TENSILE STRENGTH AND ORGANIC CARBON OF SOIL AGGREGATES UNDER LONG-TERM NO TILLAGE IN SEMIARID ARAGON (NE SPAIN)

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Abstract

Tensile strength (TS) of soil aggregates is recognized as a useful parameter to detect structural changes associated with soil management. Although conservation tillage has been encouraged as a management alternative to preserve soil and water resources in semiarid Aragon (NE Spain), little information concerning soils on which these techniques are applied is available for this region. The main objective of this study was to assess the effect of long-term no tillage (NT) on TS, rupture energy (*E*) and organic carbon (OC) of soil surface aggregates (0-5 cm depth) in five different cereal production areas of Aragon. In four of the sites, the study was conducted under on-farm conditions where pairs of adjacent fields under NT and conventional tillage (CT) were compared. In the last site, the study was carried out in research plots from a long-term tillage experiment where a third tillage treatment was also considered (reduced tillage). In all cases, a nearby undisturbed soil under native vegetation was included. Results indicate that NT reduced aggregate TS and *E* with respect to CT systems through lower soil disturbance and higher OC content. Aggregate size (16-8, 8-4, 4-2 and 2-1 mm in diameter) and aggregate-associated OC explained 70-80% of the variation in TS and *E*. Strength properties varied with OC in quadratic way with minimum values at about 20 g kg^{-1} of OC. This behavior can be explained by the significant interactions found between clay and OC in such a way that in the soils with the highest values of clay and OC, aggregate strength increased considerably. This study shows that, under the rainfed conditions of semiarid Aragon, NT improves soil physical conditions by reducing aggregate strength at the soil surface. This means, for example, that NT could provide a more favorable environment for seedling emergence and root growth than the traditional practices in the area.

Keywords: Aggregate strength; conservation tillage; soil organic carbon; rupture energy; dryland cereal farming.

1. Introduction

A good soil structure is essential to ensure sustainable agriculture. Many physical and biological soil processes depend, besides on the architectural organization of soil aggregates, on the internal micro-scale or aggregate structure (Horn 1990; Blanco-Canqui et al., 2005a). Aggregate structural properties influence seedling emergence and root growth, water and gas transfer, organic matter protection and dynamics, and soil susceptibility to wind and water erosion. For these reasons, there is an increasing interest in knowing the properties of individual soil aggregates to understand the behavior of the whole soil and its response to management (Park and Smucker, 2005; Munkholm et al., 2007; Blanco-Canqui and Lal, 2008a).

Despite the attention now focused on soil organic matter and soil biology, research on soil physical and mechanical properties should not be underestimated since the two aspects are closely related (Dexter et al., 2008; Ritz and Young, 2011). One of the most useful mechanical properties of soil aggregates and a very sensitive indicator of soil structural stability is the tensile strength (TS) (Dexter and Kroesbergen, 1985; Watts and Dexter, 1998). The TS is defined as the force per unit area required to break soil aggregates into smaller particles. It is considered a valuable parameter of soil microstructure since its measurement implies the formation of a fracture surface in the aggregate which usually incorporates pre-existing points of weakness, such as microcracks or pores (Horn and Dexter, 1989; Hallett et al., 1995). Tensile strength has been measured in studies that evaluate energy efficiency and ease of tillage operations (Wolf and Hadas, 1987; Munkholm and Kay, 2002), seedling emergence and root growth (Materechera et al., 1994) and wind erosion (Hagen et al., 1995). This parameter is currently being considered in the assessment of the potential of conservation tillage to improve soil physical conditions (Urbanek and Horn, 2006; Blanco-Canqui and Lal, 2007a; Abid and Lal, 2009). However, data on TS from long-term conservation tillage practices are still scarce and also variable, indicating that the impact of these practices is site specific. In fact, the literature shows that the

relationships of TS and other soil properties, such as organic carbon, are not well resolved due to many factors involved, e.g. soil texture, porosity, water content (Zhang, 1994; Imhoff et al., 2002; Munkholm and Kay, 2002).

Due to particular soil and climate conditions and inappropriate agricultural practices, Aragon (NE Spain) is a region prone to land degradation by wind and water erosion (López et al., 1998, 2001; López-Vicente et al., 2008). For this reason, the adoption of conservation tillage 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 aggregate properties of cultivated soils in Aragon has been mainly focused on water stability and size distribution of soil aggregates and it has been collected from small research plots and from single soil types (López et al., 2000; Álvaro-Fuentes et al., 2008). 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) assess the effect of long-term NT on TS of soil aggregates compared with traditional tillage practices and undisturbed soils under native vegetation in different cereal production areas of

Aragon, and (2) establish relationships between TS and aggregate-associated organic carbon (OC) to understand the role of soil OC on soil strength properties.

2. Materials and methods

2.1. Description of the study sites

Six long-term NT fields (9-21 years) 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). The selected fields were representative of the different scenarios of NT in the region and were located in areas receiving a mean annual precipitation ranging from 350 to 740 mm (Table 1). With the exception of the Peñaflor site, the study was conducted 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, three tillage treatments (NT, CT and reduced tillage, RT) were compared under the traditional cereal-fallow rotation (CF, one crop in 2 years) and under continuous cropping (CC) with barley. Within each cropping system a randomized complete block design with three replicates per tillage treatment was used. 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. Briefly, in the CT system mouldboard plough was used as primary tillage tool as traditional implement in the region. However, in two of the sites, Torres de Alcanadre (hereafter, Torres) and Artieda, farmers alternate the use of chisel plough with mouldboard plough. NT soils

were not tilled and weeds were controlled by herbicides. The RT treatment in the Peñaflor site consisted of chisel ploughing (non-inverting action) with partial incorporation of crop residues into the soil. With respect to crop residue management, the case of Artieda should be noted, the study site located in the area with the highest rainfall and hence highest production. As a common practice in this area, farmers remove the straw from the NT and CT fields to prevent later problems with seeding.

Cropping system was not the same under NT and CT in the Lanaja site (Table 1). This reflects the general trend observed in the driest areas of Aragon, where the traditional cereal fallow rotation under CT is generally replaced with the continuous cereal cropping under NT; even a legume can be introduced in rotation with cereal with a varying frequency depending on the site. A recent study on the identification of the current management practices used by Aragon's farmers has allowed us to know the diversity of cropping systems and to be aware of the reality of the conservation agriculture in the region (López et al., 2012). Therefore, following the remark made by Blanco-Canqui and Lal (2008b), the present study shows data on the effect of NT- and CT-based cropping systems on TS rather than those of tillage alone.

All soils were medium-textured soils, varying from sandy loam (the Torres site) to silty clay loam (Undués de Lerda), alkaline (pH>8; $CaCO_3$ contents of 50-560 g kg^{-1}) and generally 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 TS. 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. Even though the soil is the same (i.e., same parent material), the soil particle distribution within the profile will not be the same in the case of the ploughed soils with total soil inversion than in the non-tilled soils or in

the case of the cultivated soils vs. the undisturbed soils. All fields were nearly level with the exception of those of the Torres site where a slight slope (3-4%) was present.

2.2. Soil sampling and analyses

Tensile strength and OC content of soil aggregates were determined for the first 5 cm of soil depth. In the farmer fields, soil sampling 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 (≈20º C) and dry sieved through a nest of sieves with 16, 8, 4, 2 and 1 mm openings to obtain aggregates of four different size classes (16-8, 8-4, 4-2 and 2-1 mm in diameter).

The TS of individual soil aggregates was determined by an indirect test using the crushing method (Dexter and Kroesbergen, 1985; Dexter and Watts, 2000) with a universal testing machine (INSTRON model 5565). The tests consisted basically of crushing an individual aggregate between two flat parallel plates and recording the force required to break it. Soil aggregates were previously oven dried at 105º C during 24 h to obtain a standard condition of soil humidity (Dexter and Watts, 2000). Depending on the variability of the measurements, at least 12 aggregates of each size class and field were measured. Therefore, a minimum of 144 tests per site was made (192 in Peñaflor) (4 aggregate sizes x 3 or 4 treatments x 3 replicates x 4 tests). The compression tests were performed at a constant displacement rate of 2 mm min^{-1}. Load cells of 5 kN (kiloNewton) and 100 N (Newton) were used, respectively, for the largest aggregates, 16-8 and 8-4 mm in diameter, and the smallest ones, 4-2 and 2-1 mm.

The TS (kPa) of soil aggregates was computed using Eq. (1) (Rogowski et al., 1968):

$$TS = 0.576\ F/d^2 \qquad (1)$$

where F (N) is the breaking force and d (m) is the mean aggregate diameter. The 0.576 value is a constant based on the assumption of spherical form and perfect elastic behavior (Poisson ratio=0.5) (Dexter, 1975). On the assumption that aggregate density is constant, the value of d was estimated from Method 4 described by Dexter and Watts (2000):

$$d = d_o\,(m/m_o)^{1/3} \qquad (2)$$

where m is the mass of an individual aggregate, m_o is the mean mass of a batch of aggregates of the same size class and d_o is the mean of the openings of the upper and lower sieves for that size class.

Together with the TS measurement, the rupture energy for each soil aggregate was calculated by integrating the area under the F vs. displacement curve. The specific rupture energy (E, J kg^{-1}) was obtained by dividing the rupture energy by the aggregate mass. For the same size class, the OC content of 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, 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 and pH by standard methods (Page et al., 1982).

2.3. Statistical analysis

Within each study site, statistical comparisons among treatments were made using one-way ANOVA, assuming a randomized experiment. As in each of the sites, the fields were contiguous and sited on similar landscape position and same soil, the three sampling locations (i.e. sampling zones within each field) were used as pseudoreplicates (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). Correlation and regression analyses were performed to identify and evaluate the degree of relationship among the measured properties. Special attention was paid to the relationship of TS and E with OC as predictive variable. In these cases, simple regressions were done by averaging the four aggregate size classes for each treatment and site with the objective to eliminate the variability due to aggregate size. When data showed non-normality (Kolmogorov-Smirnov test), logarithmic transformations were performed and ANOVA conducted with the transformed data. Computations were performed using SPSS 19.0 statistical software.

3. Results and discussion

3.1. Soil tillage effects on tensile strength

Mean values of TS and E for each of the study sites are shown in Figs. 1 and 2, respectively. The TS values ranged from 20 to 700 kPa (30-1040 J kg^{-1} for E), varying not only with the soil management or tillage treatment but also with the aggregate size. Thus, the figures clearly illustrate an increase in TS, and generally also in E, with decreasing the aggregate size (differences among sizes significant at P<0.05). The higher resistance of small aggregates against applied forces is supported by previous studies (Perfect and Kay, 1994; Chan et al., 1999; Blanco-Canqui et al., 2005a,b), suggesting that they contain less points of weakness, such as microcracks and pores, and stronger bonds between particles than larger aggregates (Utomo and Dexter, 1981; Horn and Dexter, 1989).

Soil management and tillage system had a significant effect on TS and E (Figs. 1 and 2). With the exception of the NAT soils of the Undués de Lerda (hereafter, Undués) and Artieda sites, results showed a general trend of increase in TS with the degree of soil disturbance (i.e. NAT<NT<RT<CT). Within the cultivated soils, the lowest TS values were always recorded under NT, following by RT in the Peñaflor site. The magnitude of the tillage differences varied

among sites, indicating that the response is site-specific. Thus, while mean TS was 3.2 times lower under NT than under CT in the Peñaflor CF site, it was only 1.3 times in Lanaja. Similar results were shown by Blanco-Canqui et al. (2005a) who found lower TS values by a factor of 2.5 in a silt loam soil under NT than under CT. Abid and Lal (2009), also working with a soil of medium texture, observed a clear relation between aggregate strength and tillage intensity, with lower TS in NT than in CT by factors of 1.5-1.6. The same trend has been recently observed by Li et al. (2011) in a long-term tillage/stubble experiment conducted in a clay loam soil where TS values under NT were 1.4 to 2.6 times lower than those under CT. As suggested in the above studies, the low TS of NT aggregates responds to a higher biological activity, promoted by the minimum soil alteration which results in more bioporosity (faunal and root channels) and, therefore, higher susceptibility to fracture than in aggregates from tilled soils. In CT systems, tillage operations increase the aggregate TS by disrupting surface connected pores and causing rapid post-tillage consolidation (Watts and Dexter, 1998; Munkholm and Schjønning, 2004). Increment of mechanically dispersible clay and depletion of soil OC with tillage seem to be two processes involved in the formation of strong soil aggregates under CT systems. Following Dexter and Watts (2000) and Kay and Munkholm (2004), the clay dispersed by tillage in wet conditions is deposited in microcracks and pores as soil dries, thus increasing its strength. It is expected that the reduction of soil OC will promote this effect although, as it will be discussed below, the relationship between TS and OC seems to be more complex (Imhoff et al., 2002; Munkholm and Kay, 2002).

The TS and *E* results from the comparison of NT vs. CT systems could have important agronomic implications. Thus, under the conditions of semiarid Aragon, this study shows that NT practices lead to better soil physical conditions by reducing aggregate strength at the soil surface. This means, for example, that this alternative system could provide a more favorable environment for seedling emergence and root growth than the traditional practices in the area. In the NAT

soils, it would be expected that TS and *E* values would be lower than those registered under NT and, especially under CT, due to the lack of soil disturbance and the highest contents of soil OC (Table 2). However, in the present study, TS in the NAT soils showed a high variability with values ranging from 22 to 677 kPa (31-1040 J kg^{-1} for *E*) and, contrary to the expected, the stronger aggregates came from the soils with the highest OC contents, i.e. the soils of the Artieda and Undués sites (Figs. 1 and 2; Table 2). In Undués, the mean TS in the NAT soil was 1.4 times higher than that in CT (1.6 for *E*) while in Artieda it was similar in both soils (*E* was 2.2 times higher in NAT). The general trend observed in the rest of the sites on the increase in TS and *E* with the degree of soil disturbance, was not followed in these two cases. A possible explanation for this behavior could be related to the high biological activity observed in these two NAT soils. In fact, Artieda and Undués are the two study sites with the highest precipitation (≈700 mm of mean annual rainfall) and, therefore, where an abundant and diverse plant community has developed an extensive root system with numerous fine roots and root hairs growing within soil aggregates. Under these conditions, aggregate TS would increase since the radial pressure exerted by the growing roots compresses the soil around the root (Dexter, 1987), resulting in a decrease of the porosity in that zone (Bruand et al., 1996) and in an increase of the intra-aggregate bonds by root exudates (Czarnes et al., 2000). Pore disruption and blocking by dispersed clay particles is also a possible mechanism of increasing aggregate strength in these more humid environments. In any case, these results show that the increase of soil OC does not always led to a reduction in aggregate TS and support previous studies indicating that the effect of soil OC on TS is variable and the need for further local research (Kay and Munkholm, 2004; Blanco-Canqui et al., 2005b; Park and Smucker, 2005).

3.2. Aggregate tensile strength and organic carbon

With the goal to advance, as far as possible, in the understanding of the complexity of the relationships between structure and organic matter, the OC content for the different aggregate size classes was determined (Table 3). Aggregate-associated OC ranged from 9.3 (CT at Peñaflor CF) to 39 g kg^{-1} (NAT at Undués). No effect of aggregate size on OC was observed in any of the study sites; however, within each aggregate size class, differences among soil management and tillage treatments were significant in all sites (Table 3). Aggregates from the NAT soils have significant higher OC than those from the cultivated soils in the Torres, Undués and Artieda sites (1.5-2.6 times higher) and only than those from the CT and RT in Peñaflor and Lanaja (1.6-2.2 times higher). With the exception of the Artieda site, soil aggregates under NT were between 20 (Undués) and 50% (Lanaja) richer in OC than those under CT and RT. In Artieda, the management of crop residues in the NT field explains the lack of differences between cultivated soils. 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. The NAT soil of Lanaja is also notable for the relatively low OC content, similar to that of the NT soil. As detailed in Table 1, this soil is located in an abandoned agricultural terrace (>40 years) that is frequently grazed by livestock.

Figure 3 shows the TS and *E* variation as a function of aggregate-associated OC considering together all sites and treatments. A simple regression analysis showed that OC significantly affected TS in a quadratic manner ($P<0.001$) with a minimum value at about 19-20 g kg^{-1} of OC. For lower OC values, an increase in OC caused a decrease in TS and, in contrast, for OC contents higher than ≈20 g kg^{-1}, the increase in OC resulted in an increase in TS. This finding seems to support previous and contrasting results on the relationship between TS and

OC. Thus, positive relationships were found by Rahimi et al. (2000) for loam and clay loam soils and soil OC contents >20 g kg^{-1}, and by Blanco-Canqui and Lal (2007b) for a silt loam soil and a range of aggregate OC of about 15-100 g kg^{-1}. Working with three different soils (silt loam-clay loam), Blanco-Canqui et al. (2006) also reported positive correlations between both soil parameters for OC concentrations >20 g kg^{-1}. In contrast, negative relationships have been described by Abid and Lal (2009) in a silt loam soil with OC contents of 15-22 g kg^{-1} or by Blanco-Canqui et al. (2005a) with silt loam soils and aggregate OC ranging from about 10 to 70 g kg^{-1}. No or little effect of soil OC on TS was also reported in other studies (Watts and Dexter, 1997; Blanco-Canqui et al., 2005b). These contrasting results indicate that other soil properties may be influencing TS, such as soil texture (Imhoff et al., 2002), organic matter type (Ekwue, 1990) or soil porosity (Zhang, 1994). From all soil variables considered in the present study, besides OC, clay content was significantly and positively correlated with the strength properties (r=0.630 for TS and r=0.552 for *E; P*<0.001). Furthermore, positive interactions between OC and clay content were found, affecting TS and *E* as follows:

$$TS = 1749 - 864 \log OC - 369 \log clay + 0.094 (OC \times clay) \quad r^2=0.668;\ P<0.001 \quad (3)$$

$$E = 2001 - 821 \log OC - 533 \log clay + 0.123 (OC \times clay) \quad r^2=0.660;\ P<0.001 \quad (4)$$

This interaction may explain the quadratic variation of the strength properties with the OC and, more precisely, the unexpected high values of TS and *E* registered in the NAT soils of the Undués and Artieda sites where the highest OC is accompanied by relatively high clay content (≈300 g kg^{-1}). Interactions between the soil mineral and organic fractions have been found in previous studies. Thus, Imhoff et al. (2002) indicated that, while at high clay+silt content an increase in OC resulted in an increase in TS, at low clay+silt content the increase in OC caused a decrease in TS. Park and Smucker (2005) and Blanco-Canqui et al. (2006) also showed that OC contributed to strengthening aggregates in more clayey soils but it reduced aggregate strength in

coarser textured soils. According to these studies, strong bonding of organic substances with clay particles upon soil drying is a major mechanism for increasing aggregate TS in clay and silt loams. Likewise, the increase in OC causes a higher porosity in coarser textured soils than in fine soils, thus contributing to the loss of soil strength.

Stepwise multiple regression analyses were carried out to obtain predictive equations for TS and *E*. With the objective to provide simple equations and, taking into account the quadratic relation between aggregate OC and strength properties, we decided to establish different equations for OC higher and lower than a fixed threshold value of 20 g kg^{-1}. The most predictive equations are shown in Table 4 and Fig. 4 and explained between 68 and 84% of the total variation in TS and *E* as a function of aggregate size and aggregate OC. Note that, for OC contents <20 g kg^{-1}, the regression was better described by a curvilinear function (log TS or log *E*) while for higher contents, the linear regression is more significant. This can be also deduced from the Fig. 3, where a more pronounced curvilinear form can be observed for OC <20 g kg^{-1} than for that >20 g kg^{-1}. In any case, these significant relationships were considered satisfactory considering the heterogeneity of soil, climate and management conditions.

3.3. Relationship between aggregate tensile strength and specific rupture energy

Perfect and Kay (1994) recommended the use of *E* over TS for the characterization of dry aggregate strength in tillage studies. These authors explained that tension is not the only form of loading and that soil compression and shear also occur during tillage (Vomocil and Chancellor, 1969). Unlike TS, *E* is an integral parameter and, therefore, no assumptions are necessary regarding the exact mode of loading by which the soil fails.

In the present study, a high correlation between *E* and TS (Fig. 5) was expected given the same data trend, similar response to soil management and tillage, and very similar prediction equations. Thus, the more resistant an aggregate is to breaking, more energy is required to

pulverize it. There are relatively few tillage studies determining *E* and even less comparing *E* and TS. Munkholm and Kay (2002), in two different experiments carried out on the same soil type, found similar trend between *E* and TS in one of the experiments and clear differences in the other one. In the later case, the authors attributed the lack of correlation between the two strength variables to a complex soil pore structure which results in fracture at more points within the soil mass. This is due to the fact that *E* not only depends on the force needed to break the weakest intra-aggregate bond (i.e., TS) but also on the nature of the total bonds within the aggregate. In this sense, a further analysis of *E* could provide fruitful information about the distribution and strength of the inter- and intra-aggregate bonds and, ultimately, about the hierarchical organization of soil structure.

4. Conclusions

Results from this study indicate that soil management and tillage exert a great influence on soil strength properties in rainfed cereal areas of Aragon. Long-term NT reduced aggregate TS and *E* with respect to CT systems through lower soil disturbance and higher OC content at the soil surface (0-5 cm depth). Aggregate size and aggregate-associated OC explained 70-80% of the variation in TS and *E*. The relation with OC was complex since, for soils with OC lower than about 20 g kg^{-1}, TS and *E* were reduced with the increase in OC. In contrast, for OC higher than 20 g kg^{-1}, the strength properties increased with increasing in OC. This behavior was explained by the interaction of OC with the clay content in such a way that in the soils with the highest values of both OC and clay, the aggregate strength was considerably high. This was the case of some of the NAT soils considered in this research. Overall, results from this study suggest that aggregate TS and *E* can be used as sensitive indicators of soil structural changes associated with tillage and management systems.

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References

Abid, M., Lal, R., 2009. Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration. Soil Till. Res. 103, 364-372.

Álvaro-Fuentes, J., Arrúe, J.L., Gracia, R., López, M.V., 2008. Tillage and cropping intensification effects on soil aggregation: Temporal dynamics and controlling factors under semiarid conditions. Geoderma 145, 390-396.

Álvaro-Fuentes, J., Cantero-Martínez, C., López, M.V., Paustian, K., Denef, K., Stewart, C.E., Arrúe, J.L., 2009. Soil aggregation and soil organic carbon stabilization: Effects of management in semiarid Mediterranean agroecosystems. Soil Sci. Soc. Am. J. 73, 1519-1529.

Blanco-Canqui, H., Lal, R., Owens, L.B., Post, W.M., Izaurralde, R.C., 2005a. Mechanical properties and soil organic carbon of soil aggregates in the northern Appalachians. Soil Sci. Soc. Am. J. 69, 1472-1481.

Blanco-Canqui, H., Lal, R., Lemus, R., 2005b. Soil aggregate properties and organic carbon for switchgrass and traditional agricultural systems in the southeastern United States. Soil Sci. 170, 998-1012.

Blanco-Canqui, H., Lal, R., Post, W.M., Izaurralde, R.C., Owens, L.B., 2006. Rapid changes in soil carbon and structural properties due to stover removal from no-till corn plots. Soil Sci. 171, 468-482.

Blanco-Canqui, H., Lal, R., 2007a. Regional assessment of soil compaction and structural properties under no-tillage farming. Soil Sci. Soc. Am. J. 71, 1770-1778.

Blanco-Canqui, H., Lal, R., 2007b. Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. Soil Till. Res. 95, 240-254.

Blanco-Canqui, H., Lal, R., 2008a. Corn stover removal impacts on micro-scale soil physical properties. Geoderma 145, 335-346.

Blanco-Canqui, H., Lal, R., 2008b. No-tillage and soil profile carbon sequestration: An on-farm assessment. Soil Sci. Soc. Am. J. 72, 693-701.

Bruand, A., Cousin, I., Nicoullaud, B., Duval, O., Begon, J.C., 1996. Backscattered electron scanning images of soil porosity for analyzing soil compaction around roots. Soil Sci. Soc. Am. J. 60, 895-901.

Czarnes, S., Dexter, A. R., Bartoli, F., 2000. Wetting and drying cycles in the maize rhizosphere under controlled conditions. Mechanics of the root-adhering soil. Plant Soil 221, 253-271.

Chan, K.Y., Dexter, A.R., McKenzie, D.C., 1999. Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic Vertisol. Aust. J. Soil Res. 37, 903-911.

Christopher, S.F., Lal, R., Mishra, U., 2009. Regional study of no-till effects on carbon sequestration in the Midwestern United States. Soil Sci. Soc. Am. J. 73, 207-216.

Dexter, A.R., 1975. Uniaxial compression of ideal brittle tilths. J. Terramech. 12, 3-14.

Dexter, A.R., Kroesbergen, B., 1985. Methodology for determination of tensile strength of soil aggregates. J. Agric. Eng. Res. 31, 139-147.

Dexter, A.R., 1987. Compression of soil around roots. Plant Soil 211, 69-86.

Dexter, A.R., Watts, C.W., 2000. Tensile strength and friability. In: Smith K.A. and Mullins, C.E. (Eds.), Soil and Environmental Analysis: Physical Methods, 2nd ed., Marcel Dekker, New York, pp. 405-433.

Dexter, A.R., Richard, G., Arrouays, D., Czyz, E.A., Jolivet, C., Duval, O., 2008 Complexed organic matter controls soil physical properties. Geoderma 144, 620-627.

Ekwue, E.I., 1990. Organic-matter effects on soil strength properties. Soil Till. Res. 16, 289-297.

Hagen, L.J., Schroeder, B., Skidmore, E.L., 1995. A vertical soil crushing-energy meter. Trans. ASAE 38, 711-715.

Hallett, P.D., Dexter, A.R., Seville, J.P.K. 1995. Identification of pre-existing pore space on soil fracture surfaces using dye. Soil Till. Res. 33, 163-184.

Horn, R., Dexter, A.R., 1989. Dynamics of soil aggregation in irrigated desert loess. Soil Till. Res. 13, 253-266.

Horn, R., 1990. Aggregate characterization as compared to soil bulk properties. . Soil Till. Res. 17, 265-289.

Imhoff, S., da Silva, A.P., Dexter, A., 2002. Factors contributing to the tensile strength and friability of Oxisols. Soil Sci. Soc. Am. J. 66, 1656-1661.

Kay, B.D., Munkholm, L.J., 2004. Management-induced soil structure degradation-Organic matter depletion and tillage. In: Schjønning, P. et al. (Eds.), Managing Soil Quality: Challenges in Modern Agriculture, Oxford Univ. Press, pp. 185-197.

Li, L., Chan, K.Y., Niu, Y., Li, G., Oates, A., Dexter, A., Huang, G., 2011. Soil physical qualities in a Oxic Paleustalf under different tillage and stubble management practices and application of *S* theory. Soil Till. Res. 113, 82-88.

López, M.V., Arrúe, J.L., Sánchez-Girón, V., 1996. A comparison between seasonal changes in soil water storage and penetration resistance under conventional and conservation tillage systems in Aragón. Soil Till. Res. 37, 251-271.

López, M.V., Sabre, M., Gracia, R., Arrúe, J.L., Gomes, J., 1998. Tillage effects on soil surface conditions and dust emission by wind erosion in semiarid Aragón (NE Spain). Soil Till. Res. 45, 91-105.

López, M.V., Gracia, R., Arrúe, J.L., 2000. Effects of reduced tillage on soil surface properties affecting wind erosion in semiarid fallow lands of Central Aragón. Eur. J. Agron. 12, 191-199.

López, M.V., Gracia, R., Arrúe, J.L., 2001. An evaluation of wind erosion hazard in fallow lands of semiarid Aragon (NE Spain). J. Soil Water Conserv. 56, 212-219.

López, M.V., Arrúe, J.L., Álvaro-Fuentes, J., Moret, D., 2005. Dynamics of surface barley residues during fallow as affected by tillage and decomposition in semiarid Aragon (NE Spain). Eur. J. Agron. 23, 26-36.

López, M.V., Blanco-Moure, N., Limón, M.A., Gracia, R. 2012. No tillage in rainfed Aragon (NE Spain): Effect on organic carbon in the soil surface horizon. Soil Till. Res. 118, 61-65.

López-Vicente, M., Navas, A., Machín, J., 2008. Modelling soil detachment rates in rainfed agrosystems in the south-central Pyrenees. Agric. Water Manage. 95, 1079-1089.

Materechera, S.A., Kirby, J.M., Alston, A.M., Dexter, A.R., 1994. Modification of soil aggregation by watering regime and roots growing through beds of large aggregates through beds of large aggregates. Plant and Soil 160, 57-66.

Moret, D., Arrúe, J.L., López, M.V., Gracia, R., 2007. Winter barley performance under different cropping and tillage systems in semiarid Aragon (NE Spain). Eur. J. Agron. 26, 54-63.

Munkholm, L.J., Kay, B.D., 2002. Effect of water regime on aggregate-tensile strength, rupture energy, and friability. Soil Sci. Soc. Am. J. 66, 702-709.

Munkholm, L.J., Schjønning, P., 2004. Structural vulnerability of a sandy loam exposed to intensive tillage and traffic in wet conditions. Soil Till. Res. 79, 79-85.

Munkholm, L.J., Perfect, E., Grove, J., 2007. Incorporation of water content in the Weibull model for soil aggregate strength. Soil Sci. Soc. Am. J. 71, 682-691.

Page, A.L., Miller, R.H., Keeney, D.R., (Eds.), 1982. Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties, 2nd edn. Agronomy No. 9. ASA, Madison, WI.

Park, E.J., Smucker, A.J.M., 2005. Erosive strengths of concentric regions within soil macroaggregates. Soil Sci. Soc. Am. J. 69, 1912-1921.

Perfect, E., Kay, B.D., 1994. Statistical characterization of dry aggregate strength using rupture energy. Soil Sci. Soc. Am. J. 58, 1804-1809.

Rahimi, H., Pazira, E., Tajik, F., 2000. Effect of soil organic matter, electrical conductivity and sodium adsorption ratio on tensile strength of aggregates. Soil Till. Res. 54, 145-153.

Ritz, K., Young, I.M., (Eds.), 2011. The Architecture and Biology of Soils. Life in Inner Space. CABI International, London, UK. 256 p.

Rogowski, A.S., Moldenhauer, W.C., Kirkham, D., 1968. Rupture parameters of soil aggregates. Soil Sci. Soc. Am. Proc. 32, 720-724.

Urbanek, E., Horn, R., 2006. Changes in soil organic matter, bulk density and tensile strength of aggregates after percolation in conservation and conventional tilled soils. Int. Agrophysics. 20, 245-255.

Utomo, W.H., Dexter, A.R., 1981. Age-hardening of agricultural top soils. J. Soil Sci. 32, 335-350.

Vallés, M., 2009. Análisis de una muestra de explotaciones agrarias vinculada con la práctica de la agricultura de conservación. Informaciones Técnicas del Dpto. de Agricultura y Alimentación del Gobierno de Aragón. Nº 205, 12 p.

Vomocil, J.A., Chancellor, W.J., 1969. Energy requirements for breaking soil samples. Trans. ASAE 12, 375-388.

Watts, C.W., Dexter, A.R., 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. Soil Till. Res. 42, 253-275.

Watts, C.W., Dexter, A.R., 1998. Soil friability: Theory, measurement and the effects of management and organic carbon content. Eur. J. Soil Sci. 49, 73-84.

Wolf, D., Hadas, A., 1987. Determining efficiencies of various mouldboard ploughs in fragmenting and tilling air-dry soils. Soil Till. Res. 10, 181-190.

Zhang, H., 1994. Organic matter incorporation affects mechanical properties of soil aggregates. Soil Till. Res. 31, 263-275.

Figure legends

Figure 1. Tensile strength (TS) of soil aggregates of different size classes 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 aggregate size, different letters indicate significant differences at $P<0.05$.

Figure 2. Specific rupture energy (*E*) of soil aggregates of different size classes 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 aggregate size, different letters indicate significant differences at $P<0.05$.

Figure 3. Variation in aggregate tensile strength (TS, —●—) and specific rupture energy (*E*, - - ○- -) with aggregate organic carbon (OC) from soils under different tillage and management systems (cultivated soils under conventional and conservation tillage and natural soils).

Figure 4. Relationships between measured and predicted soil strength properties (TS, tensile strength and *E*, specific rupture energy) using Eqs. of Table 4 for organic carbon (OC) contents lower (A) and higher than 20 g kg^{-1} (B).

Figure 5. Relationship between aggregate tensile strength (TS) and specific rupture energy (*E*) 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	Land use and management
Peñaflor CC	41º 44' 30" N 0º 46' 18" O (259 m elev.)	355	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	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	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	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	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	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.

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. Organic carbon content (g kg^{-1}) of soil aggregates of different size classes as affected by land use 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.

		Aggregate size class (mm)			
Site	Treatment	16-8	8-4	4-2	2-1
Peñaflor CC	CT	11.7	11.4	11.9	12.0
	RT	11.4	11.3	11.7	12.1
	NT	14.1	14.8	15.4	15.8
	NAT	19.6	22.3	21.5	21.5
	LSD[a]	6.8	2.1	2.0	1.9
Peñaflor CF	CT	9.7	9.6	9.4	9.5
	RT	10.4	10.5	9.4	9.7
	NT	14.5	14.6	13.7	14.0
	NAT	19.6	22.3	21.5	21.5
	LSD	2.7	1.4	2.1	1.6
Lanaja	CT	10.1	10.1	10.7	11.0
	NT	15.2	15.3	16.4	17.6
	NAT	16.7	16.1	16.6	18.3
	LSD	2.6	3.4	4.1	4.1
Torres de Alcanadre	CT	10.5	10.3	9.8	10.1
	NT	15.4	15.0	12.2	13.7
	NAT	21.7	19.3	13.9	16.7
	LSD	4.2	2.4	2.2	2.3
Undués de Lerda	CT	17.9	16.8	16.6	16.8
	NT	21.6	20.8	20.6	21.1
	NAT	39.0	37.4	37.4	38.6
	LSD	2.4	1.8	1.6	4.0
Artieda	CT	12.5	11.1	10.0	11.3
	NT	12.8	10.1	10.6	12.1
	NAT	29.3	28.6	28.4	28.9
	LSD	4.2	5.8	6.2	5.3

[a] LSD, least significant difference ($P<0.05$).

Table 4. The optimum regression equations to estimate soil aggregate tensile strength (TS, kPa) and specific rupture energy (E, J kg^{-1}) as a function of aggregate organic carbon (OC, g kg^{-1}) and aggregate diameter (d, mm).

Strength property	OC (g kg^{-1})	Equation	r^2	P	n
TS	<20	$\log TS = 4.01 - 0.511 \log d - 1.34 \log OC$	0.702	<0.0001	54
	>20	$TS = -61 - 330 \log d + 21\ OC$	0.836	<0.0001	17
E	<20	$\log E = 2.62 + 0.638/d - 0.048\ OC$	0.675	<0.0001	54
	>20	$E = 1524 - 22\ d - 25261/OC$	0.749	<0.0001	16

Fig. 1

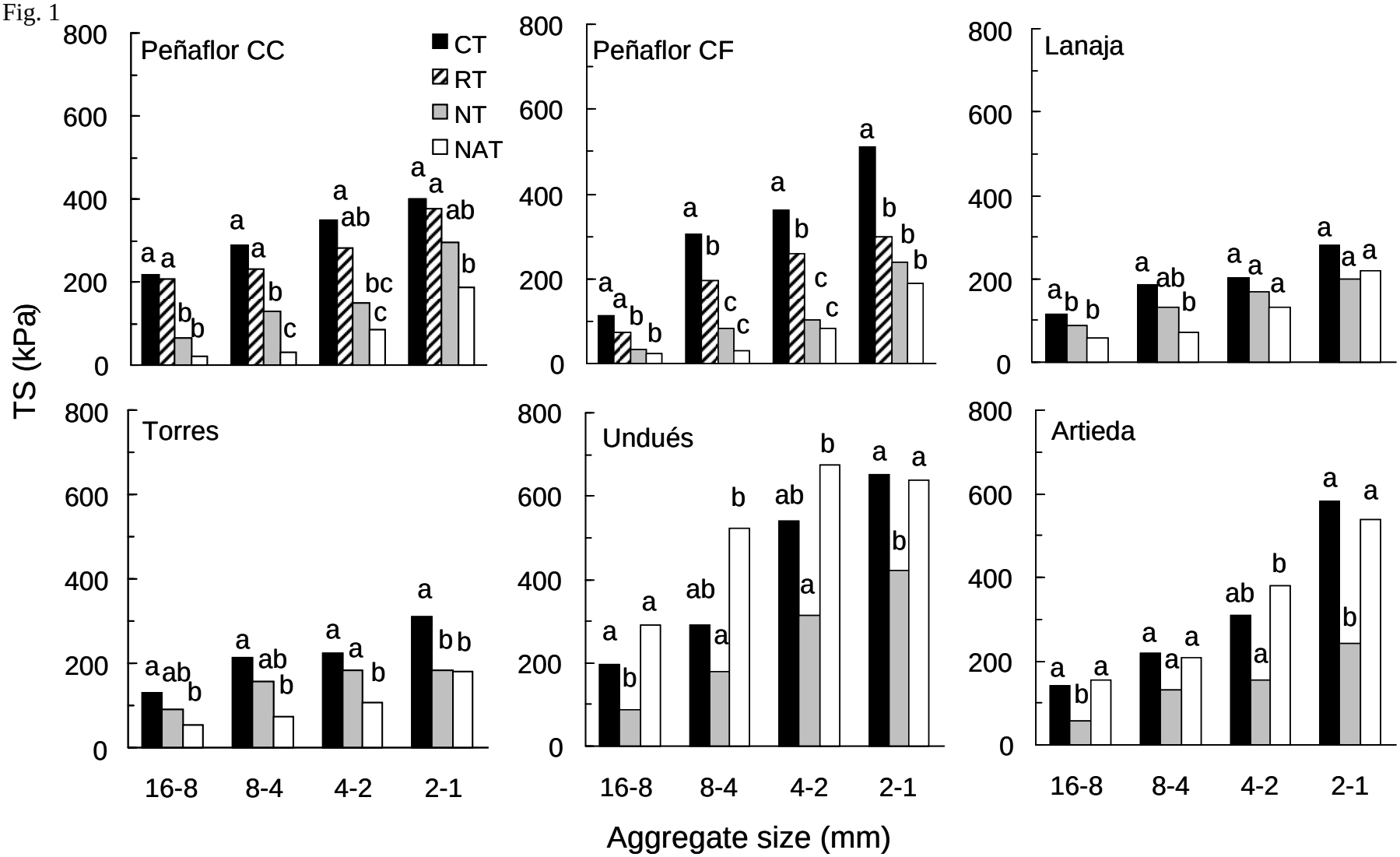
Peñaflor CC
Peñaflor CF
Lanaja
Torres
Undués
Artieda
CT
RT
NT
NAT
TS (kPa)
0
200
400
600
800
16-8
8-4
4-2
2-1
Aggregate size (mm)

Fig. 2

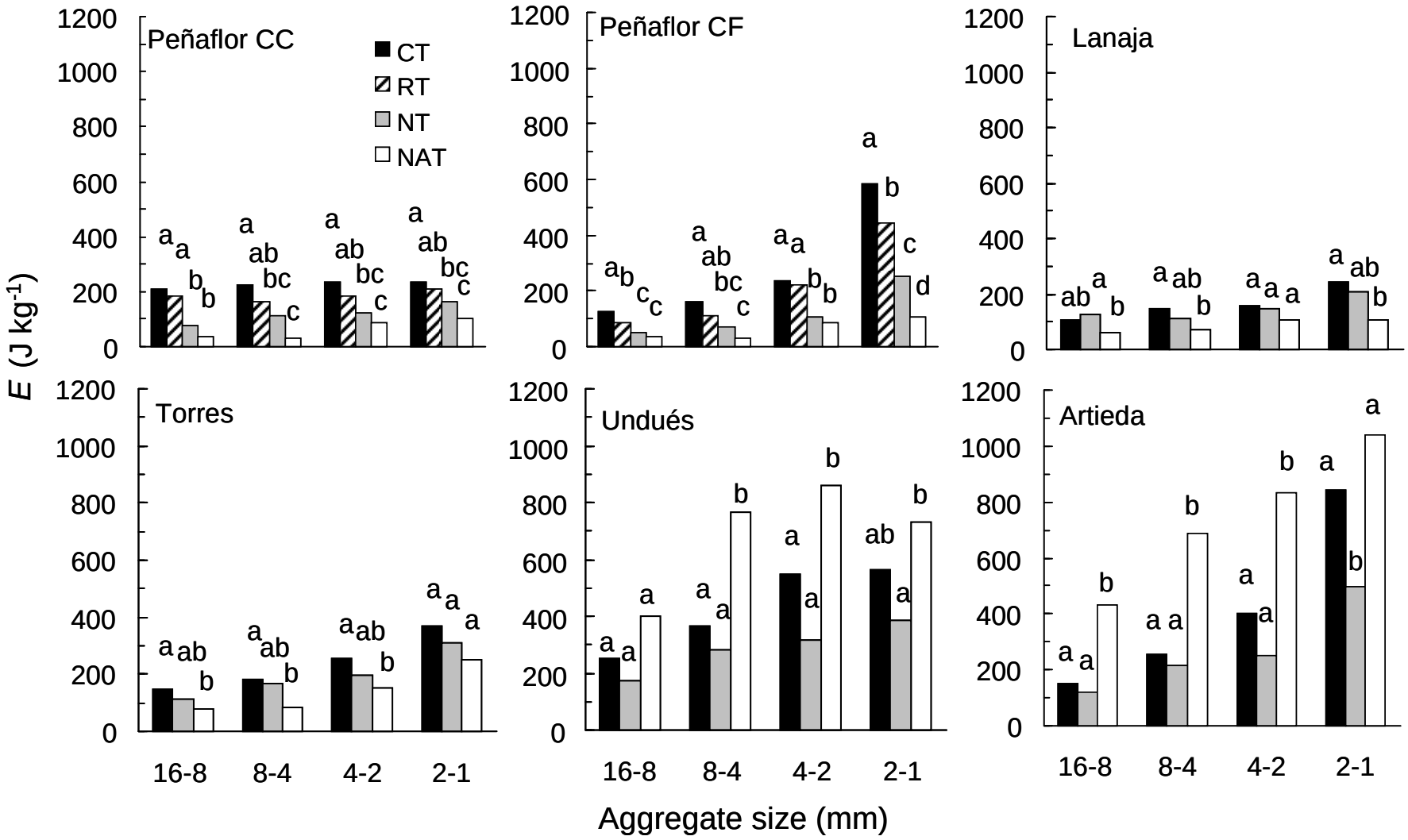
Peñaflor CC
Peñaflor CF
Lanaja
Torres
Undués
Artieda
CT
RT
NT
NAT
E (J kg-1)
Aggregate size (mm)
16-8
8-4
4-2
2-1
0
200
400
600
800
1000
1200

Fig. 3

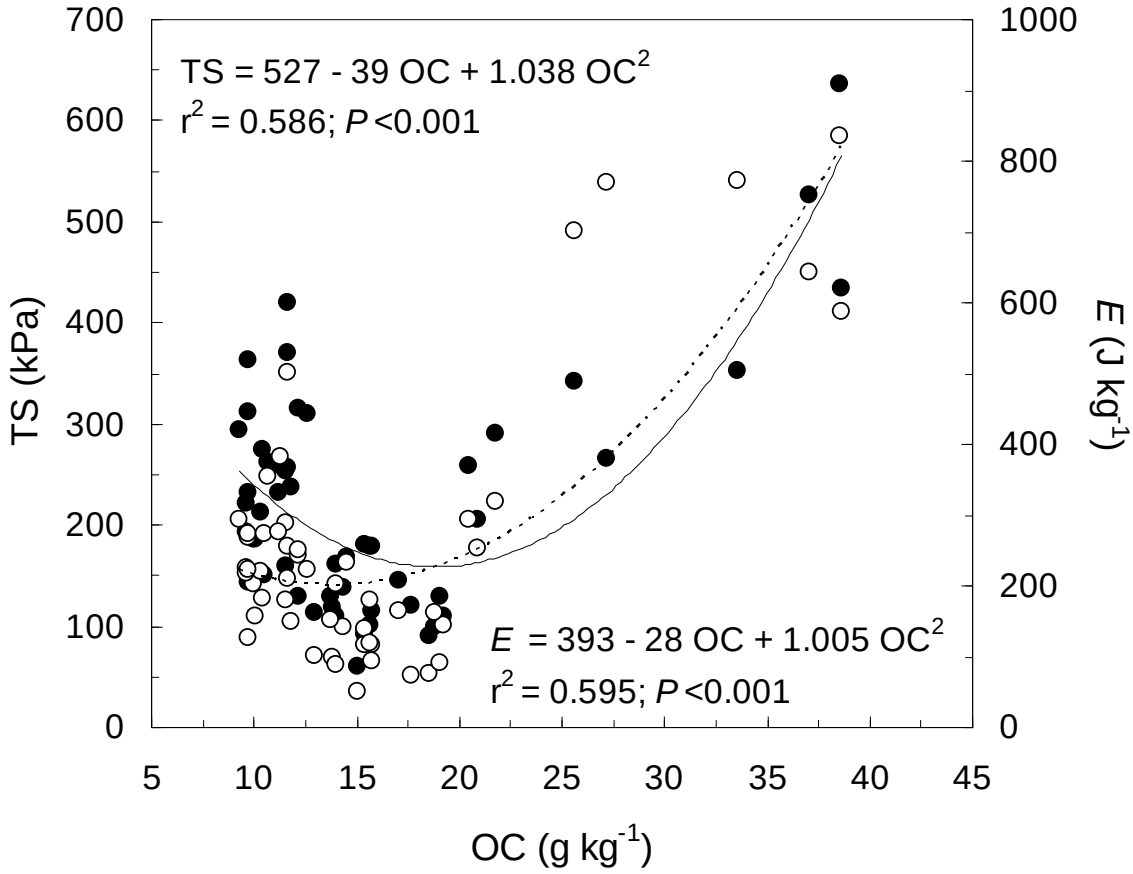
TS = 527 - 39 OC + 1.038 OC2
r2 = 0.586; P <0.001
E = 393 - 28 OC + 1.005 OC2
r2 = 0.595; P <0.001
TS (kPa)
E (J kg-1)
OC (g kg-1)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
5
10
15
20
25
30
35
40
45

Fig. 4

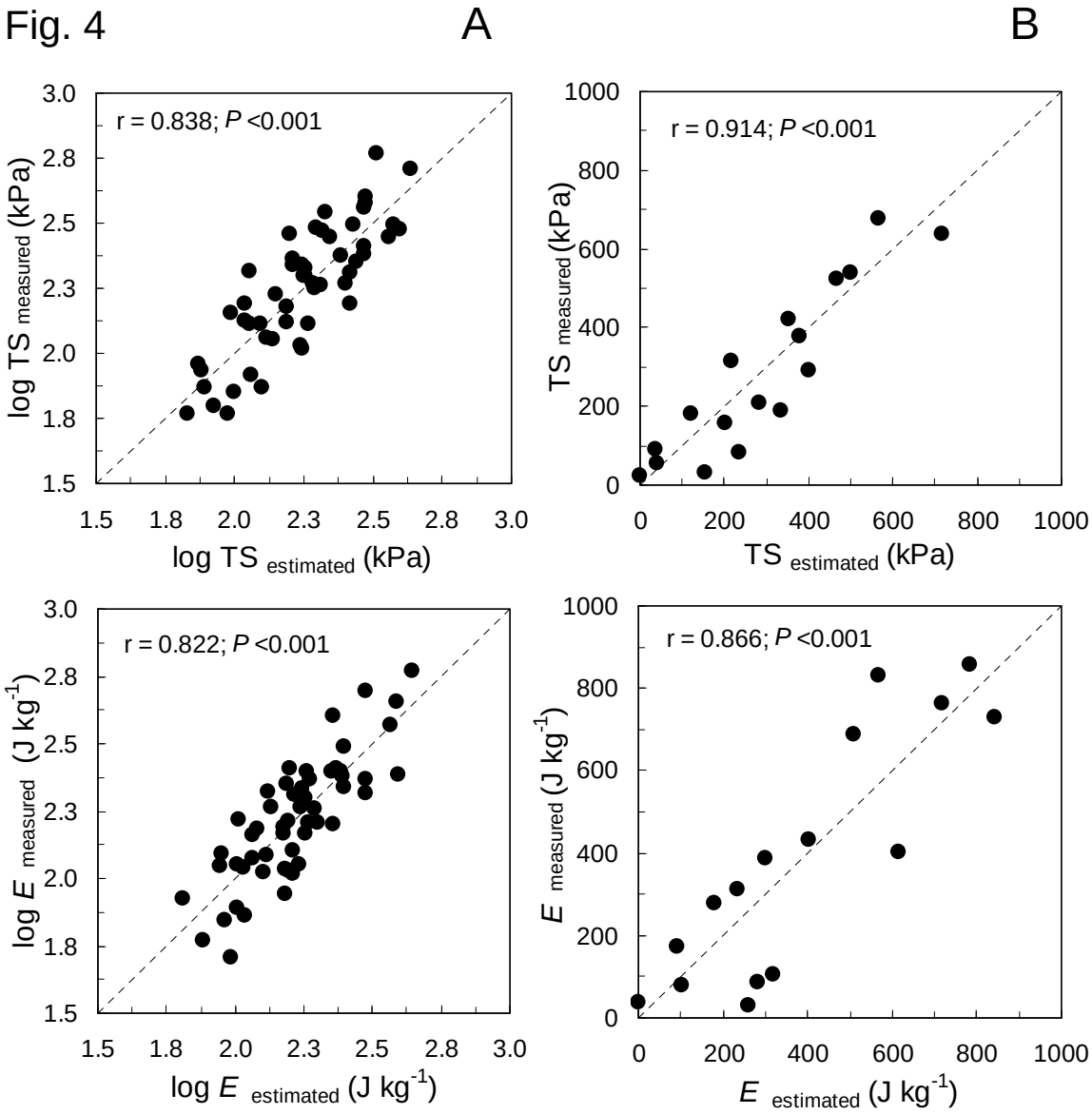
A
B
r = 0.838; P <0.001
log TS measured (kPa)
log TS estimated (kPa)
r = 0.914; P <0.001
TS measured (kPa)
TS estimated (kPa)
r = 0.822; P <0.001
log E measured (J kg-1)
log E estimated (J kg-1)
r = 0.866; P <0.001
E measured (J kg-1)
E estimated (J kg-1)

Fig. 5