

Application of Soil Quality Index to Assess the Status of Soils Submitted to Intensive Agriculture in the Irrigated Plain of Doukkala, Moroccan Semiarid Region

Bouchra El Bourhrami^{1*}, Khalid Ibno Namr¹, Hiba Et-Tayeb¹, Vasu Duraisamy²

¹ Laboratory of Geoscience and Environmental Techniques, Faculty of Science, Chouaib Doukkali University, El Jadida, 24000, Morocco

² National Bureau of Soil Survey and Land Use Planning Nagpur, Amravati Road, Maharashtra, 440033, India

* Corresponding author's e-mail: elbourhrami.b@ucd.ac.ma

ABSTRACT

In the irrigated areas, intensive agriculture has led to soil degradation and declining crop yields; therefore, the durability of soil resources is influenced. In order to assess the soil quality changes in the Zemamra area from the highest plain of Doukkala (523 000 ha), in the semi-arid region of Morocco, the soil samples taken from the horizon 0–30 cm were analysed for physical and chemical parameters (Clay, Sand, Silt, SOM, pH, TN, P₂O₅, K₂O, CEC, MgO, CaO, SAR, Na₂O, EC, CaCO₃, NO₃-N, NH₄-N, B, Mn, Zn, Fe, and Cu). The data obtained were statistically processed to search for soil quality indices (SQIs). The main findings show that the soil surface has more sand than clay (Sand = 55%, Clay = 31%), an accumulation of phosphorus (P₂O₅ = 33.34 mg/kg), moderate soil organic matter (1.789%), and carbonate contents of about (2.6%). Soil Structure Stability Index (SSSI<5%) indicated that soil structure is degraded. The selection of the Minimum Data Set by principal component analysis allowed retaining four indicators (cationic exchange capacity, boron, exchangeable potassium, and manganese). After scoring the selected indicators, the soil quality indices thus obtained classified the soils as having low to moderate quality (SQIs<0.55). The indicators: sand, phosphorus, boron, manganese, and zinc are negatively correlated to SQIs, while clay, silt, cationic exchange capacity, pH, soil organic matter, and carbonates are positively correlated. Micronutrients: boron and zinc negatively impact soils at low concentrations.

Keywords: soil quality index, minimum data set, degradation, irrigated, semi-arid.

INTRODUCTION

The sustainability of soil resources has received much attention in recent decades. Indeed, intensive agriculture is exerting pressure on soils to maintain good crop productivity, but it has generated negative consequences on soils and environments. It has constantly modified physical, and chemical properties of soils, contributing to their degradation, and the impact is felt on the sustainability of these resources and crop yields (Rahoui et al. 2000; Nikolskii et al. 2019). This degradation worries farmers in arid and semi-arid areas where soils are intensively cultivated (Ibno Namr et Mrabet 2004; Issoufou et al. 2020). In these

zones, the deficit of water in soils for crops has been compensated by irrigation, an agricultural practice that contributes on its part to improve plant productivity without taking into account the negative consequences on soil quality (Adejumobi et al. 2014). Thus, the semi-arid climate also plays a major role in modifying soil properties (Vasu et al. 2016; Getie et al. 2020). In the semi-arid areas of Morocco, soils are intensively cultivated especially in the Doukkala plain, one of the highest irrigated perimeters, with a total surface area of 523000 ha. There, agriculture has constantly modified soil properties and generated adverse effects on this resource. Since then, yields have decreased year after year (Rahoui et al. 2000). Several

studies carried out in this area for a long time have revealed that: conventional tillage, irrigation, excessive fertilization, and bad restitution of crop residues were the main causes of soil degradation (Badraoui et al. 2000; Naaman et al. 2015). The consequences were: loss of soil organic matter, soil compaction, and salinisation by irrigation water. The impact of this degradation did not only affect the soils but also extended it towards the environment, essentially the groundwater (Soudi et al. 2000; El Achheb et al. 2001). Studying the long-term effects and identifying changes of agriculture on soil properties in irrigated conditions requires an assessment of soil quality.

Soil quality, defined as the capacity of soils to retain and release water and nutrients, maintain its biodiversity and resist to the effects of practices that may contribute to soil degradation (Karlen et al. 1997), has become an increasingly useful tool for assessing the impact of agricultural practices on soil sustainability (Amorim et al. 2020). It has long been assessed by physical properties, processes, and chemical characteristics that can be measured and can monitor soil changes, but interpreting individual soil indicators and comparing them to certain standards was insufficient (Vidal et al. 2017). Recently, these indicators have shown a great performance in modelling and assessing soil quality, by introducing them into equations for calculating soil quality indices (SQI) (Andrews et al. 2002; Amorim et al. 2020).

Developing SQI requires at first selecting a Minimum Data Set of indicators (MDS), transforming the selected indicators into unitless values, and then introducing them into equations to calculate SQI (Andrews et Carroll 2001; Bastida et al. 2008; Vasu et al. 2016). It is a powerful tool for assessing the impact of intensive agriculture and irrigation on soil quality and identifying changes in soil properties at different scales; local, regional and national (Amorim et al. 2020).

On the basis of these clarifications, this work was carried out in an important irrigated perimeter of Morocco, with the following objectives: (1) Assessing the quality of soils under intensive agriculture; (2) Identifying changes in soil properties using the soil quality indices.

MATERIALS AND METHODS

Study area

The Doukkala area is a part of the large unit of the western Moroccan Meseta. In geomorphological aspect, the area is divided into three large units: the coastal edge, the Sahel and the plain. The latter is characterized by quaternary deposits. Soils are irrigated by Oum Er-rbiaa river waters as the second important river in Morocco. The Zemamra sector, study area, is located in the north western part of Doukkala plain (Fig. 1). It is one of the most

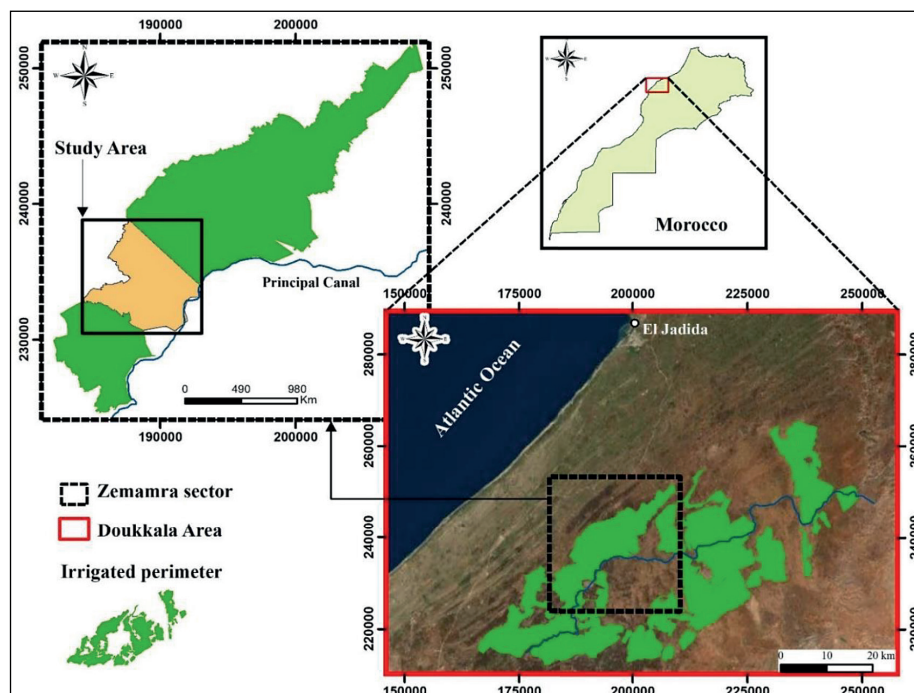


Fig. 1. Location map of study area

important agricultural zones in the irrigated perimeter covering 16,000 ha. The date of its watering was in 1982, with sprinkler irrigation. Soils are irrigated by waters driven from the principal canal with length of 111 km. This area is characterised by a semi-arid climate, with a temperate and mild winter and a generally hot and dry summer. The average annual rainfall is about 330 mm [107–790 mm]. The average temperature is about 18°C with a minimum of 4°C and a maximum of 40°C (ORMVAD 2016). The slope in the study area does not exceed 5%. Soil studies reveal that Zemamra contains six soil types according to Taxonomy classification 2014: vertisols, mollisols, calcistolls, ultisols, histosols and fluvents (Geoffroy 1964; ORMVAD 2016). The cultivations exploited are sugar beet as an important industrial crop, fodder crops, and cereals (wheat, and corn). Sugar beet and cereals cultivated in Zemamra especially and Doukkala in general participate in the national production reaching with 38% and 22%, respectively (ORMVAD 2016). Mineral fertilization (NPK) is used to maintain productivity.

Soil sampling and laboratory analysis

Using an auger, 59 samples were collected in the 0–30 cm horizon. In the laboratory, they were air-dried, then crushed and sieved at 2 mm. These samples were analysed for physical and chemical parameters: texture elements: clay, fine sand (F. Sand), coarse sand (C. Sand), fine silt (F. Silt) and coarse silt (C. Silt) by means of a Robinson pipette; pH was determined using a pH meter (1/5), total organic matter (SOM) by the Walkley & Black method, total nitrogen (TN) by the Kjeldahl method, available phosphorus (P_2O_5) by the Olsen method, exchangeable potassium (K_2O), magnesium (MgO), calcium (CaO), sodium (Na_2O) by atomic absorption and flame photometer, cation exchange capacity (CEC) by the Metson method, total carbonates ($CaCO_3$) by Bernard's calcimeter, nitrates (NO_3-N) by the chromotropic acid method, ammonium (NH_4-N) by colorimetry (blue indophenol), electrical conductivity (EC) by a conductivity meter, and sodium absorption ratio (SAR) is expressed by the equation used in the work of Murray and Grant 2007. The trace elements studied were: Boron (B), Iron (Fe), Manganese (Mn), Zinc (Zn) and Copper (Cu).

The Soil Structure Stability Index (SSSI) relating soil resistance to external disturbance forces was evaluated using the following formula from (Pieri 1992):

$$SSSI = \frac{1.724 * OC}{(Silt + Clay)} * 100 \quad (1)$$

where: OC – organic carbon.

The SSSI classification used is:

- SSSI > 9% – stable structure,
- 7% < SSSI < 9% – low risk of structural degradation,
- 5% < SSSI < 7% – high risk of degradation,
- SSSI < 5% – structurally degraded soil.

Soil quality index (SQI)

Three main steps to calculate soil quality index were as follows: (1) selecting a minimum data set (MDS), (2) scoring indicators, (3) calculating soil quality indices.

Selecting minimum data set

Its importance resides in selecting indicators that reflect the information of the soil system quality. In order to achieve this goal, statistical methods have been used and justified as performant including Principal Component Analysis (PCA) (Andrews et al. 2002; Rodrigo-Comino et al. 2019; Mahajan et al. 2020). The components with eigenvalues greater than 1 were selected. The MDS approach aims to select the parameters with highest weight factors for each component (Andrews et al. 2002; Pawlas et al. 2019). This approach avoids data redundancy; for this reason, it is important to verify the correlation between the selected indicators of all components. Pearson correlation keeps just the indicators with high weighting factors and not correlated. The MDS indicators must be independents (Andrews et al. 2002; Pawlas et al. 2019).

Scoring indicators

Three methods were tested (2 linear and 1 non-linear) for scoring the MDS indicators. These transforming approaches are based on the role of indicator in soils using the “More is Better”, and “Less is Better” criteria (Andrews et al. 2001). The first linear method is the simplest, expressed by two equations (a) and (b) for the “More is better” and “less is better” criteria, respectively (Nabiollahi et al. 2017):

$$S - L1 = \frac{Xi}{Xmax} \quad (a)$$

$$S - L1 = \frac{X_{min}}{X_i} \quad (b)$$

where: S-L1 – score of the indicator, X_i – sample value, X_{max} – maximum value.

The second linear method is expressed by equations (c) and (d) for the “More is Better” and “Less is Better” criteria, respectively (Andrews et al. 2002):

$$S - L2 = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (c)$$

$$S - L2 = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad (d)$$

where: S-L2 – score of the indicator, X_i – sample value, X_{max} – maximum value, X_{min} – minimum value.

The non-linear method is expressed by the following equation according to (Andrews et al. 2002):

$$S - NL = \frac{1}{\left(a + \left(\frac{x}{X_0}\right)^b\right)} \quad (2)$$

where: S-NL – score of the indicator determined by the non-linear method, a – maximum value of scores (equal to 1), x – sample value, X_0 – mean of the indicator, b – equal to -2.5 for the indicator with the “More is Better” criterion, and 2.5 for the indicator receiving the “Less is Better” criterion. The scores obtained by the different methods are between 0 and 1.

Calculating soil quality indices

Two mathematical equations are used to combine scores of MDS indicators: additive and weighted. The additive is described in the works of (Andrews et al. 2002; Maulood et Darwesh 2019), and is represented by the following equation:

$$SQI - A = \sum_{n=1}^n S_i/n \quad (3)$$

where: S_i – indicator score, n – number of MDS indicators.

For the weighted method, scores are multiplied by a coefficient calculated from PCA results (Bastida et al. 2008; Mahajan et al. 2020). It is represented below:

$$SQI - W = \sum_{n=1}^n W_i * S_i \quad (4)$$

where: S_i – score of the indicator, W_i – coefficient calculated from PCA results.

Soil quality index sensitivity

The SQI is evaluated by sensitivity analysis, a method described by (Masto et al. 2008), and expressed by the following equation:

$$S = \frac{SQI_{max}}{SQI_{min}} \quad (5)$$

where: S – sensitivity, SQI_{max} – maximum SQI value, and SQI_{min} – minimum SQI value. A high soil sensitivity index is more sensitive to changes and disturbances due to practices.

The SPSS software was used for statistical treatments concerning PCA, Pearson correlation, and ANOVA for means comparison. Excel was also used to calculate the scores of indicators and soil quality indices.

RESULTS AND DISCUSSION

Soil properties

The study of texture elements allows the characterization of soils in the area. Table 1 shows the grain size composition of soils in the 0–30 cm horizon. It was observed that F. Sand is the most present in this superficial horizon with an average percentage of 42%, followed by clay (31%). It was also noted that F. Sand especially, can attain a maximum of 67% of the total soil texture. The soil tends to be rich in fine sand at the surface. Silt is the least dominant in soils.

The projection of the textural elements on the texture diagram (USDA 1996) shows that most soils in the study area have a Sandy-Clay-Loam texture. The other textures present in the soils are Clay-Loam, Sandy-Clay and Clay (Fig. 2).

The soils in the area, essentially vertisols, have been described as clay-sandy at the surface (Geoffroy 1964; Badraoui et al. 2000). This type of soil is the most clayey with clay contents of 40 to 55% (Geoffroy 1964). According to Geoffroy’s first description of soils in 1964, and those presented in (Fig. 2), it can be seen that soils tend to have more sand in the surface

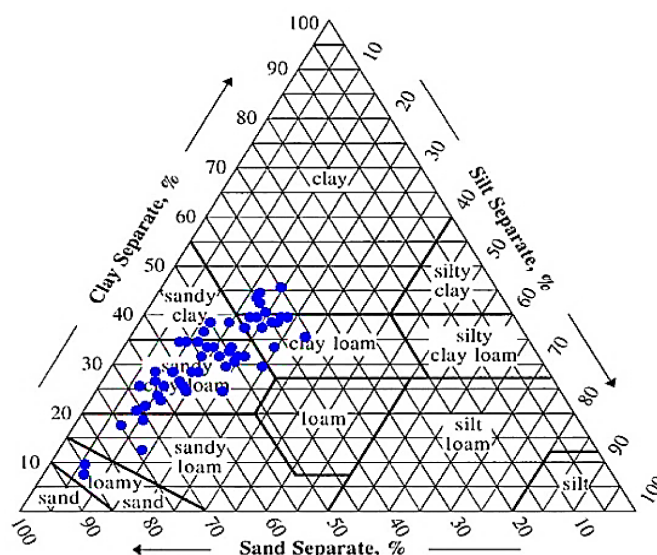


Fig. 2. Textural diagram of soils

Table 1. Granulometric composition of soils and concentration of trace elements

| Indicator | Units | Min | Max | Mean | SD | Skeewness | Kurtosis | CV |
|--------------------------|-------|------|-------|--------|-------|-----------|----------|-------|
| <i>Textural elements</i> | | | | | | | | |
| Clay | % | 7.8 | 45 | 31.116 | 8.252 | -0.811 | 0.67 | 0.265 |
| C. Sand | % | 6 | 25.6 | 12.988 | 3.883 | 0.647 | 0.61 | 0.299 |
| F. Sand | % | 30.4 | 67.1 | 42.132 | 8.821 | 0.691 | 0.052 | 0.209 |
| C. Silt | % | 1.8 | 9.5 | 5.168 | 1.71 | 0.364 | 0.006 | 0.331 |
| F. Silt | % | 1.3 | 18.3 | 8.898 | 4.236 | 0.261 | -0.733 | 0.476 |
| <i>Trace elements</i> | | | | | | | | |
| B | mg/kg | 0.16 | 1.21 | 0.349 | 0.173 | 2.758 | 10.914 | 0.496 |
| Fe | mg/kg | 1.5 | 21.35 | 10.219 | 4.601 | 0.334 | -0.257 | 0.45 |
| Mn | mg/kg | 2.04 | 16.03 | 6.169 | 2.759 | 1.38 | 2.068 | 0.447 |
| Zn | mg/kg | 0.2 | 1.73 | 0.608 | 0.321 | 1.268 | 1.593 | 0.528 |
| Cu | mg/kg | 0.18 | 0.91 | 0.461 | 0.144 | 1.184 | 1.641 | 0.313 |

Min – Minimum; Max – Maximum ; SD – Standard deviation; CV – Coefficient of variation; C – Coarse; F – Fine; B – Boron; Fe – Iron; Mn – Manganese; Zn – Zinc; and Cu – Copper.

horizon, with a decrease in fine elements (clay and silt). The increase of sand over clay and silt can be explained by the agricultural practices exercised. In the area, the restitution of crop residues to soils is almost null, the farmer by his repeated and superficial tillage, keeps the first 10 centimetres uncovered. Wind and water, during the first rains of September, carry away the fine elements and increase the percentage of sand (Geoffroy 1964; Souidi et al. 2000). The loss of fine elements is also caused by the sugar beet crop exploited in the area (Badraoui et al. 2000; Naaman et al. 2015). It should be considered that the sector of Zemamra is beet-oriented; when the land is harvested, the soil remains stuck on the sugar beet pivots. This loss has

been estimated at about 22,000 tons of soil/year at regional scale (Souidi et al. 2000; Naaman et al. 2015). The loss of fine elements negatively impacts the soils by low retention of fertilizing elements (Jensen et al. 2019).

For trace elements, they are recommended according to the sensitivity and needs of the crops cultivated in the area. There is no norm of interpretation for the soil in Morocco, but there are standards established to assess the contents of trace elements to the availability of the element for the crop. As it has been mentioned, the standards established at the national level are the most useful to assess the data of soil analysis. Indicators of this work were compared to standards developed by Moroccan organizations (DIAEA 2008).

According to the soil assessment standards used in Morocco for all indicators presented (DIAEA 2008), soil pH is alkaline. They are poor to moderately poor in organic matter (1.789%). For fertilisers, soils are poor in TN (0.099%), rich to very rich in K_2O (191.714 mg/kg), and well provided with P_2O_5 (33.339 mg/kg). Magnesium is the second cation, after calcium, to saturate the clay-humic complex. Both elements occur in high quantities in the soils, participating in a high CEC (25.725 meq/100 g). These soils have low (2.607%) to very low (min = 0.1%) total carbonate content. Nitrates and ammonium are present with low quantities in the soils. EC (mean = 0.156 dS/m), and SAR (1.115) indicate that the soils in general are not saline.

In order to explain the moderate to poor contents of organic matter, all soil types in the Zemamra area began to lose significant quantities of organic matter according to measurements from 1987 to 1997 (Badraoui et al. 2000). This status can be explained by the bad restitution of crop residues after harvest in the area. On the other hand, clays are closely related to organic matter; the loss of fine elements as mentioned in the previous paragraph may lead to the loss of organic matter (Jensen et al. 2019). It was found that 60% of SOM is concentrated in soil particles with a diameter less than 0.25 mm for soils when sugar beet is harvested (Naaman et al. 2015). It should be noted that the organic matter could reach 2.47% for fractions with a diameter less than 0.10mm. These fractions include silts, and clays stuck on the sugar beet (Souidi et al. 2000). The loss in organic matter is also related to the number of years of irrigation. Naaman et al. in 2001 showed an average organic matter loss of 48% and a total nitrogen loss of about 47% over 30 years in the study area. The annual loss in SOM in the Doukkala irrigated perimeter is estimated at 30 kg per hectare per year. On a regional scale, vertisols and mollisols are the most affected by this loss (30% and 36%, respectively; Souidi et al. 2000). The richness of the soils by P_2O_5 and K_2O is explained by the excessive mineral fertilization to maintain crop productivity. It has also been observed that total nitrogen found in the soil is low, which can be explained by the leaching character of this element under irrigation. The studies in the region have shown that this loss is due to the number of years of irrigation; for total nitrogen, the loss is of the order of 13% for a 5-year watering period and amounts to 47% for 30 years. The

loss of nitrogen during agricultural intensification is mainly in the hydrolysable fraction, which corresponds to the easily biodegradable fraction of total nitrogen (Naaman et al. 2001). These losses had negative consequences on the environment, mainly on groundwater which is contaminated by nitrates (Rahoui et al. 2000; El Achheb et al. 2001; Jamaa et al. 2020). The irrigation water loaded with fertilizers in the irrigated areas of the Doukkala region leaches into the subsoil towards the groundwater. In parallel to mineral fertilization, Doukkala is witnessing a fairly significant use of manure, particularly for forage and vegetables, which contribute significantly to the nitrogen mass balance (El Achheb et al. 2001). These inputs were estimated at 800 tonnes/year in the Zemamra case (Rahoui et al. 2000). The low percentage of total carbonates in the soil can be explained by its leaching due to the long-term effect of sprinkler irrigation.

According to the classification of the soil structural stability index, the soils of Zemamra are degraded (Table 2). This degraded structure may be the result of agricultural practices in the study area. The loss of fine elements and organic matter can be one of the main causes of this problem. The loss of soil humic stock has serious consequences on the physical and chemical behaviour of the soil; soils tend to become harder, more compact, vulnerable to erosion, and retain less water (Rahoui et al. 2000, Batey 2009). On the other hand, sprinkler irrigation, especially with high flow rates, increases soil compaction. The contact of irrigation water drops with the soil causes soil compaction and increases the resistance of soils to penetration (Serem et al. 2016). Thus, the passage of heavy equipment and machinery during harvesting may be also responsible for this degradation.

Selected and scored MDS

By PCA, six components resulted with eigenvalues greater than 1 and express 80.119% of the total soil quality information (Table 3). According to Table 3, the indicators in the PC1 with the highest weighting factors are CEC, Clay, CaO, F. Sand, C. Sand, and MgO. Through a Pearson correlation (Table 4), CEC is retained in the MDS. PC2 is represented by SAR, Na_2O , EC, and B, which are highly correlated (Table 5), only SAR is selected. Mn is retained from PC3. The SOM is selected from PC4. K_2O is selected from PC5 and

Table 2. Characterisation of the physical and chemical indicators of soils (n = 59)

| Indicator | Units | Min | Max | Mean | SD | Skeewness | Kurtosis | CV |
|-------------------------------|-----------|-------|--------|----------|----------|-----------|----------|-------|
| pH | – | 7.5 | 9.9 | 8.716 | 0.445 | -0.548 | 1.260 | 0.051 |
| SOM | % | 0.75 | 3.03 | 1.789 | 0.434 | 0.288 | 0.923 | 0.243 |
| TN | % | 0.04 | 0.17 | 0.099 | 0.025 | 0.269 | 0.921 | 0.250 |
| CN | – | 9.695 | 11.311 | 10.462 | 0.361 | 0.296 | -0.409 | 0.035 |
| K ₂ O | mg/kg | 85 | 361 | 191.714 | 64.597 | 0.799 | 0.250 | 0.337 |
| P ₂ O ₅ | mg/kg | 8 | 128 | 33.339 | 24.621 | 1.740 | 3.937 | 0.738 |
| MgO | mg/kg | 238 | 2271 | 1400.982 | 432.656 | -0.345 | 0.427 | 0.309 |
| CaO | mg/kg | 1484 | 8596 | 5330 | 1528.693 | -0.311 | -0.491 | 0.287 |
| CEC | még/100 g | 5.6 | 36.6 | 25.725 | 6.898 | -0.936 | 0.709 | 0.268 |
| NO ₃ -N | mg/kg | 0.07 | 3.62 | 0.831 | 0.802 | 2.031 | 3.956 | 0.965 |
| NH ₄ -N | mg/kg | 0.02 | 0.61 | 0.263 | 0.116 | 0.233 | 0.536 | 0.441 |
| CaCO ₃ | % | 0.1 | 15.9 | 2.607 | 3.819 | 1.928 | 3.104 | 1.465 |
| Na ₂ O | mg/kg | 52 | 1470 | 403.036 | 286.939 | 1.616 | 2.907 | 0.712 |
| EC | dS/m | 0.09 | 0.41 | 0.156 | 0.058 | 1.974 | 5.772 | 0.373 |
| SAR | – | 0.243 | 3.966 | 1.115 | 0.746 | 1.762 | 3.493 | 0.670 |
| SSSI | – | 2.67 | 7.65 | 4.13 | 1.01 | 1.13 | 1.54 | 0.24 |

Min – Minimum; Max – Maximum ; SD – Standard deviation; CV – Coefficient of variation; SOM – Soil organic matter; TN – Total Nitrogen; K₂O – Potassium; P₂O₅ – Phosphorus; MgO – Magnesium; CaO – Calcium; CEC – Cationic exchange capacity; NO₃-N – Nitrates; NH₄-N – Ammonium; CaCO₃ – Total carbonates; Na₂O – Sodium; EC – Electrical conductivity; SAR – Sodium absorption ratio; SSSI – Structure stability index.

Table 3. Results of PCA

| Description | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 |
|----------------------------------|---------------|--------------|---------------|--------------|--------------|--------------|
| Eigen-value | 9.129 | 4.046 | 2.394 | 1.815 | 1.534 | 1.111 |
| % variance explained | 25.796 | 16.976 | 13.297 | 10.588 | 7.702 | 5.761 |
| Cumulative % | 25.796 | 42.771 | 56.068 | 66.656 | 74.358 | 80.119 |
| Eigenvectors | | | | | | |
| Texture | | | | | | |
| Clay | 0.914 | 0.225 | -0.064 | 0.152 | 0.044 | -0.15 |
| C. Sand | -0.745 | -0.18 | 0.121 | -0.367 | -0.264 | 0.025 |
| F. Sand | -0.863 | -0.241 | 0.202 | -0.264 | -0.157 | -0.006 |
| C. Silt | 0.669 | 0.054 | 0.073 | 0.082 | 0.298 | 0.211 |
| F. Silt | 0.421 | 0.226 | -0.36 | 0.587 | 0.376 | 0.185 |
| Physical and chemical indicators | | | | | | |
| pH | 0.273 | 0.337 | -0.722 | 0.124 | 0.143 | -0.13 |
| SOM | 0.406 | 0.245 | 0.145 | 0.798 | 0.145 | -0.09 |
| TN | 0.407 | 0.219 | 0.15 | 0.83 | 0.068 | -0.061 |
| CN | -0.223 | 0.161 | -0.066 | -0.473 | 0.567 | -0.189 |
| K ₂ O | 0.355 | -0.012 | 0.213 | 0.216 | 0.715 | -0.029 |
| P ₂ O ₅ | -0.572 | 0.158 | 0.566 | 0.21 | 0.144 | 0.007 |
| MgO | 0.764 | 0.292 | 0.156 | 0.207 | -0.193 | 0.138 |
| CaO | 0.884 | 0.101 | -0.232 | 0.181 | 0.158 | -0.142 |
| CEC | 0.932 | 0.142 | -0.134 | 0.186 | 0.001 | -0.12 |
| CaCO ₃ | 0.176 | -0.004 | -0.478 | 0.277 | 0.651 | 0.093 |
| NO ₃ -N | 0.313 | 0.511 | 0.133 | 0.027 | 0.275 | -0.104 |
| NH ₄ -N | -0.016 | -0.169 | 0.04 | -0.051 | -0.035 | 0.925 |
| Na ₂ O | 0.315 | 0.915 | 0.028 | 0.088 | -0.058 | 0.023 |
| EC | 0.302 | 0.867 | -0.12 | 0.178 | 0.239 | -0.064 |
| SAR | 0.217 | 0.931 | 0.066 | 0.06 | -0.083 | 0.043 |
| Trace elements | | | | | | |
| B | -0.149 | 0.858 | 0.179 | 0.142 | -0.018 | -0.212 |
| Fe | 0.289 | 0.201 | 0.684 | -0.222 | 0.142 | -0.35 |
| Mn | -0.04 | 0.037 | 0.747 | 0.01 | -0.168 | 0.001 |
| Zn | -0.27 | 0.346 | 0.601 | 0.242 | 0.077 | 0.409 |
| Cu | -0.036 | 0.128 | 0.642 | 0.225 | 0.116 | 0.055 |

C – Coarse; F – Fine; B – Boron; Fe – Iron; Mn – Manganese; Zn – Zinc; Cu – Copper, SOM – Soil organic matter; TN – Total Nitrogen; K₂O – Potassium; P₂O₅ – Phosphorus; MgO – Magnesium; CaO – Calcium; CEC – Cationic exchange capacity; NO₃-N – Nitrates; NH₄-N – Ammonium; CaCO₃ – Total carbonates; Na₂O – Sodium; EC – Electrical conductivity; SAR – Sodium absorption ratio.

Table 4. Pearson correlation between indicators of PC1

| Description | Clay | C. Sand | F. Sand | MgO | CaO | CEC |
|-------------|---------------------|---------------------|---------------------|--------------------|--------------------|-----|
| Clay | 1 | | | | | |
| C. Sand | -0.805 ^a | 1 | | | | |
| F. Sand | -0.943 ^a | 0.822 ^a | 1 | | | |
| MgO | 0.758 ^a | -0.589 ^a | -0.716 ^a | 1 | | |
| CaO | 0.909 ^a | -0.819 ^a | -0.909 ^a | 0.624 ^a | 1 | |
| CEC | 0.962 ^a | -0.790 ^a | -0.928 ^a | 0.759 ^a | 0.946 ^a | 1 |

^a The correlation is significant at the level of 0.01.

C – Coarse; F – Fine; MgO – Magnesium; CaO – Calcium; CEC – Cationic exchange capacity.

Table 5. Correlation between selected indicators of all principal components

| Description | CEC | B | SAR | Na ₂ O | EC | K ₂ O | pH | Mn | SOM | TN | NH ₄ -N |
|--------------------|--------------------|---------------------|--------------------|--------------------|--------------------|--------------------|---------------------|-------|--------------------|--------|--------------------|
| CEC | 1 | | | | | | | | | | |
| B | 0.008 | 1 | | | | | | | | | |
| SAR | 0.323 ^b | 0.747 ^a | 1 | | | | | | | | |
| Na ₂ O | 0.427 ^a | 0.728 ^a | 0.990 ^a | 1 | | | | | | | |
| EC | 0.457 ^a | 0.726 ^a | 0.833 ^a | 0.867 ^a | 1 | | | | | | |
| K ₂ O | 0.346 ^a | 0.075 | 0.043 | 0.096 | 0.320 ^b | 1 | | | | | |
| pH | 0.451 ^a | 0.177 | 0.292 ^b | 0.359 ^a | 0.507 ^a | 0.121 | 1 | | | | |
| Mn | -0.15 ^a | 0.238 | 0.114 | 0.081 | -0.114 | -0.036 | -0.579 ^a | 1 | | | |
| SOM | 0.543 ^a | 0.294 ^b | 0.356 ^a | 0.415 ^a | 0.508 ^a | 0.429 ^a | 0.203 | 0.107 | 1 | | |
| TN | 0.540 ^a | 0.278 ^b | 0.343 ^a | 0.400 ^a | 0.477 ^a | 0.402 ^a | 0.181 | 0.115 | 0.993 ^a | 1 | |
| NH ₄ -N | -0.154 | -0.301 ^b | -0.153 | -0.167 | -0.202 | -0.032 | -0.190 | 0.058 | -0.123 | -0.093 | 1 |

^a The correlation is significant at the 0.01 level.

^b The correlation is significant at the 0.05 level.

CEC – Cationic exchange capacity; B – Boron; Na₂O – Sodium; EC – Electrical conductivity; K₂O – Potassium; Mn – Manganese; SOM – Soil organic matter; TN – Total Nitrogen; K₂O – Potassium; P₂O₅ – Phosphorus; MgO – Magnesium; CaO – Calcium; CEC – Cationic exchange capacity; NO₃-N – Nitrates.

NH₄-N from PC6. A simple correlation between these indicators (Table 5) allowed the selection of four indicators in the independent MDS, which are: CEC, B, Mn, and K₂O.

CEC is an important indicator of soil fertility potential. It plays an important role in the retention of water and bioavailability of nutrients that are essential to plants (Saidi et al. 2012). Cationic exchange capacity has been selected as a soil quality indicator of MDS in several works (Vasu et al. 2016; Jahany et Rezapour 2019). This importance allows attributing the “more is better” criterion to CEC. Potassium is also a major element in ensuring soil fertility. In the Zemamra area, from the first studies of soil, it was recommended to add potassium for improving soil fertility. It is used in the form of mineral fertilizer (NPK), mainly for sugar beet, which is grown on large parcels in the area and requires a lot of potassium for its nutrition (Badraoui et al. 2000; Zengin et al. 2008). Finding K₂O as an indicator of soil quality in this study is similar to the results of (Amorim et al. 2020). Its high quantity

in the soil promotes good quality and therefore good productivity. It has received the “more is better” criterion. Boron and manganese are two micronutrients added in the soils of the area for a good yield of sugar beet, mainly as an important industrial crop, and for alfalfa. The wheat grown in the area is also highly sensitive to Mn (Sinaj et al. 2017). Boron was selected as an indicator in the work of (Mahajan et al. 2020), and Mn as an indicator in the work of (Rodrigo-Comino et al. 2019). Low quantity of these elements in the soil is satisfactory for good soil quality. Both elements have been given the “less is better” criterion, as a high concentration of these elements in the soil can generate the risk of toxicity.

Table 6 summarizes the parameters and criteria used to calculate the scores of the MDS indicators. The CEC has the highest score, since it is retained from the first main component, followed by B, Mn and K₂O.

Three types of transformations were tested, two linear (L1 and L2) and one non-linear (NL). For the CEC, it was found that the L1 method had

Table 6. Scores of MDS Indicators

| Indicators | Scoring curves | Linear | | Non Linear | | Weight |
|------------------|----------------|--------|-------|------------|----------|--------|
| | | Min | Max | Mean(x0) | Slope(b) | |
| CEC | More is better | 5.6 | 36.6 | 25.725 | -2.5 | 0.322 |
| B | Less is better | 0.16 | 1.21 | 0.349 | 2.5 | 0.212 |
| Mn | Less is better | 2.04 | 16.03 | 6.169 | 2.5 | 0.166 |
| K ₂ O | More is better | 85 | 361 | 191.714 | -2.5 | 0.096 |

CEC – Cationic exchange capacity; B – Boron; K₂O – Potassium; Mn – Manganese.

the highest scores with a mean of 0.703, followed by the L2 (0.649) and the NL method (0.486). For K₂O, it is the L1 method that has the highest scores with a mean of (0.531) followed by the NL method (0.470) and the L2 method (0.386). For B and Mn, it is the L2 method that gives the highest scores of mean of (0.820) and (0.705) respectively, followed by the NL method and the L1 method.

The multiple comparisons of the means of scores for each indicator were done by ANOVA. The test of homogeneity was verified for CEC, K₂O, and Mn ($p > 0.05$). For CEC, a difference exists between the methods ($F = 18.926$; $p < 0.05$). This difference is observed between NL and L1 on the one hand and NL and L2 on the other ($p < 0.05$, Fig. 3a). No difference between L1 and L2. For K₂O, the difference is observed between the linear methods ($F = 7.339$; $p = 0.001$, Fig. 3b). For Mn, the difference exists between all methods ($F = 37.979$; $p < 0.05$, Fig. 3d). For boron, the difference is observed between L1, L2, and L2 and NL (Fig. 3c). On average, the linear methods give the highest values and these findings are similar to those of (Mahajan et al. 2020).

Testing different methods is intended to select which one is suitable for the conditions in the study area. Several studies have obtained very good results using linear methods (Debi et al. 2019; Davari et al. 2020), while others have found the non-linear method to be the most efficient for introducing scores into a SQI (Bilgili et al. 2017; Nehrani et al. 2020).

Assessment of soil quality

The SQIs can be calculated using the equations below. The specific weights for each indicator were presented:

Additive

$$A-L1 = (Sc_{L1}CEC + Sc_{L1}B +$$

$$+ Sc_{L1}Mn + Sc_{L1}K_2O)/4 \quad (6)$$

$$A-NL = (Sc_{NL}CEC + Sc_{NL}B + Sc_{NL}Mn + Sc_{NL}K_2O)/4 \quad (7)$$

$$A-L2 = (Sc_{L2}CEC + Sc_{L2}B + Sc_{L2}Mn + Sc_{L2}K_2O)/4 \quad (8)$$

Weighted

$$W-L1 = Sc_{L1}CEC \cdot 0.322 + Sc_{L1}B \cdot 0.212 + Sc_{L1}Mn \cdot 0.166 + Sc_{L1}K_2O \cdot 0.096 \quad (9)$$

$$W-NL = Sc_{NL}CEC \cdot 0.322 + Sc_{NL}B \cdot 0.212 + Sc_{NL}Mn \cdot 0.166 + Sc_{NL}K_2O \cdot 0.096 \quad (10)$$

$$W-L2 = Sc_{L2}CEC \cdot 0.322 + Sc_{L2}B \cdot 0.212 + Sc_{L2}Mn \cdot 0.166 + Sc_{L2}K_2O \cdot 0.096 \quad (11)$$

where: Sc – indicator score

Table 7 presents the SQIs calculated by the different methods. The values are generally between 0 and 1; the nearer to 1, the soil quality becomes very good.

It can be observed that the A-L2 method overestimated the soil quality values with a mean value of 0.64 and has the lowest sensitivity index, so it is less sensitive to changes in soil quality. SQIs calculated by A-L1, A-NL, and W-L2 have the following means, respectively (0.54; 0.51 and 0.57). A-L1 and A-NL have the following sensitivity indices (2.388 and 2.343). SQIs calculated by W-L1 and W-NL have the following means (0.455 and 0.410). Note that W-NL gave the lowest SQI values but showed the highest sensitivity index (2.717). According to the SQI classification by Marzaioli et al. 2010 (SQI < 0.55, poor quality; 0.55 < SQI < 0.7, moderate quality; SQI > 0.7, good quality), the soils of Zemamra are generally considered poor to moderate quality. All indices are highly correlated (Table 8).

Soil quality index validation

According to Table 9, all SQIs are correlated with the textural elements. There is a positive

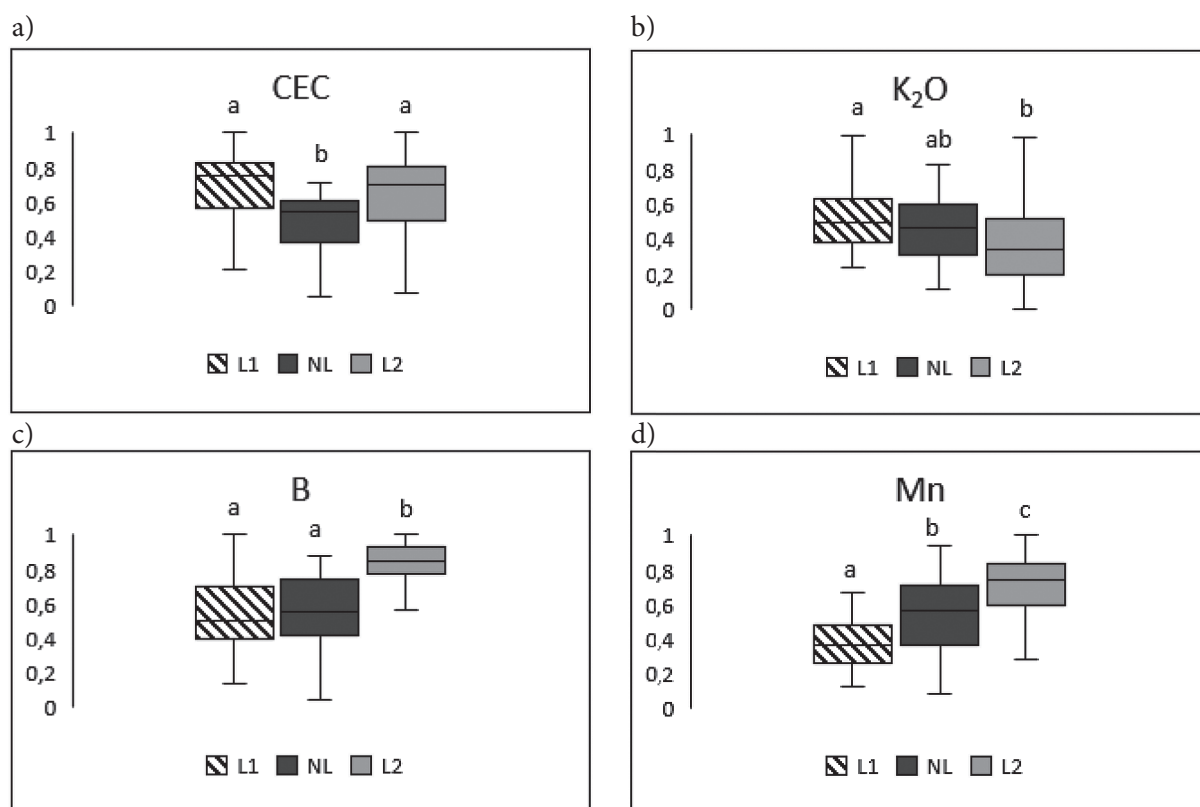


Fig. 3. Scores of CEC (a), scores of K₂O (b), scores of B (c), scores of Mn (d) using linear and non-linear methods (ANOVA, p<0.05). L – linear; NL – non-linear.

Table 7. Soil quality indices results

| Index | | Min | Max | Mean | S. D | Skeewness | Kurtosis | CV | S |
|-------|------|------|------|------|------|-----------|----------|------|------|
| SQI | A-L1 | 0.34 | 0.81 | 0.54 | 0.11 | 0.18 | -0.65 | 0.20 | 2.39 |
| | W-L1 | 0.26 | 0.61 | 0.46 | 0.09 | -0.21 | -0.87 | 0.20 | 2.39 |
| | A-NL | 0.31 | 0.72 | 0.51 | 0.12 | -0.06 | -1.17 | 0.22 | 2.34 |
| | W-NL | 0.21 | 0.56 | 0.41 | 0.09 | -0.23 | -1.08 | 0.23 | 2.72 |
| | A-L2 | 0.43 | 0.86 | 0.64 | 0.12 | -0.06 | -1.03 | 0.19 | 1.99 |
| | W-L2 | 0.32 | 0.72 | 0.54 | 0.10 | -0.31 | -0.95 | 0.19 | 2.23 |

SQI – Soil quality index; SK – Skeewness; CV – Coefficient of variation; S – Sensitivity; A-L – Additive linear; A-NL – Additive non-linear; W-A – weighted linear; W-NL – Weighted non-linear.

Table 8. Pearson correlation between SQIs

| Index | | SQI | | | | | |
|-------|------|--------------------|--------------------|--------------------|--------------------|--------------------|------|
| | | A-L1 | A-NL | A-L2 | W-L1 | W-NL | W-L2 |
| SQI | A-L1 | 1 | | | | | |
| | A-NL | 0.979 ^a | 1 | | | | |
| | A-L2 | 0.950 ^a | 0.959 ^a | 1 | | | |
| | W-L1 | 0.964 ^a | 0.955 ^a | 0.914 ^a | 1 | | |
| | W-NL | 0.949 ^a | 0.973 ^a | 0.959 ^a | 0.985 ^a | 1 | |
| | W-L2 | 0.919 ^a | 0.936 ^a | 0.956 ^a | 0.960 ^a | 0.961 ^a | 1 |

SQI – Soil quality index; A-L – Additive linear; A-NL – Additive non-linear; W-A – weighted linear; W-NL – Weighted non-linear; ^a – The correlation is significant at the 0.01 level.

Table 9. Correlation of SQIs with textural elements and trace elements

| Index | | Textural Elements | | | | | Trace Elements | | | | |
|-------|------|--------------------|---------------------|---------------------|--------------------|--------------------|---------------------|---------------------|--------|---------------------|--------|
| | | Clay | C. Sand | F. Sand | C. Silt | F. Silt | B | Mn | Fer | Zn | Cu |
| SQI | A-L1 | 0.591 ^a | -0.505 ^a | -0.648 ^a | 0.439 ^a | 0.489 ^a | -0.432 ^a | -0.534 ^a | -0.062 | -0.372 ^a | -0.137 |
| | A-NL | 0.553 ^a | -0.460 ^a | -0.611 ^a | 0.381 ^a | 0.463 ^a | -0.487 ^a | -0.634 ^a | -0.114 | -0.427 ^a | -0.218 |
| | A-L2 | 0.624 ^a | -0.561 ^a | -0.680 ^a | 0.484 ^a | 0.535 ^a | -0.399 ^a | -0.580 ^a | -0.019 | -0.347 ^a | -0.115 |
| | W-L1 | 0.717 ^a | -0.580 ^a | -0.749 ^a | 0.460 ^a | 0.494 ^a | -0.421 ^a | -0.488 ^a | -0.043 | -0.416 ^a | -0.173 |
| | W-NL | 0.649 ^a | -0.518 ^a | -0.689 ^a | 0.403 ^a | 0.468 ^a | -0.490 ^a | -0.579 ^a | -0.112 | -0.457 ^a | -0.245 |
| | W-L2 | 0.759 ^a | -0.641 ^a | -0.789 ^a | 0.500 ^a | 0.545 ^a | -0.400 ^a | -0.525 ^a | -0.017 | -0.402 ^a | -0.161 |

SQI – Soil quality index; A-L – Additive linear; A-NL – Additive non-linear; W-A – weighted linear; W-NL – Weighted non-linear; C – Coarse; F – Fine; B – Boron; Fe – Iron; Mn – Manganese; Zn – Zinc; Cu – Copper; ^a – The correlation is significant at the 0.01 level. ^b – The correlation is significant at the 0.05 level.

correlation between the calculated indices and clay on the one hand as well as between the SQIs and silts (F. Silt and C. Silt) on the other hand. A negative correlation is observed between sand (F. Sand and C. Sand) and SQIs. These positive correlations can be explained by the major role of fine elements in maintaining soil quality. They allow the retention of nutrients. The loss of these elements from the soils through conventional tillage, sugar beet harvesting, irrigation, and bad restitution of crop residues leads to the degradation of soil quality. On the other hand, this loss can increase the sand content in the surface horizon of the soil and causes the leaching of several nutrients.

It was noticed that trace elements (B, Mn, and Zn) are negatively correlated with SQIs. B can negatively and indirectly influence soil quality (Shireen et al. 2018). Indeed, according to the literature, the average soil boron concentrations that are considered deficient are 0.19 ppm in Nepal, 0.27 ppm in Nigeria, 0.39 ppm in Sierra Leone, and 0.42 ppm in India. Toxic concentrations of 0.68, 1.02, and 1.26 ppm were measured in Pakistan, Hungary, and Mexico, respectively. Recently, it has been suggested that 0.5-2.0 ppm represents the optimal range for Boron in the soil, while lower and higher values indicate deficiency and toxicity (Brdar-Jokanovic 2020). Comparison of the average concentration of Boron (B = 0.349 mg/kg) in this study with that in the world shows that the soils in the study area are deficient in B, whereas it is negatively correlated with the calculated SQIs. In order to explain this contradiction, there are some studies on this subject. Firstly, soil pH is known to affect boron adsorption and the availability of boron to plants (Goldberg et al. 2000). When pH increases, the rate of boron uptake is significantly reduced, especially

when pH exceeds 8 (Läuchli and Grattan 2012) where boron speciation begins to shift gradually from boric acid to anionic borate (Allison 2017). Secondly, the phosphorus accumulated in the soil decreases the B uptake by the plant, so high B concentrations in the soil must be found, which is not observed in these results compared to world standards. This contradiction can be explained by the following reason: low B concentrations can negatively impact the soil (Yau et al. 1995). Thus, the problem of B toxicity under cereal crops in Morocco is increasingly encountered in semi-arid areas of the country (Sillanpää, 1982; Yau et al. 1995). On the other hand, the strong correlation of B with salinity elements (EC, SAR, Na₂O, Table 5) may justify its negative impact on soil quality. The positive correlation between B and EC is significant at the 0.01 level. This result is similar to the results of (Chouliaras et al. 1990). Chouliaras et al. (1990), found that an average increase of 0.63 ppm in water-soluble B corresponds to a 0.5 mS/cm increase in soil electrical conductivity in the 1:5 aqueous extract. Thus, the mechanism of B toxicity is still a matter of speculation (Wimmer et al. 2003); hence the impact of boron on soil quality is not yet known (Gabriela et al. 2017). The authors of the presented paper suggest that soil trace element levels should be taken into consideration when applying fertiliser to soils in the study area.

A negative correlation between the calculated SQIs and Zinc and Mn was also noted (Table 9). This correlation can be explained by the negative effect of Zinc and Mn on soil microorganisms (Wyszkowska et al. 2012). Trace elements are toxic to soil microorganisms; they inhibit microbial activities and modify the diversity of microbial communities (Fazekašová et al. 2020). The impact of trace elements in soils is

Table 10. Correlation between SQIs and soil physical and chemical indicators

| | | Physical and chemical indicators | | | | | | | | | | | | | | |
|-------|------|----------------------------------|-------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|-------------------|--------|-------|--------------------|--------------------|--------|
| Index | | K ₂ O | P ₂ O ₅ | MgO | CaO | CEC | CaCO ₃ | pH | SOM | TN | Na ₂ O | SAR | CE | NH ₄ -N | NO ₃ -N | CN |
| SQI | A-L1 | 0.575 ^a | -0.462 ^a | 0.406 ^a | 0.675 ^a | 0.661 ^a | 0.489 ^a | 0.392 ^a | 0.236 | 0.229 | -0.054 | -0.141 | 0.139 | 0.083 | 0.182 | -0.103 |
| | A-NL | 0.491 ^a | -0.522 ^a | 0.354 ^a | 0.676 ^a | 0.640 ^a | 0.479 ^a | 0.442 ^a | 0.176 | 0.171 | -0.104 | -0.190 | 0.099 | 0.043 | 0.143 | -0.088 |
| | A-L2 | 0.634 ^a | -0.482 ^a | 0.407 ^a | 0.734 ^a | 0.691 ^a | 0.525 ^a | 0.443 ^a | 0.315 ^b | 0.302 ^b | -0.038 | -0.132 | 0.165 | -0.007 | 0.169 | -0.070 |
| | W-L1 | 0.418 ^a | -0.553 ^a | 0.524 ^a | 0.783 ^a | 0.795 ^a | 0.414 ^a | 0.424 ^a | 0.266 ^b | 0.266 ^b | 0.032 | -0.063 | 0.165 | 0.045 | 0.199 | -0.173 |
| | W-NL | 0.352 ^a | -0.591 ^a | 0.456 ^a | 0.751 ^a | 0.743 ^a | 0.416 ^a | 0.446 ^a | 0.197 | 0.199 | -0.038 | -0.130 | 0.106 | 0.042 | 0.148 | -0.160 |
| | W-L2 | 0.454 ^a | -0.583 ^a | 0.535 ^a | 0.846 ^a | 0.834 ^a | 0.445 ^a | 0.473 ^a | 0.344 ^a | 0.339 ^b | 0.046 | -0.056 | 0.181 | -0.031 | 0.181 | -0.150 |

SQI – Soil quality index; A-L – Additive linear; A-NL – Additive non-linear; W-A – weighted linear; W-NL – Weighted non-linear; SOM – Soil organic matter; TN – Total Nitrogen; K₂O – Potassium; P₂O₅ – Phosphorus; MgO – Magnesium; CaO – Calcium; CEC – Cationic exchange capacity; NO₃-N – Nitrates; NH₄-N – Ammonium; CaCO₃ – Total carbonates; Na₂O – Sodium; EC – Electrical conductivity; SAR – Sodium absorption ratio. ^a – The correlation is significant at the 0.01 level. ^b – The correlation is significant at the 0.05 level.

not yet well known (Sudhakaran et al. 2018). Unfortunately, standards and thresholds for the toxicity of trace elements in soil are not established for the conditions of the Doukkala plain where the study area is a part. On the other hand, the characterisation of the biological indicators of the soils of the area goes back to a study carried out by Bryssine and his collaborators in 1964, who reported that trace elements can influence the biological properties of soils including microfauna. Therefore, the biological indicators of the current state of soils for comparison purposes seem important to be studied. Probably, introducing biological indicators into soil quality indices can reveal the information about the effects of trace elements on soil quality.

According to Table 10, K₂O is positively correlated with SQIs. This major element is strongly absorbed by the sugar beets, hence its addition to the soil improves soil fertility (Mahajan et al. 2020). P₂O₅ is negatively correlated with soil quality. This can be explained by the excess of phosphorus in the soil added in mineral form. The accumulation of P in soils can lead to a reduction in the plant's ability to absorb nutrients such as trace elements (B, Mn, and Zn). The dynamics of boron is strongly related to the phosphorus present in the soil (Gabriela et al. 2017). The absorption capacity of B decreases under an increase of P. Therefore, the interactions between P and B in soils must be taken into account when deciding on phosphorus fertilization (Gabriela et al. 2017). It has been suggested that the manganese uptake by wheat is inhibited by a physiological characteristic of the plant, influenced by increased phosphorus concentration, rather than by a direct effect of soil chemistry

on manganese availability (Nilsen et al. 1992). This is confirmed by the high Mn content in Zemamra soils (Mn = 6.169 mg/kg > 4 mg/kg) that exceeds the toxicity threshold according to the norms of FAO 1989, thus a positive correlation between phosphorus and manganese was found (Results not shown).

Phosphorus is the most important element that interferes with the absorption of zinc by plants. The absorption capacity of zinc is reduced by high phosphorus use, and zinc in plants and in soil is antagonistic to phosphorus (Mousavi 2011). It is suggested that the phosphate content in the soils of the region should be taken into consideration before mineral fertilization of the soil.

A positive correlation is observed between the exchangeable bases (CaO, MgO) and SQIs (Table 10). They contribute to the saturation of the clay-humic complex of soils by increasing the cation exchange capacity (Table 4). This is confirmed by the high CEC in the soil (Table 2). There is also a positive correlation between SQIs and CaCO₃ (Table 9). CaCO₃ forms with organic matter a stable form (Humates) in soils (Geoffroy 1964; Sánchez-Navarro et al. 2015). Leaching of carbonates from the surface horizon through irrigation may be another form of loss of organic matter in Zemamra soils. It is also probable that carbonates are related to the clay, and loss through leaching of the latter may be responsible for the loss of CaCO₃. It has been suggested that in some areas it may impact the soil quality positively (Sánchez-Navarro et al. 2015), but the role that carbonates play in improving soil quality is not yet well known (Zammanian et al. 2016).

CONCLUSIONS

This is the first work carried out using soil quality indices to evaluate the changes in soil properties in the irrigated area of Zemamra in the Doukkala plain. Soils are subjected to changes due to the agricultural practices applied to make soil quality low to moderate. The bad management of crop residues, conventional tillage, and irrigation contribute to the depletion of soils in fine elements (clay and silt) of the surface horizon and an increase in sand contents. This generates a loss of humic stock and leaching of total carbonates. Soil structure has been deteriorated. Soil quality indexing methods have been efficient tools to characterise the soils after long term exploitation under intensive agriculture and irrigation. Excessive mineral fertilisation caused P accumulation in the soil. Accumulated P reduces the absorption of microelements (B, Mn, and Zn) by plants. On the other hand, negative correlations between these elements and soil quality indices indicate that the concentration of trace elements even if it is low (B, Mn, and Zn) may negatively impact the soil quality.

Acknowledgements

This work was funded by the National Centre for Scientific and Technical Research (CNRST) in Rabat, Morocco.

REFERENCES

- Adejumobi M.A., Ojediran J.O., Olabiyi O.O. 2014. Effects of irrigation practices on some soil chemical properties on OMI irrigation scheme. *International Journal Engineering Research and Applications*, 4(10 Part 2), 29-35
- Alewoye Getie M., Legesse S.A., Mekonnen M., Aschalew A. 2020. Soil properties and crop productivity strategies as a potential climate variability adaptation option in Adefwuha Watershed, Ethiopia. *Earth Systems and Environment*, 4, 359-368
- Allison N. 2017. Reconstructing coral calcification fluid dissolved inorganic carbon chemistry from skeletal boron: An exploration of potential controls on coral aragonite B/Ca. *Heliyon*, 3(8), e00387
- Amorim H.C., Ashworth A.J., Wienhold B.J., Savin M.C., Allen F.L., Saxton A.M.,... & Curi N. 2020. Soil quality indices based on long-term conservation cropping systems management. *Agrosystems, Geosciences & Environment*, 3(1), e20036
- Andrews S.S., Karlen D.L., Mitchell J.P. 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agric. Ecosyst. Environ.* 90, 25–45
- Badraoui M., Agbani M., Soudi B. 2000. Evolution de la qualité des sols sous mise en valeur intensive au Maroc 2–3
- Bastida F., Zsolnay A., Hernández T., García C. 2008. Past, present and future of soil quality indices: a biological perspective. *Geoderma*, 147(3-4), 159-171
- Batey T. 2009. Soil compaction and soil management—a review. *Soil use and management*, 25(4), 335-345
- Bilgili A.V., Küçük Ç., Van Es.H.M. 2017. Assessment of the quality of the Harran Plain soils under long-term cultivation. *Environmental monitoring and assessment*, 189(9), 460
- Brdar-Jokanović M. 2020. Boron toxicity and deficiency in agricultural plants. *International Journal of Molecular Sciences*, 21(4), 1424
- Chouliaras N., Tsadilas C., Mavromatis E. 1990. Accumulation of boron in greenhouse soils. [researchgate.net](https://www.researchgate.net)
- Davari M., Gholami L., Nabiollahi K., Homae M., Jafari H.J. 2020. Deforestation and cultivation of sparse forest impacts on soil quality (case study: West Iran, Baneh). *Soil and Tillage Research*, 198, 104504
- DIAEA /DRHA /SEEN 2008. Direction de l'irrigation et de l'aménagement de l'espace Agricole, Service des Expérimentations, des Essais et de la Normalisation –Rabat
- El Achheb A., Mania J., Mudry J. 2001. Processus de salinisation des eaux souterraines dans le bassin Sahel-Doukkala (Maroc occidental). In *First International Conference on Saltwater Intrusion and Coastal Aquifers-Monitoring, Modeling and Management*, Essaouira, Morocco
- FAO 1998. Evaluation des Terres pour l'Agriculture Pluviale - Bulletin Pédologique de la FAO - 52
- Fazekašová D., Fazekaš J. 2020. Soil Quality and Heavy Metal Pollution Assessment of Iron Ore Mines in Nizna Slana (Slovakia). *Sustainability*, 12(6), 2549
- Gabriela M., Pavel Č., Radek V., Martin K., Miroslava P., Kateřina M.,... Tomáš L. 2017. Boron availability and uptake under increasing phosphorus rates in a pot experiment. *Plant, Soil and Environment*, 63(11), 483-490
- Geoffroy J.L., 1964. Les sols du casier Zemamra et mise en valeur en fonction de la pédologie. *Office National des irrigations*, 1-64
- Goldberg S., Lesch S.M., Suarez D.L. 2000. Predicting boron adsorption by soils using soil chemical parameters in the constant capacitance model. *Soil Science Society of America Journal*, 64(4), 1356-1363
- Ibno Namr K., Mrabet R. 2004. Influence of

- agricultural management on chemical quality of a clay soil of semi-arid Morocco. *Journal of African Earth Sciences*, 39(3-5), 485-489
21. Issoufou A., Maman G., Soumana I., Kaiser D., Konate S., Sabiou M., Mahamane A. 2019. Termite footprints in restored versus degraded agro-systems in South-West Niger. *Land Degradation & Development*
 22. Jamaa H., El Achheb A., Namr K.I. 2020. Spatial variation of groundwater quality and assessment of water table fluctuations in Plio-Quaternary aquifer formations in Doukkala Plain, Morocco. *Groundwater for Sustainable Development*, 11, 100398
 23. Jahany M., Rezapour S. 2019. Assessment of the quality indices of soils irrigated with treated wastewater in a calcareous semi-arid environment. *Ecological Indicators*, 109, 105800
 24. Jensen J.L., Schjønning P., Watts C.W., Christensen B.T., Peltre C., Munkholm L.J. 2019. Relating soil C and organic matter fractions to soil structural stability. *Geoderma*, 337, 834-843
 25. Läuchli A., Grattan S.R. 2007. Plant growth and development under salinity stress. In *Advances in molecular breeding toward drought and salt tolerant crops* (pp. 1-32). Springer, Dordrecht
 26. Mahajan N.C., Mrunalini K., Prasad K.K., Naresh R.K., Sirisha L. 2020. Soil quality indicators, building soil organic matter and microbial derived inputs to soil organic matter under conservation agriculture ecosystem: a review. *Int. J. Curr. Microbiol. App. Sci*, 8(2), 1859-1879
 27. Marzaioli R., D'Ascoli R., De Pascale R.A., Rutigliano F.A. 2010. Soil quality in a Mediterranean area of Southern Italy as related to different land use types. *Applied Soil Ecology*, 44(3), 205-212
 28. Masto R.E., Chhonkar P.K., Singh D., Patra A.K. 2007. Alternative soil quality indices for evaluating the effect of intensive cropping, fertilisation and manuring for 31 years in the semi-arid soils of India. *Environ. Monit. Assess.* 136, 419–435
 29. Maulood P., Darwesh D. 2020. Soil Quality Index Models for Assessing Walnut Orchards in Northern Erbil Province, Iraq. *Polish Journal of Environmental Studies*, 29(2)
 30. Mousavi S.R. 2011. Zinc in crop production and interaction with phosphorus. *Australian Journal of Basic and Applied Sciences*, 5(9), 1503-1509
 31. Murray R.S., Grant C.D. 2007. The impact of irrigation on soil structure. *Land and Water Australia*, 1-31
 32. Nabiollahi K., Taghizadeh-Mehrjardi R., Kerry R., Moradian S. 2017. Assessment of soil quality indices for salt-affected agricultural land in Kurdistan Province, Iran. *Ecological Indicators* 83, 482–494
 33. Naman F., Soudi B., Adlouni C.E., Chiang C.N. 2015. Bilan humique des sols sous intensification agricole: cas des sols du périmètre irrigué des Doukkala au Maroc. Humic balance of soils under intensive farming: the case of soils irrigated perimeter of Doukkala in Morocco. *J. Mater. Environ. Sci.* 6, 3574–3581
 34. Nehrani S.H., Askari M.S., Saadat S., Delavar M.A., Taheri M., Holden N.M. 2020. Quantification of soil quality under semi-arid agriculture in the northwest of Iran. *Ecological Indicators*, 108, 105770
 35. Nikolskii Yu.N., Aidarov I.P., Landeros-Sanchez C., Pchyolkin V.V. 2019. Impact of Long-Term Freshwater Irrigation on Soil Fertility. *Irrigation and Drainage Journal*
 36. Neilsen D., Neilsen G.H., Sinclair A.H., Linehan D.J. 1992. Soil phosphorus status, pH and the manganese nutrition of wheat. *Plant and Soil*, 145(1), 45-50
 37. Karlen D.L., Mausbach M.J., Doran J.W., Cline R.G., Harris R.F., Schuman G.E. 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal*, 61(1), 4-10
 38. Pieri C.J. 2012. Fertility of soils: A future for farming in the West African savannah (Vol. 10). Springer Science & Business Media
 39. Rahoui M., Soudi B., Badraoui M., Marcoen J.M. 2000. Situation actuelle de la qualité des sols et des eaux dans le périmètre irrigué des Doukkala. Séminaire 'Intensification agricole et qualité des sols et des eaux', Rabat, 2-3 Novembre 2000, 13–24
 40. Rodrigo-Comino J., Keshavarzi A., Bagherzadeh A., Brevik E.C. 2019. The use of multivariate statistical analysis and soil quality indices as tools to be included in regional management plans. A case study from the Mashhad Plain, Iran. *Cuadernos de Investigación Geográfica*, 45(2), 687-708
 41. Saidi D. 2012. Importance and role of cation exchange capacity on the physicals properties of the Cheliff saline soils (Algeria). *Procedia Engineering*, 33, 435-449
 42. Sánchez-Navarro A., Gil-Vázquez J.M., Delgado-Iniesta M.J., Marín-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
 43. Serem P.K., Kipkorir E.C., Ng'etich W.K. 2016. Effects of sprinkler irrigation on physical properties of soil and on the yields of green gram. *Journal of Agricultural and Crop Research*, 4(3), 35-42
 44. Shireen F., Nawaz M.A., Chen C., Zhang Q., Zheng Z., Sohail H.,... & Bie Z. 2018. Boron: functions and approaches to enhance its availability in plants for sustainable agriculture. *International Journal of Molecular Sciences*, 19(7), 1856
 45. Sillanpää M. 1982. Micronutrients and the nutrient status of soils: a global study (Vol. 48). Food & Agriculture Org

46. Soudi B., Rahoui M., Chiang C., Abousaleh M.B.A. 2000. Eléments méthodologiques de mise en place d'un système de suivi et de surveillance de la qualité des eaux et des sols dans les périmètres irrigués. Séminaire 'Intensification agricole et qualité des sols et des eaux', Rabat, 2-3 Novembre, 105-120
47. Sudhakaran M., Ramamoorthy D., Savitha V., Balamurugan S. 2018. Assessment of trace elements and its influence on physico-chemical and biological properties in coastal agroecosystem soil, Puducherry region. *Geology, Ecology, and Landscapes*, 2(3), 169-176
48. USDA (United States Department of Agriculture) 2017. Soil survey manual. [In:] Agriculture Handbook No. 18 (soil science division staff., editor). Washington: 1–154
49. 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
50. Vidal B. 2017. Soil quality, properties, and functions in Life Cycle Assessment: an evaluation of models. *J. Clean. Prod.* 140, 502–515
51. Wimmer M.A., Mühling K.H., Läuchli A., Brown P.H., Goldbach H.E. 2003. The interaction between salinity and boron toxicity affects the subcellular distribution of ions and proteins in wheat leaves. *Plant, Cell & Environment*, 26(8), 1267-1274
52. Wyzkowska J., Borowik A., Kucharski M., Kucharski J. 2012. Effect of cadmium, copper and zinc on plants, soil microorganisms and soil enzymes. *Journal of Elementology*, 18(4)
53. Yau S.K., Nachit M.M., Ryan J., Hamblin J. 1995. Phenotypic variation in boron-toxicity tolerance at seedling stage in durum wheat (*Triticum durum*). *Euphytica*, 83(3), 185-191
54. Zengin M., Gökmen F., Gezgin S. 2008. Effects of different fertilizers with potassium and magnesium on the yield and quality of potato. *Asian Journal of Chemistry*, 20(1), 663.