Running Title: AGGREGATION AND ORGANIC MATTER IN MOUNTAIN SOILS

Aggregate Development and Organic Matter Storage in Mediterranean Mountain Soils

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ABSTRACT

Soil aggregation and organic matter of seven soils from the pre-Pyrenean range in Catalonia (NE Spain) were studied, in order to assess their quality as carbon sinks and also to select the best soil management practices to preserve their quality. The soils are classified as Calciustepts, Ustifluvents, Ustorthents, and Calciudolls. Main analyses were for aggregate stability, organic carbon and micromorphology.

The highest amount of organic carbon is found in alluvial, deep soils (228 Mg C ha^{-1}), and the lowest is in a shallow, stony soil with a low plant cover (78 Mg C ha^{-1}). Subsurface horizons of degraded soils under pastures are the ones with smaller and less-stable aggregates. In general, the intrapedal textural porosity is not affected upon disruption after fast wetting. Fresh residues of organic matter (OM) are found mostly in interaggregate spaces. Within the aggregates there are some organic remains that are beginning to decompose, and also impregnative nodules of amorphous OM. Although OM is evenly distributed among the aggregate fractions, the larger blocky peds have more specific surface, contain less decomposed OM and have a lower organic/mineral interphase than smaller crumb aggregates, which in turn are more stable. Soil carbon storage is affected primarily by the OM inputs in the surface horizons. The mechanisms favouring structuration through biological activity, creating small aggregates with intrapedal stable microporosities will be the most effective to store organic carbon over the mid and long term period.

Key Words: aggregate stability, Catalonia, soil carbon storage, soil organic matter

INTRODUCTION

Mineralization and organic matter (OM) oxidation are the main causes of carbon (C) loss to the atmosphere due to anthropic activities. Mineralization is favoured by a change from rangeland to agricultural uses, exposing soils to the surface, breaking aggregates and making OM available for microbial activity and atmospheric agents (Batjes and Bridges, 1992). These processes imply porosity changes, aggregate size variations and

alteration of energy and matter fluxes (Izaurralde and Cerri, 2002), which result in the conversion of C to CO_2 (Reicoski and Lindstrom, 1993), and nutrient release from organic matter.

Among OM components, particulate organic matter (POM) includes any organic fragment with a recognizable structure > 53 μm. It is often considered the active pool with relatively fast turnover times (<10 years, Krull *et al.*, 2004). It represents a fraction that decomposes and releases microbial exudates that promote the formation of microaggregates (Six *et al*., 2000a, 2000b). It is not only the location of OM but the accessibility to decomposing microorganisms that affects the stability of organic carbon (OC) in the soil. Kooistra and van Noordwijk (1995) stress the importance of the heterogeneity of organic matter distribution of the soil at different observational scales, and for this purpose, micromorphological analyses are especially useful. Optical polarizing microscopy uses morphological criteria and degree of decomposition (Stoops, 2003), which can be used to classify functional groups with relevance in OM dynamics (Blazejewski *et al*., 2005). The relation beween microstructure, OM and (micro)biological activity has been studied by optical microscopy (Letey 1991, Brussaar and Kooistra 1993, Brock 1987), and has been applied in the improvement of contaminated soils (Adesodun *et al*., 2008), management of pastures and forests (Davidson *et al.*, 2002, 2004; Kodesova *et al*., 2007) or effects of soil management (Bonel *et al*., 2005; Kapur *et al.*, 2007).

The objective of this study is to assess the physical protection of organic carbon stocks within soil macroaggregates, their influence on soil porosity and relation with soil organic carbon content, by comparing several soils along an altitudinal gradient in a mountain area that is subjected to land use changes through agriculture abandonment. We use a micromorphological approach that allows us to observe the spatial relationships between soil organic and mineral components within the structural units.

MATERIALS AND METHODS

The physical environment

The study area is located in the Ribera Salada watershed in Catalonia (NE Iberian Peninsula) belonging to the tributary network of the Ebro river and situated in the southern part of the Pyrenean mountain range. The relief is tabular with slopes often higher than 20 %. The substrate consists of massive conglomerates, calcareous sandstones and siltstones. Soils are shallow, calcareous and stony. A description of the complete soil survey can be found in Orozco *et al*. (2006). The predominant land use is forestry, from brook forest to subalpine and submediterranean vegetation. The agricultural zone is mainly planted with potatoes, alfalfa and cereals with a low level of nitrogen fertilization. There are also high mountain grasslands with low levels of trampling. The climate is mainly Mediterranean and varies to subalpine in the highest parts of the basin.

Experimental plots

Seven experimental plots from the pre-pyrenean range in Catalonia (NE Spain) were selected covering altitudinal (760 to 1420 m) and land use (pasture, forest) ranges. The

pastures were established during the 1950's after abandonment of agriculture. The soils are classified as Typic and Lithic Calciustepts, Ustifluvents, Ustorthtents, Haplustepts and Calciudolls (SSS 2006, Table I).

TABLE I
Soil and land use of the plots located in the Ribera Salada catchment.

Station	Altitude m	Soil use	Soils (SSS 2006)
Torra	800	*Quercus ilex* forest	Typic Calciustepts
Canalda	760	Brook forest	Typic Ustifluvents
Cogulers shady	860	*Pinus sylvestris* forest	Typic Ustorthents
Cogulers sunny			Typic Calciustepts
Prat	1138	Pasture	Typic Haplustepts
Cal Ramonet pasture	1420	Mountain pasture	Typic Calciudolls
Cal Ramonet forest		*Pinus uncinata* forest	

Soil sampling and characterization

Surface and subsurface horizons of the soils were described following SINEDARES (CBDSA, 1983) and sampled for morphological, physical, chemical, mineralogical and micromorphological analyses. Part of the bulk sample was sieved to obtain the fine earth. The rest was passed through a set of sieves to obtain four fractions (1--2 mm, 2--4 mm, 4--8 mm, >8 mm) corresponding to macroaggregate classes for organic matter and micromorphological analyses. This sieving was carried out with air-dry samples with a minimal disturbance of the natural aggregates, in order to obtain the fractions that were more similar to those obtained when assessing structure in the field. The physico-chemical analyses of fifteen samples were done according to Porta *et al*. (1986), MAPA (1993) and Page *et al*. (1982). Particle-size distribution was determined by the pipette method, after organic matter removal with H_2O_2 and dispersion with Na-hexametaphosphate. Cation-exchange capacity was determined by displacement with 1M NH_4OAc (pH 7) and the exchangeable cations measured by atomic absorption. Bulk density was measured in the field by the hole method (Nacci *et al*., 1999), in order to obtain estimations of the carbon stored in the profiles.

Total carbon and total nitrogen were analyzed by the dry combustion Dumas method, with a TRUSPEC CN (LECO) elemental analyser. We analyzed the bulk samples and the four aggregate fractions (1--2 mm, 2--4 mm, 4--8 mm and >8mm) that were retained by dry sieving. Organic carbon was determined by the same method after removal of carbonates by HCl fumigation (Harris *et al*., 2001). Organic carbon was also analized by the Walkley-Black method (Porta *et al*.,1986).

Structural stability methods

We determined the structural stability of the aggregates <2 mm, of eleven samples by two methods: Le Bissonnais, modified by Amézketa *et al*. (1996) and the HEMC method

(Pierson and Mulla, 1989). The first one consists of measuring the mean diameter after fast (*FWD*) and slow (*SWD*) wetting of microaggregates. For each treatment, the mean weighted diameter is calculated. From these two values, an index of aggregate stability (*AS = FWD/SWD*) was derived, in such a way that stable aggregates will yield values near 1.

The HEMC method (Pierson and Mulla, 1989; Levy and Mamedov, 2002) measures the changes of the sizes of interaggregate pores when they are subjected to fast wetting compared to slow wetting. In this method, the wetting process of the aggregates is accurately controlled, and the energy of hydration and entrapped air are the only forces responsible for aggregation breakdown. It consists of measuring the water retention curves (High-Energy-Moisture-Characteristic curves, HEMC) of the aggregates in a suction funnel with a porous ceramic plate, at high matric potentials. The saturated sample is subjected to desorption from 0 and 20 hPa pressure heads, at intervals of 2 cm. The experimental values were adjusted to a Log-Normal curve (Kosugi, 1996) using the RETC 6.0 software (Van Genuchten *et al.*, 1991). Two HEMC are obtained per sample, by two different pre-treatments: the first one is slowly wetted by capillarity, the second one is submerged in a water layer deep enough to just cover all the aggregates (fast wetting). From each curve, a structural index is calculated:

$$Structural\ Index(SI) = \frac{drained\ pore\ volume}{\left|modal\ matric\ potential\right|}$$

The drained pore volume is defined from the water capacity curve ($d\theta/d\psi$), as the area below the curve and above its baseline. The latter represents the rate of water loss due to aggregate shrinkage rather than pore emptying (Collis-George & Figueroa, 1984; Levy and Mamedov, 2002). The modal potential is the maximum value of the water capacity curve, θ being the water content (kg kg^{-1}) and ψ the matric potential (cm). As aggregate slake and the pore sizes distribution changes, the modal suction increases and the volume of drainable pores decrease. These changes cause the value of the structural index decreases (Pierson & Mulla, 1989). The stability index *S* is calculated as: *S = SI (fast wetting)/SI (slow wetting)*. A high stability will yield values near unity, indicating that a fast wetting does not change pore characteristics. A collapse of aggregates after fast wetting, on the contrary, will mean a change of pore volume or diameter, normally lower, which results in a *S* value near 0.

Micromorphology and image analyses

Vertical thin sections, 13 cm long, 5.5 cm wide, were made from air-dried undisturbed soil blocks of seven horizons, according to the methods described in Murphy (1986). Because of their nature, no special drying methods were required in order to maintain their original structure. They were studied with the petrographic microscope (Olympus BX51) following the guidelines of Stoops (2003), mainly at magnifications of 2x and 4x but also 10x for special pedofeatures. Thin sections were also made of four aggregate fractions of each sample: 1--2 mm, 2--4 mm, 4--8 mm and >8 mm. Image analyses were performed with ImageJ, a public domain Java image processing program (Rasband, 2008).

Porosity measurements

Ten fields for undisturbed samples and five fields for each aggregate class were randomly selected from the respective thin sections. Two images were taken from each field with the petrographic microscope, under parallel polarized light (PPL) and under partly crossed polarizers (PXPL). The sizes of the images were 6.1 x 4.4 mm for the undisturbed samples and 1.2 x 0.88 mm for the aggregates. The PXPL image was edited and binarized by an upper and lower threshold that selected the gray levels corresponding to the pore space, disregarding the brightest (quartz grains) and darkest (organic particles and opaques) particles. The PPL image was used as control to remove the solid particles with gray levels similar to the pores and artifacts such as air bubbles. Outliers were removed and only the objects larger than 20 μm (undisturbed samples) and 4 μm (aggregate samples) were retained for measurements, which corresponds to the minimum equivalent diameter of the pores that have been measured by the image analyser software (ImageJ, Rasband, 2008). From each image, field parameters (area percentage, perimeter and number of objects) and object parameters (size, perimeter, circularity defined as $4\pi \text{ area} \cdot \text{perimeter}^{-2}$ and feret diameters) were obtained.

Particulate organic matter

Images of particulate organic matter (POM) larger than 4 μm contained in each aggregate class were obtained from the petrographic microscope with vertical incident light (IL), in the same fields as the porosity measurements. The process of image editing was similar to that of the porosity, except for the threshold which selected only the darkest spots. PPL images of the same field were used as visual control to remove artifacts. Opaque elements as iron oxides did not interfere, because the soils did not show redoximorphic features. Also, the baseline of opaque minerals was low and constant through all the sites, since the lithology of the parent material is calcareous, contains low amounts of opaques and is very homogeneous. Besides, the minerals had a reflection behaviour different from the OM. The same field and object parameters as for porosity were calculated for POM.

Statistical methods

Statistical analysis was performed with the PAST v. 1.53 programme (Hammer *et al.*, 2001). F and t tests were used for mean separation. Linear regressions were used for comparisons between methods. ANOVA was used with Tukey's test for pairwise comparisons.

RESULTS

Organic matter storage

The soils are sandy loam, calcareous and with carbon contents (LECO method) between 0.13 and 0.65 g kg^{-1} (Table II).

TABLE II

Soil characteristics and soil carbon storage

Soil	Depth	Horizon	Tex-ture	pH	$CaCO_3$ eq.	Organic Carbon (Walkley-Black)	Organic Carbon (LECO)	Nitrogen	C/N	Bulk Density	Carbon storage **	Land use
	cm				g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}		kg m^{-3}	Mg C ha^{-1}	
Canalda	0--14	A	L-SL	7.7	2.147	0.636	0.646	0.0494	16.8	1210	228	Riparian forest
	14--34	Bw	L-SL	8.3	3.128	0.188	0.491	0.0182	18.0			
Cogulers shady	0--17	A	L	7.8	1.905	0.260	0.482	0.0285	15.5	1130	192	Pine forest
	17--35	Bw	SL	8.2	2.066	0.274	0.489	0.0245	14.3			
Torra	0--13	A	SL	7.4	0.009	0.212	0.341	0.0205	13.4	1270	85	Oak forest
	13--30	Bw	SL	8.3	0.035	0.089	0.131	0.0148	8.8			
Prat	0--15	A	SL	7.7	0.045	0.291	0.421	0.0393	23.4	1360	164	Pasture
	15--30	Bw1	SL	8.3	0.064	0.145	0.195	0.0182	7.6			
	30--42	Bw2		8.6	0.051	0.177	0.235	0.0440	8.2			
Cogulers sunny	0--17	A	SL	8.6	3.129	0.157	0.362	0.0206	9.6	1270	166	Pine forest
	17--30	Bwk	L	8.3	3.133	0.307	0.533	0.0374	14.4			
Cal Ramonet Forest	0--12	A	SL	7.5	0.154	0.259	0.216	0.0316	16.7	1220	110	Pine forest
	12--40	AB		8.2	0.132	0.141	0.230	0.0144	13.8			
Cal Ramonet Pasture	0--10	Ap	SL	8	0.331	0.189	0.359	0.0299	9.5	1150	78	Pasture
	10--20	Ap		8.2	0.397	0.164	0.317	0.0240	10.1			

Both OC determinations are positively correlated (R**=0.55), according to the following linear regression: $OC_{LECO} = 1.410\ OC_{W\text{-}B}$. This relation indicates that not all the organic carbon is oxidized by the Walkley-Black method, or that there are other sources of carbon, as charcoal from pasture burning, that are not adequately quantified by these methods. Subsurface horizons sometimes have higher C content than surface horizons, due to the fluventic character and to mass movements along steep slopes. C/N ratios indicate a mull or moder humus type, due to the presence of conifers and grasses. The highest amount of organic carbon stored (228 Mg ha^{-1}) is found in alluvial soils. The lowest (78 and 85 Mg ha^{-1}) correspond to stony soils with low plant cover and overgrazed.

Organic carbon content in each macroaggregate class of surface and subsurface horizons is found in Fig. 1.

Fig. 1. Organic carbon content of macroaggregates grouped according to type of horizon. Bars indicate half of the standard deviation (n=5 surface horizons, n=6 subsurface horizons). Values of the aggregate classes are compared within each group (letters a,b, $P<0.10$) and between groups (letters x,y*). Average values followed with the same letter are not significantly different.

When treated as a whole there are no significant differences of OC content, but within the surface horizons, the largest macroaggregates (4--8 mm) have less OC than the rest. Besides, the aggregates < 4 mm have significantly more OC in the surface than in the subsurface horizons. No differences are observed when grouped according to type of vegetation or land use.

Aggregate stability

The values of the two stability indices for aggregates < 2 mm are plotted in Fig. 2, grouped according to the type of horizon (surface / subsurface).

Fig. 2. Structural stability indices of the studied horizons for aggregates < 2 mm: Stability index *S* (Pierson and Mulla, 1989) and Aggregate Stability index *AS* (from Amézketa *et al*., 1996), grouped according to the type of horizon: surface (left) and subsurface (right). Values are the average of 2 replications.

Neither sample depth nor land use affect aggregate stability. Walkley-Black organic carbon content is positively correlated with R = 0.69 ($P<0.05$) with the stability of aggregates estimated with the method of Amézketa *et al*. (1996), and negatively correlated (R = -0.60, $P<0.10$) with the structural index of Pierson and Mulla (1989). It suggests that a higher OC content maintains the size of the aggregates after a fast wetting, but diminishes the volume and/or the size of the pores within them.

Porosity, aggregation and organic residues

The undisturbed soil samples of three A and four Bw horizons show a strong aggregation, either as rounded (crumb) aggregates (Fig. 3) or subangular blocks.

Fig. 3. Microphotograph of horizon A, Cal Ramonet Forest. Fresh root residues (RR) between peds and amorphous organic matter (AOM) within peds. Image length 6.1 mm. PPL.

The latter predominate in B horizons, although mixed (compound) microstructures are often found. Table III shows the main micromorphological characteristics of the samples regarding porosity, aggregation and organic matter.

TABLE III

Micromorphological characteristics of the soils

Soil	Depth cm	Horizon	Microstructure	Porosity	c/f ratio and related distribution	Coarse elements	Organic components
	cm			(%)			
Cal Ramonet Forest	0--10	A	Highly separated crumb, css.	Complex packing voids; fissures, moderately accommodated, horizontal (50)	1/3 Double space porphyric	Medium sand, quartz	Very frequent root and leaf sections, fresh and slightly decomposed between peds, more decomposed within peds; organic pigment and punctuations.
Cogulers sunny	0--10	A	Highly separated granular, fss and vfss.	Complex packing voids, biopores (50)	1/1 Close porphyric	Coarse sand of calcareous sandstone, fine and very fine sand of quartz and sparite	Frequent root and leaf sections, fresh and slightly decomposed, some of them phlobaphenized; very abundant organic pigment and punctuations.
Cogulers shady	0--15	A	Moderately separated subangular blocky vcss and css, juxtaposed with granular vfss due to faunal activity.	Complex packing voids; fissures, moderately accommodated (50)	2/1 Close porphyric	Coarse and very coarse sand of quartz and sparite, Sand and gravels of quartztitic sandstone	Frequent root and leaf sections, fresh and slightly decomposed between peds, more decomposed within peds; frequent physical decomposition by faunal activity; organic amorphous residues; organic pigment and punctuations.
	15--30	Bw	Moderately separated subangular blocky vcss and css.	Planar voids, partly accommodated; intrapedal vughs and chambers, css (55)	2/1 Close porphyric	Very coarse sand of quartz, quartzites and calcareous sandstone. Very fine sand of quartz and sparite.	Root sections, fine, slightly decomposed, some of them phlobaphenized. Organic pigment and punctuations.
Prat	13--28	Bw1	Highly separated granular, bimodal distribution of peds: mss and fss	Complex packing voids (60)	3/1 Close porphyric	Medium sand of quartzite and quartz.	Black amorphous residues, vfss, intra and interaggregate.
	28--40	Bw2	Moderately separated subangular blocky, mss.	Fissures and chambers, partly filled with smaller rounded aggregates. Complex packing voids (50)	2/1 Close porphyric	Medium sand of quartzite and quartz.	Few root sections and plant residues. Frequent organic pigment and amorphous organic matter and punctuations, irregularly distributed in peds. Abundant faunal activity, mixing soil materials.
Torra	13--30	Bw	Moderately separated subangular blocky, mss	Fissures, moderately accommodated; and chambers (35)	3/1 Close porphyric	Very coarse sand and gravels of calcarous sandstone; medium sand of quartz and quartzite.	Organic pigment; root sections and tissue remains, moderately decomposed between peds, highly decomposed within peds.

Vcss: very coarse sand size; css: coarse sand size; mss: medium sand size; fss: fine sand size; vfss: very fine sand size

The high aggregate separation is due to moderately accommodated planar voids between blocks, but also to compound and complex packing voids between rounded aggregates and/or sands and gravels. Organic matter is mainly found as fresh root sections and leaf residues between peds, which become moderately decomposed when found within the peds (Fig. 3). In the same horizons there is evidence of the mixture of amorphous organic matter, mostly by faunal activity, which originates aggregates with heterogeneous distribution of organic matter content, and allows one to find all gradations of organic matter, from plant residues and cells to organic pigment. The latter is found either concentrated as moderately impregnative orthic nodules, or uniformly mixed in the micromass.

The edition and binarization of these images allows the quantification of the porosity, which is shown in Table IV.

TABLE IV.

Image analyses of pores > 20 μm (equivalent diameter) on undisturbed samples. Values without letters or followed by the same letter are not significantly different within a column (P<0.05, n=10).

Soil	Depth	Horizon	Field parameters			Pore parameters		
			Total porosity	Total perimeter	Number	Area	Perimeter	Circularity
	cm		%	mm mm^{-2}	count mm^{-2}	mm^2	mm	
Cal Ramonet Forest	0--10	A	29.22 bc	5.70 b	10.89	0.0289 ab	0.506	0.7356 ab
Cogulers sunny	0--10	A	25.27 b	4.56 ab	9.72	0.0471 a	0.631	0.5711 a
Cogulers shady	0--15	A	24.48 b	4.94 ab	17.42	0.0169 b	0.312	0.7194 ab
	15--30	Bw	22.84 b	4.93 ab	16.19	0.0197 ab	0.362	0.7563 b
Prat	13--28	Bw1	36.76 c	5.95 b	10.46	0.0394 ab	0.593	0.7559 b
	28--40	Bw2	22.60 b	6.18 b	15.94	0.0144 b	0.403	0.7190 ab
Torra	13--30	Bw	10.34 a	3.18 a	13.31	0.0109 b	0.295	0.7471 b

Fig. 4 displays the boxplots of the image variables showing significant differences between samples. The less porous sample is the Bw horizon of Torra, a degraded soil under an oak forest with a subangular blocky structure. This horizon also has the lowest specific surface, indicated by a low total perimeter. The most porous horizon is the upper Bw of the pasture soil of Prat. It has a very well developed crumb structure with large packing pores in between. The largest and more circular pores are found in the A horizon of Cogulers sunny under forest, which correspond to equant packing voids (connected pores due to packing of equidimensional particles, Stoops, 2003) and biopores due to a high faunal activity.

Fig. 4. Boxplots of total area, total perimeter, pore area and pore circularity of six horizons. Solid lines in boxes indicate median values. Boxes show the 25--75 % quartiles. Whisker caps indicate the minimal and maximal values (n=10). Boxes followed with the same letter are not significanly different*. RForA: Ramonet Forest, A horizon; CSuA: Cogulers Sunny, A horizon; CShA: Cogulers Shady, A horizon; CShBw: Cogulers Shady, Bw horizon; PBw1: Prat, Bw1 horizon; PBw2: Prat, Bw2 horizon; TBw: Torra, Bw horizon.

Table V and Fig. 5 show some of the parameters of image analyses of the porosity and particulate organic matter of the aggregates.

Fig. 5. Boxplots of pore parameters and particulate organic matter (POM) of aggregates. Solid lines in boxes indicate median values. Boxes show the 25--75 % quartiles. Whisker caps indicate the minimal and maximal values (n=8). Boxes followed with the same letter are not significanly different ($P<0.10$).

TABLE V

Summary of the image analyses of pores and organic matter (> 4 μm equivalent diameter) in aggregates. Values without letters or followed by the same letter are not significantly different within a column (P<0.10, n=8).

Aggregate class	Porosity					Organic matter				
	Total porosity	Total perimeter	Number	Pore area	Pore circularity	Total area	Total perimeter	Number	Object Area	Object Circularity
	%	mm mm^{-2}	count mm^{-2}	mm^2		%	mm mm^{-2}	count mm^{-2}	mm^2	
1--2 mm	8.67	9.49 a	97.3	0.00256	0.64	1.62 a	6.16 a	102.7 a	0.000234	0.69
2--4 mm	7.96	8.94 a	98.5	0.00220	0.66	1.85 a	3.98 bc	84.6 a	0.000250	0.76
4--8 mm	10.73	9.78 a	102.3	0.00136	0.66	1.10 b	2.68 b	58.6 b	0.000197	0.70
> 8 mm	14.07	15.79 b	180.4	0.00112	0.68	1.78 a	4.73 ac	100.8 a	0.000237	0.73

No differences between horizon type nor position have been found, but for some properties there are differences between aggregate classes: large aggregates tend to be more porous and have more specific surface than smaller ones (significance level of 10 %). The specific surface of POM increases in the three smaller aggregate classes. This means a higher interphase of POM with mineral material as the aggregate size diminishes. A high degree of digitation of the particles could be the reason for this behaviour, as it is observed in thin sections.

DISCUSSION AND CONCLUSIONS

The structure of these soils is characterized by large macroaggregates with high porosities, but this porosity is probably not very stable. Kay (1997) indicates that the macropores are unstable unless the process of creating the pore does not substantially increase the OC content of the pore wall, as it happens with root channels or some faunal pores. In our case the smallest macroaggregates are less porous, have less specific surface and contain more OM than the larger ones. This is in agreement with the observations of Jastrow and Miller (1997) and Angers and Chenu (1997).

The analyses of the stability indices of the aggregates < 2 mm and the microscopical observations suggest that the process of aggregate breakdown is controlled by fissuration of large peds (crumbs or subangular blocks), which does not mean a collapse of intrapedal packing voids or biopores, which remain in smaller aggregates. Organic matter evolution observed in undisturbed blocks results in morphologies from fresh plant remains to amorphous organic masses with diffuse boundaries, that break down and become incorporated within the mineral material mostly by biological activity. Thus, it would be the OM decomposition rates that control the formation and stabilization of microaggregates, as observed by Jastrow and Miller (1997), rather than the mere presence of organic structures such as roots or hyphae. The higher decomposition degree in the smaller aggregates is shown by a higher organic/mineral interphase, that corresponds to a process of progressive matrix impregnation by the remaining OM in the form of amorphous impregnative nodules, sometimes digitated, that probably provide the aggregates with a higher stability. In a system with a regular supply of organic matter residues such as roots or litter, the cycle of organic matter turnover would evolve from fresh organic remains to occluded organic carbon in the smallest aggregates, in agreement with the model of Six *et al*. (2000a). Initially, macroaggregates are formed around fresh residues, namely coarse intraaggregate particulate organic matter (iPOM), since these residues promote microbial activity that produces cohesive compounds (Golchin *et al*., 1994; Jastrow, 1996; Six *et al*., 1999), and are a source of organic C. Our micromorphological observations (shape and amount of POM in aggregates) are in aggreement with the analytical ones of Fonte *et al.* (2010), who stress the importance of POM in the stability of large macroaggregates under forest. Similarly, Huang *et al.* (2010) show that OM supply promotes the formation of microaggregates within macroaggregates, leading to more stabilization of new POM.

The results provide micromorphological evidence for the importance of OM supply in forest and range environments: soils with organic inputs tend to form stable aggregates, which in turn can protect soil OM (SOM) from decomposition, leading to further

aggregate stabilization. This is in agreement with Álvaro-Fuentes *et al*. (2009), Fernández-Ugalde *et al.* (2009) and Xi *et al.* (2010), who found that no tillage promoted OM accumulation in microaggregates and a better structure. However, in soils degraded by erosion or compaction, the disruption of aggregates exposes previously protected OM to decomposing agents, leading to a greater loss of SOM and a further destabilization of aggregates (Jastrow and Miller, 1997). In our case, organic matter storage seem more effective in small aggregates of surface horizons: they are more stable and contain more carbon than larger aggregates. They correspond to crumbs smaller than 1 mm (Table III).

Any physical disturbance on forest soils (logging, rainfall, erosion) may break down aggregates, which implies OM losses; but despite this loss, the remaining smaller aggregates, if the system is not excessively degraded, are the ones that may store OC in a more effective way.

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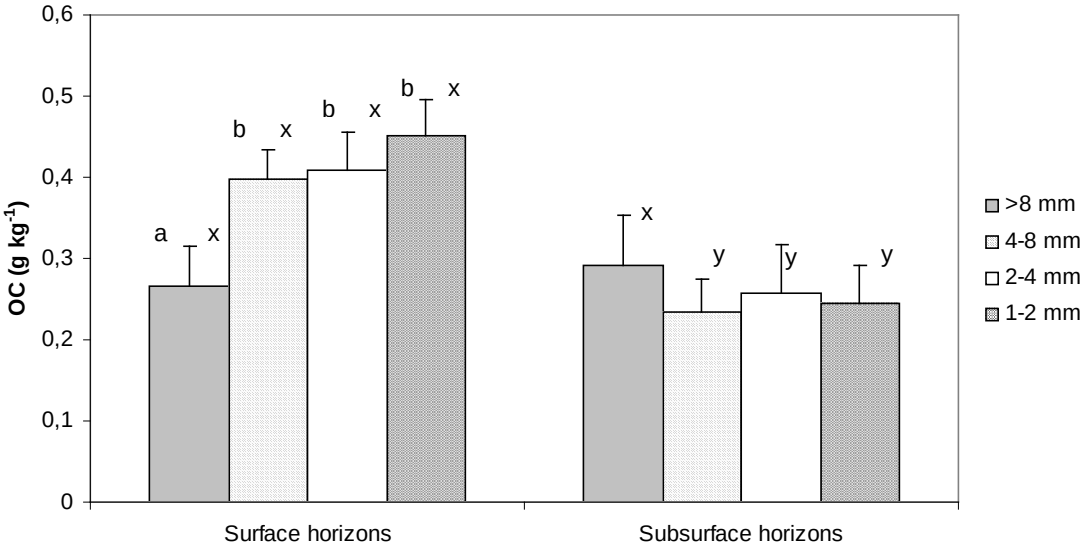
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OC (g kg-1)
a x
b x
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>8 mm
4-8 mm
2-4 mm
1-2 mm
Surface horizons
Subsurface horizons

Fig 1.

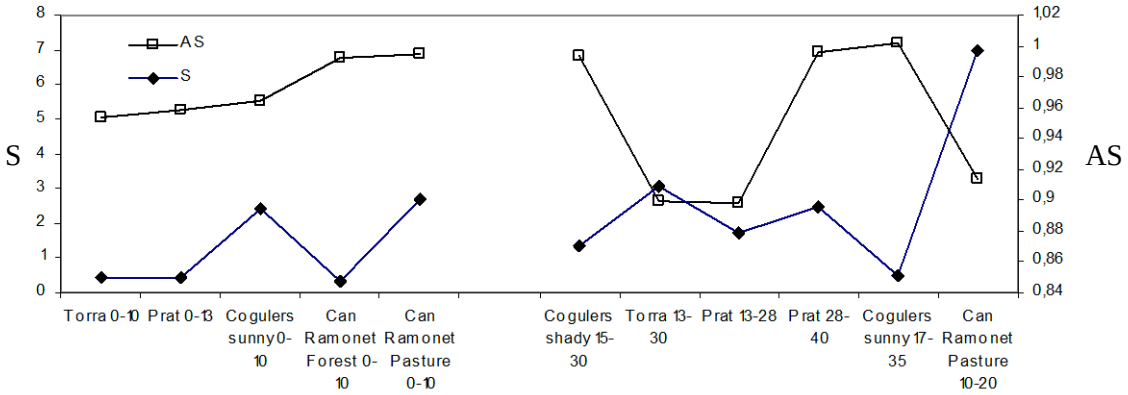
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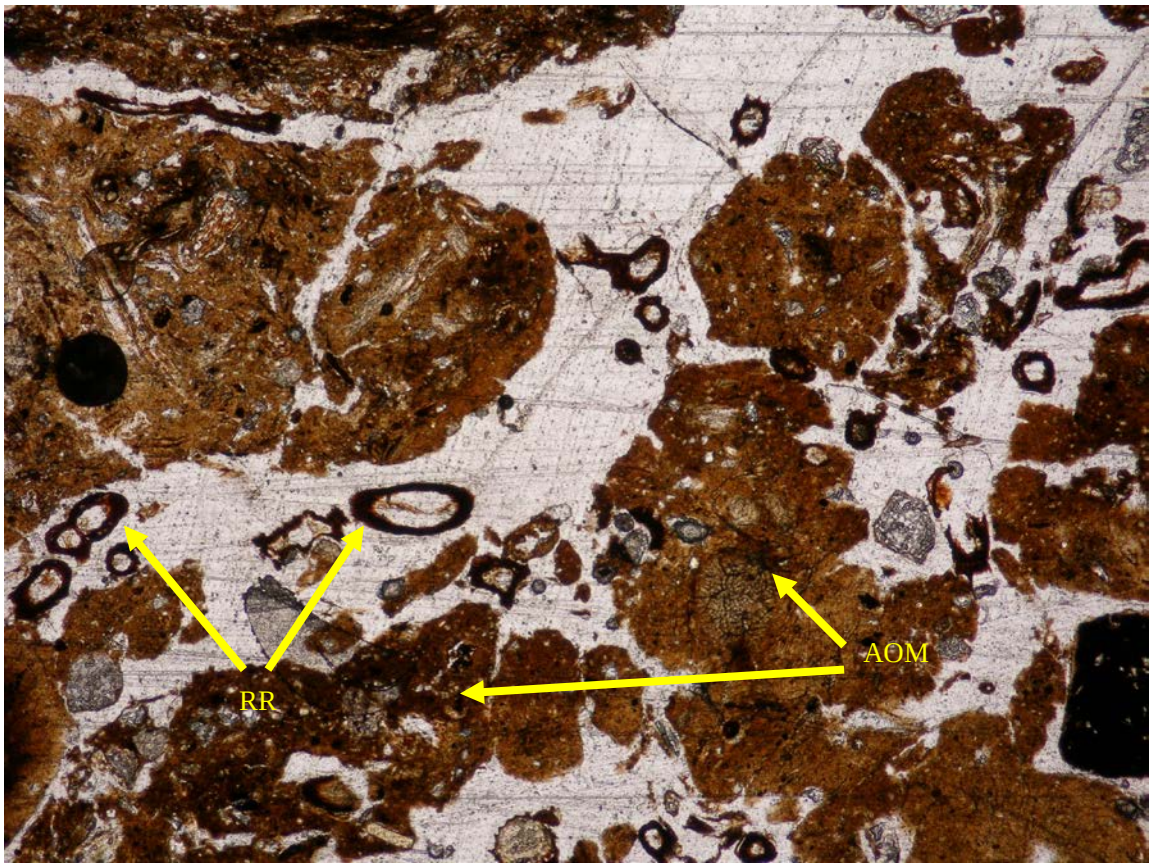
Fig. 2.



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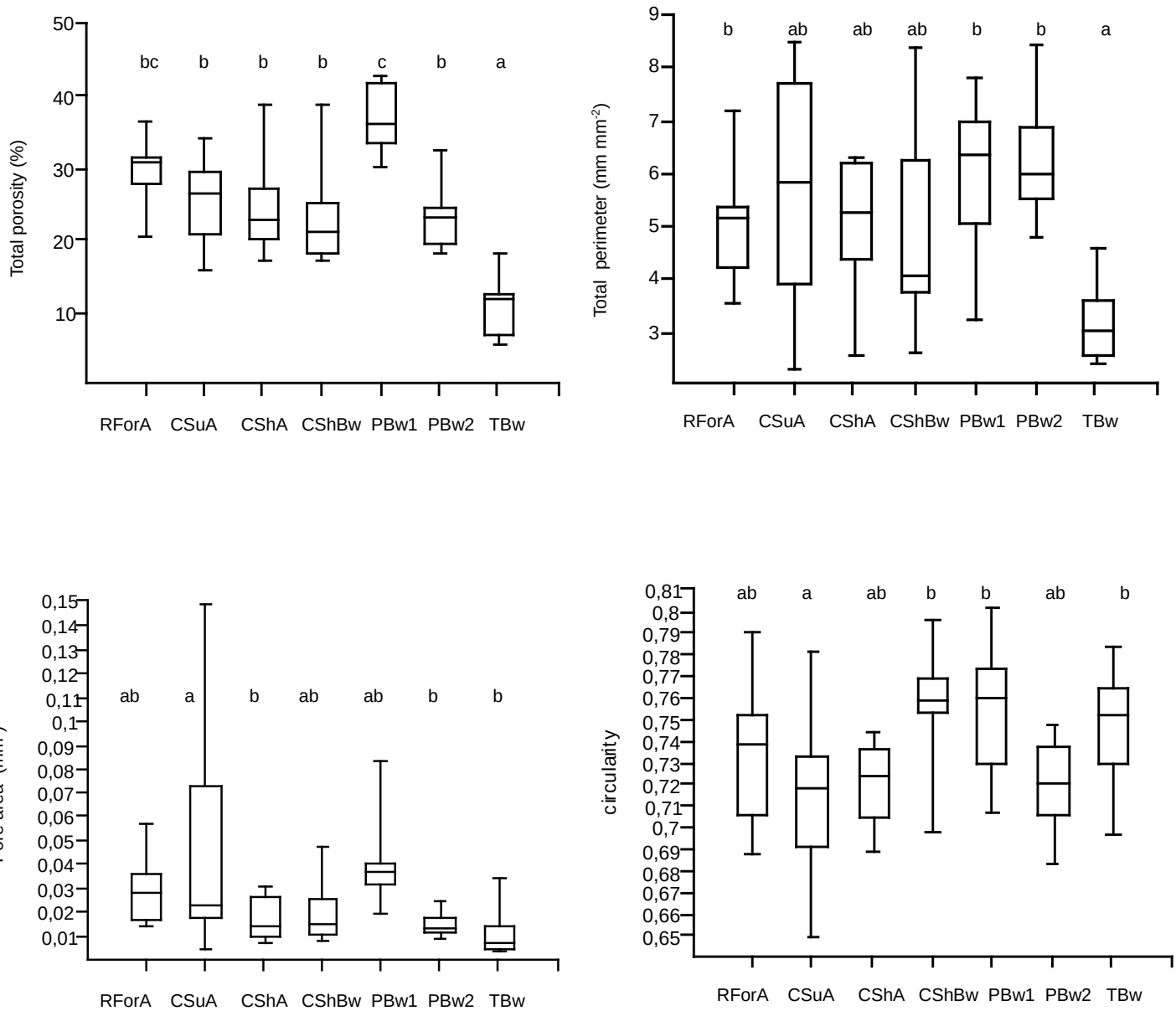

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558 Fig. 4.

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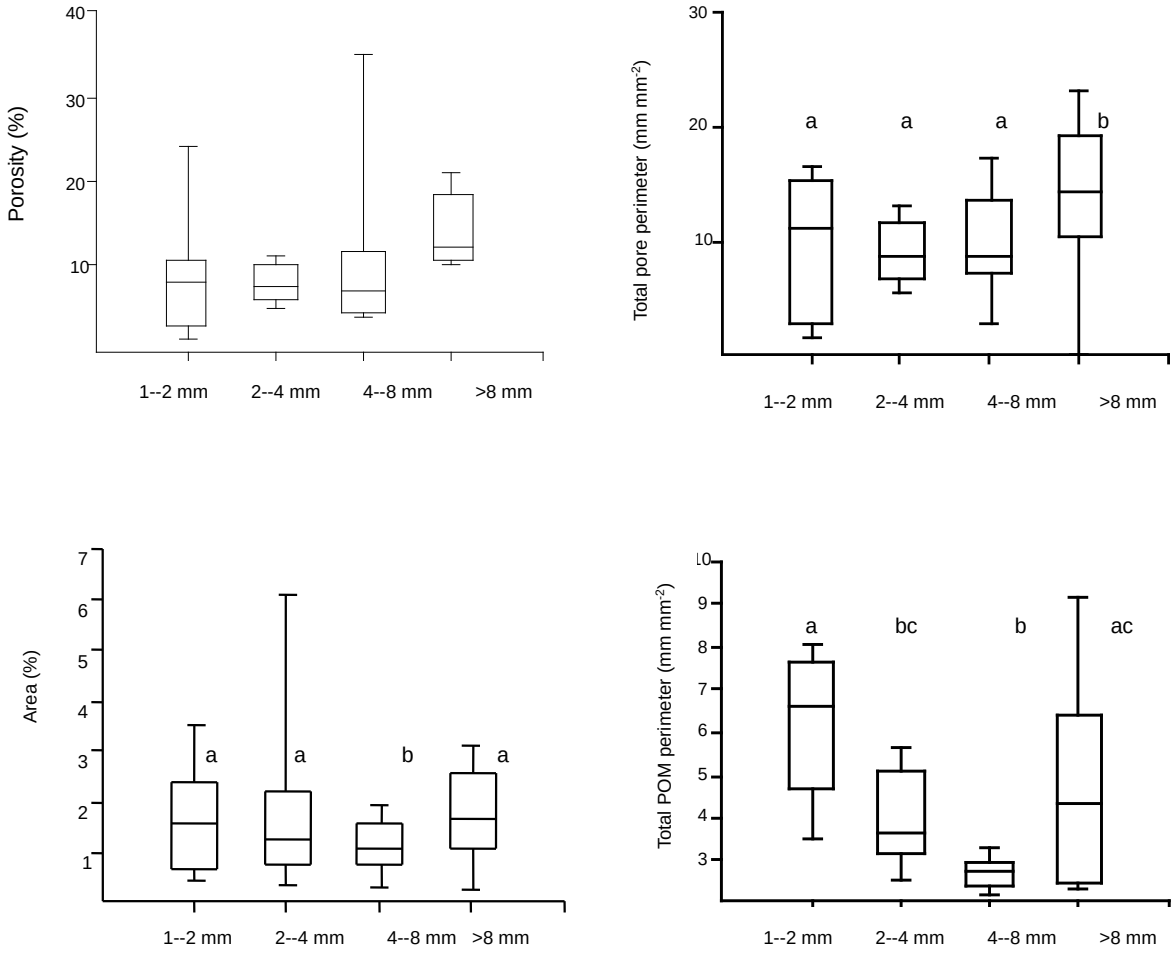

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562 Fig. 5.