Effects of conservation and standard tillage on soil physico-chemical properties and overall quality in a semi-arid agrosystem

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Abstract

Shifting agricultural operations to more sustainable management practices is needed in the face of a changing climate. In this study, the short-term effects of three tillage systems (no-tillage, minimum tillage, and conventional tillage) on a wide selection of soil properties in a semi-arid agrosystem of eastern Tunisia were assessed. The studied soil properties included saturation percentage, bulk density, penetration resistance, mean weight diameter, electric conductivity, soil reaction, soil organic matter, carbonates, available phosphorus and exchangeable potassium. The impacts of tillage systems on soil quality indices (SQI) developed based on the total set of properties (SQI-T), or a minimum set (SQI-M) selected through principal component analysis, were also investigated. Relative to conventional tillage, no tillage increased bulk density, penetration resistance and electrical conductivity, whereas minimum tillage affected only saturation percentage and pH. No-till and minimum tillage did not enhance soil quality relative to conventional tillage. The SQI-T and SQI-M were highly correlated (r=0.93) to each other suggesting that the outcomes of the two indices are comparable. Principal component analysis efficiently selected the most influential indicators of the effects of tillage systems on soil quality. Farmers in the study region are encouraged to consider minimum tillage during the early years of transition from standard to no-tillage systems to avoid rapid decline in soil quality and consequent yield loss.

Keywords: Soil quality index; Indexing approaches; Conventional tillage; Minimum tillage and No tillage.

Introduction

Conventional intensive agriculture has contributed to feeding people all over the world; however, it has also degraded the quality of environmental and natural resources worldwide (Gomiero 2018; FAO 2019). Borelli et al. (2020) stated that the main agricultural land uses (annual crops, permanent crops, and managed pasture) were estimated to cause more than 50% of the total predicted soil erosion at a global scale, threatening food security and environmental sustainability. Consequently, the sustainability of agricultural production has emerged as an issue of public concern, and soil quality assessment has been suggested as a tool to manage soil resources for eco-friendly future use. The incorporation of soil quality aspects is crucial for a comprehensive assessment of land use impact (De Laurentiis *et al.* 2019).

Soil quality refers to the capacity of a soil to perform a wide range of functions that support ecosystem services, and human health and well-being (Bünemann *et al.* 2018; Corstanje *et al.* 2017). Soil quality is prone to change depending on management (Lal 1993; Delelegn *et al.* 2017) and can be inferred from soil properties (de Obade and Lal 2016a). Wide ranges of properties have been suggested as indicators, and they are often combined into a soil quality index (SQI) to integrate and summarize the data (Andrews et al. 2002a; Armenise *et al.* 2013; Rojas *et al.* 2016). Such SQI facilitates monitoring of changes resulting from soil management over time (Hussain *et al.* 1999; Veum *et al.* 2015).

Several statistical tools have been used to develop soil quality indices. Regression methods such as reduced and partial least squares have been used to synthesize soil physical and chemical properties into a SQI (Masto et al. 2008; de Obade and Lal 2016a). Factorial analysis (Raiesi and Kabiri 2016; Reis et al. 2019), discriminant analysis (Nehrani et al. 2020), and principal component analysis (PCA) (Ghaemi *et al.* 2014; Duval *et al.* 2016) have been employed for the selection of a minimum data set (MDS). The PCA has been shown to be highly effective for this purpose (Bhaduri and Purakayastha 2014; Martínez *et al.* 2020). Tillage as a fundamental management practice in agricultural production systems has long been known to impact soil physical, chemical and biological properties as well as the overall quality (Mrabet *et al.* 2001; Busari *et al.* 2015; Hammac *et al.* 2016; Raiesi and Kabiri 2016). Soil quality indexing approaches have been used to evaluate these impacts, e.g. they explain complex changes in response to different tillage practices (Hussain et al. 1999; Mei et al. (2019), and were useful in identifying the long-term effects of tillage practices on soil quality (Aziz et al. 2013; Swanepoel et al. 2015).

Farmers and decision makers need concise, easily understood information on the impacts of tillage systems on soil quality. In this context, soil quality indexing approaches have proven to be efficient; however, these aspects are rarely addressed in Tunisian cropping systems. Consequently, the objectives of this study are to assess the impact of conservation versus conventional tillage systems on various soil physical and chemical characteristics and to use these to develop soil quality indices based on two different indexing approaches.

Materials and methods

Study site and soil sampling

The study was carried out at the experimental station of the Technical Center of Organic Farming (TCOF) located in Sousse region, Eastern Tunisia (35°55’12.82”N; 10°34’00.51’’E). The climate is Mediterranean, semi-arid, with mean annual air temperature of about 17.5°C and with mean annual precipitation of 400 mm, most of which is received during winter Amami et al (2021). The soil is classified as Fluvisol (IUSS Working Group

WRB 2015). It is slightly alkaline with a sandy clay loam texture (67% sand, 7% silt and 26% clay) at the surface layer (0-10 cm) The sand fraction is a mixture of fine, medium and coarse sand. Prior to performing the tillage treatments, the soil was characterized by a BD of 1.69 g cm-3, water content of 13.27%, a total porosity of 32.8%, SOM of 2.01%, EC of 0.98 dS m-1 and a pH of 7.54.

The study site was certified organic in 2001 and was since used for growing rotated vegetable crops. Soil preparation was performed by primary and secondary tillage operations using moldboard plow and harrows, respectively. The field trials were set up according to a randomized complete block design with 9 plots and 3 replications for each tillage treatment system. The experimental plots were 25 m long and 4 m wide each (100 m^2) and were separated by 2 m wide buffer zones. The experiment was initiated on 15 January 2019 with three tillage treatments: i) conventional tillage (CT) to ~36 cm by a moldboard plow (2 passes); ii) minimum tillage (MT) to ~14 cm by a tine cultivator (2 passes); and iii) no tillage (NT). On 21st January 2019, all plots were sown with winter faba bean (Vicia faba L.). During the four months growing period of faba bean crop, two to three irrigation events were applied per week. No fertilizers were applied. On 4 May 2019, tillage treatments were again performed and faba bean residues were buried under CT and MT. Under NT treatment, residues were left on soil surface. Since this date (i.e. 4th May) no crops were grown on the study site. Tillage treatments were repeated on 2nd August and 16th November 2019 on bare soils.

Within each plot, samples of disturbed soil were collected at three locations from the surface layer (0–10cm) to form composite samples. In addition, two undisturbed soil samples were collected per plot using cylindrical cores on 22nd November 2019. In total, 9 composite disturbed samples and 18 undisturbed samples were collected and prepared for physical and chemical analysis.

Soil analyses

The saturation percentage (SP) was determined by the saturation paste method (Richards 1954). The soil paste was prepared by adding distilled water to a 200 g air-dried and sieved (<2 mm) soil sample until complete saturation. SP was calculated as follows:

$$SP = \frac{Mw}{Ms} \times 100 \quad (1)$$

where M_w is the mass of added water, Ms is the mass of oven-dried soil. Bulk density (BD) was measured at 0–5 cm by the core method using 100 cm^3 cylinders (Blake and Hartge 1986). The penetration resistance (PR) was measured to 30 cm depth at two points per subplot using a hand pushed electronic penetrometer with a conical point of 1 cm^2, a point angle of 60° and a drive shaft 80 cm long (Eijkelkamp Penetrologger 06.15.SA). Measurements were automatically recorded every 1 cm. The PR values of the surface layer (0–5 cm) were computed as weighted depth averages. Water-stable aggregates were estimated using the fast-wetting test (Le Bissonnais 1996) as described in Ibrahimi et al. (2019). The mean weight diameter (MWD) of water-stable aggregates was computed by totaling the products of aggregate fraction weight and mean diameter of aggregate classes as follows:

$$MWD = \sum_{i=1}^{n} w_i \, x_i \quad (2)$$

Where, w_i is the aggregate fraction on sieve i relative to the total sample weight and x_i is the mean diameter of the soil aggregate size fractions retained on sieve i.

The soil-saturated paste was vacuum filtered and the electrical conductivity (EC) was measured in the collected extract (Rhoades et al. 1999). The organic carbon (SOC) content was determined by dichromate oxidation (Pansu and Gautheyrou 2006) and organic matter (SOM) content was calculated as SOM = 1.72 * SOC. The pH was measured in a 1:2.5 soil/water suspension, available phosphorus (P) was extracted in 0.5 M sodium bicarbonate pH 8.5 (Olsen 1954) and exchangeable potassium (K) was extracted by pH 7, 1 M ammonium acetate (Jones 1999). The volume of carbon dioxide released by excess hydrochloric acid (Pansu and Gautheyrou 2006) determined the carbonate content ($CaCO_3$).

Soil quality indexing

Two approaches were used to develop soil quality indices. The first approach was based on the total data set, i.e., using all measured soil attributes to derive the SQI (SQI-T) (Fig. 1). The same procedure was repeated to develop soil quality indices based only on either physical (SQI-P) or chemical attributes (SQI-C). The second approach was based on a minimum data set to derive the SQI (SQI-M) (Fig. 1). Following this approach, the ten measured physico-chemical indicators were subjected to PCA as a dimension reduction method. The selection of components was based on the Kaiser criterion and the Scree plot, which displays the cumulative variance explained by each principal component (PC) (Armenise *et al.* 2013). Thus, PCs with eigenvalues > 1 and which are above the inflection point in the Scree plot were retained. Soil variables with the highest loadings under each PC were chosen. When more than one indicator was retained under a single PC, correlation analysis was used to check for redundancy.

In both approaches (i.e. SQI-T and SQI-M) the selected indicators were normalized through scoring functions. These functions are characterized, as "*more is better*" (M, Eq.1), "*less is better*" (L, Eq.2) and "*optimum*" (O, Eq.3) and were computed as follows:

$$M(x) = \begin{cases} 0,1 & x < x_1 \\ 0,9 \times \dfrac{x - x_1}{x_2 - x_1} + 0,1 & x_1 < x < x_2 \\ 1 & x > x_2 \end{cases} \quad (1)$$

$$L(x) = \begin{cases} 1 & x < x_1 \\ 1 - 0,9 \times \dfrac{x - x_1}{x_2 - x_1} & x_1 < x < x_2 \\ 0,1 & x > x_2 \end{cases} \quad (2)$$

$$O(x) = \begin{cases} 0,1 & x < x_1 \\ 0,9 \times \dfrac{x - x_1}{r_1 - x_1} + 0,1 & x_1 < x < r_1 \\ 1 & r_1 < x < r_2 \\ 1 - 0,9 \times \dfrac{x - r_2}{x_2 - r_2} & r_2 < x < x_2 \\ 0,1 & x > x_2 \end{cases} \quad (3)$$

where, x is the measured soil property value, x_1 and x_2 are the lower and the upper threshold values, respectively. Likewise, r_1 and r_2 are the lower and the upper values of the optimal range, respectively.

The upper, lower and optimum threshold values for the studied soil attributes were retrieved from literature (Table 1), which is common practice in the absence of site-specific values (Masto et al. 2008; Armenise et al. 2013; Sağlam et al. 2015; de Obade and Lal 2016a).

The SQI was calculated by integrating indicator scores by an additive approach (Eq. 4) for the SQI-T, SQI-P and SQI-C and a weighted additive approach (Eq. 5) for the SQI-M.

$$SQI - T = \sum_{i=1}^{n} \frac{S_i}{n} \quad (4)$$

$$SQI - M = \sum_{i=1}^{n} W_i \, S_i \quad (5)$$

where S_i is the score attributed to each indicator, n is the total number of indicators included in the TDS or the MDS and W_i is the weight of the variables derived from the PCA.

Statistical analysis

For each indicator and SQI, a one-way ANOVA followed by the Duncan test was used to characterize significant differences among tillage treatments at $P < 0.05$. Before performing the parametric statistical analysis, normality and homogeneity of variance of the data were checked by the Shapiro-Wilk and Levene tests, respectively. A standardized PCA of all data was performed by using the *prcomp* package. Pearson correlation coefficients among soil quality indicators and indices were calculated using all soil samples from the different tillage treatments. All statistical analyses were carried out using R (R Core Team 2017).

Results and discussion

Responses of soil physical quality indicators to tillage management

Except for MWD, conservation tillage systems induced significant ($P< 0.05$) changes in all studied physical attributes as compared to conventional tillage (Fig. 2). These findings conform to other similar studies which have shown that conventional, reduced and no-tillage systems altered soil physical attributes in the short-term (~~Chen et al. 2005~~; Salem et al. 2015). The SP values of the studied soil under all tillage treatments ranged between 36 and 42% corresponding to the SP range (20% < SP < 45%) for coarse soils (Kargas et al. 2018). The differences between SP under CT and NT and under MT and NT were not significant (P>0.05) suggesting that tillage operations had no effect on SP compared to NT treatment. These findings are reasonable given that the soil used in our study has the same texture and no significant difference in SOM was found between these tillage treatments, because SP depends mostly on the SOM content (Mbagwu and Okafor 1995) and texture type (Slavich and Petterson 1993). The comparison between MT and CT in terms of their effects on SP revealed that this soil parameter was 14.9% significantly lower (P<0.05) under MT than CT system. Extended investigation is needed to elucidate the mechanisms behind these observations.

There were significant higher BD (1,693g/cm^3) and PR (0.951daN/cm^2) values under NT compared to CT and MT treatments (Fig. 2). The increase in PR under NT compared to CT system was 149%. The increase in BD under NT compared to CT system was 16.4%. Thus, from a physical quality indicator perspective, both BD and PR indicate that NT had a negative effect in comparison to CT, and PR and BD are important, dynamic physical indicators prone to change due to tillage management (Swanepoel et al. 2015). An intensive meta-analysis by Li et al. (2020) found that, relative to CT, NT increased soil BD and PR within various agro-ecosystems. Mosaddeghi et al. (2009) reported similar short-term outcomes for a sandy loam soil, and for two and five year's studies by Khorami et al. (2018) and Lopez-Garrido et al. (2014), respectively. The lack of a significant differences in BD and PR ($P<0.05$) between MT and CT systems for the 0–5 cm layer in our study suggests that minimum tillage by using a tine cultivator could be an interesting management option to alleviate soil compaction.

The MWD values under all tillage treatments did not exceed 0.3 mm, suggesting a high aggregate instability (Le Bissonnais 1996). Though the MWD under NT was slightly higher than CT (12%) and MT (14%) treatments the difference was not significant (P<0.05) (Fig. 2). Kong et al. (2009) and Laudicina et al. (2017) reported similar findings after one year, and Raiesi and Kabiri (2016) reported that soil MWD was less sensitive to tillage practices than other physical properties. A global meta-analysis on soil physical properties under conservation tillage showed that the effect size of MWD increased with increasing duration of NT (Li et al. 2019). Similarly, based on a global data set, Li et al. (2020) reported an improvement of MWD under NT systems regardless of environmental and agricultural factors.

Responses of soil chemical quality indicators to tillage management

In comparison to CT (1,28 mmho /cm), NT (0,98 mmhoq; /cm) caused a 23.1% decrease in EC (P<0.05) (Fig. 3); nonetheless, the EC under all treatments was < 1.5 dS m^{-1} indicating that salinity was not a problem at the site. The higher EC under CT is most likely due to soil mixing during the tillage process. Greater leaching of salt under NT is unlikely. Water infiltration measurements carried out at the same site showed higher infiltration under CT and MT than NT (Amami et al., 2021). Qingjie et al. (2014) also reported a significant decrease in EC under NT relative to conventional tillage with plowing. In contrast, Marnez et al. (2013) reported higher EC under NT in the top 2 cm soil depth, but no significant differences for 2–5 cm or 5–15 cm. In our study, soil pH under MT (7.59) increased significantly by 1.24% relative to the CT (7.49) treatment (Fig. 3). Asenso et al. (2018) reported a similar result after one and two years. In contrast, Raiesi and Kabiri (2016) found that pH tended to decline over time in response to tillage and Sharma et al. (2014) found that the tillage practices had no significant effect on soil pH. In general, different tillage practices appear to cause little difference in soil pH (Li et al. 2019). As for CaCO3 content, no significant differences were observed between CT and MT and between CT and NT treatments. A significant increase of CaCO3 content was observed under MT compared to NT. Knowing that the CaCO3 content of this soil, before starting the experiment, was around 3%, it seems that MT reduced the loss of CaCO3 compared to NT and CT. Similar findings were reported by Murillo et al. (2004) who found that minimum vertical tillage and disc harrowing decreased the loss of CaCO3 at the soil surface compared to traditional tillage by moldboard plow. Carbonate content has been reported to be affected under both CT and NT (Neugschwandtner et al., 2014; Ye et al., 2020). Tillage affects CaCO3 content through the induced changes in the soil water regime, enhanced leaching and by bringing, carbonate particles to the surface layer of the soil profile (Murillo et al., 2004; de Soto et al., 2017; Ye et al., 2020). In our study area, long-term investigations are needed to elucidate the mechanisms behind changes in CaCO3 content under tillage and no-till regimes taking into account other factors related to cultivation practices (fertilization, irrigation, …) and local geochemical conditions.

The SOM contents were 2.01, 1.63 and 1.56% under NT, MT and CT (Fig. 3); however, the differences were not statistically significant ($P>0.05$). Similar results were found by Asenso et al. (2018), Sağlam et al. (2015), Raiesi and Kabiri (2016), and Laudicina et al. (2017); however, after three and five years, the latter authors reported significant higher SOM under NT compared to MT (field cultivator) treatments. Tillage systems with minimum soil disturbance are generally reported to increase SOM content relative to conventional tillage (Lopez-Garrido et al. 2014; Khorami et al. 2018), and in most cases, the effect requires 5–10 y to be expressed (Lopez-Garrido et al. 2014; Qingjie et al. 2014). One possible explanation of these observations is that CT promotes residue decomposition through the mineralization process (rapid) which outweighs humification (slow) leading to rapid SOM loss.

Soil quality indices

The PCA analysis revealed that the three first PCs (PC1, PC2 and PC3) had eigenvalues > 1 and explained 81% of the total variability (Table 2). In the Scree plot, these three components are in the steep curve before the first point corresponding to the flattened part. Therefore, PC1, PC2 and PC3 were retained for further analysis. The PC1 with an eigenvalue of 4.33 explained 43% of the variance and for this component EC, SOM, BD and PR had the highest weights (Table 2). The PC2 had an eigenvalue of 2.67 and explained 27% of the variance, and for this component, SP and pH had the highest factor loadings (Table 2). PC3 explained 11% of the variance and had an eigenvalue of 1.1, and the variable, K, had the highest factor loading of 0.56 (Table 2). The highly weighted factors under each PC were subjected to correlation analysis to reduce redundancy.

Considering the variables under PC1 (i.e. EC, SOM, BD and PR), the results of the multivariate correlation analysis revealed high significant correlations between EC and PR ($r = -0.81$, $P = 0.01$) and between BD and PR ($r = 0.73$, $P = 0.05$) (Table 3). Given the fact that PR had lower factor loading than EC and BD it was not considered for the MDS. As for SOM, since it is considered as a keystone soil quality indicator and its crucial role in regulating many soil functions (e.g. Singh et al. 2014), this soil attribute was retained for the MDS although it was well correlated with BD and had lower loading. The SP and pH variables retained under PC2 were highly correlated ($r = 0.83$, $P = 0.01$) (Table 3). Since pH had lower factor loading than SP, it was eliminated from the MDS. Finally, the variables EC, SOM, BD, K and SP were retained for the MDS. With the exception of SP, the other retained variables were frequently included in the MDS in many previous studies

(Swanepoel et al. 2015; Sharma et al. 2014; Bhaduri and Purakayastha 2014; de Obade and Lal 2016b). The SP variable that was often not considered by previous soil quality related research seems to be an interesting indicator of soil quality in our study area. The retained variables are assumed indicators that best represent tillage-induced changes in soil quality under our experimental conditions. These indicators had different weights in the final MDS index and were ranked in decreasing order as follows: EC>BD = SOM> SP > K.

Among the 10 indicators forming the TDS, the pH, K and PR greatly influenced the SQI-T under all tillage treatments (Fig. 4). These attributes contributed to the SQI-T by 16.3, 15.4 and 14.9%, respectively. As for the SQI-M, EC had the highest contribution (42.5%) followed by SP (21.1%) (Fig.4).These two soil attributes are therefore the most powerful indicators compared to the rest of the MDS. Conversely, the parameters having the lowest contributions to SQI are considered as limiting factors. The comparison of indicator contributions to SQIs between the different treatments revealed that BD is one of the most limiting parameters for soil quality under NT in the study area (Fig. 4).

Plotting the SQI-M values against SQI-T revealed that the two indices were positively correlated (r = 0.93, P = 0.001), suggesting that the approaches yield similarly useful indices at our study site (Table 4). Moreover, both SQI-T and SQI-M are highly correlated to SQI-P, but show no correlation with SQI-C (Table 4). This therefore suggests that under the study conditions, soil quality expressed by either SQI-T or SQI-M was mainly influenced by the soil physical attributes.

SQI rating across tillage management systems

The computed SQI-T based on all measured attributes was 0.59, 0.60 and 0.64 under NT, MT and CT treatments, respectively, indicating the medium soil quality of the study site. The differences in SQI-T between NT, MT and CT systems were non-significant (Fig. 5). That is, on our short-term time scale, NT could not be preferred to CT as a sustainable management system. This finding agrees with numerous previous studies, which show that NT needs time to have significant impacts on soil quality (Sağlam et al. 2015; Hammac et al. 2016; Reis et al. 2019; Li et al. 2019; Li et al. 2020).

In order to give an insight into the contribution of the physical and chemical indicators separately to the overall soil quality, the SQI-T was segregated into its physical and chemical components, which were compared under all tillage treatments (Fig.5). This showed significant higher SQI-P under CT compared to the MT and NT systems (Fig. 5). However, the SQI-C was non-significant indicating that the integrated chemical indicators did not vary between tillage treatments (Fig. 5). Thus, it appears that under our study conditions the variation in soil quality across tillage systems was mostly due to the physical attributes. The results showed also that no significant differences were found between MT and NT systems for both the SQI-P and SQI-C indices (Fig. 5). Similarly, Swanepoel et al. (2015) found that tillage did not affect the soil chemical quality and concluded that the differences in soil quality between tillage practices were mostly due to soil physical and biological quality. Lopez-Garrido et al. (2014) showed for a Xerofluvent soil that five years of NT greatly worsened physical soil conditions despite the concomitant chemical improvements.

Overall, considering the outcomes of SQI-T and its components, SQI-P and SQI-C, it seems that the lower physical quality of the soil under NT was counter acted by greater chemical quality derived from this system (less EC, higher SOM content). These findings show the importance of considering physical attributes (such us BD and PR) in assessing soil quality in the study region.

Significant higher SQI-M (P<0.05) was found under CT compared to both MT and NT (Fig. 6). The latter two treatments did not significantly differ (P>0.05) from each other (Fig. 6). The lowest SQI-M rating under NT can be explained by its higher BD which is a "less is better" scored attribute and considered as a powerful indicator of the studied soil quality. Compared to SQI-T, SQI-M better discriminated among the tillage treatments. The SQI-M was computed based on the most sensitive indicators to tillage treatments while SQI-T included all (sensitive and non-sensitive) attributes. Therefore, SQI-M is more suitable for the assessment of soil quality in our study area. This finding is consistent with an earlier study by Chen et al. (2013) who reported that an SQI based on TDS (20 indicators) showed less sensitivity and worse correlation with soybean grain yield than an MDS (8 indicators) based SQI.

Lastly, in our hands, the approach based on PCA was superior to that based on TDS when developing SQIs, which corroborates the results of numerous previous studies (Andrews et al. 2002b; Masto et al. 2008; Duval et al. 2016). Moreover, it is intuitively reasonable that SQI based on selection of soil attributes that have the dominant influence on soil functions should be more efficient and useful than a complex set of indicators that include less influential properties (Singh et al. 2014; Yao et al. 2014).

Conclusion

The short term findings indicate that, compared to CT after one year of application, NT and/or MT tillage treatments affected the soil physico-chemical attributes, SP, BD, PR, EC and pH. These soil attributes were the most sensitive indicators and could provide early warning of soil quality degradation in the study area. Additionally, the two developed SQIs (SQI-T and SQI-M) showed that conservation tillage resulted in a similar or slightly lower soil quality in comparison to CT. The PCA derived SQI, i.e. SQI-M, was more sensitive than SQI-T and therefore more appropriate for evaluating tillage management practices in the study area. The better performance of MT over NT in terms of alleviation of soil compaction, and the high degree of similarity of soil quality between the two systems as shown by SQI-T and SQI-M, lead us to suggest that a good strategy for farmers in the study area would be to use minimum tillage to full adoption of no-tillage soil management.

Conflicts of Interest

The authors declare no conflicts of interest

Declaration of Funding

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Data Availability Statement

The data used to generate the results in the paper are not available now

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Table 1. Applications, linear scoring functions and threshold values for the studied soil quality indicators

Indicator	Application	Scoring functions	x_1*	x_2*	Source**
SP (%)	Indicates soil texture, water-holding capacity and cation exchange capacity	O	30	60	This study
BD (g cm^{-3})	Indicates compaction and porosity	L	1.3	1.8	Prasad et al (2017)
PR (dNa cm^{-2})	Measure of soil physical resistance or compaction	L	0.2	4	Mukherjee and Lal (2014)
MWD (mm)	Indicates aggregate stability	M	0.4	2	Le Bissonnais (1996)
EC (dS m^{-1})	Indicates soil salinity level	L	0.2	4	Prasad et al (2017)

pH	Indicates soil acidity/alkalinity level and affects macro- and micro-nutrient availability	O	5.5	8.5	Prasad et al (2017)
SOM (%)	Reflects nutrient reserve and cycling, structure stabilization and convenient biological environment	M	1	4	Moebius-Clune et al (2016)
$CaCO_3$ (%)	Indicates nutrient availability (especially phosphorus) and affects soil pH and the exchange complex	L	0.5	10	Rowell (2014)
P (g kg^{-1})	Indicates available phosphorus content for plant growth	M	7.5	150	Mausbach and Seybold (1998)
K (g kg^{-1})	Indicates exchangeable potassium content for vigorous plant growth	M	45	525	Mausbach and Seybold (1998)

* x_1, x_2: lower and upper values of indicators, respectively; ** references for threshold limits. SP: saturation percentage, BD: bulk density, PR: penetration resistance, MWD: mean weight diameter, EC: electric conductivity, pH: soil reaction, SOM: soil organic matter, $CaCO_3$: carbonates, P: available phosphorus, K: exchangeable potassium.

Table 2. Principal component analysis of soil quality parameters as influenced by different tillage management

Components	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**

Eigenvalues	4.33	2.67	1.10	0.82	0.57
Variance (%)	43	27	11	8	6
Cumulative variance (%)	43	70	81	89	95
Eigenvectors					
SP	-0.143	**0.574**	0.055	-0.002	0.126
EC	**-0.397**	0.051	0.437	0.159	0.128
pH	0.010	**-0.542**	-0.290	-0.055	0.424
SOM	**0.382**	-0.070	0.420	-0.122	0.417
$CaCO_3$	-0.259	-0.439	-0.070	-0.037	-0.428
P	0.368	0.084	0.038	0.493	-0.517
K	0.205	-0.385	**0.562**	0.034	-0.170
BD	**0.420**	0.026	0.018	0.402	0.254
PR	**0.392**	0.041	-0.450	-0.054	-0.007
MWD	0.318	0.133	0.143	-0.740	-0.266

Bold face factor loadings were considered highly weighted and underlined were retained in MDS. SP: saturation percentage, BD: bulk density, PR: penetration resistance, MWD: mean weight diameter, EC: electric conductivity, pH: soil reaction, SOM: soil organic matter, $CaCO_3$: carbonates, P: available phosphorus, K: exchangeable potassium.

Table 3. Correlation between measured physico-chemical soil quality indicators based on all soil samples

	SP	**EC**	**pH**	**SOM**	**$CaCO_3$**	**P**	**K**	**BD**	**PR**	**MWD**
SP	1									
EC	0.35	1								

pH	-0.83**	-0.23	1							
SOM	-0.31	-0.42	0.09	1						
$CaCO_3$	-0.53	0.37	0.51	-0.45	1					
P	-0.16	-0.59	-0.25	0.46	-0.43	1				
K	-0.68*	-0.16	0.34	0.58	0.20	0.29	1			
BD	-0.17	-0.62	-0.01	0.70*	-0.52	0.72*	0.36	1		
PR	-0.20	-0.81**	0.07	0.44	-0.39	0.56	0.03	0.73*	1	
MWD	0.00	-0.57	-0.26	0.58	-0.43	0.32	0.23	0.31	0.52	1

SP: saturation percentage, EC: electric conductivity, pH: soil reaction, SOM: soil organic matter, $CaCO_3$: carbonates, P: available phosphorus, K: exchangeable potassium, BD: bulk density, PR: penetration resistance, MWD: mean weight diameter.

* Significant at the *P*=0.05 level; ** Significant at the *P*=0.01 level

Table 4. Pearson's correlation matrix for the different calculated soil quality indices. The SQIs were computed based on total data set (SQI-T), minimum data set (SQI-M), physical indicators (SQI-P) and chemical indicators (SQI-C)

	SQI-T	**SQI-M**	**SQI-P**	**SQI-C**
SQI-T	1			
SQI-M	0.93***	1		
SQI-P	-0.86**	0.89**	1	
SQI-C	-0.22	-0.38	-0.69*	1

* Significant at the *p*=0.05 level; ** Significant at the *p*=0.01 level; *** Significant at the *p*=0.001 level

Fig. 1. Schematic of the quality indexing procedure. Physical indicators: SP: saturation percentage, BD: bulk density, PR: penetration resistance, MWD: mean weight diameter. Chemical indicators: EC, pH, SOM, carbonates as $CaCO_3$, available P, exchangeable K. Soil

quality indices: SQI-T: soil quality index based on total data set; SQI-P: soil quality index based on physical attributes; and SQI-C: soil quality index based on chemical attributes.

Fig. 2. Effects of tillage treatments on soil physical properties. CT: conventional tillage, MT: minimum tillage, NT: no-tillage. The bars represent standard deviations. Different letters 5

Fig. 3. Effects of tillage treatments on soil chemical properties. CT: conventional tillage, MT: minimum tillage, NT: no-tillage. The bars represent standard deviations. Different letters between treatments indicate significant differences ($P< 0.05$).

Fig. 4. Relative contribution of the physico-chemical indicators in forming the soil quality indices. (A): contribution (%) to SQI-T; (B): contribution (%) to SQI-M.

Fig. 5. Effects of tillage treatments on soil quality. (A): soil quality index based on total data set (SQI-T); (B): soil quality index based on physical attributes (SQI-P); (A): soil quality index based on chemical attributes (SQI-C). CT: conventional tillage; MT: minimum tillage; NT: no-tillage; Different letters indicate significant differences ($P<0.05$) among tillage treatments; NS: non-significant at $P<0.05$; Error bars indicate standard deviation.

Fig. 6. Effects of tillage treatments on soil quality based on soil quality index derived from minimum data set (SQI-M). CT: conventional tillage; MT: minimum tillage; NT: no-tillage; Different letters indicate significant differences ($P<0.05$) among tillage treatments; Error bars indicate standard deviation.