Geoderma 354 (2019) 113872

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Comparison of methods for evaluating soil quality of semiarid ecosystem and evaluation of the effects of physico-chemical properties and factor soil erodibility (Northern Plateau, Spain)

Fernando Santos-Francés[a], Antonio Martínez-Graña[b,*], Carmelo Ávila-Zarza[c], Marco Criado[a], Yolanda Sánchez[b]

[a] Department of Soil Sciences, Faculty of Agricultural & Environmental Sciences, University of Salamanca, 8 Avenue Filiberto Villalobos, 119, 37007 Salamanca, Spain
[b] Department of Geology, Faculty of Sciences, University of Salamanca, Plaza de la Merced s/n., 10 37008 Salamanca, Spain
[c] Department of Statistics, Faculty of Environmental Sciences, Avenue Filiberto Villalobos, 119, 37007 Salamanca, University of Salamanca, Spain

ARTICLE INFO

Handling Editor: Alex McBratney

Keywords:
Soil quality index
Semiarid agrarian ecosystem
Northern plateau of Spain
Factor analysis

ABSTRACT

The objective of this study was to compare two different methods for the calculation of the soil quality index for agricultural land in the province of Salamanca in the semiarid ecosystem of the Northern Plateau, Spain. The integrated quality index (IQI) and Nemoro quality index (NQI) were applied using the following indicator selection methods: total data set (TDS) and minimum data set (MDS). A total of 16 soil parameters were used for the TDS method. The evaluation of the soil quality index using only the properties of surface soil provides incomplete information because crop productivity is influenced by both the surface and subsoil properties [e.g. lithic contact, petrocalcic horizon, clayey horizon (Bt)]. The quality indexes were calculated using data from 75 soil profiles considering the soil surface properties (between 0 and 25 cm depth) and control section properties (between 0 and 100 cm).

The results show that the consideration of soil properties of both the surface and subsurface horizons is very important to establish a good relationship between soil quality, soil functions, and agricultural management.

The results based on the IQI index provide a better estimate of the soil quality compared with the NQI index; higher values were obtained with the TSD than with the MSD. However, the results obtained from the IQIMSD method provide an adequate evaluation of the soil quality. This is relevant because the use of a limited number of indicators reduces the analysis cost and increases the sampling density.

1. Introduction

The evaluation of the soil quality has gained widespread interest in the last two decades and its importance is expected to increase, as the needs to protect and preserve soil and to know its basic functions are being realised (Nortcliff, 2002).

One of the most limiting aspects of soil quality assessments is the lack of a universally accepted method for the development of soil quality indexes. Currently, new indexes are excessively developed, which seems to be endemic and unjustified; researchers should place greater emphasis on evaluating the suitability of existing indexes before developing new ones (Qi et al., 2009).

Quality indices are obtained by integrating different soil property indicators, which provide information on soil functions (Aparicio and Costa, 2007).

For the selection of indicators for a soil quality index, it is important to consider all information about the study area and expert opinions (Andrews et al., 2004). However, the implementation of experimental analyses in large areas is difficult because it requires a large number of soil quality indicators. It is important to develop evaluation methods that use a minimum number of indicators to improve the work efficiency and reduce labour time and expenses. Andrews et al. (2002a) and Shukla et al. (2006) obtained a minimum set of indicators from a total data set (TDS) using factor analysis and highlighted the high consistency of the two data sets (total and minimum) with respect to the evaluation of the soil quality.

During indicator scoring, data normalisation is required because the indicators are usually expressed using different numerical scales. The

* Corresponding author.
E-mail addresses: fsantos@usal.es (F. Santos-Francés), amgranna@usal.es (A. Martínez-Graña), caaz@usal.es (C. Ávila-Zarza), marcocn@usal.es (M. Criado), yolanda.ss@usal.es (Y. Sánchez).

https://doi.org/10.1016/j.geoderma.2019.07.030
Received 31 March 2019; Received in revised form 11 July 2019; Accepted 14 July 2019
Available online 20 July 2019

linear scoring method has been used for data normalisation. Based on this method, the linear relationship between the quality score and measured data is established using the sensitivity of the indicator to changes in the soil quality.

Subsequently, the scores of the selected indicators are combined in a soil quality index by using several mathematical operations such as averaging, adding, and multiplying (Svoray et al., 2015; Amirinejad et al., 2011). The integrated quality index (IQI) is a method that considers differences in the contribution of each indicator to the soil quality (Bi et al., 2013); weight assignments are based on expert opinions or statistical analysis (Glover et al., 2000). The influence of limiting factors on the soil quality was highlighted in several studies; thus, the Nemoro quality index (NQI) was used based on which the soil quality is evaluated using minimum and average indicator scores (Rahmanipour et al., 2014).

Many of the soil quality assessments that have been carried out to date are based on the properties of the surface soil horizon (Andrews et al., 2002a, 2002b; Armenise et al., 2013). Studies that use data from the full soil profile are limited (Moncada et al., 2014; Vasu et al., 2016; Zhijun et al., 2018). It is easy to measure and evaluate the properties of the superficial soil layer. However, these properties provide incomplete information because the soil functions are driven by paedogenic processes in the soil control section. The evaluation of the soil quality using the properties of surface soil and subsoil will help to identify the properties that have the maximum influence on basic soil functions.

The development of the crops and volume of the harvests depend on the soil conditions with respect to the extension and growth of their roots. On deep soils, with good permeability, with high water retention, etc. a great diversity of cultivated plants can grow vigorously. On the contrary, if the characteristics of the profile impede the root development (e.g. based on the presence of calcareous crusts and/or lithic contact), the plant growth is hindered and the volume of the harvest diminishes. Hewitt (2004) determined that the soil productivity is influenced by the subsoil characteristics (control section).

In the present study, different soil quality indexes were calculated using the properties of the superficial soil horizon (arable layer, 0–25 cm) in addition to the properties of all horizons of the soil profile (control section, 0–100 cm).

The agricultural aptitude of soils can be evaluated with different methods, which generally are qualitative. The most widely used methods are the evaluation of the land (FAO, 1976), Storie index (Storie, 1978), and parametric approach (Sys et al., 1991). However, recent literature soil quality assessment advocates the development and definition of a quantitative index (Merril et al., 2013; Askari and Holden, 2015); therefore, the soil quality index is of great importance. These indexes are common and simple tools that can be used for the quantification of the soil quality, improve the understanding of soil ecosystems, and allow for more efficient management (Andrews et al., 2002a; Qi et al., 2009).

The development of a quantitative soil quality index must follow three steps: (1) selection of indicators, (2) assignment of scores to selected indicators, and (3) integration of indicators in an index (Karlen et al., 2003). The calculation of a soil quality index starts with the definition of indicators, that is, the physical, chemical, and biological soil properties, which are sensitive to changes of natural and anthropogenic factors (Doran and Jones, 1996). Among the indicator selection methods, the TDS and minimum data set (MDS) have been widely used for the evaluation of the soil quality (Doran and Parkin, 1994; Larson and Pierce, 1991).

Agricultural expansion and population growth are among the main widespread causes of soil degradation in most terrestrial ecosystems. Consequences are the overexploitation of agroecosystems and change in the land use from natural ecosystems (e.g. forests and pastures) to farmland, which have a significant negative influence on the soil quality (Rahmanipour et al., 2014). Better knowledge of the soil quality is important to improve the sustainable management of land use (McGrath and Zhang, 2003), provide warning signs of adverse trends, and identify problem areas (Bindraban et al., 2000). Although the evaluation of the quality of agricultural land has progressed in recent years, in large part due to the emphasis on environmental change at the global level, the improvement of the evaluation of the soil quality is imperative for the development of sustainable agriculture and can also be used to judge the sustainability of land management and land use systems (Wang and Gong, 1998). Therefore, the objectives of this study were: (1) to evaluate the quality of different soil types (Alfisols, Inceptisols, and Entisols) with different land use types (agricultural and grassland) in the Northern Plateau of Spain using two methods of indicator selection (TDS and MDS) and two index models (IQI and NQI) and considering the properties of the most superficial horizon (0–25 cm) in addition to the properties of the control section of the soils (0–100 cm); (2) to establish the most suitable quality index models for this region using a statistical approach and linear relationships; and (3) to create soil quality index maps to identify areas with poor quality and avoid further degradation based on the adjustment of their agricultural use.

2. Materials and methods

2.1. Description of the study area

The study area (Fig. 1) is located in the north-eastern part of the province of Salamanca (Spain). Geographically, the study region is located in the Northern Plateau, Spain. It covers a total area of 770 km^2 with flat to gently undulating topography. The Los Montalvos Mountain represents the highest altitude, that is, 942 m above sea level. It is located on a syncline formed by Armorican quartzites and slates of the basament (Ordovician–Silurian age). At the intermediate level, plains that were carved into the horizontal sediments predominate (Paleógeno–Negeno). The lowest one is the floodplain of the Tormes River, on alluvial deposits (Pleistocene–Holocene), with a height slightly lower than 760 m. The maximum drop is therefore 182 m, providing a clear idea of the little accused of relief.

The climate is characterised by cold winters and hot and dry summers, with an average annual precipitation and temperature of 400 mm and 12 °C, respectively. Rainfall is mainly concentrated in the winter period (October to March). The average temperature in summer (June, July, and August) is 21 °C and that in winter is 6 °C. These temperatures define a climate with short and relatively cool summers and long and rather rough winters. The frost period lasts from mid-October to mid-May. The soils in this region have a xeric moisture regime and mesic temperature regime.

Based on the classification according to the USDA soil taxonomy method (Soil Taxonomy, 2014) and World Reference Base for Soil Resources (WRB) of the FAO (IUSS Working Group WRB, 2015), the soils in the study area are Alfisols (Luvisols), Inceptisols (Cambisols), and Entisols (Fluvisols, Arenosols, Regosols, and Leptosols). Plains that were carved into Cenozoic sediments predominate in this region. The soils are powerful and fertile, which allowed the establishment of high-yield rainfed agriculture. 'The fertility of the lands of the plateau' and 'goodness of its grains' were already celebrated at the time of the conquest of Hispania by the Romans, to the point that this region is considered to be the 'granary of Spain' (Peña Sánchez, 1987). Based on expert opinions, the best soils in this region are deep soils (Alfisols), with a frank superficial horizon (Ap) texture and low organic matter (OM) content due to its degradation due to the effect of the crop for several years. Centuries, with a subsurface horizon of argillic type (Bt), in many cases with clays of the group of smectites, with high water retention (the soils have a xeric humidity regime, which leads to a deficit in the water balance in the soil from April to October), with the presence of a horizon of accumulation of carbonates and a pH close to neutrality (optimum for most crops), with high cation exchange capacity and with a high degree of saturation in bases. On the contrary, a

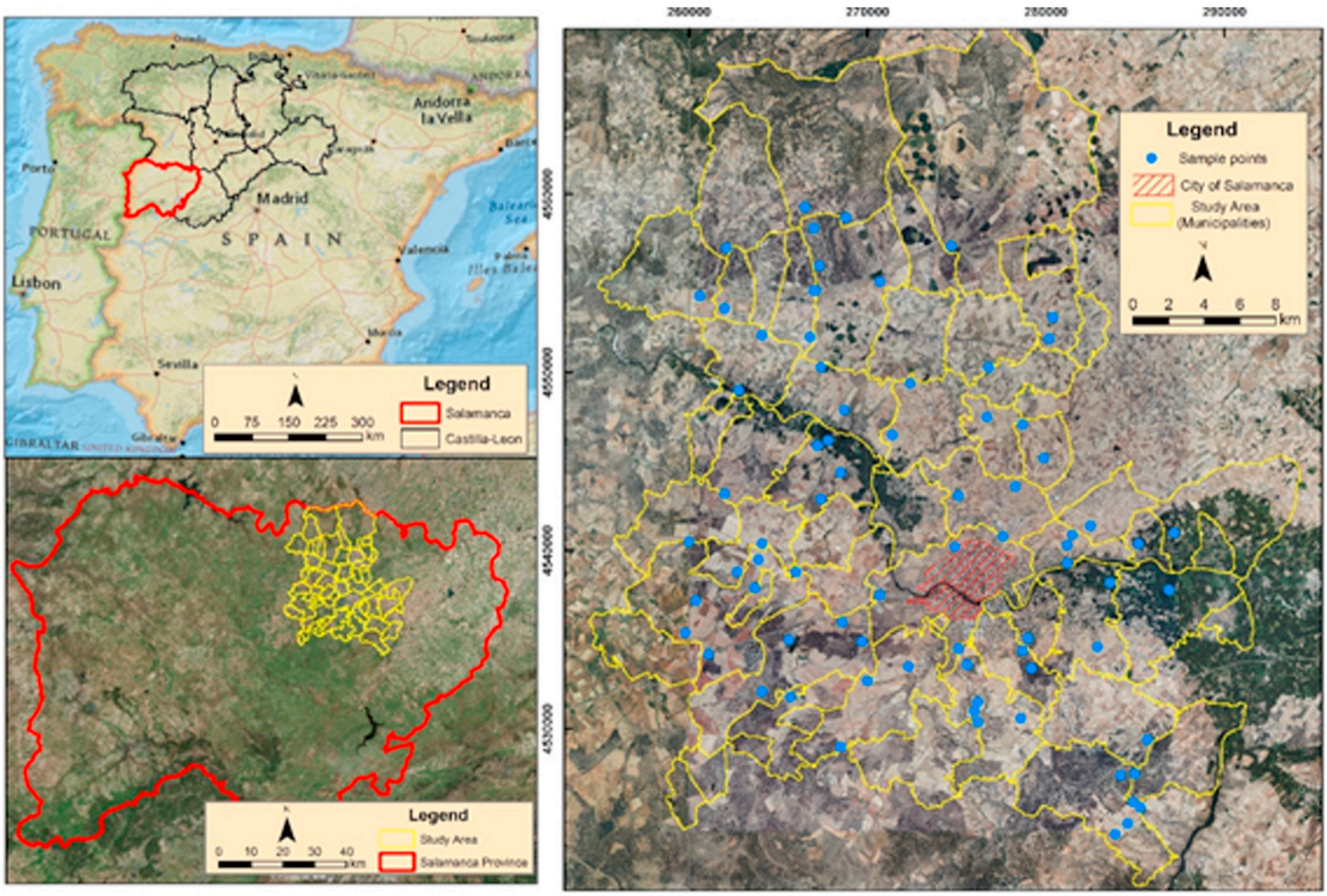

Fig. 1. Study area and sampling points.

steeper landscape can be observed at the northern and southern limits of the study area. It developed on the Palaeozoic scale, with thin soils (Entisols), a lithic contact near the surface that prevents root development, high degree of erosion, and low fertility, which traditionally has been dedicated to extensive livestock (pasture; Fig. 2).

2.2. Sampling and soil analysis

To generally characterise the study area, 300 samples were collected from 75 soil profiles from the soil layer (0–25 cm) and subsurface horizons (0–100 cm). Each sample consists of several subsamples that were collected at three different points. The samples were air-dried, shredded, and sieved through a 2-mm sieve before performing the following chemical and physical analyses (Table 1): sand and clay content, pH, electrical conductivity (EC), OM, extractable bases of change (Na, K, Ca, and Mg), cation exchange capacity (CEC), percentage of $CaCO_3$ equivalent (TNV), apparent density (BD), water retention at 33 kPa and 1500 kPa (GWC 33 kPa and GWC 1500 kPa), coefficient of linear extensibility (COLE), and soil erodibility factor (K). The latter was calculated using the equation established by Wischmeier and Smith (1978) Eq. (1):

$$100K = [10 - 4 * 2.71 * T1.14 * (12 - OM)] + [4.2 * (E - 2) + 3.23 * (P - 3)] \quad (1)$$

where T is the parameter corresponding to the texture in the most superficial 15 cm Eq. (2):

$$T = [(100 - Ac) * (L + Armf)] \quad (2)$$

where Ac = Clay, L = Silt, Armf = Very fine sand, OM = Organic matter (OC * 1.72), E = structure parameter, P = Permeability.

These sixteen indicators, available for the entire study area, were included in a TDS and were chosen for their sensitivity in the evaluation of soil quality and have been suggested by several authors due to their influence on soil fertility, nutrient supply, root growth and soil porosity (Biswas et al., 2017; Cheng et al., 2016; Das et al., 2016; Mukhopadhyay et al., 2014; Sánchez-Navarro et al., 2015; Sione et al., 2017). Also, in order to take into account both natural processes and human impacts due to agricultural practices and land use change, the soil erosion factor (K) was included as part of the quality index (Nabiollahi et al., 2018). The unpredictable precipitations (meteorological phenomenon called "cold drop"), typical of the Mediterranean areas, are generally associated with erosion processes that lead to an important loss of soil. In addition, certain anthropogenic actions such as agriculture can accelerate these problems, causing adverse and lasting effects on soil properties (Doran et al., 1996; Miralles et al., 2009).

2.3. Statistical analysis

The SPSS version 25 software was used for the statistical analyses. Based on the results, different values of interest were obtained: arithmetic mean, range, standard deviation, coefficient of variation, kurtosis, and correlation coefficients between the quality indexes. In addition to regression, correlation, and Kappa index analyses, factor analysis (FA) was performed for each indicator.

The spatial distribution of soil quality classes obtained by spatial interpolation was mapped using geostatistical analyses. Interpolation is the process of predicting values for unknown locations based on information about the geographical location of sampled points (Xie et al., 2011).

The degree of the spatial variability of quality indices was

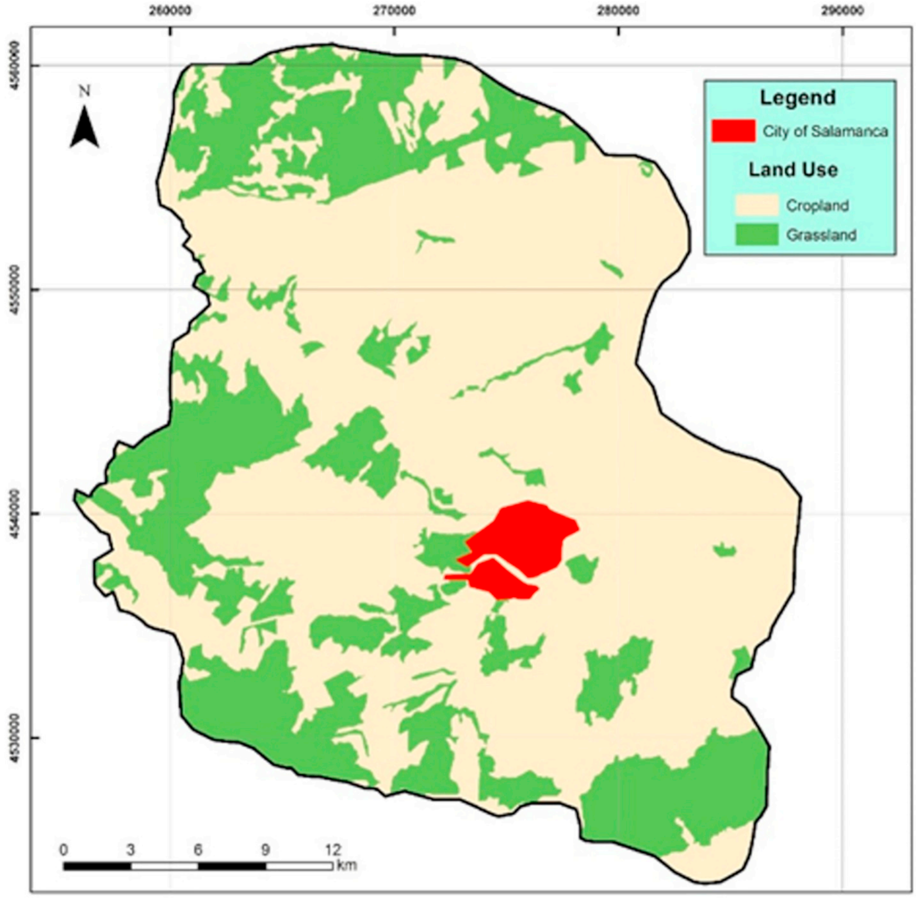

Fig. 2. Map of land uses.

calculated with GIS analysis (ArcGis v. 10.5; ESRI, 2014) using spatial analysis tools, geostatistical analysis extensions, and universal kriging.

2.4. *Evaluation of the soil quality index*

2.4.1. *Indicator scores*

Scores are considered to be quality indicators of measurable soil properties that influence the ability to perform agricultural or environmental production functions (Arshad and Martin, 2002).

In this study, three standard scoring functions were used; scores ranging from 0 to 1 were assigned with the linear scoring method (Liebig et al., 2001). Based on the sensitivity of the soil quality indicator, three function types were applied: (1) The 'More is better' function was applied to CEC, GWC_{33}kPa, GWC_{1500}kPa, removable bases (Na, K, Ca and Mg), and OM because of their effect on the soil fertility and water availability (Sánchez-Navarro et al., 2015; Rahmanipour et al., 2014; Raiesi, 2017). The indicator value was divided by the highest value such that the highest value received a score of 1; (2) The 'Less is better' function was applied to the K factor and BD because its high evaluation indicates that it restricts the degradation and the decrease of the soil porosity (Andrews et al., 2002a, 2002b). In this case, the lowest value was divided by each indicator value such that the lowest value received a score of 1; (3) The 'optimal range' function was applied to the clay and sand contents, COLE, $CaCO_3$ content, and pH. In this case, threshold values or optimal ranges were identified: 35% and 60% for the clay and sand contents, respectively; 15% for the $CaCO_3$ content; 0.050 for COLE, and 6.5–7.5 for pH (Liebig et al., 2001; Andrews et al., 2004; Rahmanipour et al., 2014). Scores were assigned using the 'more is better' or 'less is better' functions depending on whether the indicator value was below or above the optimal range. For example, if the soil pH is between 6.5 and 7.5, it is considered to be within the optimum range and a value of 1 is assigned. If the pH value is

Table 1
Methods used in laboratory analyzes for selected indicators.

Indicator	Method
Granulometric analysis (sand and clay percentage)	Robinson pipette (USDA, 1996)
Organic material	Dichromate oxidation (Walkley and Black, 1934)
Apparent density (BD)	Paraffin (Barahona and Santos Francés, 1981)
Water retention at 33 and 1500 kPa (GWC)	Pressure membrane (Richards, 1947)
Cation exchange capacity (CEC)	Ammonium acetate at pH 7 (USDA, 1996)
Change of removable bases change (Na, K, Ca, and Mg)	Ammonium acetate at pH 7 (USDA, 1996)
Electric conductivity (EC)	Saturated soil paste and conductivity meter (Richards, 1970)
pH	Potentiometric method (1:1 -soil–water-)
$CaCO_3$ equivalent (ECC)	Bernard calcimeter (USDA, 1996)
COLE	Richards Membrane (USDA, 1996)
Soil erosion (K)	Equation from Wischmeier and Smith, 1978

below 6.5, the 'more is better' criterion is considered and, on the contrary, if the pH value is > 7.5, the 'less is better' criterion is considered.

Data from all horizons of the soil profiles were used to calculate the quality index. The weighted average between 0 and 25 and 0–100 cm depths was calculated to obtain a single index value for each soil profile. The quality indexes were calculated for both depths.

2.4.2. Minimum selection of the data set

The selection of the MDS leads to a loss of information from indicators that were not selected but avoids problems such as redundancy of information and tedious laboratory work (Qi et al., 2009).

To select a representative MDS, FA was used as data reduction tool and to determine the most important properties to be included in the MDS (Doran and Parkin, 1994; Andrews et al., 2002a; Rahmanipour et al., 2014). The Varimax rotation method was used to obtain a simple solution of the matrix of 'loads' with which each variable contributes to each of the factors. Based on this rotation, it is possible to maximise the variance of the loads of each factor. Loads tend to take high or low values; therefore, each variable tends to have a high load in a single factor.

The number of factors was selected such that the eigenvalues are > 1 or very close to 1 and the explained variance is > 71% (Andrews et al., 2002b). It was also assumed that soil variables with high factor loads are the soil properties that best represent changes in the soil quality. These are the properties of the soil that have absolute values of ~20% of the load of the highest factor (Andrews et al., 2002b; Govaerts et al., 2006). Therefore, a model with four factors was chosen.

2.4.3. Weight allocation and soil quality indexes

For each indicator method (TDS and MDS), weights were assigned by considering the commonality of each indicator obtained from FA. The commonality values indicate the portion of the variance that is explained by each indicator. It varies between zero and one and a high value suggests a greater contribution of the indicator to the soil quality (Johnson and Wichern, 1992). The weights for each indicator considered in this study were derived from the communality relation of each indicator with the sum of all communality indicators (Shukla et al., 2006; Liu et al., 2014).

The IQI [Doran and Parkin, 1994; Eq. (3)] and NQI [Han and Wu, 1994; Qin and Zhao, 2000; Eq. (4)] were calculated for all qualified indicators 'n' and weighted in the TDS and MDS methods for each sample:

$$IQI = \sum_{i=1}^{n} Wi\ Ni \tag{3}$$

Where W_i is the weight of each indicator, N_i is the indicator score and n the number of indicators.

$$NQI = \sqrt{\frac{P^2ave + P^2\min}{2}\ x\ \frac{n-1}{n}} \tag{4}$$

where P_{ave} is the average of the indicators selected at each sampling point and P_{min} it is the minimum of the scores of the indicators selected in each site.

2.4.4. Soil quality classes

Five classes were evaluated for each soil quality index. The range of each quality index was divided by the number of desired intervals (5) and the result was used as the width of each interval. By adding this value to the lowest value of the corresponding index, the upper limit of the first interval was obtained. This process was repeated until the upper range of the quality index was reached.

3. Results and discussion

3.1. Physical and chemical properties

The physical soil fertility informs the user about the capacity of the soil to provide an adequate physical environment for the growth of the crop roots. The soil must have a low compaction or apparent density such that it does not exerts an excessive mechanical resistance to the advance of the root. In addition, the soil must have a porosity that facilitates the aeration, drainage, and storage of water to cover the needs of the plants in dry periods. Examples of indicators of the soil quality are: bulk density (BD), granulometry of the soil, humidity retained at 33 kPa, and humidity retained at 1500 kPa.

The chemical fertility of the soil refers to the capacity of the soil to retain and supply nutrients necessary for the crop, such as nitrogen, phosphorus, and potassium (N, P, and K), and microelements (e.g. iron, copper, zinc, and boron). In a conventional agricultural system, the nutrients originate from both the mineralisation of OM and weathering of minerals and from synthetic fertilisers. However, in both cases, they are controlled by the pH, which determines the chemical status of the elements, and cation exchange capacity, CEC, which determines the retention or storage capacities of the nutrients.

The main properties of the soils studied are the following:

- Most of the horizons are argillic (Bt). The superficial horizons of cultivated soils (Ap) have a higher clay content than the A horizons with natural vegetation (pastures) because the A horizons and upper part of the Bt horizons are mixed by plowing in many cultivated lands. Most clay soils of the sector have 'vertic' characteristics.

- The A horizons of the soils located in areas with natural vegetation (grasslands) have two times the organic carbon content (1.8%) than surface horizons of cultivated soils (0.8%), which highlights the rapid degradation of OM in superficial horizons because of the effect of the crop. A basic function of the soil is to act as a carbon sink. Arable soils generally have low organic carbon contents, while the values of soils with permanent vegetation cover are higher. The conversion of natural land to farmland is one of the largest sources of anthropogenic carbon emissions and has led to the release of ~200 Pg C over the past 250 years worldwide (Fitzsimmons et al., 2004; Jarecki and Lal, 2003).

- Calcareous soils predominate in the study region. The vertical distribution of the carbonate content along the profile increases with increasing depth. Calcic horizons (Ck) show the highest percentages.

- The average pH value of the soils of the studied sector is slightly acidic (6.1). However, two completely different soil populations are observed, that is, acidic soils and calcareous or basic soils, with pH values ranging from 3.4 to 8.3.

- The average conductivity of the saturation extract is 0.83 dS m^{-1}. Only some soil horizons, which formed on alluvial deposits with very fine texture in small depressions, have somewhat elevated conductivities between 2 and 4 ds m^{-1}.

- The CEC of most of the soils is between 1 and 69 cmol kg^{-1}, with an average value of 18.2 cmol kg^{-1}. Soils with vertic characteristics have the greatest CEC and the Xerofluvents have the lowest one.

- The apparent density of the soils is on average 1.72 g cm^{-3}. The E and B horizons have higher and lower mean values, respectively. The soils with vertic characteristics have a lower bulk density.

- The water retention capacity of soils is on average 9.24%. The B horizons have the highest water content and the C and E horizons exhibit the lowest values. The soils with the highest water retention developed on loam and clay and those with minimum values are Xerofluvents, which formed on sand.

- The COLE of most samples is between 0.005 and 0.260 mm cm^{-1}. The average value is 0.041 mm cm^{-1}. The superficial (A) and eluvial (E) horizons show the lowest values and the B horizons exhibit the highest COLE.

Table 2 shows the main statistics for the 16 indicators measured at each sampling point.

Table 2
Descriptive statistics of the soil properties (0–100 cm).

Properties	Mean	Minimum	Maximum	Standard deviation	Kurtosis	Coef. of variation (%)
Sand (%)	51.91	1.04	98.79	22.35	−0.88	43.06
Clay (%)	26.85	0.67	85.90	18.73	−0.11	69.78
OC (%)	0.68	0.02	7.32	0.83	24.77	123.04
$CaCO_3$ (%)	3.78	0.00	64.62	10.17	14.07	269.33
BD (gcm^{-3})	1.72	0.82	2.23	0.22	0.55	12.57
GWC_{33kPa} (%)	21.00	1.60	54.84	11.00	0.06	52.40
$GWC_{1500kPa}$ (%)	11.76	0.74	42.42	7.94	0.56	67.49
COLE ($mm\,cm^{-1}$)	0.041	0.000	0.260	0.044	4.09	106.54
pH	6.13	3.35	8.30	1.24	−1.06	20.23
Na ($cmol\,kg^{-1}$)	0.30	0.00	10.24	0.79	94.29	266.36
K ($cmol\,kg^{-1}$)	0.28	0.02	1.95	0.24	21.60	87.27
Ca ($cmol\,kg^{-1}$)	15.04	0.00	60.13	12.71	−0.13	84.51
Mg ($cmol\,kg^{-1}$)	3.51	0.00	46.92	4.78	32.24	136.14
CEC ($cmol\,kg^{-1}$)	18.16	1.12	68.90	12.70	1.05	69.90
CE ($dS\,m^{-1}$)	0.83	0.07	4.01	0.75	4.73	90.21
K ($t\,m^2\,h\,ha^{-1}\,J^{-1}\,cm^{-1}$)	0.43	0.19	0.88	0.13	2.19	59.09

3.2. Factorial analysis

3.2.1. Properties of the control section (0–100 cm) of the soils

The results obtained from FA provide a solution with four factors when considering a criterion of eigenvalues > 1. The charges were obtained by rotating the factors. The results are shown in Table 3. The Kaiser–Meyer–Olkin test (KMO) resulted in a value of 0.826, which indicates the excellent adaptation of the sampling. The factors are described below.

Factor 1 has high loads in the fine and coarse granulometric variables (clay and sand percentages) and in those that covariate with them such as the water retention parameters, COLE, exchange capacity, and extractable bases. Sand presents negative charges. This factor is 'granulometric or textural' and can be defined as 'the increase in the clay content and decrease of the sand content in the soils lead to an increase in the CEC; water retention; COLE; and Na, K, Ca, and extractable Mg'. This factor has the greatest weight with respect to the identity of the soils because it explains 42.86% of the variance.

Factor 2 is 'compositional' and involves variables that express the calcium carbonate content and extractable Ca. Some variables covary with the carbonates, for example, the pH increases with increasing calcium carbonate and extractable Ca contents.

Factor 3 only carries a high load with respect to the BD. Note that organic carbon has a load in the order of 0.537 (negative). This factor can be defined as 'the increase of OM leads to a decrease in the apparent soil density'. It is important to highlight the low importance of the OM content for the soil in the studied sector, which is expected because the study area is an agricultural region with low organic carbon content.

Factor 4 shows a high load with respect to the conductivity of the saturation extract. This factor represents the soil salinity.

Based on the commonality analysis and weights of the indicators (Table 4), the water retention at 1500 and 33 kPa as well as the extractable Ca, CEC, and clay content show the highest weights (between 0.083 and 0.079). On the contrary, the extractable Na and K and organic carbon show the lowest weights (between 0.032 and 0.056), while the remaining properties exhibit intermediate values (between 0.079 and 0.063).

The MDS that best describes the soils of the region should consist of one, two, or three representatives of the factors with the highest loads. Therefore, the following indicators were selected: GWC1500kPa, clay percentage, and CEC (F1); $CaCO_3$ and pH (F2); BD (F3); and CE (F4).

3.2.2. Properties of the control section (0–25 cm) of the soils

The solution based on results obtained from FA considering the properties of the surface horizon of the soils also has four factors under eigenvalues > 1. The charges were obtained by rotating the factors. The results are shown in Table 5. The KMO test resulted in a value of 0.749, which is lower than that obtained for the control section (0–100 cm). The factors are described below.

Factor 1 shows high loads with respect to the fine and coarse granulometric variables (clay and sand percentages) and in those that

Table 3
Reordered matrix of rotated factors (soils from 0 to 100 cm). The bold numbers represent factor loads selected for the MDS.

	F1	F2	F3	F4
E-values	6.429	1.711	1.376	1.157
Variance (%)	42.859	11.407	9.171	7.714
Accumulated variance (%)	42.859	54.266	63.437	71.152
$GWC_{1500kPa}$ (%)	**0.926**			
Clay (%)	**0.916**			
CEC ($cmol\,kg^{-1}$)	**0.893**			
GWC_{33kPa} (%)	0.872			
COLE ($mm\,cm^{-1}$)	0.814			
Sand (%)	−0.805			
Mg ($cmol\,kg^{-1}$)	0.700			
Na ($cmol\,kg^{-1}$)	0.481			
$CaCO_3$ (%)		**0.841**		
pH		**0.811**		
Ca ($cmol\,kg^{-1}$)	0.600	0.675		
BD ($g\,cm^{-3}$)			**0.810**	
OC (%)			−0.537	
EC ($dS\,m^{-1}$)				**0.823**
K ($cmol\,kg^{-1}$)	0.445			0.624

Table 4
Results of the estimated commonality and the weight of each indicator based on the TDS and MDS methods (for soil horizons between 0 and 100 cm).

0–100 cm	TDS		MDS	
	Commonality	Weight	Commonality	Weight
Sand (%)	0.764	0.072		
Clay (%)	0.845	0.079	0.922	0.175
OC (%)	0.339	0.032		
$CaCO_3$ (%)	0.760	0.071	0.739	0.141
BD ($g\,cm^{-3}$)	0.689	0.065	0.487	0.093
GWC_{33kPa} (%)	0.868	0.081		
$GWC_{1500kPa}$ (%)	0.887	0.083	0.928	0.176
COLE ($mm\,cm^{-1}$)	0.721	0.068		
pH	0.754	0.071	0.752	0.143
Na ($cmol\,kg^{-1}$)	0.339	0.032		
K ($cmol\,kg^{-1}$)	0.600	0.056		
Ca ($cmol\,kg^{-1}$)	0.865	0.081		
Mg ($cmol\,kg^{-1}$)	0.670	0.063		
CEC ($cmol\,kg^{-1}$)	0.867	0.081	0.859	0.163
CE ($ds\,m^{-1}$)	0.707	0.066	0.572	0.109

Table 5
Reordered matrix of rotated factors (soil from 0 to 25 cm). The bold numbers represent the factor loads selected for the MDS.

	F1	F2	F3	F4
E-values	7.122	1.983	1.559	1.223
Variance (%)	44.512	12.393	9.746	7.642
Accumulated variance (%)	44.512	56.905	66.651	74.293
CE (ds m^{-1})	**0.834**			
K (cmol kg^{-1})	**0.832**			
Clay (%)	0.790	0.423		
CEC (cmol kg^{-1})	0.745	0.485		
$GWC_{1500kPa}$ (%)	0.609	0.465	0.574	
Ca (cmol kg^{-1})		**0.836**		
pH		**0.804**		
$CaCO_3$ (%)		0.770		
OC (%)			**0.931**	
GWC_{33kPa} (%)	0.421		**0.708**	
COLE (mm cm^{-1})			0.593	0.427
Mg (cmol kg^{-1})			0.558	
K (t m^2 h ha^{-1} J^{-1} cm^{-1})				**−0.843**
Sand (%)	−0.501		−0.439	0.626
BD (g cm^{-3})				0.556
Na (cmol kg^{-1})				

covariate with them such as the water retention and CEC Sand represents negative charges. However, the highest loads were obtained for the CE and extractable K. This factor has the greatest weight with respect to the identity of the soils because it explains 44.51% of the variance.

Factor 2 involves variables that express the calcium carbonate and extractable Ca content. The pH correlates with the carbonates; it increases with increasing calcium carbonate and extractable Ca contents.

Factor 3 shows high loads for the organic carbon content and water retention.

Factor 4 represents the soil erodibility (K).

Based on the commonality analysis and weights of the indicators (Table 6), the water retention at 1500 and 33 kPa as well as the extractable Ca, CEC, and organic carbon and sand and clay contents received higher weights (between 0.078 and 0.073). On the contrary, Na and the apparent density have the lowest weights (between 0.008 and 0.033), while the remaining properties show intermediate values (between 0.068 and 0.059).

The MDS that would best describe the soil quality should consist of the following indicators: CE, extractable K and Ca, pH, organic carbon, water retention, and soil erodibility (K).

Table 6
Results for the estimated commonality and weight for each indicator based on the TDS and MDS methods (for the arable soil layer between 0 and 25 cm).

0–25 cm	TDS		MDS	
	Commonality	Weight	Commonality	Weight
Sand (%)	0.911	0.077		
Clay (%)	0.903	0.076		
OC (%)	0.877	0.074	0.860	0.163
$CaCO_3$ (%)	0.706	0.059		
BD (g cm^{-3})	0.397	0.033		
GWC_{33kPa} (%)	0.862	0.073	0.810	0.154
$GWC_{1500kPa}$ (%)	0.928	0.078		
COLE (cm cm^{-1})	0.807	0.068		
pH	0.724	0.061	0.834	0.158
Na (cmol kg^{-1})	0.091	0.008		
K (cmol kg^{-1})	0.712	0.060	0.706	0.134
Ca (cmol kg^{-1})	0.891	0.075	0.777	0.148
Mg (cmol kg^{-1})	0.685	0.058		
CEC (cmol kg^{-1})	0.883	0.074		
CE (dS m^{-1})	0.780	0.066	0.770	0.146
K (t m^2 h ha^{-1} J^{-1} cm^{-1})	0.729	0.061	0.506	0.096

3.3. Soil quality index

3.3.1. Properties of the control section (0–100 cm)

The IQITDS soil quality index proposed in this paper can be calculated using Eq. (5). The variables are ordered according to the load values of the coefficients:

$$IQI_{TDS} = (0.083 \times GWC_{1500kPa} + 0.081 \times GWC_{33kPa} + 0.081 \times CEC + 0.081 \times Ca + 0.079 \times Clay + 0.072 \times Sand + 0.071 \times CaCO_3 + 0.071 \times pH + 0.068 \times COLE + 0.066 \times EC + 0.065 \times BD + 0.063 \times Mg + 0.056 \times K + 0.032 \times OC + 0.032 \times Na) \quad (5)$$

The IQIMDS soil quality index proposed in this work can be calculated using Eq. (6):

$$IQI_{MDS} = (0.176 \times GWC_{1500kPa} + 0.175 \times Clay + 0.163 \times CEC + 0.143 \times pH + 0.141 \times CaCO_3 + 0.109 \times EC + 0.093 \times BD) \quad (6)$$

Based on the IQI and NQI for the TDS, which was obtained from the properties of all soil horizons (0–100 cm), the soil quality of the study area can be classified into five classes (Table 7).

Fig. 3 shows that the spatial patterns of the soil quality derived from the IQITDS, IQIMDS, and NQITDS methods are similar (considering soil properties between 0 and 100 cm). The soil quality of the study area is mainly moderate (Grade III, green areas). Based on the IQITDS, IQIMDS, and NQITDS models, the highest proportions of the study area (83%, 71.4% and 70.2%, respectively) present moderate soil qualities (Table 8). Based on the same models, 16%, 26.7%, and 29.4%, respectively, of the surface soils are low-quality soils (Grade II, yellow areas). Only few soils in the study area (1%, 2%, and 0.3%, respectively) have high soil qualities (Grade IV, light blue areas) and are imperceptible in the maps. They are characterised by soils with very low and very high qualities. However, the soil quality was notably underestimated with the NQIMDS method because areas with low soil quality are dominant (72.1%), 27.9% of the surface has a moderate soil quality, and are imperceptible the areas with soil very high quality, high and very low quality.

In general, the study area can be divided into three different soil-quality regions based on the heterogeneity of different soil types: (1) moderate-quality region (green zone) in the central part of the map, which corresponds with the predominance of Inceptisols; (2) high-quality region (light blue zone) in the central and eastern parts of the map, which corresponds with the predominance of Alfisols; and (3) low-quality region (yellow zone) in the north-western and south-eastern parts of the map, which corresponds with the predominance of Entisols.

Based on the expert opinions of agricultural technicians and farmers, the soils of this region in general are of moderate–high quality, especially with respect to the cultivation of rainfed cereals. These opinions are consistent with the results obtained with the IQITDS, IQIMDS, and NQITDS indexes, which indicate a moderate quality.

3.3.2. With the properties of the control section (0–25 cm) of the soils

The IQITDS soil quality index proposed in this work is given by Eq. (7). The variables that make up the equation are ordered according to the value of the load of the coefficients:

$$IQI_{TDS} = (0.078 * GWC_{1500kPa} + 0.077 * Sand + 0.076 * Clay + 0.075 * Ca + 0.074 * CEC + 0.074 * OC + 0.073 * GWC_{33kPa} + 0.068 * COLE + 0.066 * EC + 0.061 * pH + 0.061 * K - erosion + 0.060 * K + 0.059 * CaCO_3 + 0.058 * Mg + 0.033 * BD + 0.008 * Na) \quad (7)$$

The IQIMDS soil quality index proposed in this work is given by Eq. (8):

Table 7
Classification of soil quality grades (0–100 cm).

Index	Method	Soil quality grade				
		I (Very low)	II (Low)	III (Moderate)	IV (High)	V (Very high)
IQI	TDS	$0.21 < IQI_{TDS} < 0.29$	$0.29 < IQI_{TDS} < 0.37$	$0.37 < IQI_{TDS} < 0.45$	$0.45 < IQI_{TDS} < 0.52$	$0.52 < IQI_{TDS} < 0.61$
	MDS	$0.25 < IQI_{MDS} < 0.34$	$0.34 < IQI_{MDS} < 0.43$	$0.43 < IQI_{MDS} < 0.52$	$0.52 < IQI_{MDS} < 0.61$	$0.61 < IQI_{MDS} < 0.71$
NQI	TDS	$0.13 < NQI_{TDS} < 0.18$	$0.18 < NQI_{TDS} < 0.23$	$0.23 < NQI_{TDS} < 0.28$	$0.28 < NQI_{TDS} < 0.33$	$0.33 < NQI_{TDS} < 0.38$
	MDS	$0.17 < NQI_{MDS} < 0.23$	$0.23 < NQI_{MDS} < 0.29$	$0.29 < NQI_{MDS} < 0.35$	$0.35 < NQI_{MDS} < 0.41$	$0.41 < NQI_{MDS} < 0.48$

$$IQI_{MDS} = (0.834 * pH + 0.810 * GWC_{33kPa} + 0.777 * Ca + 0.770 * EC + 0.706 * K + 0.506 * K\text{–}erosion + 0.163 * OC) \quad (8)$$

The IQI and the NQI for TDS, obtained from the properties of the surface horizons of the soils (0–25 cm), classified the soil quality of the study area into five classes (Table 9).

As shown in the Fig. 3, the global spatial patterns of soil quality derived from the IQITDS, NQITDS and NQIMDS methods are similar (considering the properties of the surface horizons of soils, between 0 and 25 cm). The soil quality of the study area is preferably low (Grade II) - yellow areas. For the IQI model, the majority of the surface of the study area (71.3% and 87.2%, according to the TDS and MDS methods, respectively) are occupied by low quality soils (Table 10). Of the two maps that represent the IQITDS index and IQIMDS, there are two green patches that represent moderate-quality soils, occupying 17.3% and 10.9% respectively, in the northwest quadrant and in the south from the IQITDS map appears a surface that occupies 9.3% of the area, with soils of very low quality -zones of red color- that correspond to soils (Entisoles) dedicated to grasslands.

Only a small area (2%) has soils with a high degree of quality - areas of light blue color.

Table 8
Area in hectares that correspond to each grade of soil (0–100 cm).

Index	Method	Soil quality grade				
		I (Very low)	II (Low)	III (Moderate)	IV (High)	V (Very high)
IQI	TDS	0.089	15,462.45	80,030.49	1017.54	0.041
	MDS	0.109	25,739.57	68,950.61	1820.29	0.041
NQI	TDS	93.38	28,345.18	67,751.22	320.81	0.020
	MDS	0.116	69,575.55	26,934.86	0.081	0.007

When the NQI index method was applied, 60.6% and 66.6%, according to the TDS and MDS methods, respectively, present a low grade of quality; and 22.4% and 20.6% present a very low quality level. In the four maps, areas with very high quality soils are imperceptible. In short, if we compare the two indices used to calculate the quality, when the NQI index is applied, the quality of the soils of the region studied decreases.

Based on the expert opinions of agricultural technicians and farmers, these results do not match with the results obtained with the four quality indices, which provide low–very low soil quality values

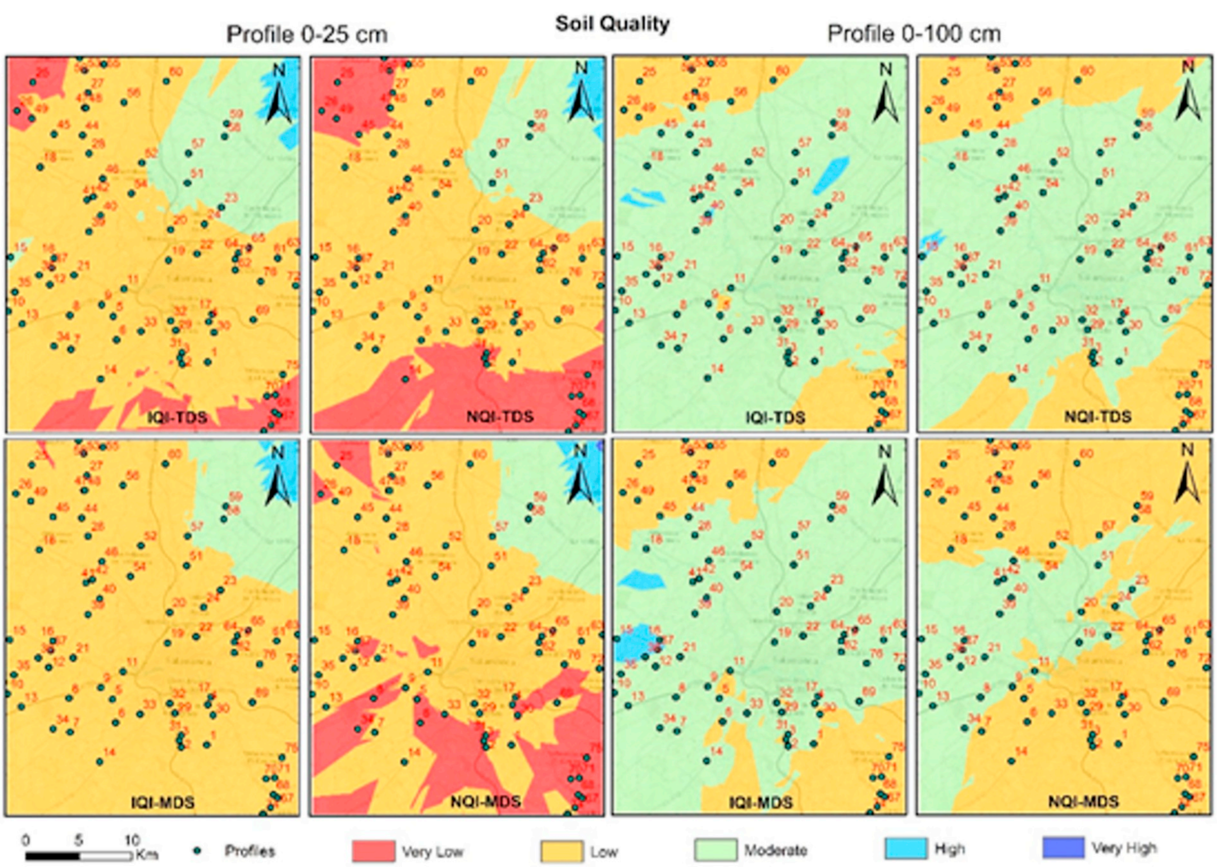

Fig. 3. Spatial distribution of soil quality indexes (0–25 cm and 0–100 cm).

Table 9
Classification of the soil quality grade (0–25 cm).

Index	Method	Soil quality grade				
		I (Very low)	II (Low)	III (Moderate)	IV (High)	V (Very high)
IQI	TDS	$0.18 < IQI_{TDS} < 0.27$	$0.27 < IQI_{TDS} < 0.36$	$0.36 < IQI_{TDS} < 0.44$	$0.44 < IQI_{TDS} < 0.53$	$0.53 < IQI_{TDS} < 0.63$
	MDS	$0.18 < IQI_{MDS} < 0.28$	$0.28 < IQI_{MDS} < 0.37$	$0.37 < IQI_{MDS} < 0.47$	$0.47 < IQI_{MDS} < 0.56$	$0.56 < IQI_{MDS} < 0.67$
NQI	TDS	$0.13 < NQI_{TDS} < 0.19$	$0.19 < NQI_{TDS} < 0.24$	$0.24 < NQI_{TDS} < 0.30$	$0.30 < NQI_{TDS} < 0.35$	$0.35 < NQI_{TDS} < 0.42$
	MDS	$0.11 < NQI_{MDS} < 0.17$	$0.17 < NQI_{MDS} < 0.22$	$0.22 < NQI_{MDS} < 0.28$	$0.28 < NQI_{MDS} < 0.33$	$0.33 < NQI_{MDS} < 0.40$

Table 10
Area in hectares corresponding to each soil grade (0–25 cm).

Index	Method	Soil quality grade				
		I (Very low)	II (Low)	III (Moderate)	IV (High)	V (Very high)
IQI	TDS	8939.27	68,801.46	16,724.80	2045.05	0.027
	MDS	131.46	84,201.33	10,503.84	1673.96	0.020
NQI	TDS	21,634.52	58,496.86	14,649.46	1729.75	0.020
	MDS	19,921.65	64,292.21	10,417.61	1833.06	46.08

considering the properties of the surface horizons of the soils (between 0 and 25 cm).

Our results show that the consideration of the properties of the subsurface soil horizons is of great value for the evaluation of the soil quality. The calculation of the soil quality index for the soil control section (0–100 cm) indicates a better relationship of the index with the crop productivity than the assessment of the properties of the soil surface (0–25 cm) alone. In addition, because the climate in this region is semiarid and the soil moisture regime is xeric, the soils have a moisture deficit from June to October. The yield of rainfed crops mainly depends on the moisture content of the subsurface horizons of the soil profile (Pal et al., 2012).

Our results show that the IQI model performs best with respect to the calculation of the soil quality index in the Northern Plateau of Spain. In this model, the soil quality was determined using all indicators; however, the analysis was guided by several important indicators and higher weights were assigned to key indicators. In contrast, the NQI model uses the average values of all indicators and lowest score indicator, which leads to a higher weighted value. In other words, while the IQI assigns the score to each indicator independently, the NQI only considers the indicator with the lowest score.

3.3.3. *Relationship between the soil quality indexes and vertical distribution of the soil properties*

The results of the quality index calculations considering all properties of the soil control section between 0 and 100 cm show that the soils with high quality correspond to Alfisols (vertic and calcic Rhodoxeralfs and Haploxeralfs). These soils cover flat surfaces (plateaus), are not very stony, and have variable thicknesses (between 70 and 120 cm) depending on the degree of erosion. These soils and the surface they cover are in an anthropic erosion phase caused by deforestation and agricultural work. The erosion phase is indicated by the morphology of the current profile; the epipedon is mixed with primitive eluvial horizons and the Bt horizon by plowing. The epipedon is reddish-brown and has a clayey-sandy texture. The argillic horizon is approximately 40 to 50 cm thick; it is red and has a clayey or clayey-sandy texture. It is common that these soils have vertic properties (fine cracks that are filled with material from the Ap horizon and show slickensides at depth). The Ck horizon is generally pulverulent and passes, at depth, to originate a lattice of carbonates, whose power is several meters. Based on the analytical data, the clay percentage is > 30% in all horizons; the clay content, water retention, CEC, and COLE are high, especially in the argillic horizon. Note that the crop yield in this region mainly depends on the moisture stored in the soil profile, which in turn depends on the quantity and nature of the clay minerals. In addition, the pH values vary between 6 and 7, representing values that are considered to be optimal for most rainfed crops.

Fig. 4 shows that the distribution curves of the properties of the two soils that appear in the upper part are very spaced at depth, that is, they are distributed throughout the whole graph due to the medium–high water retention, CEC, clay content, and COLE values. The characteristics of these soils coincide with the characteristics based on expert opinions: 'these are the soils with the highest quality in the region'.

Soils with moderate quality generally correspond with Inceptisols (typic and vertic Haploxerepts). The absence of stoniness and brown color of the horizons, which is due to the blending process, are common characteristics of these soils. In the A and B horizons, clay-sandy and clayey-sandy textures predominate, respectively; the C horizons are dominated by sandy or sandy-loam textures. The thicknesses of these soils are very variable and ranges between 70 and 100 cm. They have a slightly calcareous Ap horizon and a 20 to 50 cm thick cambic horizon. Very thin cracks filled with material from the Ap horizon are often present in these horizons. The C horizon consists of yellowish–brown sandstone. Based on the analytical data, the clay content is below 30% in all horizons; the clay content, water retention, and CEC are moderately high, especially in the cambic horizon. The pH values vary between 5 and 7. The two soil profiles in the middle of Fig. 4 show that the depth distribution curves of the soil properties occupy approximately 50% of the graph; the clay content, water retention, and CEC have average values; therefore, 'the soils of this region are of moderate quality'. The COLE distribution curve presents high values only for soils with vertic characteristics (see graph).

Soils with very low quality generally correspond to Entisols (e.g. Xerofluvents, Xeropsamments). The two soil profiles in the bottom of Fig. 4 show that the depth distribution curves of the most important analytical data of the soils are grouped (closely together or tightly) in the left part of the graphs because the values corresponding to the clay content, water retention, and CEC are very low. The profile classified as Xerofluvent is a soil formed by a single ochric epipedon that rests on alluvial deposits constituted by an alternation of sand and gravel. Note that this soil does not have carbonates. The texture along the profile is very sandy. The COLE value is not shown in the graph because it is insignificant. The pH values vary between 5 and 6.

The profile classified as Xeropsamment is developed on arcotic sand or sandstone with lightly cemented mineral grains. This soil has a yellowish-brown epipedon and a sandy texture; the coarse sand content reaches 40%. The C horizon consists of an alternation of several layers of sandstone with varying compaction; the upper layers are loose and the lower ones are somewhat cemented and have scattered edges. Based on the depth, there are gray discolorations and spots due to hydromorphic processes. The analytical data indicate an acidic soil (pH between 4 and 6), which is very poor in plant nutrients, has a small water retention value, and a saturation below 50%.

Therefore, we can approximate the quality by plotting the distribution of the vertical soil properties in a graph.

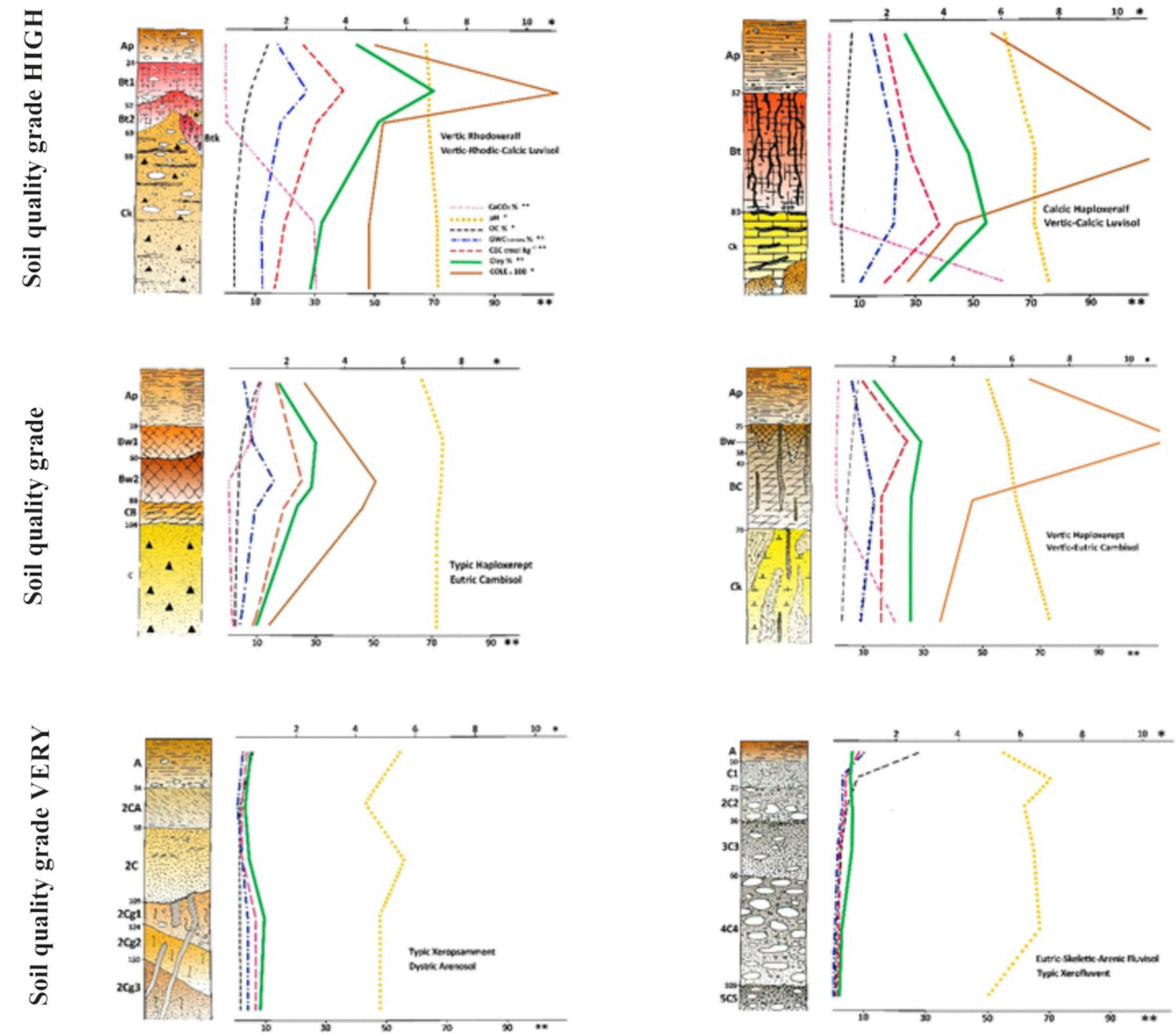

Fig. 4. Vertical distribution of the properties of six soils with different qualities.

3.3.4. *Soil quality based on the soil type and land use*

The mean values for the four quality indices used for the TDS and MDS methods and 0–100 cm samples are higher for arable land than for pastures (Tables 11 and 12). The mean quality indices used for the TDS method and 0–25 cm samples are also higher for arable land than for pastures. However, the quality indices used for the MDS method and 0–25 cm samples are greater for pastures than for cropland.

Note that the most fertile soils have been used for agriculture for several thousand years in this region; on the contrary, shallow soils with abundant rocki- or stonyness, a very sandy texture, and low CEC have been used only and exclusively for grassland.

The mean values for the four quality indices used for the TDS and MDS methods and 0–100 cm samples are high for Alfisols, medium for Inceptisols, and low for Entisols. The mean quality indices used for the TDS and MDS methods and the 0–25 cm samples are higher for Inceptisols.

3.3.5. *Land use and land loss rate*

The results show that the average erodibility rates are slightly higher for crops (K = 0.23) than for grassland (K = 0.21), although significant differences were not observed. Fig. 5 shows the erodibility factor of the soils in the study area. The soils that present the greatest erodibility developed on quartzites and slate (Ordovician–Silurian) in the southern part of the region with the highest slopes (8%–15%).

3.3.6. *Validation of quality indexes*

To compare the performance of different indices, the accuracy of the classification for each grade was assessed (very high, high, moderate, low, and very low quality) using the Kappa statistic and correlation coefficients (Qi et al., 2009; Rahmanipour et al., 2014). For the Kappa analysis, the sites were classified using the five soil quality grades described above. The Kappa value was calculated and shows the following levels of agreement: (1) 0 < 0.05; (2) very low: 0.05–0.2; (3) low: 0.2–0.4; (4) moderate: 0.4–0.55; (5) good: 0.55–0.7; (6) very good: 0.7–0.85; (7) almost perfect: 0.85–0.99; and (8) perfect: 1 (Monserud and Leemans, 1992; Borja et al., 2008). Based on the evaluation of the agreement between the quality grades determined with the IQITDS and IQIMDS indices and by considering the properties of the soils between 0

Table 11
Average soil quality indexes based on the soil use and type.

Index	Method	0–100 cm					0–25 cm				
		Land use		Soil type			Land use		Soil type		
		Grassland	Crops	Entisol	Inceptisol	Alfisol	Grassland	Crops	Entisol	Inceptisol	Alfisol
IQI	TDS	0.35	0.43	0.34	0.39	0.42	0.30	0.33	0.30	0.35	0.30
	MDS	0.40	0.49	0.39	0.44	0.49	0.31	0.30	0.31	0.35	0.28
NQI	TDS	0.22	0.26	0.21	0.24	0.26	0.19	0.21	0.20	0.23	0.20
	MDS	0.26	0.30	0.25	0.28	0.30	0.18	0.17	0.18	0.20	0.16

Table 12
Yield of the crops (Kg ha^{-1}), between the years 2009 and 2017.

	Wheat	Barley	Oats	Rye	Triticale	Lentils	Chickpeas
Mean	2698	2369	1877	1704	2186	564	744
Minimum	1171	1254	600	627	587	300	600
Maximum	3916	3809	3192	2649	3240	1000	950

and 100 cm, a Kappa value of 0.7 (very good) was obtained. Based on the comparison of the concordance between the NQITDS and NQIMDS indexes, the Kappa value is 0.5 (moderate).

Based on the evaluation of the agreement between the soil grades determined with the IQITDS and IQIMDS indices and by considering the properties of the soils between 0 and 25 cm, a Kappa value of 0.3 (low) was obtained. Based on the comparison of the agreement between the NQITDS and NQIMDS indexes, the Kappa value is 0.4 (moderate).

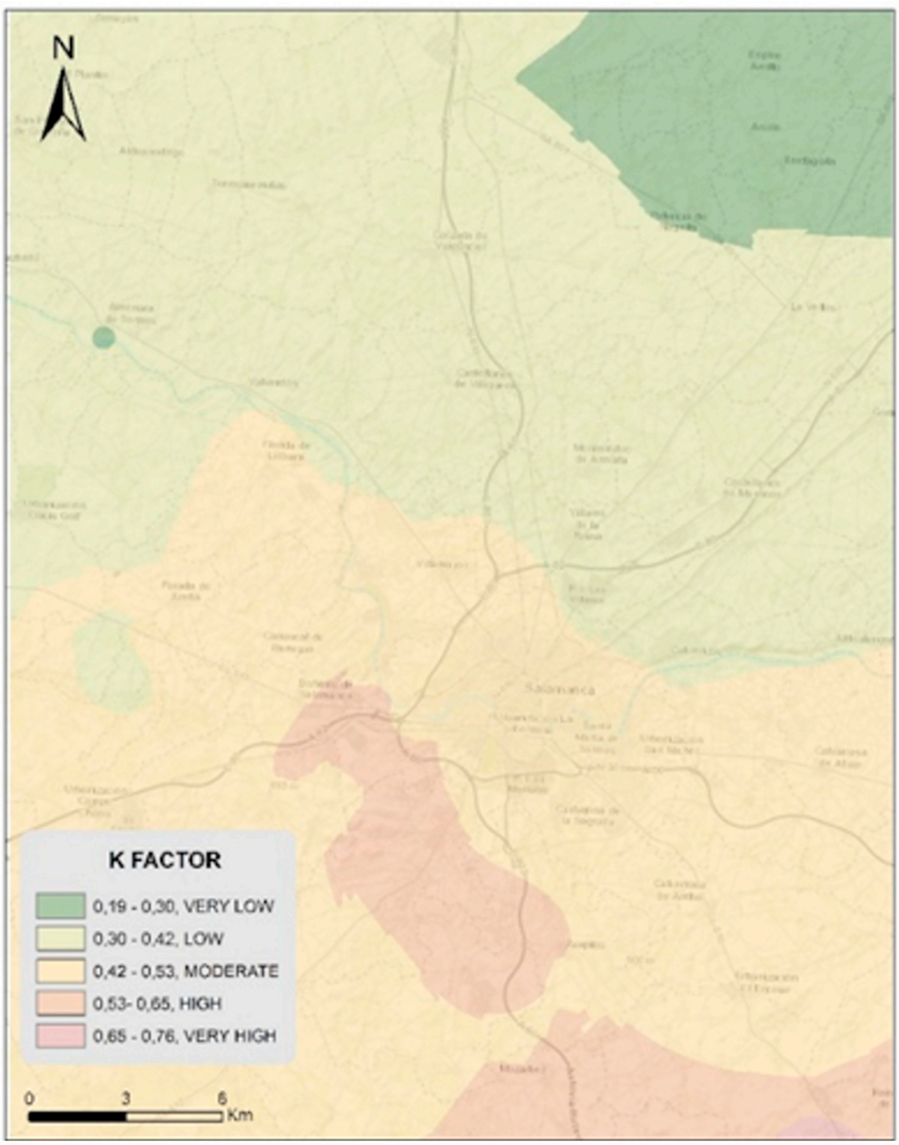

Fig. 5. Erosionability of soils in the study region.

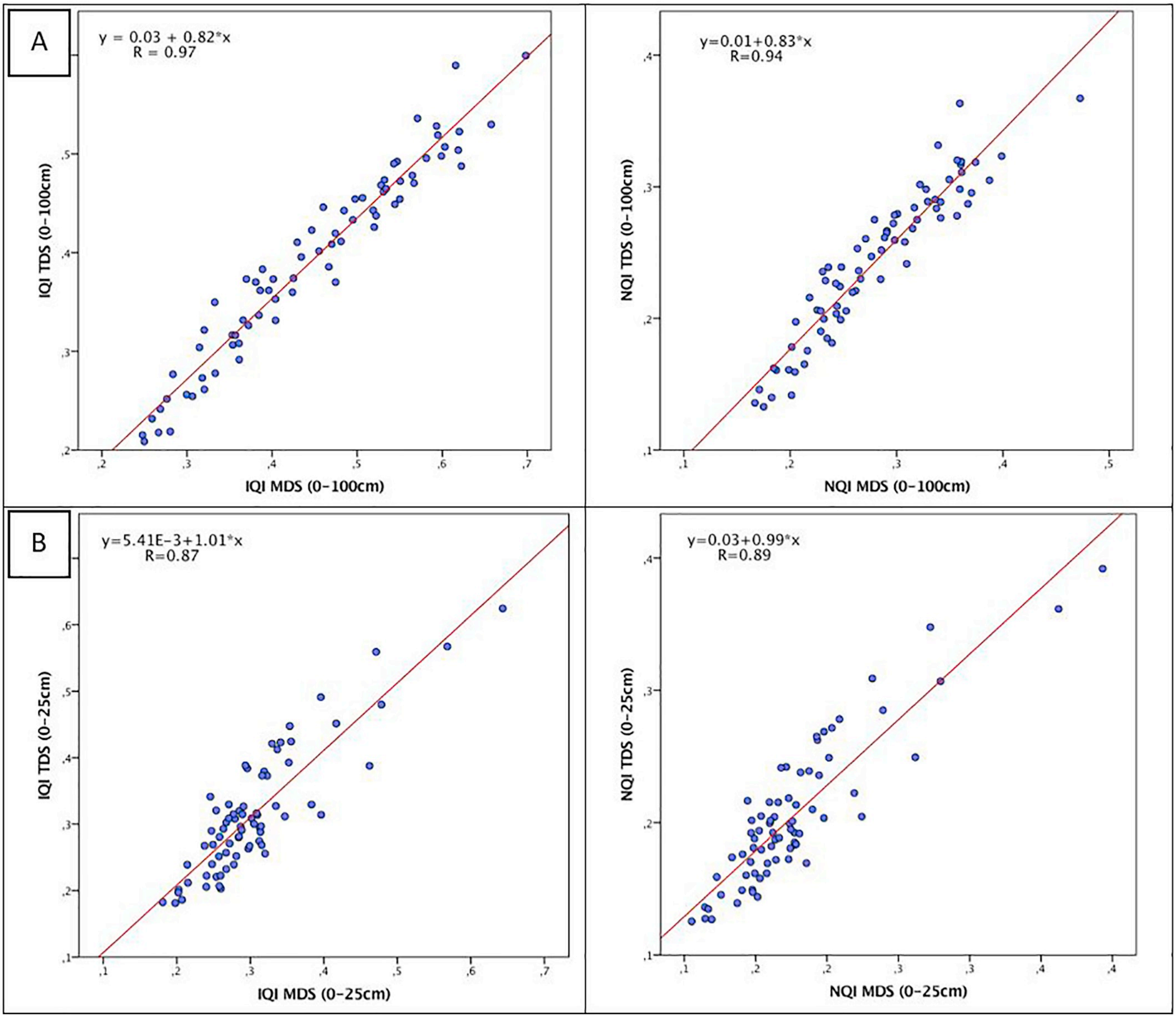

Fig. 6. Linear relationship between the indicators used for the TDS and MDS methods and IQI and NQI indices: A) considering the properties of soils between 0 and 100 cm, and B) considering the properties of soils between 0 and 25 cm.

The linear relationships between the different indicator methods (Fig. 6) show higher correlation coefficients only when the properties of soils between 0 and 100 cm and the IQI model were used (R = 0.97). When the properties of the surface horizon (0–25 cm) of the soils were used, the highest correlation coefficient is obtained with the NQI model (R = 0.89); it is lower.

4. Conclusions

The use of the IQI and NQI quality índices by Wang and Gong (1998) and Sun et al. (2003) has some clear advantages over other indices: (1) soil researchers and farmers easily understand both types of indices, due to their intuitive nature; (2) both indices incorporate information based on mathematical methods, which leads to greater confidence in the results.

In this study it was determined that IQITDS is the quantitative evaluation index of the most accurate soil quality, since it took into account all soil parameters (between 0 and 100 cm) and gave the most consistent results in the region studied. Normally, the more indicators the soil quality is better represented, but when there is a high correlation between the selected indicators, it results in a duplication of data and laboratory analyzes become cumbersome with so many soil properties. On the other hand, the elimination of some properties of the soil means the loss of information on the quality of the soil contained in the eliminated indicators, but with the MDS method the numbers of the indicators are adequate for the evaluation of the soil quality. The evaluation method that uses the minimum data set avoids duplication of data and significantly reduces labor and economic costs related to data sampling and analysis. As shown in the present study, the IQIMDS method, considering the soil between 0 and 100 cm, provides an acceptable evaluation of the soil quality on a large scale.

The results of the evaluation, based on the eight calculated quality indices (four with soil properties between 0 and 25 cm and four between 0 and 100 cm), showed that moderate-quality soil areas were dominant and represented around 80% of the total soil area in the region studied. Areas with very high quality are very limited. The soils with lower quality were distributed both in the south and in the north of the studied region.

The quality indexes are higher in the arable land than in the grasslands and the valuation is higher in the Alfisols, average in the

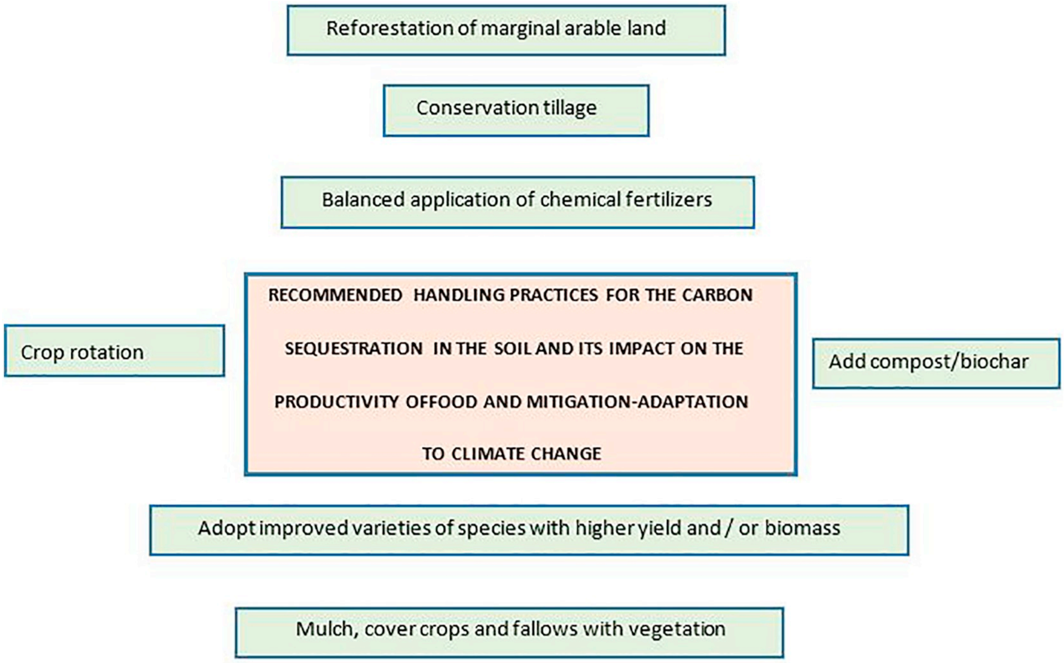

Fig. 7. Recommended management practices for carbon sequestration in agricultural soils of the studied region.

Inceptisols and lower in the Entisols.

The bad practices, so widespread in the conventional management of agricultural soils, lead to important environmental problems such as soil degradation, loss of biodiversity, water pollution, excess CO_2 emissions into the atmosphere, etc. An alternative to avoid these environmental problems would be, compared to the traditional system, the application of techniques of conservation and ecological management of the soil. These practices have in common a more effective contribution of organic matter, less intensity of tillage, limitation in the use of agrochemicals, etc. With such practices an increase of the quality of the soil is obtained, improving its fertility, retaining more water in the same one, and diminishing the susceptibility to the compaction and the erosion (Fig. 7).

Acknowledgements

This research was funded by projectsJunta Castilla y LeónSA044G18.

References

Amirinejad, A.A., Kamble, K., Aggarwal, P., Chakraborty, D., Pradhan, S., Mittal, R.B., 2011. Assessment and mapping of spatial variation of soil physical health in a farm. Geoderma 160, 292–303.
Andrews, S.S., Mitchell, J.P., Mancinelli, R., Karlen, D.L., Hartz, T.K., Horwath, W.R., Pettygrove, G.S., Scow, K.M., Munk, D.S., 2002a. On-farm assessment of soil quality in California's Central Valley. Agron. J. 94, 12–23.
Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002b. A comparison of soil quality indexing methods for vegetable production systems in northern California. Agric. Ecosyst. Environ. 90, 25–45.
Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68, 1945–1962.
Aparicio, V., Costa, J.L., 2007. Soil quality indicators under continuous cropping systems in the Argentinean pampas. Soil Tillage Res. 96, 155–165.
Armenise, E., Redmile-Gordon, M.A., Stellacci, A.M., Ciccarese, A., Rubino, P., 2013. Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. Soil Tillage Res. 130, 91–98.
Arshad, M.A., Martin, S., 2002. Identifying critical limits for soil quality indicators in agroecosystems. Agric. Ecosyst. Environ. 88, 153–160.
Askari, M.S., Holden, N.M., 2015. Quantitative soil quality indexing of temperate arable management systems. Soil Tillage Res. 150, 57–67.
Barahona, E., Santos Francés, F., 1981. Un nuevo método para la determinación de densidades aparentes y del coeficiente de extensibilidad lineal (COLE), por medio de parafina. Anales de Edafología y Agrobiología, Tomo XL 5-6, 721–725.
Bi, C.J., Chen, Z.L., Wang, J., Zhou, D., 2013. Quantitative assessment of soil health under different planting patterns and soil types. Pedosphere 23, 194–204.
Bindraban, P.S., Stoorvogel, J.J., Jansen, D.M., Vlaming, J., Groot, J.J.R., 2000. Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. Agric. Ecosyst. Environ. 81, 103–112.
Biswas, S., Hazra, G.C., Purakayastha, T.J., Saha, N., Mitran, T., Roy, S.S., Basak, N., Mandal, B., 2017. Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders. Geoderma 292, 34–48.
Borja, A., Dauer, D.M., Diaz, R., Llanso, R.J., Muxika, I., Rodriguez, J.G., Schaffner, L., 2008. Assessing estuarine benthic quality conditions in Chesapeake Bay: a comparison of three indices. Ecol. Indic. 8, 395–403.
Cheng, J., Ding, C., Li, X., Zhang, T., Wang, X., 2016. Soil quality evaluation for navel orange production systems in central subtropical China. Soil Tillage Res. 155, 225–232.
Das, B., Chakraborty, D., Singh, V.K., Ahmed, M., Singh, A.K., Barman, A., 2016. Evaluating fertilization effects on soil physical properties using a soil quality index in an intensive Rice-wheat cropping system. Pedosphere 26 (6), 887–894.
Doran, J.W., Jones, A.J. (Eds.), 1996. Methods for Assessing Soil Quality, Soil Science Society of America Special Publication. vol. 49 Soil Science Society of America, Madison, WI.
Doran, J.W., Parkin, B.T., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA Inc., Madison, WI, USA, pp. 3–21 1994. (SSSA Special Publication No. 35).
Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil health and sustainability. Adv. Agron. 56, 1–54.
ESRI, 2014. Creating, Editing and Managing Geodatabases for ArcGIS Desktop. Virtual Campus. ESRI Educational Service. Environmental Systems Research Institute, Inc.
FAO, 1976. A framework for land evaluation. In: Food and Agriculture Organisation of the United States, Soil Bulletin No. 32. FAO, Rome.
Fitzsimmons, M.J., Pennock, D.J., Thorpe, J., 2004. Effects of deforestation on ecosystem carbon densities in Central Saskatchewan, Canada. For. Ecol. Manag. 188, 349–361.
Glover, J.D., Reganold, J.P., Andrews, P.K., 2000. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. Agric. Ecosyst. Environ. 80, 29–45.
Govaerts, B., Sayre, K.D., Deckers, J., 2006. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Tillage Res. 87, 163–174.
Han, W.J., Wu, Q.T., 1994. A primary approach on the quantitative assessment of soil quality. Chin. J. Soil Sci. 25, 245–247.
Hewitt, A.E., 2004. Soil Properties Relevant to Plant Growth: A Guide to Recognising Soil Properties Relevant to Plant Growth and Protection. Manaaki Wenua Press, Lincoln, New Zealand.
IUSS Working Group WRB, 2015. World Reference Base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. In: World Soil Resources Reports No. 106. FAO, Rome.
Jarecki, M., Lal, R., 2003. Crop management for soil carbon sequestration. Crit. Rev. Plant

Sci. 22, 471–502.
Johnson, R.A., Wichern, D.W., 1992. Applied Multivariate Statistical Analysis. Prentice-Hall, Englewood Cliffs, NJ.
Karlen, D.L., Andrews, S.S., Doran, J.W., Wienhold, B.J., 2003. Soil quality: human kind's foundation for survival. J. Soil Water Conserv. 58, 171–179.
Larson, W.E., Pierce, F.J., 1991. Conservation and enhancement of soil quality. In: Dumanski, J. (Ed.), Evaluation for Sustainable Land Management in the Developing World. vol. 2. IBSRAM, Bangkok, Thailand, pp. 175–203.
Liebig, M.A., Varvel, G.E., Doran, J.W., 2001. A simple performance-based index for assessing multiple agroecosystem functions. Agron. J. 93, 313–318.
McGrath, D., Zhang, C.S., 2003. Spatial distribution of soil organic carbon concentrations in grassland of Ireland. Appl. Geochem. 18, 1629–1639.
Merril, S.D., Liebig, M.A., Tanaka, D.L., Krupinsky, J.M., Hanson, J.D., 2013. Comparison of soil quality and productivity at two sites differing in profile structure and topsoil properties. Agric. Ecosyst. Environ. 179, 53–61.
Miralles, I., Ortega, R., Almendros, G., Sánchez-Marañón, M., Soriano, M., 2009. Soil quality and organic carbon ratios in mountain agroecosystems of South-East Spain. Geoderma 150, 120–128.
Moncada, M.P., Gabriels, D., Cornelis, W.M., 2014. Data-driven analysis of soil quality indicators using limited data. Geoderma 235-236, 271–278.
Monserud, R., Leemans, R., 1992. Comparing global vegetation maps with the kappa statistic. Ecol. Model. 62, 275–293.
Mukhopadhyay, S., Maiti, S.K., Masto, R.E., 2014. Development of mine soil quality index (MSQI) for evaluation of reclamation success: a chronosequence study. Ecol. Eng. 71, 10–20.
Nabiollahi, K., Golmohamadi, F., Taghizadeh-Mehrjardi, R., Kerry, R., Davari, M., 2018. Assessing the effects of slope gradient and land use change on soil quality degradation through digital mapping of soil quality indices and soil loss rate. Geoderma 318, 16–28.
Nortcliff, S., 2002. Standardisation of soil quality attributes. Agric. Ecosyst. Environ. 88, 161–168.
Pal, D.K., Wani, S.P., Sahrawat, K.L., 2012. Vertisols of tropical Indian environments. Pedology and edaphology. Geoderma 189-190, 28–49.
Peña Sánchez, M., 1987. Tierra de Campos. La integración de un espacio rural en la economía capitalista. Serie Geográfica n° 5 Secretariado de Publicaciones Universidad de Valladolid, pp. 468.
Qi, Y., Darilek, L.J., Huang, B., Zhao, Y., Sun, W., Gu, Z., 2009. Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. Geoderma 149 (3–4), 325–334.
Qin, M.Z., Zhao, J., 2000. Strategies for sustainable use and characteristics of soil quality changes in urban-rural marginal area: a case study of Kaifeng. Acta Geograph. Sin. 55, 545–554.
Rahmanipour, F., Marzaioli, R., Bahrami, H.A., Fereidouni, Z., Bandarabadi, S.R., 2014. Assessment of soil quality indices in agricultural lands of Qazvin Province, Iran. Ecol. Indic. 40, 19–26.
Raiesi, F., 2017. A minimum data set and soil quality index to quantify the effect of land use conversion on soil quality and degradation in native rangelands of upland arid and semiarid regions. Ecol. Indic. 75, 307–320.
Richards, L.A., 1947. Pressure membrane apparatus: construction and use. Agric. Eng. 28, 451–455.
Richards, L., 1970. Saline and sodic soils. Diagnosis and rehabilitation (in Spanish). In: Manual de Agricultura. Regional Technical Assistance Center, pp. 60 (172 pp.).
Sánchez-Navarro, A., Gil-Vazquez, J.M., Delgado-Iniesta, M.J., Marin-Sanleandro, P., Blanco-Bernardeau, A., Ortiz-Silla, R., 2015. Establishing an index and identification of limiting parameters for characterizing soil quality in Mediterranean ecosystems. Catena 131, 35–45.
Shukla, M.K., Lal, R., Ebinger, M., 2006. Determining soil quality indicators by factor analysis. Soil Tillage Res. 87, 194–204.
Sione, S.M.J., Wilson, M.G., Lado, M., Gonzalez, G.P., 2017. Evaluation of soil degradation produced by rice crop systems in a Vertisols, using a soil quality index. Catena 150, 79–86.
Storie, R., 1978. Storie Index Soil Rating. University of California Division of Agricultural Sciences Special Publication 3203, Oakland.
Sun, B., Zhou, S., Zhao, Q., 2003. Evaluation of spatial and temporal changes of soil quality based on geostatistical analysis in the hill region of subtropical China. Geoderma 115, 85–99.
Svoray, T., Hassid, I., Atkinson, P.M., Moebius-Clune, B.N., van Es, H.M., 2015. Mapping soil health over large agriculturally important areas. Soil Sci. Soc. Am. J. 79, 1420–1434.
Sys, C., Van Ranst, E., Debaveye, J., 1991. Land Evaluation, Part I. Principles in Land Evaluation and Crop Production Calculations. General administration for development cooperation, Brussels, pp. 40–80.
United States Department of Agriculture (USDA), 1996. Soil survey laboratory methods manual. In: Soil Survey Investigations, Report No. 42. U.S. Department of Agriculture, National Resources Conservation Services, National Soil Survey Centre, Washington D.C..
United States Department of Agriculture (USDA). Natural Resources Conservation Service, 2014. Keys to Soil Taxonomy. Soil Survey Staff.
Vasu, D., Singh, S.K., Ray, S.K., Duraisami, V.P., Tiwary, P., Chandran, P., Nimkar, A.M., Anantwar, S.G., 2016. Soil quality index (SQI) as a tool to evaluate crop productivity in semi-arid Deccan plateau, India. Geoderma 282, 70–79.
Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for the determining soil organic matter and proposed modification of the chromic titration method. Soil Sci. 37, 29–38.
Wang, X.J., Gong, Z.T., 1998. Assessment and analysis of soil quality changes after eleven years of reclamation in subtropical China. Geoderma 81, 339–355.
Wischmeier, W.H. y Smith, D.D. 1978. Predicting rainfall erosion losses. A guide to conservation planning. United States Department of Agriculture, Agriculture Handbook n° 537, Washington D.C., (58 pp).
Xie, Y., Chen, T., Lei, M., Yang, J., Guo, Q., Song, B., Zhou, X., 2011. Spatial distribution of soil heavy metal pollution estimated by different interpolation methods: accuracy and uncertainty analysis. Chemosphere 82 (3), 468–476.
Zhijun, H., Selvalakshmi, S., Vasu, D., Liu, Q., Cheng, H., Guo, F., Ma, X., 2018. Identification of indicators for evaluating and monitoring the effects of Chinese fir monoculture plantations on soil quality. Ecol. Indic. 93, 547–554.