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Effect of raindrop impact and its relationship with aggregate stability to different disaggregation forces

M.C. Ramos*, S. Nacci, I. Pla

Department of Environment and Soil Science, University of Lleida, Alcalde Rovira Roure, 191, 25198 Lleida, Spain

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Abstract

A soil surface exposed to rainfall is subjected to processes of wetting and drop impact which can lead to the formation of a seal during the rainfall, reducing infiltration and increasing erosion by increasing runoff. The objective of this research was to evaluate the relationship between the effect caused by the drop impact and the aggregate stability of the soils when they are subjected to different disaggregation forces. The aggregates were subjected to cracking (by slow wetting), slaking (by fast wetting) and mechanical breakdown (by mechanical stirring after pre-wetting in ethanol). The effect of each process was evaluated by measuring the mean weight diameter (MWDsl, MWDf and MWDst, respectively) calculated as the sum of the mass fraction of soil left in the sieve after fractionation into four size classes, ranging from <0.25 to 2 mm, multiplied by the mean aperture of the sieve meshes and divided by the initial soil weight. The effect of water impact plus wetting was quantified by the saturated hydraulic conductivity of the seal (Ks) and the time necessary to reach this value. A relative sealing index (RSI) that measured the reduction of water intake caused by sealing was defined as the relationship between the minimum value of saturated hydraulic conductivity of the seal and that reached when the drop impact was avoided. The air-dry material rupture was evaluated with a penetrometer. The main soil characteristics that determine all these processes for the study soils were analysed. Most of the studied soils were very sensitive to slaking and mechanical breakdown, while they were stable when they were subjected to slow wetting. A significant relationship was found between the minimum saturated hydraulic conductivity (Ks) and the MWDst ($R^2=0.40$, $p<0.005$), and between Ks and the MWDf ($R^2=0.69$, $p<0.05$). In both treatments, slaking and mechanical stirring, the percentage of aggregates retained in the larger sieve mesh was also significantly correlated with Ks. This result could indicate that both processes are implicated in the disaggregation produced by drop impact, which contribute to seal formation process. The less stable soils had the lowest Ks value (<1 mm h^{-1}), which was reached in a short

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* Corresponding author. Fax: +34-973-702092.
E-mail address: cramos@macs.udl.es (M.C. Ramos).

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period of time (< 10 min). The high silt content and the low organic matter control the loss of aggregation by mechanical breakdown and the formation of the seal. The RSI values indicated a 200-fold reduction in water infiltration for some soils, caused by the formation of a seal.

Keywords: Aggregate stability; Soil sealing; Hydraulic conductivity; Aggregate size distribution; Slaking; Mechanical breakdown

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1. Introduction

A soil surface exposed to rainfall is subjected to processes that can lead to the formation of a seal during rainfall and to the formation of a crust when the soil dries (Moore and Singer, 1990; Loch and Foley, 1994). Aggregate breakdown produces small soil particles that may then be displaced and reoriented into a more continuous structure, forming a surface seal. The influence of sealing on erosion processes has been studied by different authors (Le Bissonnais and Singer, 1993; Levy et al., 1994; Morin and Van Winkel, 1996, among others) in different soils, and several authors have reported that runoff and erosion susceptibility are linked to aggregate stability, especially in Mediterranean and tropical areas (Barthès and Roose, 2002).

Several methods for measuring the stability of soil aggregates have been developed (e.g., Kemper and Koch, 1966; Keryrabi and Monnier, 1968; Young, 1984; Kemper and Rosenau, 1986; Loch and Smith, 1986; Bruce-Okine and Lal, 1975; Le Bissonnais, 1988, 1989, 1990; Pierson and Mulla, 1989; Beare and Bruce, 1993; Lock and Foley, 1994; Amezketa et al., 1996). Most of them only consider aggregate stability to wetting processes or simulate drop impact, but very few times, both effects are considered together. Although the method by Le Bissonnais (1988, 1989, 1990) or that modified by Amezketa et al., 1996 include some treatment that represents the mechanical breakdown forces for the aggregates, they do not consider the additional effect of drop impact on sealing. Pla (1986), on the other hand, proposed a specific methodology to evaluate the impact of raindrop on the destruction of the structure, which gives rise to a decrease of the infiltration rate, limited by the hydraulic conductivity of the formed seal.

The objective of this research was to evaluate the relationship between the effect of the drop impact and the aggregate stability of the soils when they are subjected to different disaggregation forces (cracking, slaking and mechanical breakdown), and to analyse the soil properties that determine these processes and favour sealing.

2. Material and methods

2.1. Soils

Surface soils (0–20 cm) were sampled from 11 cultivated fields under vines and cereal crops in Catalonia (NE Spain), in which important hydric erosion processes are recorded.

The soil types are listed in Table 1. The slopes of the sites ranged from 2% to 8%. Each soil sample was air-dried, crushed and sieved according to the requirements of each treatment. Particle size distribution (USDA system), organic matter content (OM) and equivalent calcium carbonate content were determined for each soil, using the methods described in Porta et al. (1986).

2.2. Aggregate stability against different disaggregation forces

Aggregate stability against the different disaggregation forces was analysed using the method proposed by Le Bissonnais (1988, 1989, 1990) and adapted by Amezketa et al. (1996). Three different disrupting mechanisms were applied to the 1–2 mm aggregates: slaking caused by fast wetting, cracking caused by slow wetting, and mechanical breakdown caused by stirring after pre-wetting in ethanol. The use of ethanol in the pre-wetting and in the measurement of disaggregation avoids slaking of the aggregates (Amezketa et al., 1996).

In the slow wetting, 4 g of 1–2 mm aggregates was placed in 0.25-mm mesh sieves, which were wetted until saturation using a vapour chamber. Then, they were transferred to the Yoder apparatus and sieved in ethanol. In the fast wetting treatment, 4 g of air-dry 1–2 mm diameter aggregates was placed in 0.25-mm mesh sieves and gently immersed for 10 min in 100 ml of deionised water. The sieves were transferred to a Yoder apparatus and sieved in ethanol. For the stirring after pre-wetting treatment, 4 g of 1–2 mm aggregates was gently immersed in 50 ml of ethanol for 10 min. After that, the ethanol was removed and the aggregates were transferred to an Erlenmeyer flask filled with 50 ml of deionised water, and the level was adjusted to 200 ml. The Erlenmeyer was corked and agitated end over end 20 times and left for 30 min to allow coarse particles to settle. After removing by pipette the excess water, the remaining soil–water mixture was transferred to a 0.25-mm sieve and disaggregation was accomplished by sieving in ethanol. The disaggregation

Table 1
Soil type according to the USDA soil taxonomy (Soil Survey Staff, 1998) and texture, pH, organic matter (OM) and calcium carbonate content of the studied soils

Soil	Classification	Silt (2–50 μm) ($g\ kg^{-1}$)	Clay (<2 μm) ($g\ kg^{-1}$)	Fine sand (50–500 μm) ($g\ kg^{-1}$)	Coarse sand (500–2000 μm) ($g\ kg^{-1}$)	pH	OM ($g\ kg^{-1}$)	$CaCO_3$ ($g\ kg^{-1}$)
s1	Lithic Haploxeralf	466	284	237	13	6.6	21	0
s2	Typic Haploxeroll	342	285	333	40	7.9	32	60
s3	Mollic Palexeralf	391	104	326	179	6.2	18	0
s4	Typic Haploxerept	402	281	246	71	8.0	13	300
s5	Typic Haploxeralf	346	306	258	90	8.2	15	150
s6	Gypsic Haploxerept	609	71	268	52	7.5	21	110
s7	Typic Xerorthent	633	157	205	5	7.8	16	300
s8	Typic Haploxeralf	599	239	136	26	7.9	28	140
s9	Typic Xerofluvent	610	193	154	43	8.0	12	270
s10	Typic Calcixerept	551	240	197	12	8.5	7.5	360
s11	Typic Xerorthent	609	194	154	43	8.2	10	570

consisted of mechanically moving the sieves up and down, 10 times over a distance of 1.3 cm in the ethanol.

Aggregate stability was expressed as the mean weight diameter (MWD), calculated as the sum of the mass fraction of soil (W_i) left in the sieve after fractionation into four size classes, ranging from <0.25 to 2 mm, multiplied by the mean aperture of the sieve meshes (D_i) and divided by the initial soil weight (W):

$$\mathrm{MWD} = \frac{\Sigma W_i D_i}{W}$$

For each treatment, this parameter is represented as MWDsl (for slow wetting), MWDf (for fast wetting) and MWDst (for stirring after pre-wetting). Each treatment was replicated three times. The coefficients of variation (CV) for all soils and all treatments were $<15\%$.

2.3. Effect of drop impact and soil sealing

Surface soil samples were crushed and passed through a sieve of 4-mm mesh. The applied methodology was that proposed by Pla (1986) and improved by Nacci and Pla (1991). One-centimeter-thick layer of 2–4 mm dry aggregates was placed in a 10-cm-diameter Büchner funnel. A 25-cm-high cone was placed along the edge of the funnel to protect against splash losses. The aggregates were subjected to 60 min of simulated rainfall, consisting of deionised water in free-falling 3-mm-diameter drops from 2.5 m above the soils at the rate of 80 mm h^{-1}. Percolated water through the soil layer was measured at 5-min intervals. Values of saturated hydraulic conductivity were calculated over each time interval until reaching a minimum value (Ks), using the corresponding percolated volumes and the hydraulic gradients. These hydraulic gradients were calculated for each interval from the cumulative depth of rainfall and the cumulative percolated water and by assuming that when percolation occurs the soil is essentially saturated with water, and it is 1 cm thick.

The hydraulic conductivity of the soil surface not subjected to drop impact (Kcs) was calculated using a similar layer of aggregates protected with a grid, over which a constant 1-cm layer of deionised water was maintained. Each test was replicated three times.

A relative sealing index (RSI) was calculated by dividing the average minimum saturated hydraulic conductivity of the seal (Ks) and the average minimum saturated hydraulic conductivity of the soil surface (Kcs) obtained for each soil (RSI = Kcs/Ks). RSI indicates the degree of reduction in the water intake rate caused by the soil surface sealing. It also indicates the relative effect of a cover in the prevention of sealing. After each simulated rainfall, the remaining sealed soil samples were air-dried, and the resistance to rupture was measured using a penetrometer with a cylindrical probe of 8-mm diameter.

A test of means (LSI) was done to evaluate significant differences among soils and a regression analysis was performed in order to analyse relationships between the minimum hydraulic conductivity and the MWDs obtained after different treatments and some soil properties, using the Statgraphics Plus 5.0 Program.

3. Results and discussion

The soils used in this study had organic matter contents ranging from 7.5 to 32 g kg^{-1} and relatively high silt and fine sand contents (342–633 and 136–333 g kg^{-1}, respectively) (Table 1). The calcium carbonate content ranged from 0 to 570 g kg^{-1}.

3.1. Aggregate stability to cracking, slaking and mechanical stirring processes

The three applied treatments represent different wetting and energy conditions and these conditions influence the size of the aggregates remaining after disaggregation (Fig. 1). In the fast wetting treatment, the percentage of mass remaining in the sieve is similar in all sizes (ranging from 5 to 25%) except for soils s1 and s5 in which the highest fraction was 40% and 30%, respectively (Fig. 1a). The slow wetting treatment maintained a greater percentage of aggregates in the sieves of larger mesh than in the smaller ones, except for soil s10 (Fig. 1b). These percentages ranged between 10% and 78%, but in more than 50% of the studied soils were higher than 55%. However, for the stirring after pre-wetting treatment, larger differences between soils were observed (Fig. 1c). The percentages of the remaining fractions were very variable among soils. The smaller percentages in all sizes were observed in soil s10 for all treatments.

This information was used to calculate the mean weight diameters for every treatment and soil. The average values and their standard deviation of MWDsl, MWDf and MWDst for the 11 soils (s1–s11) are summarised in Table 2. The range of values differed widely, and values did not always show the same trend across the three treatments. The MWDf values ranged from 0.14 to 0.82 mm, the MWDst values from 0.18 to 1.06 mm, and the MWDsl values from 0.34 to 1.26 mm, although for this last treatment, 82% of soils had values >0.9 mm. The test of means carried out for each treatment showed that according to the MWDsl values, soil s1 was the soil with the highest MWDf (1.26 mm) and significant differences ($p < 0.05$) were observed between it and the rest of the soils, which were separated into two groups: soils s6 and s10 ($0.34 < \mathrm{MWDsl} < 0.42$ mm) and soils s2, s3, s4, s5, s7, s8, s9 and s11 ($0.78 < \mathrm{MWDsl} < 1.04$ mm). According to the MWDst, soil s1 presented the highest value while the lowest was for s10. Soils s1 and s8 (MWDst = 1.06 and 0.94 mm, respectively) and soil s9 (MWDst = 0.18 mm) were significantly different ($p < 0.05$) among them and from the rest of the soils, which could be classified into two groups: one group including soils s2, s3, s4 and s5 ($0.54 < \mathrm{MWDst} < 0.74$ mm), and another including the soils s6, s7, s9 and s11 ($0.32 < \mathrm{MWDst} < 0.46$ mm). Regarding to the MWDf values, the highest value was for soil s1 and the lowest one was for soil s10. Significant differences ($p < 0.05$) were found among soils s1, s5 and s10 (MWDf = 0.82, 0.67 and 0.14 mm, respectively) and with the rest of the soils, which are classified into two groups: soil s2, s7 and s9 ($0.18 < \mathrm{MWDf} < 0.26$ mm) and soils s3, s4, s6, s8 and s11 ($0.37 < \mathrm{MWDf} < 0.57$ mm).

The fast wetting and the stirring after pre-wetting treatments allowed better discrimination among soils than did the slow wetting treatment, although the values of MWDsl were higher than those of MWDf and MWDst. Across all three treatments, s1 was the most stable soil, while soils s6 and s10 were the least stable. The rest of the soils has intermediate values and respond in a different way to the different disaggregation processes.

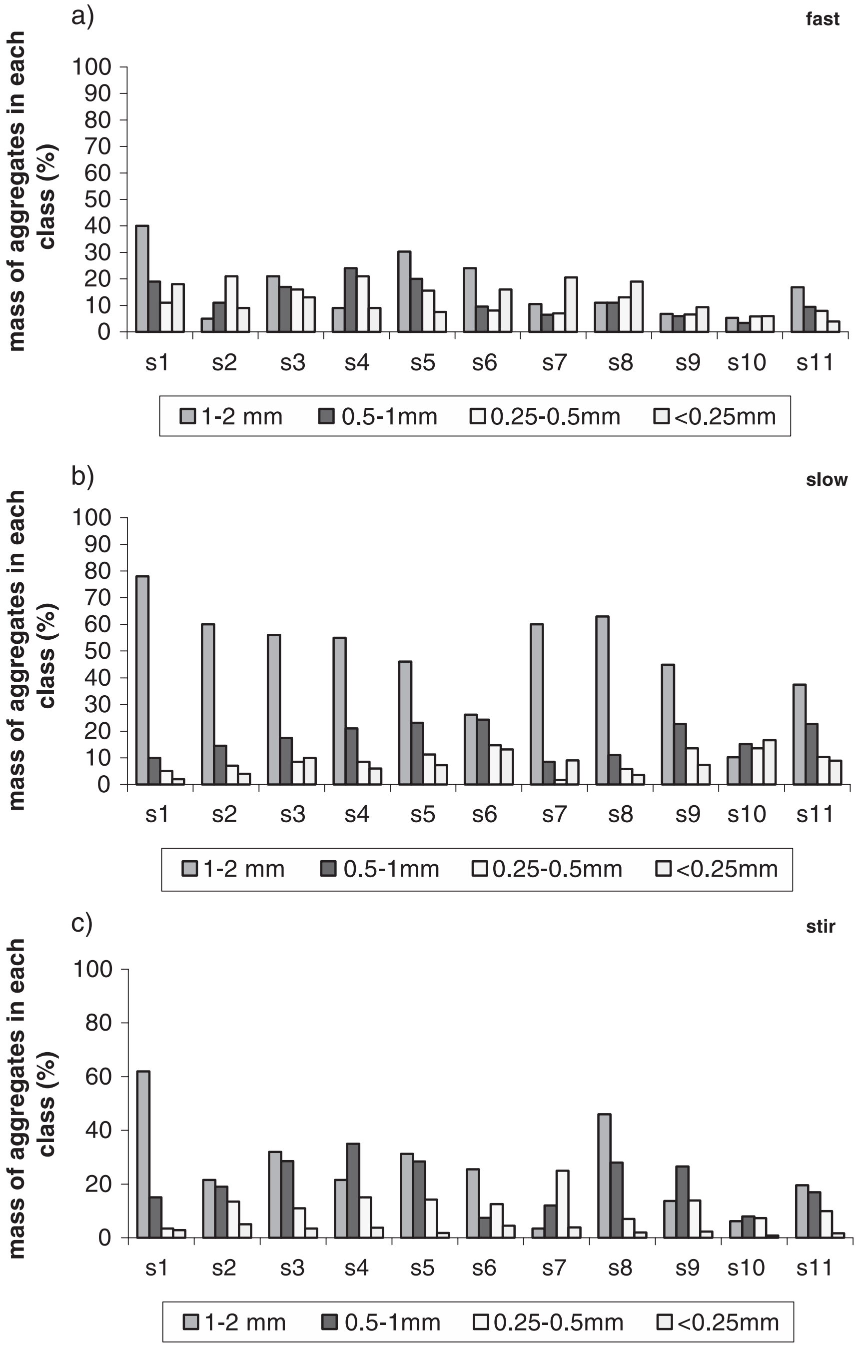

Fig. 1. Size distribution of aggregates after fractionation in four classes (0.25–2 mm) for the three treatments: (a) fast wetting, (b) slow wetting and (c) stirring after pre-wetting.

Table 2
Mean weight diameter of each soil (s1 – s11) following slow wetting (MWDsl), fast wetting (MWDf) and stirring after pre-wetting (MWDst)

Soil	MWDsl (mm)	MWDf (mm)	MWDst (mm)
s1	1.26±0.03 a	0.82±0.01 a	1.06±0.04 a
s2	1.04±0.03 b	0.25±0.02 b	0.54±0.01 b
s3	1.02±0.02 b	0.53±0.01 c	0.74±0.01 b
s4	1.04±0.05 b	0.43±0.01 c	0.66±0.01 b
s5	0.92±0.06 b	0.67±0.03 d	0.70±0.05 b
s6	0.49±0.04 c	0.42±0.05 c	0.39±0.05 c
s7	0.94±0.02 b	0.26±0.01 b	0.32±0.01 c
s8	1.05±0.02 b	0.34±0.02 c	0.94±0.08 a
s9	0.90±0.04 b	0.18±0.01 be	0.45±0.01 c
s10	0.34±0.02 c	0.14±0.01 e	0.18±0.01 d
s11	0.79±0.05 b	0.37±0.03 c	0.46±0.03 c

Different letters indicate significant differences ($p<0.05$).

The differences in the behaviour of the soils against the different disaggregation forces could be influenced by some specific soil properties that determine the response to the different treatments. Those analysed soil properties that allowed the best interpretation of the results were the organic matter and the fine sand and silt content.

With the exception of s2, the above mentioned soils with low MWDf and low MWDst values had high silt contents (>550 g kg^{-1}), which may favour mechanical breakdown (Table 1). These soils were unstable to slaking, and to mechanical breakdown caused by stirring. Soil s2 showed a similar behaviour in response to the treatments, although it has lower silt content but the highest organic matter content of all the soils (32 g kg^{-1}).

Silt contents of soils s3, s4 and s5 ranged from 340 to 400 g kg^{-1}. These soils exhibited high MWDsl, and moderate to high MWDf and MWDst values. The most relevant characteristic for these soils was the coarse sand content, the highest of all the studied soils. Their organic matter content ranged from 13 to 18 g kg^{-1}. The rest of the soils (s8 and s11) presented different response to the three treatments: s8 had relatively low MWDf and moderate values of MWDst and MWDsl, while s11 had relatively low MWDf and MWDst and moderate values of MWDsl. Both soils also had high silt content, similar to those indicated as the less stable (s6 and s10).

The three treatments helped to characterise the effects of different breakdown processes on soil aggregate stability. These breakdown processes simulate variations in rainfall conditions experienced in the field. Fox and Le Bissonnais (1998) indicated that fast wetting treatment might simulate the disaggregation process occurring during heavy storms on dry soils (such storms occur in the study area, especially during the autumn months, following a dry season (Ramos and Porta, 1994). Stirring after pre-wetting might represent the effect of continuous rainfall of low intensity (occurring in the study area especially during spring), and slow wetting might represent the effects of low intensity and dispersed rainfall types.

In view of the characteristics of the rainfall recorded in the study area, the studied soils, with the exception of soil s1, will likely suffer aggregate breakdown, especially as a result of autumn rainfall. This fragmentation will produce smaller particles that will pack together, forming a seal that will then favour runoff.

3.2. Effect of drop impact: soil sealing

Soil sealing susceptibility was evaluated by the minimum value of the hydraulic conductivity (Ks) and the time necessary to reach it. The Ks values ranged from 0.76 to 6.98 mm h^{-1}, although in more than 70% of the cases, the value was <5 mm h^{-1}, and the time to reach it <20 min (Table 3). Soils s10 and s11 were the most susceptible to sealing. Their Ks values were <1 mm h^{-1}, reached in 10–15 min. High percentages of silt and fine sand are the common characteristics of the soils with the lower Ks, which may explain this result. Soils s1 and s2 were the least susceptible to seal formation, with Ks values of >5 mm h^{-1}. Most importantly, they took >35 min to reach the minimum Ks value. They also had one of the highest contents of organic matter of all the tested soils, an observation that implies these soil properties may prevent fast sealing. The test of means of Ks indicates significant differences ($p<0.05$) among soils: s2 (6.98 mm h^{-1}); s1 (5.94 mm h^{-1}); s3, s4 and s5 (Ks = 3.2 mm h^{-1}); s6, s7, s8 and s9 ($1.6<\mathrm{Ks}<2.1$ mm h^{-1}); and s10 and s11 ($0.76<\mathrm{Ks}<0.94$ mm h^{-1}).

The results suggest that water infiltration can be significantly reduced in some soils due to fast formation of a surface seal. Minimum Ks values of 5 mm h^{-1}, reached in less than 10 min, have been proposed as a critical minimum value for rain-fed agricultural soils with gentle slopes (Pla, 1977).

The susceptibility of soils to sealing is affected by soil characteristics, such as organic matter content and percentage of medium-sized particles (silt and fine sand). In the studied soils, the Ks value decreased exponentially with the soil silt content ($R^2=0.70$, $p=0.003$; Fig. 2) and increased with the soil organic matter content ($R^2=0.67$, $p=0.004$; Fig. 3). These results are in agreement with those of Sombroek (1986), Pla (1986) and Norton (1987), who found that high content of silt and fine sand could be a good indicator of high susceptibility to soil sealing.

Table 3
Minimum value of seal hydraulic conductivity (Ks), time in which this value is reached (t_{lim}), relative sealing index (RSI) and resistance to rupture of the dry crust (RR)

Soil	Ks (mm h^{-1})	t_{lim} (min)	RSI	RR (kN m^{-2})
s1	5.94±0.06 a	35	47.5	129.0
s2	6.98±0.19 b	37	19.0	49.7
s3	3.22±0.13 c	23	49.7	138.0
s4	3.92±0.12 c	15	89.5	313.3
s5	3.25±0.10 c	10	162.5	309.2
s6	2.01±0.12 e	19	79.6	174.6
s7	1.93±0.17 e	18	110.0	238.0
s8	1.38±0.16 e	15	298.2	839.2
s9	1.68±0.12 e	15	50.6	1234.8
s10	0.94±0.15 d	15	216.0	588.0
s11	0.76±0.09 d	10	91.3	1617.0

Different letters indicate significant differences ($p<0.05$).

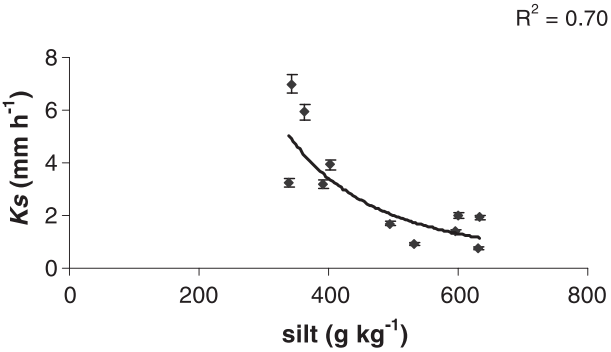

Fig. 2. Relationship between the minimum saturated hydraulic conductivity value (Ks) and the silt content.

3.3. Relationship between Ks and the MWDs

A significant relationship was found between the minimum saturated hydraulic conductivity (Ks) and MWDst ($R^2 = 0.40$, $p < 0.005$), and between Ks and MWDf ($R^2 = 0.69$, $p < 0.05$) (Fig. 4). Taking into account that low values of MWDs indicate greater disaggregation, these correlations point out the lower the Ks values, the more susceptible to sealing are the soils. In both treatments, slaking and mechanical stirring, the percentage of aggregates retained in the larger sieve mesh was also significantly correlated with Ks. However, no additional effects were observed in Ks when both treatments were considered (there was no increase in the explained variance). This result indicated that for the studied soils, although both processes are implicated in the disaggregation produced by drop impact and seal formation, slaking is the most relevant process, and MWDf could be used as a measure of soil sealing susceptibility.

The highest relative sealing index (RSI) value was that of soil s8 (Table 3), indicating a reduction in saturated hydraulic conductivity caused by sealing of about 300-fold. The soil with the least reduction in water infiltration by the seal was s1, with an RSI value of 19. In

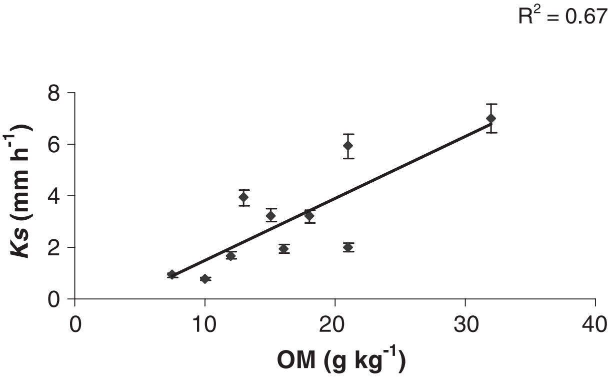

Fig. 3. Relationship between the minimum saturated hydraulic conductivity value (Ks) and the organic matter content (OM).

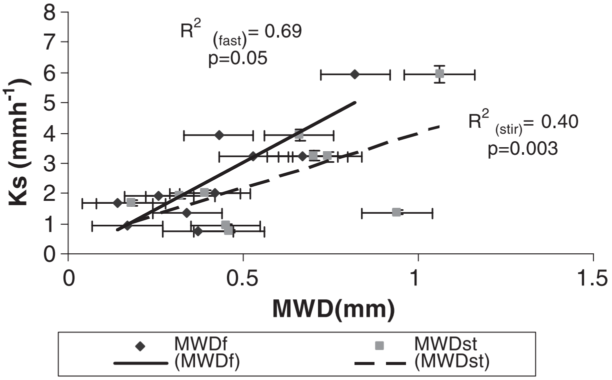

Fig. 4. Relationship between the minimum saturated hydraulic conductivity value (Ks) and the mean weight diameter resulting with fast wetting (MWDf) and with stirring after pre-wetting (MWDst).

this soil, the seal was less restrictive (Ks>5 mm h^{-1}) and took more than 20 min to form. The degree of improvement in the saturated hydraulic conductivity when direct drop impact on a soil is avoided allows us to predict which soils may benefit most from the use of a cover to improve surface infiltration of rainfall water. Such improvement was observed in all these soils. The RSI showed that especially s8 and s10 could benefit from the use of a cover, to protect the soil surface against drop impact, and to improve water intake in the profile by preventing seal formation and reducing runoff. The analysis showed significant differences for these two soils. Thus, managing land in the areas studied should, therefore, consider the implementation of management practices that provide a soil cover.

The resistance to rupture (RR) of the crust, formed after the treated soils were air-dried covered a wide range, from 50 to 1617 kN m^{-2} (Table 3). Soil s2 had the lowest value, in agreement with its high percentage of organic matter. Significant potential correlation between RR and OM content was found ($R^2 = 0.75$, $p < 0.05$), decreasing RR when OM increases (Fig. 5). On the other hand, a trend to increase RR with silt content was observed, although the correlation was not significant. Soils s11, s9 and s8 (in this order),

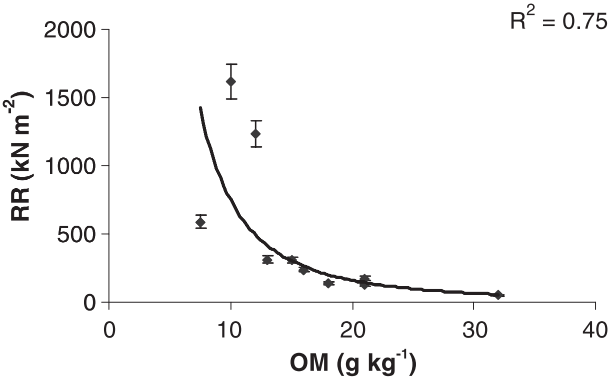

Fig. 5. Relationship between the resistance to the rupture (RR) and the organic matter content (OM).

all with more than 700 g kg^{-1} silt plus fine sand, and with relatively high contents of calcium carbonate, had the highest resistance to penetration values. The values reported might depend on the particular penetrometer used, but they do provide preliminary information about the effect of the seal and the crust that could be formed in each soil.

Among the studied soils, the highest values of resistance to penetration were observed for soils with low Ks values (ranging from 0.76 to 1.68). These were also soils with very low MWDf and MWDst.

4. Conclusions

For the studied soils the same relative trends in aggregate stability against different disaggregation forces were evident when the soils were either very stable or very unstable. However, most of the studied soils are very susceptible to the loss of stability by slaking and by mechanical stress and very susceptible to seal formation. Their saturated hydraulic conductivities were very low, and those values were reached after 10 to 30 min of simulated rain.

The minimum saturated hydraulic conductivity of the seal was significantly correlated with the mean weight diameter observed after the fast wetting and after the stirring after pre-wetting treatments. This result confirms that the effect of drop impact on disaggregation affects both slaking and mechanical breakdown. However, the stronger correlation between Ks and MWDf indicates that slaking has relatively more importance than mechanical breakdown in seal formation.

The less stable soils are those with the highest silt content. This parameter is one of the most significant ones for seal formation. The soils with a low organic matter content showed a higher susceptibility to seal formation and a higher crust resistance than did the soils containing more organic matter.

The RSI values indicate that water infiltration could increase by as much as 300 fold using a cover that reduces seal formation.

The resistance to the rupture after crust formation was influenced not only by the size distribution of soil particles, but also by the organic matter and the calcium carbonate content of the soils.

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