USE OF THE WATER RETENTION CURVE FOR THE ASSESSMENT OF SOIL QUALITY

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RESUMEN. Desde los comienzos de la física del suelo se ha usado el punto de inflexión de la curva de retención de agua bien para evaluar la estabilidad de los agregados y la capacidad de campo, o estimar la calidad comparable a la concentración de materia orgánica o a otras propiedades similares. El punto de inflexión marca la moda de la función de distribución de la probabilidad del tamaño de poros pero ¿es suficiente esta propiedad para justificar su uso como índice de calidad del suelo?
En este trabajo se explora la idoneidad de algunas propiedades de la curva de retención de agua para evaluar la calidad de un suelo.

ABSTRACT. Since the beginning of soil physics, the inflection point of the water retention curve has been used either to evaluate the stability of the aggregates and field capacity, or to estimate the comparable quality to the concentration of organic matter or other similar properties. The inflection point marks the mode of the probability distribution function of pore size but, is this property enough to justify its use as an index of soil quality?
In this work, the suitability of some properties of the water retention curve to evaluate soil quality is explored.

1.- Introduction

Soil quality is characterized, among other aspects, by its capacity to exchange mass and energy with the surroundings (e.g. Sojka et al., 2003). This exchange is controlled by the soil texture and structure, which on its turn, depends on the water retention characteristics. Water is retained in soil due to the adherence of water molecules to the walls of voids present in the soil matrix. Although part of the forces exerted onto water molecules are caused by the plane walls of voids (Or and Tuller, 1999), most of them are generated in the capillary menisci. As Or and Tuller (1999) suggested, the augmented Young-Laplace equation can be used to relate the matric component of soil water potential with the effective radius of a capillary tube. Therefore, the widely used soil water retention curve (SWRC), the graphical expression of the previous relationship, can be used as the probability density function of effective pore size (e.g. Or et al., 2000). The integral of the SWRC represents, as already Childs (1940) pointed out, the energy (J m^{-3}) implied in the retention processes.
The pore size distribution is an important property for the description of soil water behaviour. The greater pores allow a quick soil water infiltration, as well as they act as a good barrier to prevent evaporation losses during dry periods (e.g. Or et al., 2013). The mode of the distribution of pore size has been chosen for the estimation of the soil quality by Collis-George and Figueroa (1984) and Mamedov and Levy (2013), among others, to assess the aggregates stability by comparing their values in two SWRC measured during slow and fast wetting processes, in what is denominated the High Energy Moisture Characteristics (HEMC). Later, Dexter (2004) selected the SWRC mode as well but representing the matric component of the water potential by its logarithmic value in what is known as the *S*-index.
In agronomic applications the upper limit of the moisture content which remains metastable after a wetting process, the field capacity, in spite of the criticisms of the validity of this value (de Jong van Lier, 2017), is usually estimated in the SWRC matric, (e.g. Twarakavi et al. 2009, Assouline and Or, 2014; Reynolds, 2018). In particular, Assouline and Or (2014) determined the moisture content at the field capacity drawing the tangent line to the SWRC at the inflection point. Twarakavi et al. (2009) adopted the soil hydraulic conductivity equation formulated by Mualem (1976) that is based on the SWRC.
The redistribution of water in soil after the infiltration ceases depends on the air- and water-entry states usually defined in the SWRC (e.g. Wang et al., 2004). The air-entry and water-entry states characterize, respectively, the lower and the upper end of the water blob formed during redistribution of water in soils with great pores, like sands (Youngs, 1958; Peck, 1971). Haverkamp et al. (1986, 2002) proposed a functional determination of both states in different equations for the SWRC.
In all the above problems it is necessary to assess a proper function to characterize the SWRC. A great number of equations have been suggested for their fit to the SWRC measured data (e.g. Leij et al., 1997), ranging from simple analytical equations, as the Raats superclass equation (Raats, 2001; Heinen and Bakker, 2016), to other more involved forms, like exponential whose arguments contain the suction as a potential function, (Assouline et al., 1998, Groenevelt and Grant, 2004), the potential of a logarithm

of the suction, (Fredlund and Xing, 1994).
The interpretation of the SWRC as an effective pore size distribution function can be questioned as Hunt et al. (2013) commented by the not immediate assimilation of the bundle of capillary tubes to the real soil. More up-to-date and sophisticated technologies such as X-ray cross tomography may yield better approximations of the pore space. However, not being a perfect image of the soil, it is possibly one of the most cost-effective methods to be used.
The complexity of some of the proposed SWRC functions, (e.g. Assouline et al. 1998 or Fredlund and Xing 1994) and the imperfect fits to the measured data, impede very often a proper interpretation of the soil properties. Can the applications of interpolation algorithms (such as those based on cubic splines) solve this problem? The main purpose of this communication is to answer this question. Also, we explore whether several indices obtained from the shape and features of the SWRC, as the maximum value of the slope, its abscissa, the Dexter (2004) S-index, the Haverkamp et al. (2005) shape index, and the Minasny and McBratney (2003) average soil water content and matric component of the soil water potential have a relationship with some soil quality indicators like bulk density, saturated hydraulic conductivity, organic matter content, and aggregate stability.

2.- Material and Methods

Firstly, the algorithm used for interpolation of the SWRC data is briefly described, and secondly a description is included for the soils and the method to evaluate the SWRC.

2.1. Interpolation with natural cubic splines

Splines are piecewise polynomials with common values of the ordinate, the first and the second derivative values at the knots used for interpolating fitting, and smoothing data points. Developed in the forties of the last century, these were first introduced in soil science by Erh (1974), and widely used later by other authors (e.g. Kastanek and Nielsen, 2001). Cubic polynomials are the simpler curves with continuous second derivatives at the knots. The adjective natural indicates a null value for the second derivatives at the extreme knots. The determination of the spline coefficients is straightforward (e.g. Press et al., 1992 § 3.3). The knots will be selected data points. Figure 1 shows one spline fit.

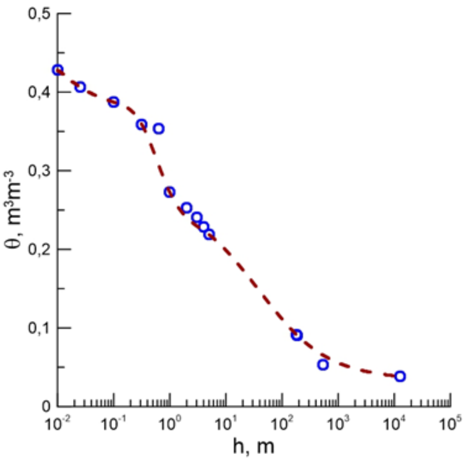

Fig. 1. Example of a natural cubic spline fit to measured SWRC data.

2.2. Experiment information

The experimental sites were located in two representative olive orchard farms in the province of Seville (Pedrera, P, and Benacazón, B) with different soil types, Typic Calcixerept and Petrocalcic Palexeralf, respectively (Soil Survey Staff, 1999) and two soil managements each (Figure 2). One management was conventional tillage (CT) consisting of weeds control by 2–4 cultivator passes at a depth of 15 cm. The second soil management system was temporary cover crop (CC) which consisted of a sown cover crop of ryegrass (*Lolium multiflorum*) along the inter tree rows every year, with the first autumn rains. In early spring depending on annual rainfall, the cover was chemically killed to avoid water and nutrient competition with the olive trees according to the local mowing date recommendations. Thus, this soil management began in fall 2001 in Pedrera and spring 2003 in Benacazón. The previous soil management systems in the whole farms were conventional tillage and spontaneous cover, respectively.

Fig. 2. View of the plots at the sampling time. Pedrera on the left and Benacazón on the right side.

Field measurements and soil sampling for laboratory analysis were performed during January and April 2005 along the inter tree rows (X) and under olive trees' canopies (C) at two different depths, 0–0.1 m (T) and 0.1–0.2 m (D).

In the case of the tillage plots, measurements and sampling coincided when soil compaction was maximum, just before the first plough pass in early spring. Selected soil chemical and physical indicators were measured: organic matter (*OM*), bulk density (*Bd*), saturated hydraulic conductivity (*Ks*), and macroaggregate stability (*AE*) (Soil Survey Staff 2009). In addition, water retention curves (SWRC) were determined using undisturbed soil cores of 98.2 cm^3 during a drying cycle using a sand box and a sand/kaolin box (Eijkelkamp Giesbeek, The Netherlands). For water potentials lower than -5 m, measurements were obtained on disturbed soil samples using a dewpoint potentiometer (WP4C, Decagon, Pullman, WA, USA).

The number of samples taken, or measurements per management, area, and depth was eight for *Bd*, *AE*, and SWRC, and four for *Ks*. More details about the experimental procedures can be consulted in Guzmán et al. (2019).

2.3. Selected SWRC indices

Soil quality is defined with Karlen et al. (1997) as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". Karlen et al. (1997, Table 1) suggested several indicators, some of which have been chosen here to be evaluated with SWRC indices. The first one is the value of the derivative at the inflection point, which is the mode of effective pore size distribution function. It represents the fraction of the porosity occupied by the most abundant pore size, *dermx*,

$$dermx = \frac{dq}{dh}(hmxs) \tag{1}$$

where θ is soil moisture (m^3 m^{-3}) and *hmxs* is the value of the suction (h in m) at the inflection point, which is used as an index, too. The third index is the shape index, P, of Haverkamp et al. (2005),

$$P = \frac{1}{\theta_s - \theta_r} \int_{\theta_r}^{\theta_s} \frac{d\left[\ln(\theta)\right]}{d\left[\ln(h)\right]} d\theta \tag{2}$$

where θ_r and θ_s are the residual and the saturated soil water contents (m^3 m^{-3}), respectively. The fourth index is the integral energy of Minasny and McBratney (2003), a moisture-averaged suction value.

$$E_I = \frac{1}{\theta_s - \theta_r} \int_{\theta_r}^{\theta_s} h d\theta \tag{3}$$

The fifth index is the integral water storage of Minasny and McBratney (2003), a suction averaged soil water content,

$$W_I = \frac{1}{h_{max} - h_{min}} \int_{h_{min}}^{h_{max}} \theta dh \tag{4}$$

where h_{min} and h_{max} are, respectively, the minimum and maximum values of the suction (m). Finally, the sixth index is the Dexter (2004) *S*-index, i.e., the derivative of the SWRC at the inflection point where the suction (in m) is represented by its logarithmic value.

$$S = \frac{dq}{d\left[\ln(h)\right]}\left[\ln(hmxs)\right] \tag{5}$$

The units of these indices are: m^3 m^{-3} per m for *dermx*, m for *hmxs*, - for *P*, m for E_I, m^3 m^{-3} for W_I, and m^3 m^{-3} per unit ln(h) for *S*. However, for simplicity they are omitted hereon.

2.4. Statistical methods

Statistical analysis was performed using the PAST software (Hammer et al., 2001) and the ggpairs package (Emerson et al., 2012) in R. Kruskal-Wallis test were performed to compare medians of non-gaussian distributions.

3. Results and discussion

From the visual inspection of most of the measured SWRC (results not shown) it is very hard to find the air-entry state, as in Fig. 1. The water content gradually decreases as the suction increases, not as in the sharp slope discontinuity point in the water retention curves shown by Haverkamp and Parlange (1986), and Haverkamp et al. (2002). Nevertheless, the static field capacity in the interpolated water retention curves can be easily estimated as described by Assouline and Or (2014).

Figures 3 and 4 show the probability distribution functions (pdf) and correlation matrix of the water retention-derived indices at Benacazón and Pedrera, respectively. In most of the cases, the pdf showed positively skewed multimodal distributions reflecting the large spatial variability of soil water retention at both sites. This multimodality mainly relates with the differences in location (inter tree rows versus under olive´s canopies) and depth (0-0.1 and 0.1-0.2 m) of the samples at both sites. In general, the *S*-index showed the highest correlations with the other indices (Fig. 3 and 4) in both fields, being the correlations higher for Benacazón than Pedrera. The highest and significant ($p<0.05$) correlations found were obtained between the two shape indices, *S* and *P*. Kruskal-Wallis tests performed on the data grouped by field yielded significantly different medians ($p<0.05$) in all indices but the shape index *P*. This analysis manifests a weak dependence of the shape index *P* on the two soil types studied here, given the large differences in soil texture between both fields. Soil management gave significant differences ($p<0.05$) between median values of *dermx*, W_I and the *S*-index at Pedrera and only between median values of *hmxs* and W_I at Benacazón.

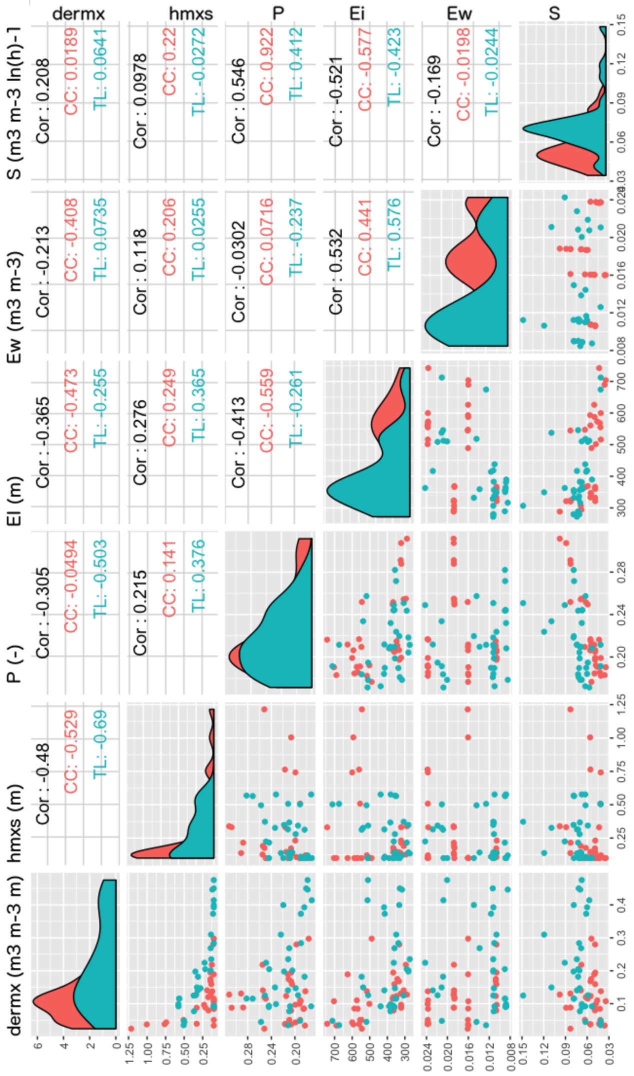

Fig. 3. Probability distribution functions and correlation matrix of the water retention-derived indices at Benacazón considering the two managements under evaluation, cover crop (CC) and conventional tillage (CT).

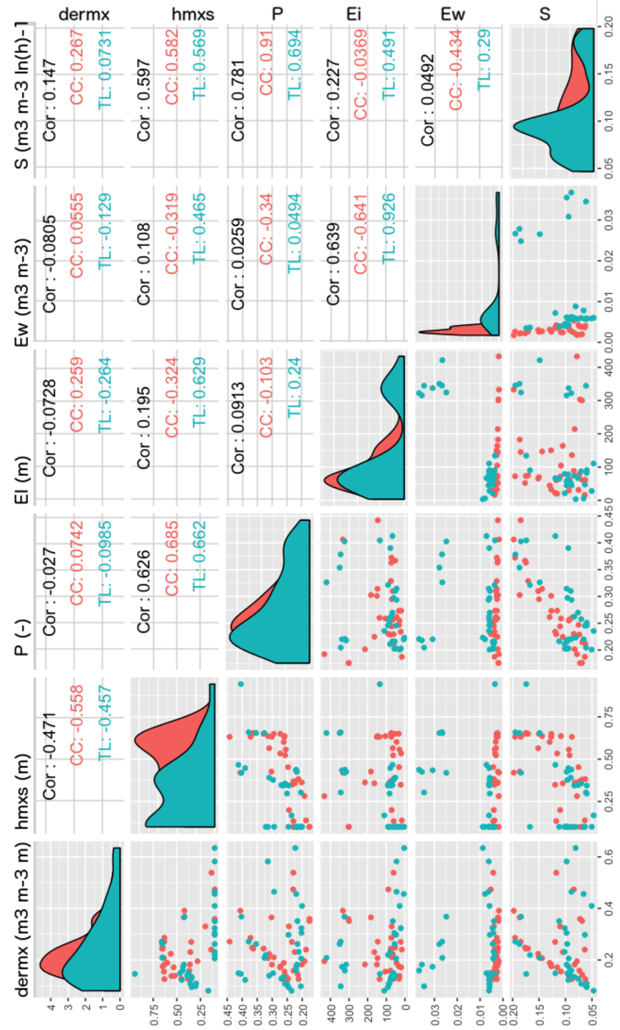

Fig. 4. Probability distribution functions and correlation matrix of the water retention-derived indices at Pedrera considering the two managements under evaluation, cover crop (CC) and conventional tillage (CT).

Regarding the soil management, the cover crop plots showed, at both locations (P and B), better indicators of soil quality, in general terms. For instance, *Bd* was lower at the 0-10 cm along the olives rows (P_CC_TC and B_CC_TC), K_s was higher at the 10-20 cm along the olives rows (P_CC_DC and B_CC_DC) and *OM* at 0-10 cm along the inter-tree rows (P_CC_TX and B_CC_TX).

No relationship was found between the SWRC P, E_I, W_I and S indices with the soil quality indicators analyzed.

The comparison between the SWRC-derived and directly measured soil quality reveals that the *dermx* and *hmxs* have better performance than the rest of indices.

Figures 5 and 6 show the possible relations between those two indices, *dermx* and *hmxs*, respectively, and the field-measured conditions: bulk density, *Bd*, field saturated hydraulic conductivity, K_s, organic matter, *OM*, and aggregate stability, *AE*.

The maximum value of the water capacity, *dermx*, and the corresponding value of the suction, *hmxs*, respond in a different way to the changes of the field-measured conditions. The higher *dermx*, and lower *hmxs* indicate an improvement of soil quality.

The large variability of the measured indicators, the bubble radius of Figs. 5 and 6, prevent the formulation or the detection of a clear relationship between soil properties and the estimated indices. However, some trends can be appreciated, especially when analysing each location (P and B) separately or grouping soil management systems (CC and CT).

In the CC treatment, the greater the *dermx* and the smaller the *hmxs*, the lower the apparent density and K_s and the

higher the *MO* content and the stability of the aggregates.
On the contrary, no such a clear relationship between the SWRC-derived indices and the field measured properties is observed in the CT treatment.

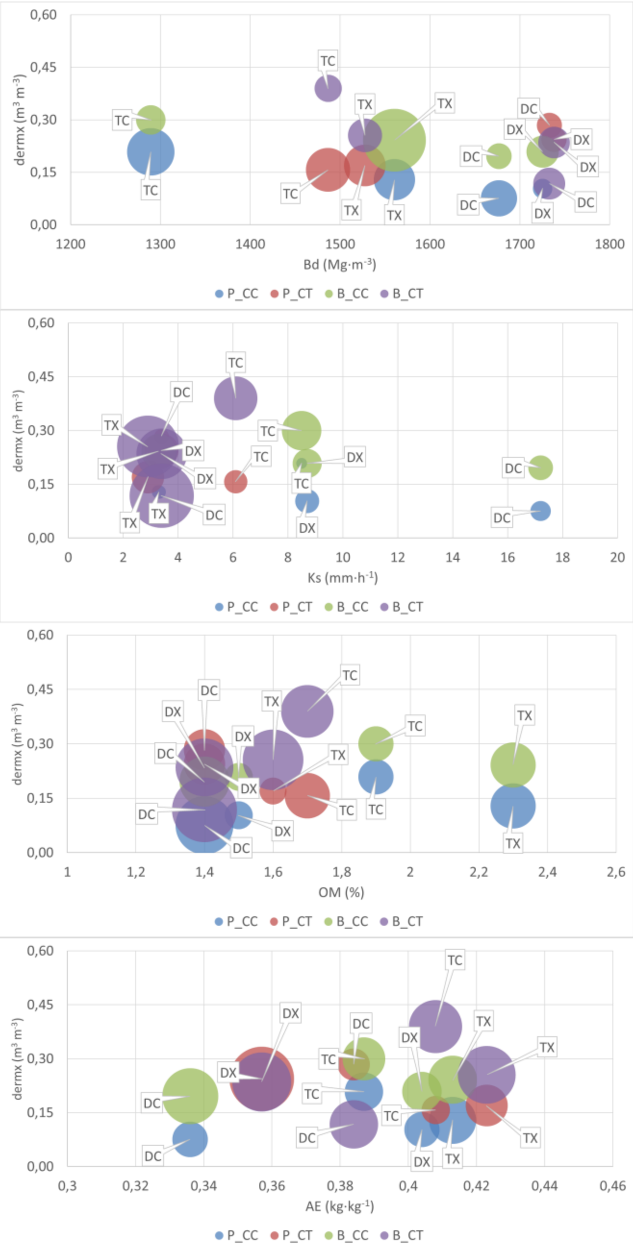

Fig. 5. Bubble plot of mean *dermx* and mean measured indicators (*Bd*, *Ks*, *OM* and *AE*) for the two locations (P and B), managements (CC and CT) and zones (TX, TC, DX and DC). The size of the bubbles indicates the variance coefficient of the indicators.

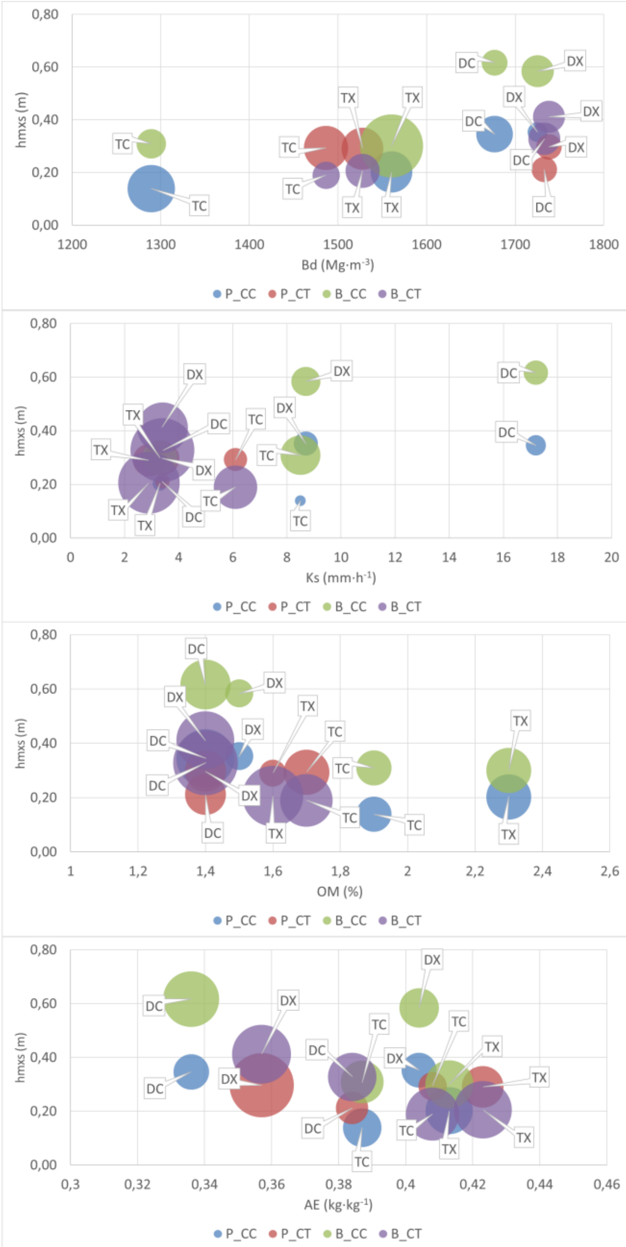

Fig. 6. Bubble plot of mean *hmsx* and mean measured indicators (*Bd*, *Ks*, *OM* and *AE*) for the two locations (P and B), managements (CC and CT) and zones (TX, TC, DX and DC). The size of the bubbles indicates the variance coefficient of the indicators.

Figure 7 presents the relation between the *S*-index and the indicators measured at the field site: *Bd*, *Ks*, *OM* and *AE*.
An *S*-index above 0.035 is usually found in non-degraded soils (Dexter, 2004). Our values show the moderate good quality of these soils, especially in Benacazón.
Analysing the *S*-index values of the SX (0–10 cm along the inter tree row), CT treatment showed similar values (*S*~0.070) at both locations, and therefore showing the fast effect of tillage in Benacazón. The implementation of cover crops leads into high *S* values, as it can be observed for B_CC, although the CC effect was not that clear in Pedrera (*S*~0.045) at the short term.
Despite the mentioned above, no strong trend is evident between the *S*-index and these indicators likely due to the

field conditions (interaction among management systems, areas, and depths) and therefore further analysis must be performed. As Andrews et al. (2004) described the indicators values can be integrated in a soil quality index.

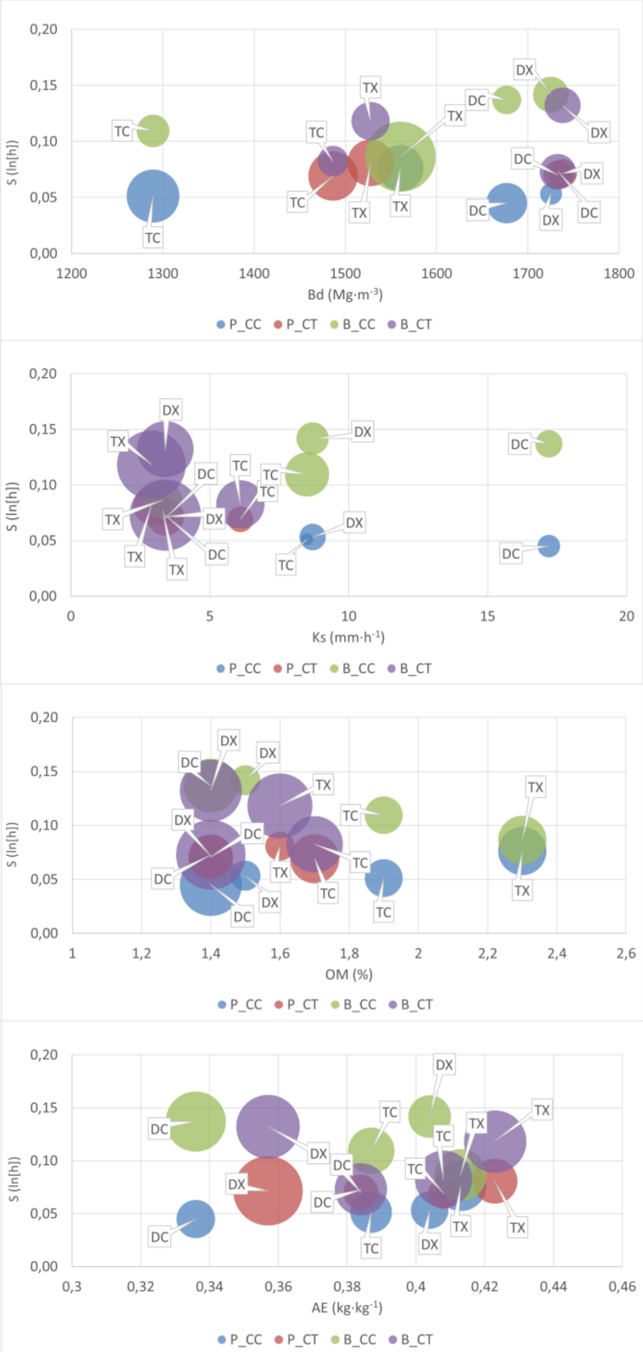

Fig. 7. Bubble plot of mean *S*-index and mean measured indicators (*Bd, Ks, OM* and *AE*) for the two locations (P and B), managements (CC and CT) and zones (TX, TC, DX and DC). The size of the bubbles indicates the variance coefficient of the indicators.

4. Conclusions

Although the fit of simple analytical functions to the soil water retention curve is not always easy, simple interpolation schemes can be used to detect some of the proposed soil quality indicators based on it.

The comparison of some of the soil quality indices with field-measured physical properties indicate that those related to the main inflection are the most appropriated.

Acknowledgements. The authors would like to thank the support received by the CATCH-C project (Grant Agreement N° 289782), projects ProTerra I–II and Biosuelo (Syngenta) and EU–FEDER funds.

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