DYNAMICS OF AGGREGATE DESTABILIZATION BY WATER IN SOILS UNDER LONG-TERM CONSERVATION TILLAGE IN SEMIARID SPAIN

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Abstract

Due to particular soil and climate conditions and inappropriate agricultural practices, Aragon (NE Spain) is a region prone to land degradation by water erosion. For this reason, the adoption of conservation tillage systems has been encouraged as an alternative to preserve soil and water in this region. However, little information concerning soils on which these techniques are applied is available. The main objectives of this study were to assess the effect of long-term no tillage (NT) on water aggregate stability in five different cereal production areas of Aragon and identify the main mechanisms involved on aggregate breakdown. The study was conducted under on-farm conditions where pairs of adjacent fields under NT and conventional tillage (CT) were compared. In all cases, a nearby undisturbed soil under native vegetation was included. Soils were slightly to highly calcareous with medium textures ranging from sandy loam to silty clay loam. Results indicate that NT increased surface aggregate stability with respect to CT systems through lower soil disturbance and higher organic carbon (OC) content at the soil surface (0-5 cm depth). Slaking was the dominant disaggregation process of the cultivated soils, representing 40-80% of total soil disruption, and was strongly and negatively affected by aggregate-associated OC. This soil property together with the silt content (weak and positive effect) explained more than 80% of the slaking variation. Swelling and clay dispersion were less frequent processes and their occurrence seemed to be associated with high silt and $CaCO_3$ contents. This study shows that, under the rainfed conditions of semiarid Aragon, NT reduces the susceptibility of soil surface to crusting and water erosion as compared to CT systems.

Keywords: Water aggregate stability; slaking; no tillage; soil organic carbon; dryland cereal farming.

1. Introduction

Characterization of near-surface soil water stability is essential to predict soil susceptibility to crusting and erosion. This acquires special relevance in agricultural soils where a stable soil structure is required for good water infiltration and aeration, optimal seedling emergence and root growth, and, finally, sustainable productivity (Carter, 2004; Bronick and Lal, 2005). Soil aggregate stability is being used as an indicator of soil quality since soil structural stability depends on the presence of stable aggregates (Amézketa, 1999; Nimmo and Perkins, 2002). However, the determination and interpretation of this parameter is often difficult due to the numerous factors affecting it as well as to the interactions among them. As it is detailed in the review of Amézketa (1999), these factors can be classified into soil internal and external factors. Internal factors include, among others, organic matter, texture, clay mineralogy, electrolyte and sesquioxides (Chenu et al., 2000; Six et al., 2000; Kaewmano et al., 2009; Reichert et al., 2009). Climate, biological activity and soil management are identified as external factors affecting water aggregate stability (Blanco-Canqui et al., 2009; Pikul et al., 2009; Peng et al., 2011). However, despite much research effort, there are still many contradictory results and further understanding of the different processes of soil destabilization in water is necessary. In addition, there are numerous different methods for measuring soil water stability which complicates the interpretation of results and the comparison among different studies (Amézketa, 1999; Díaz-Zorita et al., 2002; Nimmo and Perkins, 2002).

The wet sieving procedure proposed by Kemper and Koch (1966), and later improved by Kemper and Rosenau (1986), is the most widely used method to determine water aggregate stability (WAS). However, this method does not discriminate among the different destabilizing mechanisms of soil aggregates in water (slaking, swelling, clay dispersion and mechanical breakdown by abrasion). To overcome this limitation, Le Bissonnais (1996a) proposed a new method based on the use of pretreatments and wet sieving in ethanol. Although this method has been shown to be suitable in rainfall erosion studies (Amézketa et al., 1996; Legout et al., 2005), it is not a routine procedure in soil laboratories. This is probably because it is a laborious and time-consuming method, especially when there are many samples to analyze. Another approach was proposed by Zanini et al. (1998) who established an exponential equation to describe the dynamic features of soil aggregate breakdown as a function of wet sieving time. In this way, the loss of aggregates caused by water abrasion is separated from that due to initial wetting phase. This has not been a widely used method in spite of it has been validated and proved its usefulness to distinguish among soils and even among horizons of the same soil (Scalenghe et al., 2004; Falsone and Bonifacio, 2006).

Due to particular soil and climate conditions, Aragon (NE Spain) is a region prone to land degradation by water erosion (Lasanta et al., 1995; García-Ruiz, 2010). In addition, inappropriate agricultural practices, such as cropping systems that leave soil surfaces bare during long periods of time (fallowing), excessive tillage and overgrazing are main driving forces for agricultural soil degradation in the region. For this reason, the adoption of conservation tillage systems has been encouraged as an alternative to preserve soil and water in this region. In fact, according to previous results on soil and crop response in cereal production areas of Aragon (López et al., 2005; Moret et al., 2007; Álvaro-Fuentes et al., 2009), conservation tillage could be regarded as a viable management alternative. Furthermore, a recent survey conducted by the Department of Agriculture and Food of the Government of Aragon (Vallés, 2009) found a very positive perception of the advantages of these tillage systems by farmers and an increasing adoption in the last years, especially of no tillage (NT). However, this report also highlights the lack of knowledge about the soils on which these systems are applied.

The little available information on WAS of cultivated soils in Aragon has demonstrated the high susceptibility of these soils to surface sealing and crusting (Martí et al., 2001; Amézketa et al., 2003; Ries and Hirt, 2008). In this regard, Álvaro-Fuentes et al. (2008) showed the suitability of NT to increase wet stability of soil aggregates in semiarid Aragon. This study was carried out in small research plots and for single soil types and, however, farming practices applied by farmers in their fields can be very diverse and differ from those in experimental plots. For these reasons, direct measurements under on-farm conditions across different soils, microclimate and agronomic practices are necessary to get a broad knowledge of the potential of conservation tillage in the region (López et al., 2012). In order to remedy this lack of information, the objectives of this study were to (1) asses the effect of long-term NT on WAS compared with traditional tillage practices and undisturbed soils under native vegetation in different cereal production areas of Aragon, (2) identify the main destabilization processes of soil aggregates in water, and (3) establish relationships between WAS and aggregate-associated organic carbon (OC) to understand the role of soil OC on soil structural stability.

Material and methods

2.1. Description of the study sites

The study was conducted at six long-term NT fields (9-21 years) representative of the different scenarios of NT in the region and located in areas receiving a mean annual precipitation ranging from 350 to 740 mm (Table 1 and Fig. 1). These fields were selected from a previous study where 22 soils under NT were characterized across different rainfed cereal areas of Aragon to assess the potential of this practice to increase soil surface OC (López et al., 2012). With the exception of the Peñaflor site, the study was carried out under on-farm conditions (fields of collaborating farmers) where pairs of adjacent fields under NT and conventional tillage (CT) were compared. In Peñaflor, the study was carried out in research plots from a long-term tillage experiment at the dryland research farm of the Estación Experimental de Aula Dei (Consejo Superior de Investigaciones Científicas). In this case, tillage treatments (NT, CT and reduced tillage, RT) were arranged in a randomized complete block design with 3 replicates. More details about the Peñaflor site can be found in López et al. (1996). In all sites, an undisturbed soil under native vegetation (NAT) and close to the NT and CT fields was included in the study for comparison purposes.

Information on location and soil management characteristics for each site are shown in Table 1 and detailed in a previous study (Blanco-Moure et al., 2012). It should be noted, briefly, the case of Artieda, the study site located in the area with the highest rainfall and hence highest production. As a common practice in this area, farmer removes the straw from the NT and CT fields to prevent later problems with seeding. The information in Table 1 reflects the diversity of cropping systems and the reality of the conservation agriculture in the region (López et al., 2012). Therefore, following the remark made by Blanco-Canqui and Lal (2008a), the present study shows data on the effect of NT- and CT-based cropping systems on WAS rather than those of tillage alone.

The studied soils were medium-textured soils, varying from sandy loam to silty clay loam, alkaline (pH>8; $CaCO_3$ contents of 50-560 g kg^{-1}) and generally with low OC contents (<20 g kg^{-1} for agricultural soils). Basic properties of the study soils for the first 5 cm depth are shown in Table 2 since it was the depth at which we have focused for the characterization of the water aggregate stability. In each site, both NT and CT fields were contiguous and the NAT soil close to them, thus ensuring that soil type and topography were as similar as possible. The differences observed are attributed to the soil management itself.

2.2. Soil sampling and analyses

In the farmer fields, soil surface sampling (0-5 cm in depth) was made in three different zones within each field (NT, CT and NAT) where three soil samples were collected and mixed to make a composite sample. In the Peñaflor site, each of the composite samples came from each of the 3 tillage plots per treatment (NT, RT and CT). Once in the laboratory, soil samples were air dried at room temperature (≈20 ºC) and dry aggregates of 1-2 mm in diameter were obtained by dry sieving to determine WAS and OC content.

Water aggregate stability was measured following the single-sieve method of Kemper and Rosenau (1986) by using a modified Yoder apparatus (Yoder, 1936). Two approaches were used to estimate the relative importance of the different mechanisms of destabilization of soil aggregates in water. The first involved the application of the exponential model proposed by Zanini et al. (1998) to the wet sieving data at different time intervals. In this way, the breakdown of soil aggregates caused by water abrasion (time dependent) can be discriminated from that due to the fast wetting (slaking, swelling and clay dispersion). Following Falsone and Bonifacio (2006), the second approach included prewetting soil aggregates with ethanol to prevent aggregate disintegration by slaking (Le Bissonnais, 1996a).

In the first step, 10 g of 1-2 mm aggregates were placed on the top of a 0.25 mm mesh sieve and sieved in distilled water during 1, 5, 10, 20, 40 and 60 minutes (34 strokes min^{-1}; stoke length of 1.3 cm). After these times, the soil retained on the sieve was transferred to an aluminium pan, oven-dried and weighed. Sand correction was made by dispersing stable aggregates with sodium polyphosphate (5 g L^{-1}) and sieving through the 0.25 mm sieve. The percentage of unstable aggregates (100-WAS) after the different time intervals was fitted to the exponential model of Zanini et al. (1998):

$$y(t) = a + b\ (1\text{-}\exp(-t/c)) \qquad (1)$$

where y is the percentage of broken aggregates in a given time, t the sieving time, a estimates the losses of aggregates during fast wetting, b is the maximum estimated abrasion loss of aggregates and c is a time controlling factor equal to 1/3 of the time interval at which approximately 95% of the total loss (a+b) is reached. All determinations were done in duplicate, obtaining a minimum of 18 destabilization curves per site (24 in Peñaflor) (3 or 4 treatments x 3 replicates x 2 tests).

In the second step, another sample of 10 g of 1-2 mm aggregates was gently immersed in ethanol (96%) for 10 min before being sieving in water for other 10 min. Then, the amount of aggregates that had resisted the sieving were collected and dried, and its weight corrected for sand. The percentage of disintegrated aggregates by slaking was then calculated as the difference between the aggregate loss after 10 min of sieving with and without the ethanol pretreatment.

The OC content of 1-2 mm soil aggregates was determined directly by dry combustion with a LECO analyser (RC-612 model), without requiring correction for carbonates. For the general characterization of soils (Table 2), particle size distribution was obtained by laser diffraction analysis (Coulter LS230), OC and $CaCO_3$ contents by dry combustion with the LECO analyser, and electrical conductivity (EC) and pH by standard methods (Page et al., 1982).

2.3. Statistical analyses

At the four sites where the study was conducted in large farm fields, the NT, CT and NAT treatments were not field replicated. However, in each of the sites, the three fields were contiguous and sited on similar landscape position and same soil. Therefore, the three sampling locations within each field were used as pseudoreplicates and statistical comparisons among treatments were made using one-way ANOVA assuming a randomized experiment (Christopher et al., 2009). In the case of the Peñaflor site, the randomized complete block design with three replicates per tillage treatment (CT, RT and NT) was also applied and statistical results were compared with those obtained from the pseudoreplicate analysis.

Duncan's multiple range test was used to compare treatment means (P<0.05). Wet sieving data obtained at the different time intervals were fitted to the proposed exponential model (Eq. 1) by nonlinear regression procedure. Correlation and regression analyses were performed to identify and evaluate the degree of relationship among the measured properties. When data showed non-normality, transformations were made and ANOVA conducted with the transformed data. Computations were performed using SPSS 19.0 statistical software.

3. Results and discussion

3.1. Tillage effects on water aggregate stability

Figure 2 shows the dynamics of soil aggregate breakdown during wet sieving as function of soil management and tillage for each of the study sites. In all sites, significant differences between cultivated and NAT soils were evident during all the sieving time. With the exception of the Lanaja site, NAT soils were highly resistant to water action since the loss of aggregates after 60 min of sieving never exceeded 50% (Fig. 2 and Table 3). The high percentage of loss in the NAT soil of Lanaja (nearly 80%) can be explained because this soil is located in an abandoned agricultural terrace (>40 years) that is frequently grazed by livestock (see Table 1). In contrast, the cultivated soils showed low structural stability with losses of soil aggregates of 30-90% already after the first min of wet sieving. A general trend of decreasing soil resistance from the most humid sites (≈700 mm yr^{-1} in Undués de Lerda and Artieda; see Table 1) to the drier ones (300-500 mm yr^{-1} in Peñaflor, Lanaja and Torres) can be observed. This high susceptibility of the cultivated soils to disruption by water is common in arid and semiarid regions due to their limited biomass production, poor soil cover and, generally, low soil OC content. Zanini et al. (1998) found mean percentages of aggregate breakdown of 80% in a wide range of Italian agricultural topsoils against 18-60% in natural soils. In SE Spain, Caravaca et al. (2004) obtained disruption percentages of about 60% which represented approximately twice that in the natural soils of the area. Percentages greater than 80-90% have been registered in cultivated soils of other semiarid regions of Spain (Hernanz et al., 2002; Fernández-Ugalde et al., 2009; Martin et al., 2011), indicating the negative effect of cultivation on soil structural stability in these environments.

With respect to tillage system, soil aggregates from the NT fields were, in general, more resistant to water action than those from CT and RT though not always in a significant way (Fig. 2). This indicated a site specific response to soil management. Likewise, an exception was found in the Artieda site where aggregate losses were slightly lower under CT, especially during the first minutes of wet sieving (12% lower in 5 min; Table 3). As previously indicated, in the areas with higher rainfall and hence higher production, as it is the case of Artieda, farmers remove the straw from the field to prevent later problems with seeding. In some cases, soil cover by residues retained in the field was low (<30%) and, strictly speaking, this would not be a conservation tillage system. However, it was considered in the present study because it is a common practice in some areas of Aragon. This decrease in WAS with crop residue removal can be, probably, due to a concomitant reduction in stover-derived organic binding agents required for the formation of stable aggregates (Blanco-Canqui and Lal, 2008b). At the rest of the sites, aggregates from NT soils were between 1.1 and 2.5 times more stable compared to those from CT and RT (calculated from the 5 min values; Table 3). These figures are within the range of increments registered for different regions of the world, including Spain, (1.1-3.7 times greater with NT than with CT) (Mrabet et al., 2001; Hernández-Hernández and López-Hernández, 2002; Hernanz et al., 2002; Abil and Lal, 2008; Álvaro-Fuentes et al., 2008; Fernández-Ugalde et al., 2009; Pikul et al., 2009; Martin et al., 2011). As explained in these studies, with NT the suppression of tillage and the OC enrichment in soil surface leads to an enhanced biological activity and more stabilizing organic compounds, thus contributing to soil stability with respect to CT systems.

Water aggregate stability can be also affected by cropping system (Hernanz et al., 2002; Álvaro-Fuentes et al., 2008). In the present study, at the Peñaflor site the differences among tillage treatments were lower under the cereal-fallow rotation (CF) than under the continuous cereal cropping (CC) (Fig. 2). This was due to both an increase in WAS in CT and a reduction in NT under CF as compared with CC. In the case of the CT treatment, the soil is less frequently disturbed by tillage under CF (tillage every two years vs. all years in CC) which leads to a reduction in the aggregate breakdown and, therefore, in the formation of weak aggregates. In contrast, in the NT treatment a better soil condition was observed under CC probably due to the annual input of crop residues to the soil surface in CC and only every two years in CF. As shown below, in NT the higher OC of both bulk soil and 1-2 mm aggregates under CC than under CF seems to reinforce this idea (Table 2 and Fig. 3). Likewise, these results are supported by previous studies (Saber and Mrabet, 2002; Shaver et al., 2002; Álvaro-Fuentes et al., 2008) that conclude that, in NT soils, the suppression of long fallowing can significantly increase surface OC and WAS.

3.2. Mechanisms of aggregate destabilization by water

With the purpose of identifying the main mechanisms of aggregate destabilization by water, the exponential model proposed by Zanini et al. (1998) (see Eq. 1) was fitted to the experimental data. The adjustment was considered satisfactory with r^2 values of 0.940-0.994 (Table 3 and Fig. 2). Data on Table 3 show that abrasion by agitation in water was the main process of aggregate disruption in the NAT soils (b=9-37% aggregate losses). In contrast, in the cultivated soils, with the exception of Undués de Lerda (hereafter, Undués), initial fast wetting was the primary disruptive mechanism (a=48-91% losses). In Undués, 44% of aggregates from the CT and NT soils were broken by mechanical abrasion (b) and around of 30-40% during initial wetting (a). As discussed below, the greater resistance of the cultivated soils at this site can be related to the comparatively high OC contents in both bulk soil and 1-2 mm aggregates (Table 2 and Fig. 3).

Among the mechanisms responsible for the destabilization of soil aggregates during the initial wetting, slaking was the dominant or sole process, representing between 70 and 100% of the initial breakdown (Table 3). The unique exception was found at the Lanaja site in CT with a 30% of slaking. Slaking is caused by the compression of air entrapped inside dry aggregates during rapid wetting and it is associated with the disruption process occurring during heavy rainfall on dry soils (Le Bissonnais, 1996a; Amézketa, 1999). Intense rain after long dry periods is common in the study area (Beguería et al., 2009) and, therefore, it is expected that considerable particle detachment occurs on weak structured soils when rain starts to fall.

Slaking was also affected by soil management and tillage (Table 3). The soils most resistant were the NAT soils with low percentages of slaking (<12%). This percentage reached nearly 40% at Lanaja due to the semi-natural conditions of this field. Regarding the cultivated soils, slaking was significantly reduced with NT as compared to CT and RT (10-20% less) in 4 of the 6 study sites. The same exceptions observed for aggregate breakdowns after 5 and 60 min repeated here. Thus, in the case of Artieda, the opposite behaviour can be explained again by the negative impact of crop residue removal from the NT field. At Lanaja, the also greater slaking in NT that in CT was offset by the lower aggregate loss by swelling and clay dispersion (Table 3). With the exception of this site, soil disintegration by swelling and clay dispersion was low or null and, when it occurred, only affected the CT soils. Probably, in these highly disturbed soils, dispersion of cementing material can be facilitated by slaking (Le Bissonnais, 1996a; Zaher and Caron, 2008).

3.3. Water aggregate stability and organic carbon

With the goal to advance, as far as possible, in the understanding of the effect of soil organic matter on soil structural stability, relationships between aggregate-associated OC and different aggregate breakdown processes were established. Organic carbon contents of 1-2 mm soil aggregates for the different soil management and tillage systems at each of the study sites is shown in Figure 2. With the exception of Lanaja, aggregates from the NAT soils had the highest OC contents (1.2-2.6 times higher than cultivated soils). Regarding the cultivated soils, NT enhanced aggregate-associated OC with concentrations between 30 and 60% higher than those from CT and RT. The exception was again Artieda where OC content was nearly the same under NT and CT (Fig. 3).

Significant negative relationships (r^2=0.739-0.762; P<0.001) were obtained between aggregate-associated OC and the percentage of aggregate breakdown produced by slaking, during initial fast wetting (a) and after 60 min of wet sieving (T_{60}) (Fig. 4). These results are consistent with numerous studies showing the role of soil organic matter in the formation and stabilization of soil aggregates (Chenu et al., 2000; Bronick and Lal, 2005). In our study, the similar response of the three above processes of aggregate disruption to the change in OC (Fig. 4) seems to further support the finding that slaking is the dominant process of soil disaggregation by water in the study area. This observation implies that the beneficial effect of soil organic matter in stabilizing aggregates against slaking is crucial to control soil crusting and erosion in the region. The literature shows that soil organic matter provides this protection through two main characteristics. First, organic matter increases intra-aggregate cohesion through binding mineral particles by organic substances or through physical entanglement of soil particles by fine roots, fungi, bacteria and other microorganisms (Wuddivira et al., 2008; Chenu and Cosentino, 2011). Second, organic matter increases aggregate hydrophobicity slowing down the rate of water penetration in the aggregate porosity and stabilizing soil pores (Chenu et al., 2000; Pikul et al., 2009). These protection mechanisms could explain the very low slaking found in the NAT soils, especially at Artieda and Undués, where, besides high soil biological activity, entangled meshes of soil aggregates, fine roots and organic debris were easily observed in the field. Although to a lesser extent, this same effect of soil OC is also applicable to the NT soils. In these soils, the lack of tillage can also result in the formation and maintenance of a network of interconnected pores within soil aggregates that serves as direct conduits to the surface for air flow. In this way, slaking in the NT soils is reduced with respect to the tilled soils when aggregates are fast wetted (Pikul et al., 2009).

Figure 4 shows a fast increment in the aggregate loss for OC contents less than about 17-20 g kg^{-1}. Curvilinear relationships between WAS and OC has been also described for other soil types and conditions (Kemper and Koch, 1966; Le Bissonnais, 1996b). Following Le Bissonnais (1996b), these non-linear relations could be due to the interactions between soil organic matter and other soil cementing components. In our study, the OC content of 17-20 g kg^{-1} could be considered as a critical value for aggregate stability of the soils in Aragon. This critical value corresponds to 30-34 g kg^{-1} in organic matter and it is within the range of threshold values found in the literature for different types of soils, 15-35 g kg^{-1} (De Ploey and Poesen, 1985; Albrecht et al., 1992; Le Bissonnais and Arrouays, 1997; Kay and Munkholm, 2004). This indicates that for soils poor in organic matter, small increments in OC may conduct to a significant improvement in structural stability. Results from the present study show that this improvement can be achieved by replacing CT with NT systems.

Aggregate-associated OC did not affected soil destabilization by swelling and clay dispersion. The fact that these disruption processes were only significant in Lanaja (especially under CT) indicates that other soil properties should be influencing WAS. Correlation analysis among the different aggregate destabilization mechanisms and soil basic properties (texture, EC, pH, $CaCO_3$) showed that silt content was significantly and positively related to the percentage of disaggregation by swelling plus clay dispersion, by slaking as well as to that produced during initial fast wetting and after 60 min of wet sieving (r=0.298-0.386; P<0.05). The silt influence, although weak (explaining only 9-15% of the variation), is supported by previous observations on the instability to water of soils with high silt contents (Dimoyiannis et el., 1998; Grønsten and Børresen, 2009; Reichert et al., 2009). In Spain, Ramos et al. (2003) found an increased soil susceptibility to seal formation with silt content for cultivated soils with silt concentrations similar to ours (300-600 g kg^{-1}). Le Bissonnais (1996b) noted that the increase in soil erodibility with the amount of silt is due to the low capacity of aggregation of these particles and the facility to be transported for its small size. Other authors pointed that, in silty soils with low OC content, organic anions could not be large enough to attach the edge of mineral particles and bind them together (Emmerson, 1977; Shanmuganathan and Oades, 1983; Amézketa, 1999). According to these relations, the elevated silt content (reaching 600 g kg^{-1}) together with the low OC (11-18 g kg^{-1}) of the soils at Lanaja could explain the high soil instability at this site. Furthermore, the regression between swelling plus clay dispersion and silt content was slightly improved when $CaCO_3$ was included (Table 4). The destabilizing role of $CaCO_3$ is not surprising since there are studies showing that the direction of this effect depends on other soil properties, such as organic matter content, clay mineralogy and size distribution of the carbonate particles (Le Bissonnais, 1996b; Dimoyiannis et al., 1998; Bronick and Lal, 2005; Wuddivira and Camps-Roach, 2007). In contrast to slaking, dispersion produces elementary particles rather microaggregates, resulting in one of the most effective processes of soil destructuration (Le Bissonnais, 1996a). For this reason, the availability of a wider range of soil types could help to accurately identify the soil properties and conditions affecting soil dispersion in the study area.

Stepwise multiple regression analyses were carried out to obtain predictive equations for the different processes of soil destabilization. The most predictive equations are shown in Table 4 and explained between 80 and 90% of the total variation in soil loss by slaking, by fast wetting and in total loss after 60 min of wet sieving as a function of aggregate OC and silt content. Organic C, however, was the most important predictor variable with partial correlation coefficients of 0.865-0.873 in comparison to 0.269-0.341 from the silt content. In these analyses, the $CaCO_3$ content was dropped out of the equations, in contrast with the estimation of swelling and clay dispersion. These relationships were considered satisfactory considering the heterogeneity of soil, climate and management conditions covered in the study.

4. Conclusions

Soil management and tillage exert a great influence on water aggregate stability in rainfed cereal areas of Aragon. Cultivated soils had very low structural stability with losses of soil aggregates of 30-90% already during initial fast wetting. Long-term NT increased surface aggregate stability with respect to CT systems through lower soil disturbance and higher OC content at the soil surface (0-5 cm depth). Slaking was the dominant disaggregation process of the cultivated soils, representing 40-80% of total soil disruption. In the NAT soils, the most stable soils of the study, the main cause of aggregate breakdown was abrasion by agitation in water. Swelling and clay dispersion were less frequent processes and their occurrence seemed to be associated with high silt and $CaCO_3$ contents. In contrast, slaking was strongly and negatively affected by aggregate-associated OC. Thus, this soil property together with the silt content (weak and positive effect) explained more than 80% of the slaking variation. Overall, results from this on-farm study indicate that NT can be recommended as a viable alternative to CT to reduce the susceptibility of soil surface to crusting and erosion in cereal production areas of Aragon.

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Figure legends

Figure 1. Location of the study sites and average annual rainfall isohyets (mm).

Figure 2. Dynamics of soil aggregate breakdown (1-2 mm in diameter) during wet sieving according to soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. The curves were obtained by fitting the experimental data to the Equation (1). Bars indicate LSD (P<0.05) for comparisons at the same sieving time, where significant differences were found.

Figure 3. Organic carbon content of soil aggregates (1-2 mm in diameter) as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation. For the same study site, different letters indicate significant differences at P< 0.05.

Figure 4. Relationships between the loss of soil aggregates (1-2 mm in diameter) by different mechanisms of soil destabilization in water (*a*, fast wetting, ▬●▬; *Sk*, slaking, —○—; T_{60}, wet sieving during 60 min, - - - ∗- - -) and the aggregate-associated organic carbon (OC, g kg^{-1}). Data come from soils under different tillage and management systems (cultivated soils under conventional and conservation tillage and natural soils).

Table 1. Location and management characteristics of the studied sites (NT, no tillage; RT, reduced tillage; CT, conventional tillage; NAT, natural soil; CC, continuous cropping; CF, cereal-fallow rotation; CL, cereal-legume rotation; MP, mouldboard ploughing; Ch, chisel ploughing).

Site	Location	MAP† mm	Soil type‡	Land use and management
Peñaflor CC	41º 44' 30" N 0º 46' 18" O (259 m elev.)	355	Hypercalcic Calcisol	19-yr NT-CC barley. 19-yr CT-CC (MP) barley. 19-yr RT-CC (Ch) barley. Maintenance of crop residues in the field. Straw chopped and spread in NT/RT (>30% of soil cover by crop residues) and incorporated into the soil in CT. NAT: Typical semiarid grassland.
Peñaflor CF	41º 44' 22" N 0º 46' 30" O (259 m elev.)	355	Hypercalcic Calcisol	20-yr NT-CF. 20-yr CT-CF (MP). 20-yr RT-CF (Ch). Maintenance of crop residues. Straw chopped and spread in NT/RT (>30% residue cover) and incorporated into the soil in CT. NAT: Typical semiarid grassland.
Lanaja	41º 43' 22" N 0º 21' 19" O (422 m elev.)	433	Hypocalcic Calcisol	10-yr NT-CL followed by 4-yr NT-CC barley with maintenance of crop residues (>30% residue cover). >14-yr CT-CF (MP) and straw removed. NAT: Frequently grazed area developed over an abandoned terrace (>40-yr) with sparse vegetation and patches of low shurbs.
Torres de Alcanadre	41º 57' 52" N 0º 05' 00" O (431 m elev.)	468	Calcaric Cambisol	9-yr NT-CC cereal with maintenance of crop residues (>30% residue cover). >9-yr CT-CC cereal (MP/Ch) and straw removed. NAT: Typical Mediterranean shrubland and *Pinus halepensis.* Soil surface covered with mosses and algae.
Undués de Lerda	42º 33' 43" N 1º 07' 26" O (860 m elev.)	676	Haplic Calcisol	13-yr NT-CF. Maintenance of crop residues (>30% residue cover). >13-yr CT-CF (MP) and straw removed. NAT: Typical Mediterranean shrublandand *Pinus halepensis.*
Artieda	42º 35' 46" N 0º 59' 39" O (526 m elev.)	741	Hypocalcic Calcisol	19-yr NT-CC cereal followed by 2-yr NT-CL and straw removed (≈10-15% residue cover). >21-yr CT-CC cereal (MP/Ch) and straw removed. NAT: Typical Mediterranean shrubland.

† Mean annual precipitation.

‡ WRB (2007).

Table 2. Selected properties of the studied soils in the 0-5 cm depth (CT, conventional tillage; RT, reduced tillage; NT, no tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

Site	Treatment	pH (H_2O, 1:2.5)	EC (1:5)[a] dS m^{-1}	Sand	Silt	Clay	$CaCO_3$	Organic carbon
				g kg^{-1}				
Peñaflor CC	CT	8.1	0.61	293	456	251	449	12.0
	RT	8.3	0.26	335	444	221	452	13.0
	NT	8.3	0.27	392	406	202	446	15.1
	NAT	8.1	0.80	635	258	106	563	16.1
Peñaflor CF	CT	8.4	0.23	287	463	250	462	10.7
	RT	8.4	0.19	318	439	243	466	11.1
	NT	8.3	0.31	313	451	236	473	13.3
	NAT	8.1	0.80	635	258	106	563	16.1
Lanaja	CT	8.4	0.23	134	589	277	439	10.7
	NT	8.3	0.30	145	587	268	396	15.3
	NAT	8.3	0.24	310	516	174	310	17.6
Torres de Alcanadre	CT	8.4	0.15	584	281	135	235	10.5
	NT	8.2	0.25	615	269	116	223	13.4
	NAT	8.4	0.15	695	215	90	233	16.8
Undués de Lerda	CT	8.1	0.18	121	526	354	54	16.9
	NT	8.2	0.17	136	525	339	84	19.9
	NAT	8.1	0.24	240	469	291	108	39.4
Artieda	CT	7.9	0.37	365	393	242	177	13.1
	NT	8.2	0.19	333	431	236	228	13.2
	NAT	8.1	0.21	352	387	261	68	29.9

[a]EC, electrical conductivity.

Table 3. Disaggregation kinetic parameters and loss of soil aggregates (1-2 mm in diameter) due to different mechanisms of soil destabilization by water as affected by soil management and tillage (CT, conventional tillage; RT, reduced tillage; NT, no-tillage; NAT, natural soil). In Peñaflor, CC refers to the continuous cropping system and CF to the cereal-fallow rotation.

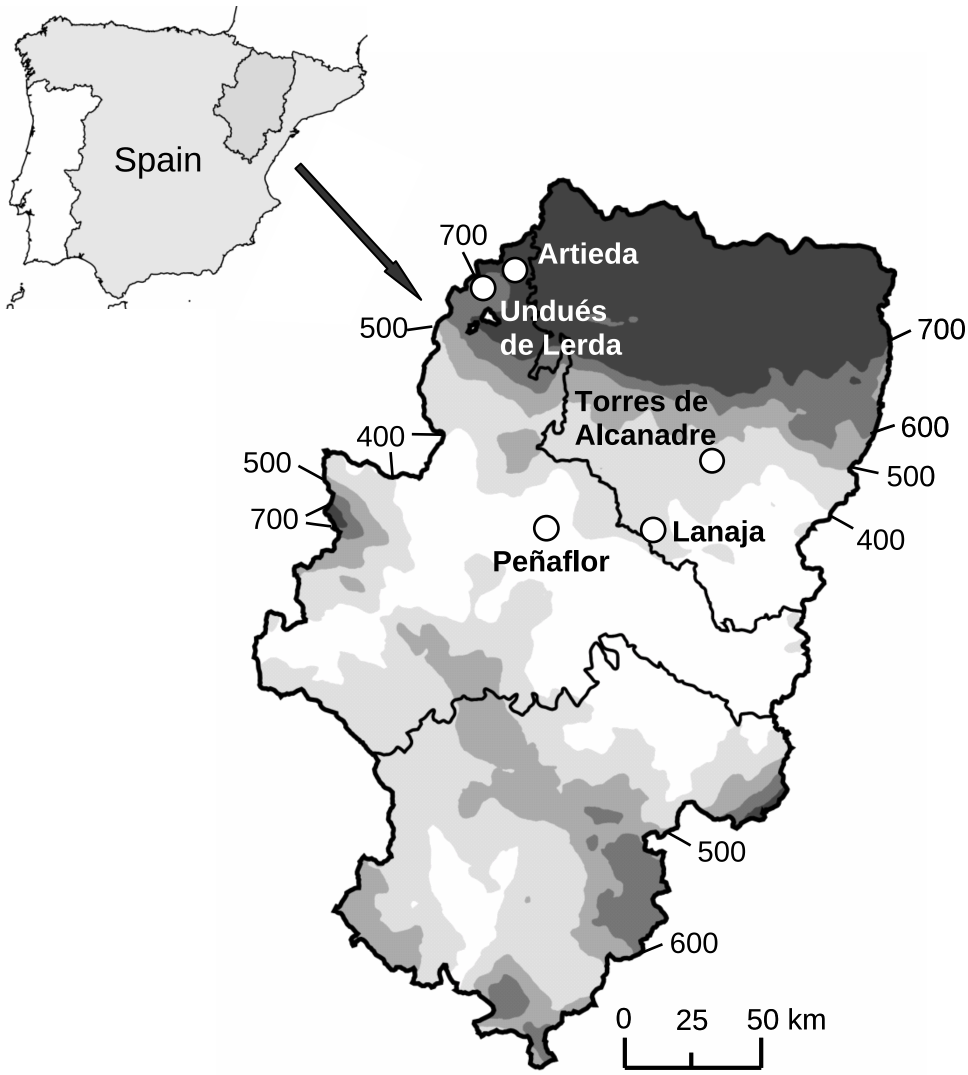
		Kinetic parameters†				Aggregate loss			
		a	*b*	*c*		In 5 min	Total	Slaking	Swelling & clay dispersion
Site	Treatment	%		min	r^2	%			
Peñaflor CC	CT	81.6	9.9	7.5	0.977	86.9	92.1	70.9	10.7
	RT	72.2	15.7	5.1	0.940	83.6	89.2	64.2	8.0
	NT	55.2	22.7	7.5	0.974	67.9	79.6	55.0	0.2
	NAT	5.5	21.1	20.6	0.983	9.5	26.4	4.9	0.6
	LSD	11.9	10.0	12.3		3.3	5.6	5.2	ns
Peñaflor CF	CT	68.0	20.9	3.8	0.977	83.7	90.6	68.0	0.0
	RT	78.4	10.5	6.2	0.958	84.7	90.0	74.3	4.1
	NT	66.8	19.6	4.0	0.987	81.5	87.2	66.5	0.3
	NAT	5.5	21.1	20.6	0.983	9.5	26.4	4.9	0.6
	LSD	16.5	ns	11.7		4.8	5.8	4.3	ns
Lanaja	CT	90.7	4.1	4.3	0.949	93.4	94.2	31.5	59.2
	NT	71.0	17.7	4.3	0.990	83.4	89.7	52.1	18.8
	NAT	37.5	37.3	5.3	0.990	61.4	76.7	37.0	0.5
	LSD	11.7	6.5	ns		8.2	6.2	7.9	6.0
Torres de Alcanadre	CT	74.2	15.6	3.6	0.968	85.9	90.6	61.6	12.6
	NT	52.4	30.9	4.5	0.991	73.4	84.7	52.3	0.1
	NAT	11.8	36.0	11.1	0.981	26.2	50.2	11.8	0.0
	LSD	6.7	8.2	4.2		10.1	13.4	10.0	9.5
Undués de Lerda	CT	36.1	43.5	3.7	0.987	69.6	81.2	36.0	0.1
	NT	28.4	43.7	6.3	0.983	55.0	73.6	28.4	0.0
	NAT	3.6	18.4	18.3	0.994	8.0	21.6	3.5	0.1
	LSD	6.0	4.2	11.6		10.6	8.6	5.3	ns
Artieda	CT	47.8	30.5	5.5	0.978	66.3	80.5	47.5	0.3
	NT	58.7	22.8	4.5	0.973	75.2	83.0	58.4	0.3
	NAT	2.5	8.9	31.5	0.948	3.5	10.6	2.0	0.5
	LSD	9.3	6.9	25.2		6.7	5.0	6.3	ns

† *a*, percentage of initial failure of soil aggregates by fast wetting; *b*, percentage of aggregate loss by mechanical abrasion; *c*, time controlling factor equal to 1/3 of the time interval at which 95% of the total loss is reached; r^2, coefficient of determination for the adjustment of experimental data to the Equation (1). LSD, least significant difference (P <0.05).

Table 4. The optimum regression equations for the estimation of loss of soil aggregates (1-2 mm in diameter) produced by fast wetting (*a*, %), slaking (*Sk*, %), swelling+dispersion (*S*+*D*, %) and the total produced after 60 minutes of wet sieving (T_{60}, %) as a function of aggregate organic carbon (OC, g kg^{-1}) and silt and $CaCO_3$ contents (g kg^{-1}).

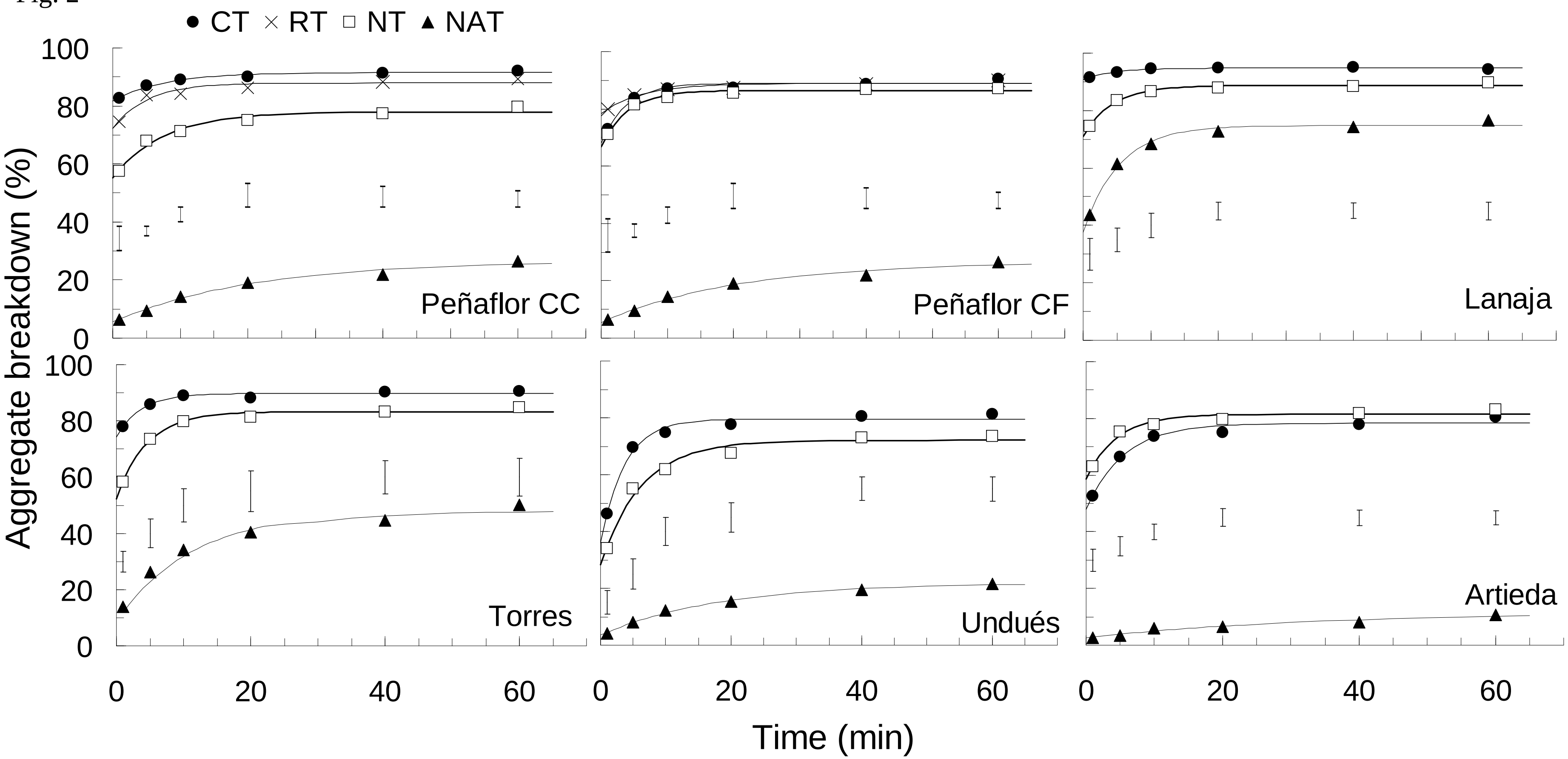
Destabilization process	Equation	r^2	*P*	n
a	log *a* = 2.88 - 0.053 OC - 182/silt	0.869	<0.0001	55
Sk	log *Sk* = 2.70 - 0.051 OC - 144/silt	0.821	<0.0001	55
T_{60}	T_{60} = 88.4 - 2.83 OC + 0.076 silt	0.878	<0.0001	55
S+*D*	*S*+*D* = -22.6 + 0.050 silt + 0.025 $CaCO_3$	0.229	<0.001	57

Fig. 1



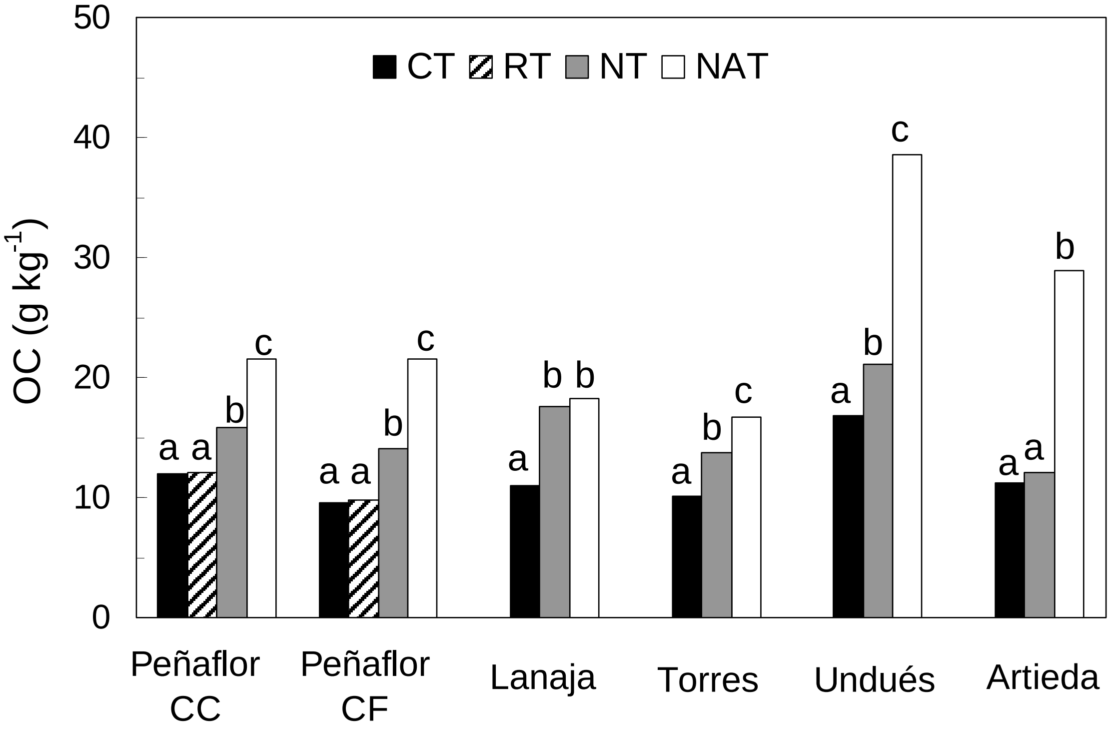
Spain
700
Artieda
Undués
de Lerda
500
700
Torres de
Alcanadre
400
600
500
500
700
Lanaja
400
Peñaflor
500
600
0
25
50 km

Fig. 2



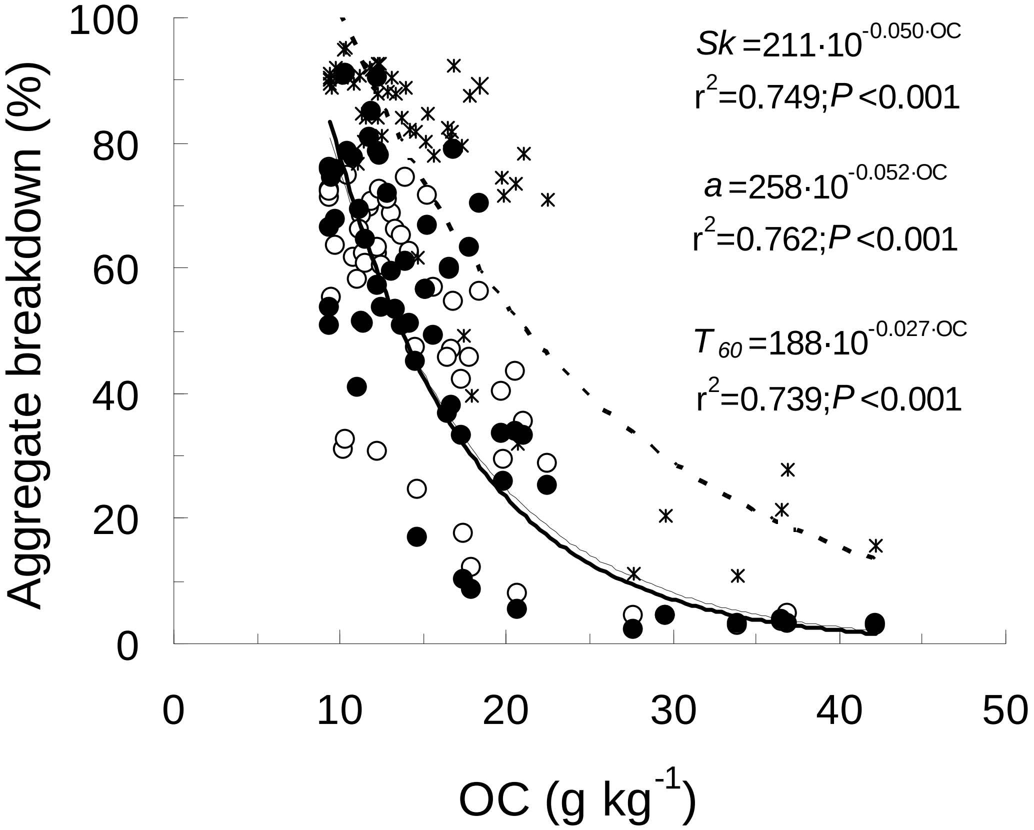
● CT × RT □ NT ▲ NAT
Aggregate breakdown (%)
Peñaflor CC
Peñaflor CF
Lanaja
Torres
Undués
Artieda
Time (min)
0
20
40
60
80
100

Fig. 3



CT RT NT NAT
OC (g kg-1)
0
10
20
30
40
50
a a b c
a a b c
a b b
a b c
a b c
a a b
Peñaflor CC
Peñaflor CF
Lanaja
Torres
Undués
Artieda

Fig. 4



Aggregate breakdown (%)
100
80
60
40
20
0
0
10
20
30
40
50
OC (g kg-1)
Sk =211·10-0.050·OC
r2=0.749;P <0.001
a =258·10-0.052·OC
r2=0.762;P <0.001
T 60 =188·10-0.027·OC
r2=0.739;P <0.001