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Effect of carbonates on the hierarchical model of aggregation in calcareous semi-arid Mediterranean soils

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ABSTRACT

Lithogenic and/or secondary carbonates are present in many semi-arid Mediterranean soils. Their role in aggregation dynamics is not completely known, and can determine the sensitivity of these soils to land-use changes and soil management. The objective of this work was to test the hierarchical model of aggregation, and to determine the relationship between aggregates formation and organic matter decomposition in calcareous soils of semi-arid Mediterranean regions, by comparing macroaggregation in the upper horizon of a calcareous soil (*Typic Calcixerept*) with a non-calcareous soil (*Typic Haploxerept*) and a decarbonated *terra rosa* (*Calcic Haploxerept*) following fresh straw addition under controlled laboratory conditions during 105 days. We hypothesized that aggregation would work according to the hierarchical model in the non-calcareous soil (NONCALC) and in the decarbonated *terra rosa* (DECALC), but not in the calcareous soil (CALC). The three soils had similar organic C concentrations and C/N ratio, but differed in their carbonates and clay minerals content: NONCALC had a similar proportion of clay-size silicates than CALC (~10%), and the DECALC had a similar proportion of total clay-sized particles than CALC (including carbonates, ~20%). An increase in the amount of macroaggregates (>250 μm) and microaggregates (50–250 μm) held within macroaggregates associated to an increase in the fungal activity when maize straw was added, a decline of macroaggregates with time associated to organic matter decomposition, a higher concentration of organic C and maize-derived C in microaggregates within macroaggregates than in free microaggregates, and a transfer of maize-derived C from macroaggregates to free microaggregates with time confirmed that aggregation worked according to the hierarchical model in NONCALC and DECALC. In CALC, however, the hierarchical model worked only partially. Macroaggregates formation was also stimulated by organic residues addition according to the model, but stable macroaggregates showed longer turnover rates and no relationship between straw decomposition and their decline was observed. From this, we postulate that carbonates can help stabilizing macroaggregates formed from fresh organic matter decomposition through abiotic processes, such as dissolution and re-precipitation. These results help to understand field data obtained in semi-arid calcareous agricultural soils, where it has been observed that aggregation is not always directly correlated to organic matter concentration, but that increases in soil organic matter can promote aggregation. They also indicate the need for considering the composition of the mineral fraction when modelling soil structure in semi-arid Mediterranean soils.

1. Introduction

The preservation of the soil physical quality is essential for the development of sustainable agriculture in Mediterranean semi-arid land. Many agricultural soils in these areas show an unstable soil structure (Virto et al., 2007; Álvaro-Fuentes et al., 2009; Fernández-Ugalde et al., 2009), that affects negatively to agricultural production (Bescansa et al., 2006) and favours land degradation processes (Le Bissonnais et al., 2007) The determination of the factors controlling structure formation and stability in these soils is thus needed for a good understanding of their sensitivity to land-use changes and management.

Abbreviations: SOM, soil organic matter; cPOM, coarse particulate organic matter (>250 μm); NONCALC, non-calcareous soil; CALC, calcareous soil; DECALC, decarbonated *terra rosa*; NONCALC−, non-calcareous soil without straw addition; CALC−, calcareous soil without straw addition; DECALC−, decarbonated *terra rosa* without straw addition; NONCALC+, non-calcareous soil with straw addition; CALC+, calcareous soil with straw addition; DECALC+, decarbonated *terra rosa* with straw addition; Magg, macroaggregates (>250 μm); magg, microaggregates (50–250 μm); s + c, silt- and clay-sized fraction (<50 μm); mMagg, microaggregates within macroaggregates(50–250 μm); M(s + c), silt- and clay-sized fraction (<50 μm) within macroaggregates (>250 μm); m(s + c), silt- and clay-sized fraction (<50 μm) within microaggregates (50–250 μm).

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Numerous studies have shown that in temperate soils in which the mineral fraction is dominated by silicates, aggregate dynamics and soil organic matter (SOM) decomposition are directly related according to a hierarchical model of aggregate formation and stabilization (Tisdall and Oades, 1982; Oades, 1984; Beare et al., 1994; Golchin et al., 1994; Angers et al., 1997; Six et al., 1999; Six et al., 2004). Following this model, the incorporation of fresh organic matter promotes the formation of macroaggregates, as a result of enhanced activity of decomposer microorganisms. This is caused by stimulation of the production of organic binding agents that can increase the cohesion among mineral particles and organic matter, and the hydrophobicity of organo-mineral unions that improves the stability of macroaggregates (Golchin et al., 1994). As organic matter is further decomposed, it is gradually more protected within newly formed microaggregates within macroaggregates, and by adsorption to reactive mineral surfaces. When the organic binding agents in macroaggregates are eventually degraded, they break down and very stable microaggregates, containing uncomplexed small organic particles and clay-sized and silt-sized organo-mineral complexes, are released and incorporated into new macroaggregates formed around newly incorporated organic residues. As a direct consequence of this model, an increase of organic C concentration with increasing aggregates size (Six et al., 2004), a higher proportion of more labile organic matter in macroaggregates than in microaggregates (Six et al., 2004), and a transfer of young organic matter from macroaggregates to microaggregates with time (Jastrow and Miller, 1998) are also expected.

Based on this, we propose that a soil behaving according to the hierarchical model should fulfil the following criteria: (1) promotion of macroaggregation with fresh organic matter addition, (2) decline of the proportion of stable macroaggregates with time after organic matter incorporation, (3) macroaggregates formation associated to microbial activity, (4) increase in the organic C concentration with aggregate-size classes, (5) higher content of more labile organic matter in macroaggregates than in microaggregates, and (6) transfer of added (more labile) organic matter from macroaggregates to microaggregates with time.

In many semi-arid soils from Mediterranean regions, where the presence of primary and/or secondary carbonates is frequent, a less strong correlation between aggregate stability and SOM dynamics than described above for the hierarchical model has been often observed (Boix-Fayos et al., 2001; Six et al., 2004; Bouajila and Gallali, 2008). This has been attributed to carbonates interacting with aggregates dynamics. For instance, the presence of polyvalent cations such as calcium can favor bonds among clay minerals (Six et al., 2004), and promote inter-molecular interactions between the organic and inorganic soil components (Baldock and Skjemstad, 2000; Clough and Skjemstad, 2000), and among organic polymers (Ojeda et al., 2003). In addition, precipitation of secondary carbonates can create permanent bridges between primary and secondary particles, as observed by Clough and Skjemstad (2000). Finally, it has also been proposed that carbonates might interact with the soil microbial activity, resulting in a lower correlation of fungal activity with water-stability of aggregates (Rilling et al., 2003; Shang and Tiessen, 2003; Bullinger-Weber et al., 2007).

The relationship between SOM decomposition and aggregate dynamics in calcareous soils is however still rather unknown (Abiven et al., 2009). For instance, despite the small correlation between SOM and aggregates stability in these soils, a number of studies have shown that increments in the proportion of labile organic matter, as those observed under no-till or following organic amendments, are associated to enhanced macroaggregates stability in semi-arid Mediterranean soils containing carbonates (Ojeda et al., 2003; Virto et al., 2007; Álvaro-Fuentes et al., 2008). Furthermore, most available data on the interaction of carbonates and fresh organic matter, and on its effect on aggregates dynamics, have been obtained by adding carbonates or other sources of calcium to non-calcareous soils (Muneer and Oades, 1989a, 1989b; Baldock et al., 1994; Grünewald et al., 2006; Wuddivira and Camps-Roach, 2007; Stewart et al., 2008). In such experiments, the original properties of soils were probably changed, for example the original pH and base saturation, which can also induce changes in the microbial activity, the turnover of SOM, and the interactions between minerals (Baldock et al., 1994; Bertrand et al., 2007).

The objective of this work was to determine to what extent the hierarchical model of aggregation applies for calcareous soils of semi-arid Mediterranean regions. That for, we tested the set of observations expected for the hierarchical model in a calcareous soil, a non-calcareous soil and a decarbonated *terra rosa* under similar agricultural management following fresh organic matter addition under controlled laboratory conditions. The three soils differed mainly in the composition of their mineral fraction, especially clay-sized particles. Based on previous knowledge, we hypothesized that aggregation would work according to the hierarchical model in the non-calcareous soil and in the

Table 1
Soil characteristics in the 0–20 cm depth. Average ± standard error ($n = 3$).

Soil Location	Non-calcareous (NONCALC) Castañares	Calcareous (CALC) Rodezno		Decarbonated *terra rosa* (DECALC) Rodezno	
Soil type	*Typic Haploxerept*	*Typic Calcixerept*		*Calcic Haploxerept* (*Palexeralf*)	
Colour	10 YR 5/4	10 YR 5/3		7.5 YR 4/4	
Chemical properties (g kg^{-1})					
Organic C	7.6 ± 0.16	8.8 ± 0.07		8.6 ± 0.11	
Total N	0.8 ± 0.02	0.9 ± 0.03		0.8 ± 0.01	
C/N ratio	9.65 ± 0.14	9.88 ± 0.20		10.65 ± 0.19	
pH (1:2.5 water)	6.13 ± 0.20	8.58 ± 0.02		8.30 ± 0.12	
Carbonates					
Total	–	221 ± 5.5	–	–	
Active (<2 μm)	–	120 ± 1.2	–	–	
Extractable Fe					
Ditionite-citrate	4.17 ± 0.38	2.42 ± 0.03		4.55 ± 0.22	
Oxalate-bicarbonate	0.23 ± 0.02	–		0.18 ± 0.00	
		Before decarbonation	After decarbonation	Before Fe extraction	After Fe extraction
Particle-size distribution (g kg^{-1})					
Sand (50–2000 μm)	556 ± 4.8	425 ± 9.5	361 ± 6.5	446 ± 14.0	371 ± 14.9
Silt (2–50 μm)	327 ± 4.3	366 ± 12.8	314 ± 6.2	338 ± 10.5	344 ± 11.6
Clay (<2 μm)	116 ± 8.9	209 ± 3.5	104 ± 7.5	215 ± 4.5	200 ± 1.1
Field capacity (% w/w)	13.07 ± 0.55	18.15 ± 0.26		17.90 ± 0.42	