using a technique similar to the one employed in this study, McBratney et al. (1992) also observed a decrease in macroporosity as a result of cultivation on the most irrigated soil. Also, the enveloping of sand and silt grains observed in profile QV can be attributed to the mechanical stress conditions.

The turbulent microstructure observed in all horizons of the QV soil may be explained in two different ways. According to Sergeyev et al. (1980), this type of microstructure is formed during compaction of clays having a honeycomb microstructure, which suggests that human activity on irrigated soils influences clay particle arrangement. One other explanation may be the dispersion of clays under sodic conditions (Keren & Shainberg,

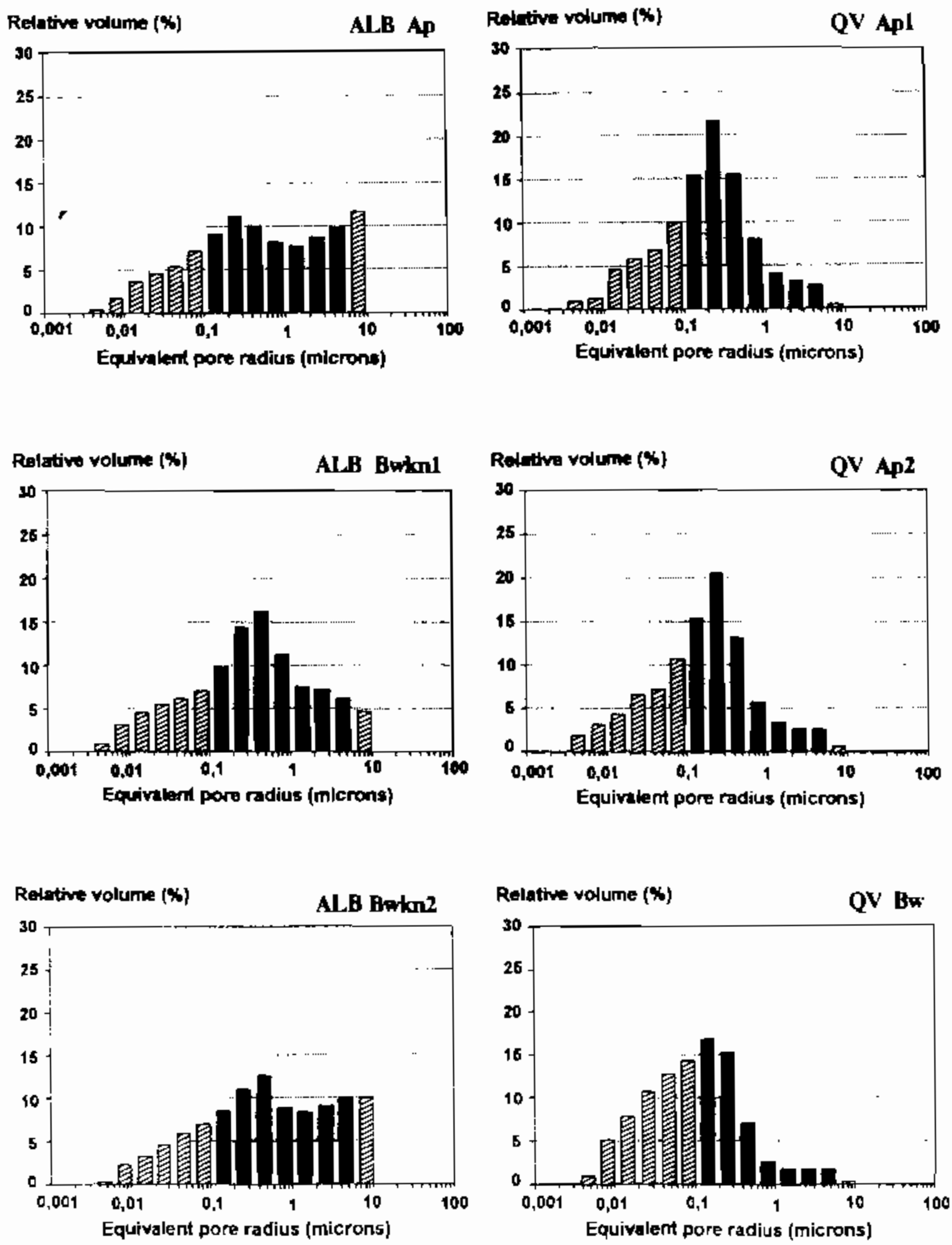

Figure 3. Pore-size distribution in the ALB and QV profiles, expressed as percentage of the cumulative volume. Black bar graphs represent pores potentially occupied by water available to plants.

1984) and a subsequent face-to-face rearrangement (O'Brien, 1971). Mechanical stress prevailed in the upper part of the soil, whereas sodic conditions, which could be more extreme, were the most important factor in the structural changes observed in the lower part.

Because pore size distribution (PSD) is one major aspect of soil structure, according to Newman and Thomasson (1979), it was appropriate to consider whether distributions measured by mercury porosimetry reflected the differences in structural properties between the soils. Also, the available water range was determined by mercury porosimetry, on the assumption that it would be consistent with characteristic data for soil water (Newman & Thomasson, 1979).

The differences in macropore volume between the two profiles studied, as well as the PSD shift in the direction of smaller pores for the QV soil, may be a result of the changes in the macro- and microstructure pointed out earlier. Changes in PSD have strong implications on soil management. First, they decreased the total available water-holding capacity (AWHC) and increased the fraction of least readily available water; second, water movement was restricted by the lack of largest-size pores in the QV profile.

According to Ringrose-Voase and Bullock (1984), the highly interconnected packing voids in the ALB soil allow rapid infiltration of water and facilitate root exploration. Moreover, vughs, which are poorly interconnected, were the dominant macropores in the QV profile and could have been formed by compaction of the structure with packing voids (Ringrose-Voase & Bullock, 1984). Based on these results, the total macroporosity may be a poor indicator for the water transmission characteristics of the QV profile.

Conclusions

Because the physicochemical and mineralogical data obtained do not allow proper evaluation of the soil quality of the profiles studied, we can conclude that more powerful diagnostic tools are needed, when soil use induces changes in soil properties affecting soil structure. In this respect, submicroscopic and porosimetric techniques highlight the soil processes involved and allow better assessment of soil quality.

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