Organic C, water repellency and soil stability to slaking at aggregate and intra-aggregate scales

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Introduction

General overview

Water repellency (WR) is a property of some soils that inhibits or delays water infiltration between a few seconds and days or weeks. Inhibited or delayed infiltration contributes to ponding and increases runoff flow generation, often increasing soil erosion risk. In water-repellent soils, water infiltrates preferentially through cracks or macropores, causing irregular soil wetting patterns, the development of preferential flow paths and accelerated leaching of nutrients.

Although low inputs of hydrophobic organic substances and high mineralization rates lead to low degrees of WR in cropped soils, it has been reported that conservative agricultural practices may induce soil WR. Although there are many studies at catchment, slope or plot scales very few studies have been carried out at particle or aggregate scale. Intra-aggregate heterogeneity of physical, biological and chemical properties conditions the transport of substances, microbial activity and biochemical processes, including changes in the amount, distribution and chemical properties of organic matter.

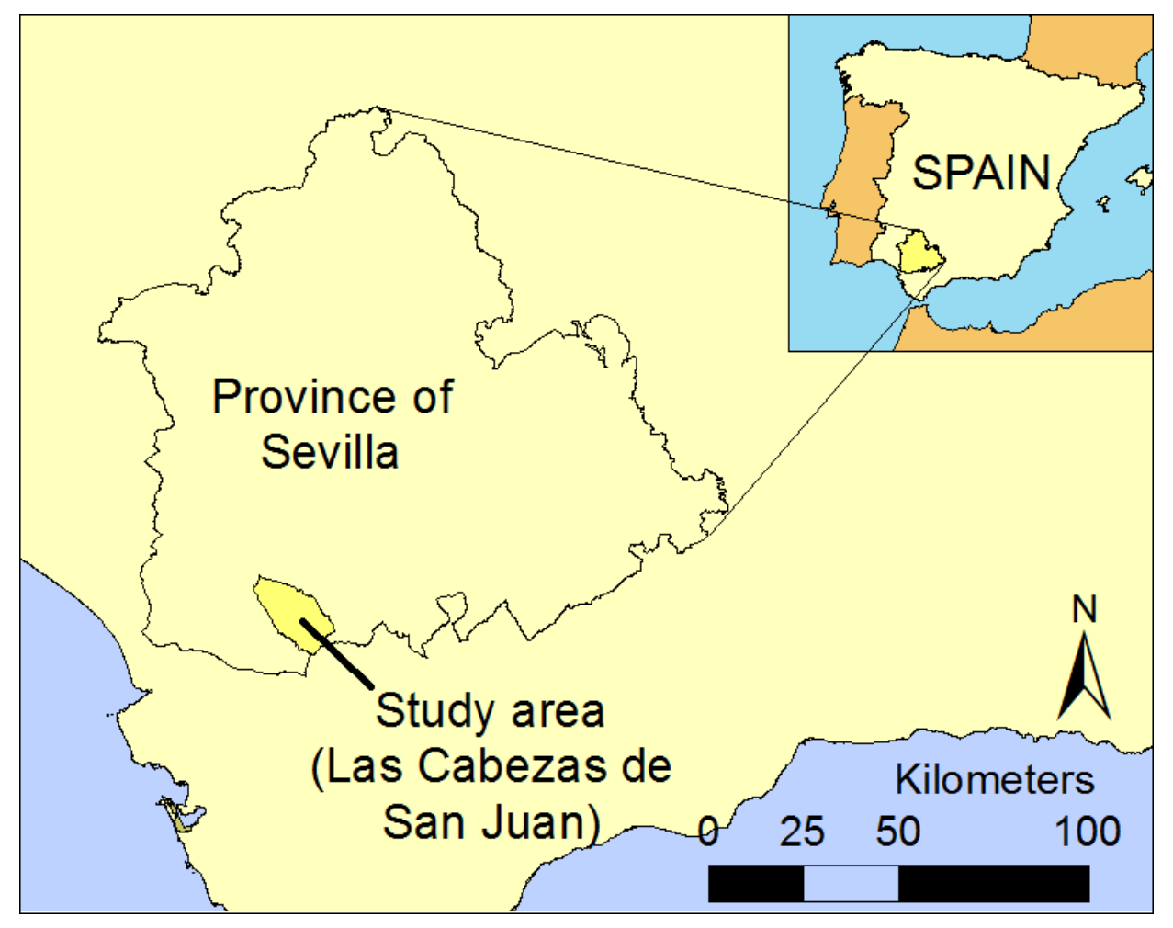

Figure 1. Study area.

Some authors have reported positive relationships between soil WR and aggregate stability, since it may delay the entry of water into aggregates, increase structural stability and contribute to reduce soil erosion risk. Organic C (OC) content, aggregate stability and WR are therefore strongly related parameters. In the case of agricultural soils, where both the type of management as crops can influence all these parameters, it is important to evaluate the interactions among them and their consequences. Studies focused on the intra-aggregate distribution of OC and WR are necessary to shed light on the soil processes at a detailed scale. It is extremely important to understand how the spatial distribution of OC in soil aggregates can protect against rapid water entry and help stabilize larger structural units or lead to preferential flow.

Objectives

The objectives of this research are to study [i] the OC content and the intensity of WR in aggregates of different sizes. [ii] the intra-aggregate distribution of OC and the intensity of WR and [iii] the structural stability of soil aggregates relative to the OC content and the intensity of WR in soils under different crops (apricot, citrus and wheat) and different treatments (conventional tilling and mulching).

Material and methods

Soil samples were collected from an experimental area (Luvic Calcisols and Calcic Luvisols) in the province of Sevilla (SW Spain; **Figure 1**) under different crops (apricot, citrus and wheat) and different management types (conventional tillage with moldboard plow) and mulching (no-tilling and addition of wheat residues at rates varying between 5 and 8 Mg/ha/year).

At each sampling site, soil blocks (50 cm long × 50 cm wide × 10 cm deep) were carefully collected to avoid disturbance of aggregates as much as possible and transported to the laboratory. At field moist condition, undisturbed soil aggregates were separated by hand. In order to avoid possible interferences due to disturbance by handling, aggregates broken during this process were discarded. Individual aggregates were arranged in paper trays and air-dried during 7 days under laboratory standard conditions.

After air-drying, part of each sample was carefully divided for different analyses: [i] part of the original samples was sieved (2 mm) to eliminate coarse soil particles and homogenized for characterization of OC and N contents, C/N ratio and texture; [ii] part of the aggregates were dry-sieved (0.25-0.5, 0.5-1 and 1-2 mm) or measured with a caliper (2-5, 5-10 and 10-15 mm) and separated in different sieve-size classes for determination of WR and OC content; [iii] aggregates 10-15 mm in size were selected for obtaining aggregate layers using a soil aggregate erosion (SAE) apparatus (**Figure 2**) and WR and OC content were determined at each layer; finally, [iv] in order to study the relation between stability to slaking, WR and OC, these properties were determined in 90 air-dried aggregates (about 10 mm in size) selected per treatment (mulched or conventional tillage) and crop (apricot, citrus and wheat). In this case, every set of aggregates was randomly divided in three groups (n = 30) for assessing stability to slaking, WR and OC, respectively.

For analysing stability to slaking, selected aggregates were placed on a 1.5-mm sieve and immersed in distilled water (20 mm depth) during 5 min, and the time for 50% loss of structural integrity was recorded (**Figure 3**). If structural integrity of aggregates is maintained after 5 min, immersion was repeated 5 times and the soil material remaining on the sieve was dried and weighted.

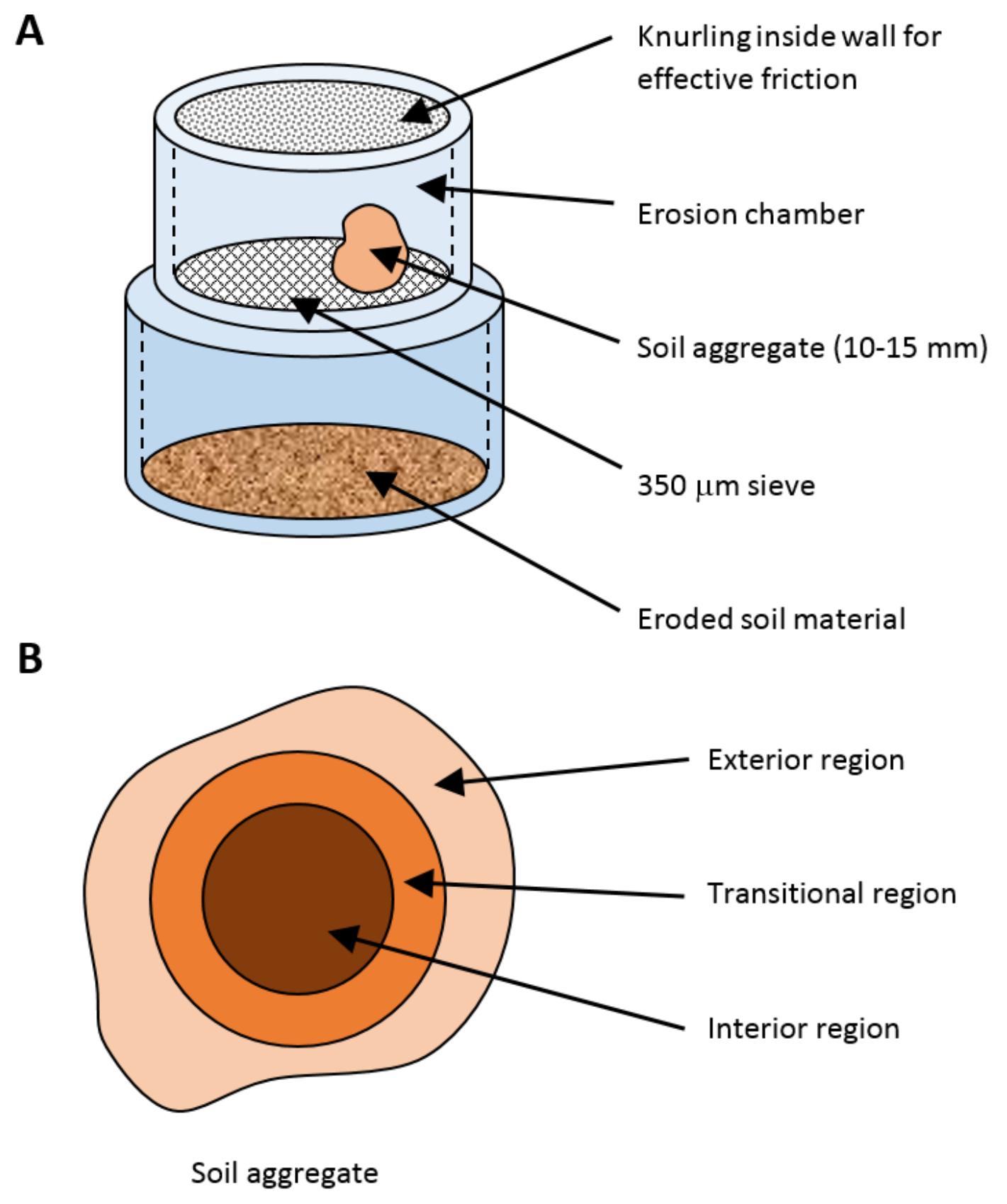

Figure 2. (A) Diagram of the SAE chamber (re-drawn from Park and Smucker, 2005). (B) Layers obtained by abrasion of soil aggregates.

Figure 3. Detail of the stability to slaking test.

Table 1. Results of the ANOVA for organic C content by factors crop, treatment and size fraction (at each group, mean values followed by the same letter did not show significant differences) and results of the Kruskal-Wallis analysis of EPT data by factors crop, treatment and size fraction.

Factor	Group	N	Organic C content (%)		EPT			
			Mean ± standard deviation	ANOVA, p-value	Median	Minimum	Maximum	Kruskal-Wallis, p-value
Crop	Apricot	60	2.00 ± 0.93 b	0.0062	3	2	4	> 0.05
	Citrus	60	1.74 ± 0.89 ab		3	2	4	
	Wheat	60	1.50 ± 0.88 a		3	2	5	
Treatment	Conventional tillage	90	1.00 ± 0.35	0.0000	2	1	3	0.0000
	Mulch	90	2.49 ± 0.57		4	2	5	
Size fraction	0.25-0.5 mm	30	2.20 ± 1.10 b	0.0159	3.5	3	5	0.0000
	0.5-1 mm	30	1.91 ± 0.90 ab		3.5	3	5	
	1-2 mm	30	1.66 ± 0.77 a		3	2	5	
	10-15 mm	30	1.42 ± 0.72 a		2	1	3	
	2-5 mm	30	1.69 ± 0.86 a		2.5	2	4	
	5-10 mm	30	1.49 ±0.76 a		2.5	2	4	

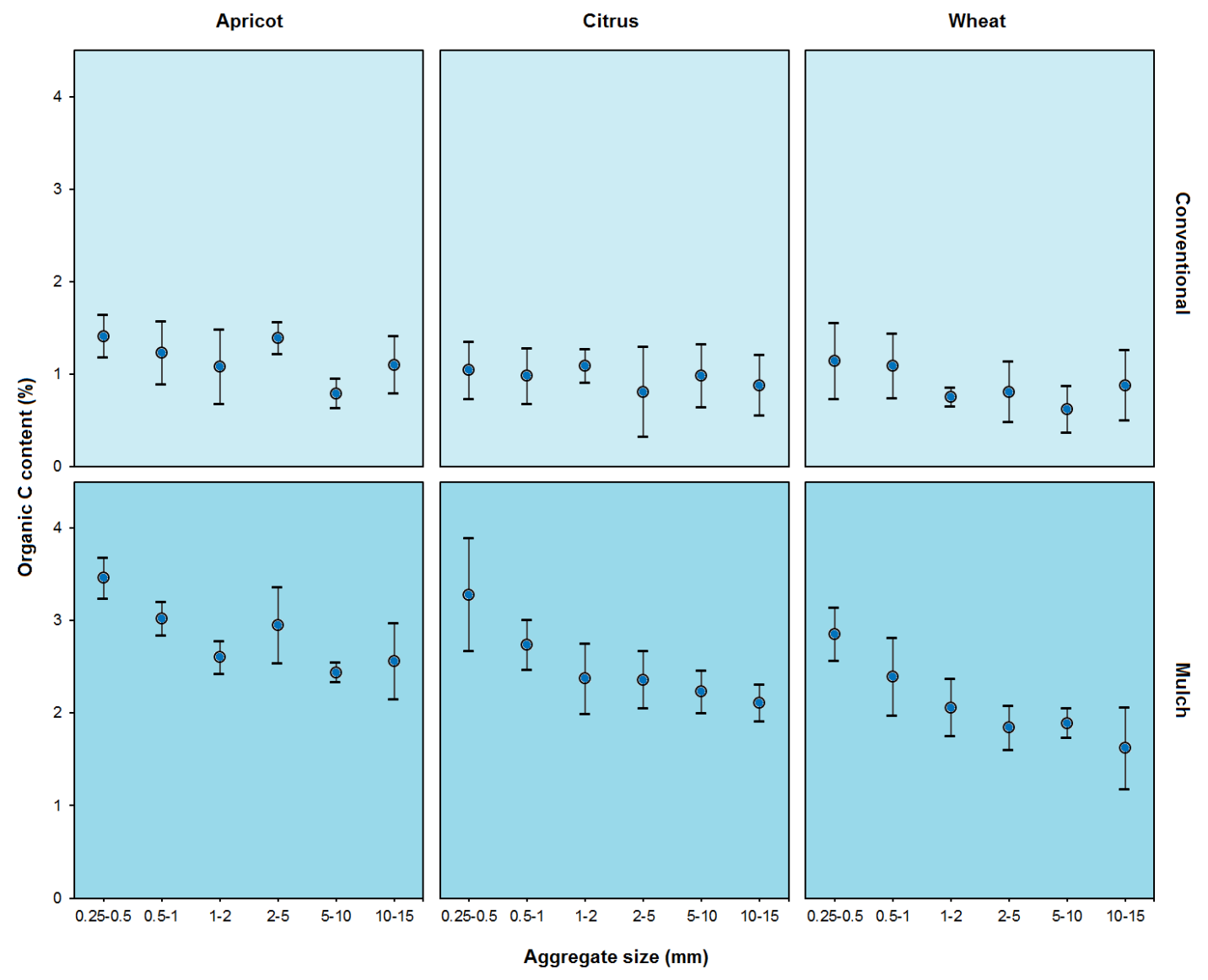

Figure 4. Mean content of organic carbon in differently sized aggregates (0.25-0.5, 0.5-1, 1-2, 2-5, 5-10 and 10-15 mm) from mulched and conventionally managed soils under apricot, citrus, and wheat.

Results and discussion

Organic C

OC content in the fine earth fraction of soils under different crops did not show important variations, although it increased significantly from conventionally tilled to mulched soils (**Table 1**). The distribution of OC content in aggregates with different size varied among soils under different crops, generally increasing with decreasing size (**Figure 4**). In addition, low organic matter inputs and high mineralization rates in conventionally tilled soils may lead to low OC concentrations independently of the size of aggregates and negligible differences. At the intra-aggregate level, OC concentrated preferably in the exterior layer of differently sized aggregates and of aggregate coatings and interior from conventionally tilled soils (**Table 2**), probably because of recent organic inputs or leachates. In the case of mulched soils, higher concentrations were observed, but no significant differences among aggregate regions were found. Our findings suggest that higher inputs of organic residues result in higher OC content but not always in a heterogeneous intra-aggregate distribution.

Distribution of water repellency in sieve-size aggregates

Figure 5 shows the variation of the intensity of WR, determined by the ethanol method, for different aggregate sieve sizes. The EPT value did not show great variations among differently sized aggregates under different crops in the 0-10 cm layer, but increased significantly from conventionally tilled to mulched soils (**Table 1**). Coarser aggregates were generally wettable, while finer aggregates showed slight water repellency.

Distribution of water repellency in aggregate regions

Regardless of variations in the distribution of OC in different layers of aggregate from conventionally tilled soils, great or significant differences in the distribution of water repellency at the intra-aggregate level were not found (**Table 2**). In case of mulched soils such differences were not significant.
It can be assumed that mulching increased soil WR, but did not condition the distribution of hydrophobicity at the intra-aggregate level. Differences in chemical characteristics of organic matter, if existing, are not responsible of the intra-aggregate distribution of WR.

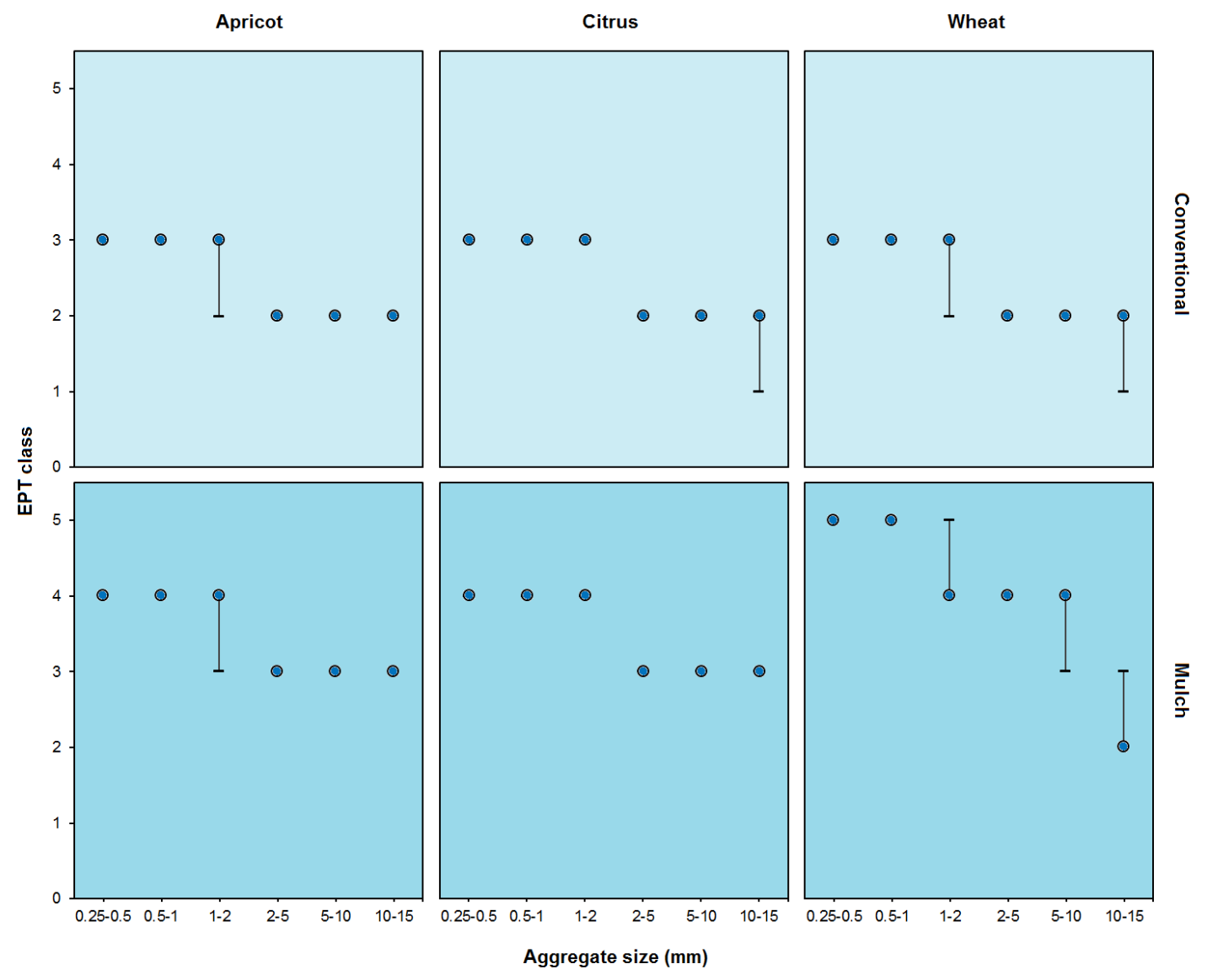

Figure 5. Intensity of WR (median EPT class) in differently sized aggregates (0.25-0.5, 0.5-1, 1-2, 2-5, 5-10 and 10-15 mm) from mulched and conventionally managed soils under apricot, citrus, and wheat. Vertical bars show the range of variation.

Stability to slaking

Stability to slaking varied between crops and treatments (**Table 3**). Median slaking values varied between 3 (apricot and citrus) and 4 (wheat) in conventionally tilled soils and between 4 (apricot and citrus) and 5 (wheat) in mulched soils. In all cases, stability to slaking in mulched soils was 1 unit greater than in conventionally tilled soils. High positive significant correlations were observed between slaking stability and the intensity of WR in most cases (**Table 4**). In contrast, poor (only when all cases were computed together) or non-significant correlations were found between slaking stability and OC. Although soil WR was generally correlated with slaking stability (only conventionally tilled soils under wheat showed no correlation), greater Spearman's correlation coefficients were observed in mulched soils. The intensity of WR seems to be the main responsible of slaking stability, as differences in OC content between conventionally tilled (1.35-1.55%) and mulched soils (4.60-5.25%) cannot explain differences in slaking.

Table 2. Results of the ANOVA for organic C content of soil samples (mean values followed by different letters showed significant differences for the same use and treatment) and results of the Mood's median test (Median test, p) for intensity of soil WR of soil samples from each crop and treatment for different aggregate layers. N=30 for each case.

Crop	Treatment	Layer	Organic C content (%)		Intensity of WR		
			Mean ± standard deviation	ANOVA, p-value	Mean	Range	Median test, p
Apricot	Conventional tillage	Exterior	1.25 ± 0.38 c	< 0.0001	2	(1, 3)	> 0.05
		Transitional	0.94 ± 0.29 b		2	(1, 3)	
		Interior	0.59 ± 0.20 a		2	(1, 3)	
	Mulch	Exterior	2.93 ± 0.49 a	> 0.05	2	(1, 4)	> 0.05
		Transitional	2.97 ± 0.52 a		3	(1, 4)	
		Interior	2.88 ± 0.50 a		3	(2, 4)	
Citrus	Conventional tillage	Exterior	1.03 ± 0.35 c	< 0.0001	2	(1, 3)	> 0.05
		Transitional	0.79 ± 0.29 b		2	(1, 3)	
		Interior	0.34 ± 0.13 a		2	(1, 3)	
	Mulch	Exterior	2.77 ± 0.66 a	> 0.05	2.5	(1, 4)	> 0.05
		Transitional	2.73 ± 0.72 a		3	(1, 4)	
		Interior	2.76 ± 0.73 a		3	(2, 4)	
Wheat	Conventional tillage	Exterior	0.96 ± 0.38 c	< 0.0001	2.5	(1, 3)	0.0100
		Transitional	0.71 ± 0.28 b		2	(1, 3)	
		Interior	0.43 ± 0.19 a		2	(1, 3)	
	Mulch	Exterior	2.28 ± 0.54 a	> 0.05	3	(1, 4)	> 0.05
		Transitional	2.24 ± 0.60 a		2	(1, 4)	
		Interior	2.28 ± 0.71 a		3	(2, 4)	

Table 3. Median vales and ranges (between parentheses) of slaking classes determined in aggregates from soil samples under each crop and treatment. Differences between medians from aggregates under different treatments were significant for all crops (Wilcoxon p-value = 0.0000).

Crop	Treatment	N	Slaking
Apricot	Conventional tillage	30	3 (2, 4)
	Mulch	30	4 (3, 6)
Citrus	Conventional tillage	30	3 (2, 4)
	Mulch	30	4 (4, 6)
Wheat	Conventional tillage	30	4 (3, 5)
	Mulch	30	5 (4, 6)
All cases		180	4 (2, 6)

Table 4. R-Spearman coefficients for slaking/EPT, slaking/OC and EPT/OC. N is 180 (all cases) and 30 (groups). (*) P-value ≤ 0.0.5.

Crop	Treatment	Slaking/EPT	Slaking/OC	EPT/OC
Apricot	Conventional tillage	0.7111 *	0.0913	0.2272
	Mulch	0.9387 *	0.2526	0.1908
Citrus	Conventional tillage	0.8686 *	-0.0901	-0.0117
	Mulch	0.9949 *	0.0558	0.0456
Wheat	Conventional tillage	0.0089	0.2142	-0.1995
	Mulch	0.9919 *	-0.0323	-0.0320
All cases		0.8699 *	0.5245 *	0.4317 *

General implications of results

Evidence of more intense WR on the surface of smaller aggregates is in contrast with the results observed by other authors, who found a trend of increased repellency with increasing aggregate size in severely degraded soils, apparently due to the eluviation of organic compounds and greater microbial activity in macropores. Our results show an opposite trend in agricultural soils, with more intense WR in finer aggregates (mostly below 2 mm), and this trend is even more pronounced in mulched soils, with higher organic matter inputs. This is in agreement with increased organic matter concentration in finer aggregates, as observed in conventionally tilled and mulched soils. Hydrophobic microbial exudates are produced mainly in the surface of macroaggregates in contact with macopores. Consequently, it may be suggested that hydrophobic compounds are leached from coarser to finer aggregates, where biological activity is reduced. In contrast to soils where WR concentrates in the surface of macroaggregates and water infiltration is more efficient, more intense WR in the surface of finer aggregates may limit infiltration rates. Inhibited infiltration caused by water-repellent fine aggregates may contribute to increased runoff rates, what has been previously observed at high organic matter input rates. Consequently, more research is required to determine the effect of WR induced by low or moderate mulching rates in runoff generation, water dynamics and possible implications for nutrient transport or water retention in the root zone.
Our results show that subcritical to moderate WR and increased OC concentration contribute to stability of aggregates in mulched soils. On one hand, WR contributes to decreased slaking stress by reducing the energy release rate caused by entrapped air bubbles during wetting, and, on the other hand, organic substances increase bonding strength between mineral soil particles. Several authors have highlighted the combined role of organic cementing substances and hydrophobic compounds in increasing the stability of soil aggregates. This is especially relevant for agricultural soils, as increased aggregate stability leads to infiltration through macropores, so reducing erosion risk and surface sealing.

Conclusions

The OC content varied in function of soil use, treatments and aggregate size. In general, mulching contributed to enhance soil WR in cropped soils under apricot, citrus and wheat. The OC content varied between aggregates of different size, generally decreasing with increasing diameter. This trend was more intense in mulched than in conventionally tilled soils.
The distribution of OC content in aggregates from mulched soils was homogeneous. Aggregates from conventionally tilled soils showed lower contents, but irregularly distributed, with larger concentrations in the exterior layer of aggregates. This gradient may be caused by recent organic matter inputs.
The intensity of WR (assessed by the EPT) increased with mulching and decreasing aggregate size. Higher intensities of WR found in finer aggregates may be caused by higher OC concentrations, especially in mulched soils. Small or no differences were found among aggregate layers from soils under different uses and treatments. Although OC content did not show any influence in aggregate stability to slaking, the intensity of WR contributed to enhanced stability, especially in mulched soils under all crops considered.
Further research is required to study the impact of these results on runoff generation, soil erosion risk and water dynamics and associated nutrient transport in soils showing subcritical to moderate WR. These issues are especially relevant for conservative management of agricultural soils. Future studies should also consider the effect of the redistribution of hydrophobic substances between and within micro-and macro-aggregates, as well as physical, chemical and biological processes involved.