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EFFECTS OF CROP RESIDUES AND TILLAGE OPERATIONS ON SOIL QUALITY INDICES

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Abstract. Tillage and plant residues influence soil attributes and, consequently, soil quality. Therefore, suitable management and maintaining the stability of soil structure is important. This study was performed to evaluate the effects of tillage systems on soil quality during a 4-year crop rotation (wheat, canola, wheat and tomato) at the Agricultural Research Center of Khorasan Razavi province (Iran) from 2011 to 2015. The study was conducted as a randomized complete block design in a factorial arrangement with 3 replications. For this purpose, conventional tillage (CT), minimum tillage (MT) and no-tillage (NT) systems together with three rates of plant residues (0, 1,500, and 3,000 kg ha^{-1}) were applied annually after harvesting. Soil quality was determined by using the integrated quality index (IQI) and Nemoro quality index (NQI) based on total data set (TDS) and minimum data set (MDS). In total, 23 physical, chemical, and biological soil characteristics were considered as TDS and 7 out of these were selected as MDS for use in the principal component analysis (PCA). Soil quality in different tillage treatments was determined and the most appropriate indices and effective characteristics for soil quality assessment were selected. Correlation coefficients between IQI_{TDS} and IQI_{MDS} (r = 0.69) and between NQI_{TDS} and NQI_{MDS} (r = 0.76) showed that NQI was a better indicator for assessing soil quality. The NQI_{TDS} provided a more accurate and comprehensive assessment of soil quality. However, using MDS reduced the cost and time with proper precision. Soil quality in MT and NT treatments was more desirable than the CT system, and the addition of plant residues improved the soil quality. According to the results of NQI_{TDS}, IQI_{TDS}, and IQI_{MDS}, soil quality in the NT system with 3,000 kg ha^{-1} of plant residues and the MT system with 1,500 and 3,000 kg ha^{-1} of plant residues were more favorable than other soil tillage treatments. Soil characteristics that decreased soil quality in the conven-

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tional tillage were soil structure, macro and micronutrients, while in conservation tillage it was micronutrients, especially Zn.

Keywords: crop residues, conservation tillage, conventional tillage, soil quality

INTRODUCTION

Soil quality may be influenced by agricultural practices, especially tillage. Therefore, proper management and maintaining the stability of the soil structure is important. Using incorrect management practices can reduce soil quality through erosion, pollution and physical degradation (Amiri *et al*. 2017). Soil tillage leads to a change in agricultural sustainability and soil quality through changing the soil characteristics (Andrews *et al*. 2002). Generally, conventional and conservation tillage practices are used in agricultural lands. In conventional tillage, plowing and cultivating practices eliminate all plant residues and prevent the growth of all plants except the main crop (Aparicio and Costa 2007). In the conservation tillage method, at least 1,500 kg ha^{-1} of the field surface is covered with plant residues (Black and Hartege 1986).

Soil cultivation creates suitable conditions for the growth and development of plant roots (Andrews *et al*. 2002). On the other hand, soil degradation adversely affects soil quality through erosion and changes its physical, chemical and biological properties. Soil tillage has short- and long-term effects on soil quality. The quantity and quality of plants can also be influenced by various soil tillage systems. Soil quality has been defined as the capacity of a given soil for production in an ecosystem and land use to maintain biological fertility, to improve environmental quality and to help plant and animal health (Bremner and Mulvaney 1982). Soil quality assessment is necessary for sustainable soil management. The main aspect of soil quality assessment is usually based on the cumulative assessment of soil characteristics (Castro *et al*. 1998, Chen *et al*. 2013, Dexter 2004, Doran and Jones 1996, Doran and Parkin 1994). Human activities affect soil quality indicators over time, therefore, these changes depend on the type of soil management operations (Eltiti 1999). Soil properties that affect soil quality are a set of physical, chemical, and biological characteristics, or a combination of them (Gee and Bauder 1986).

The soil quality index has been determined based on the total data set (TDS) of soil characteristics and minimum data set (MDS) (Ghaemi 2014, Gholoubi 2018, Govaerts *et al*. 2006, Gugino *et al*. 2009, Ranjbar *et al*. 2016). These characteristics should be responsive, flexible, easily measurable and related to management operations and environmental changes (Jarecki and Lal 2003, Karlen 1998). Principal component analysis (PCA) is the most common method for identifying and determining the MDS that affects soil quality and reduces repetitive information in the initial data set (Kemper and Rosenau 1986). Various models such as integrated quality index (IQI) and Nemoro quality index (NQI) have been introduced to calculate the soil quality index (Lal *et al*. 1990).

Weights of TDS and MDS indicators, which were used for determination of IQI and NQI indices were assigned by the communality of each soil property, which were calculated by statistical standardized factor analysis. The ratio of indicator communality to accumulative communality of total indicators for individual TDS and MDS were considered as the weighting of each property. The communality and factor analysis of each indicator were calculated by Jump 8 Software.

Evaluating the various soil management effects, such as different soil tillage systems on soil quality, can be made through several physical, chemical and biological considerations. Some studies indicated that in the short term there was no significant difference between conventional and conservation tillage in soil quality (Lindsay Norvell 1978), while other studies showed that conservation tillage, such as chisel plow and no-tillage improved soil physical indicators more than the conventional tillage (Andrews *et al*. 2002). The effect of management practices such as tillage and plant residues on soil quality especially in arid regions of Iran has not been studied. Therefore, this study aimed to evaluate the effects of conventional and conservation tillage (minimum and no-tillage) systems together with plant residues during a 4-year rotation on soil quality indices, including the IQI and NQI.

MATERIALS AND METHODS

Study area

The study area is located at the Agricultural and Natural Resources Research Center of Khorasan-Razavi (Iran). The latitude and longitude are 59°37'E and 36°12'N, respectively, with a total area of 220 ha. The average altitude of this site is 1,010 m, the mean of annual rainfall and temperature is 260 mm and 13.5°C, respectively. The physiographic unit of this station is a low slope (less than 10%) alluvial plain and its soil is classified into two orders of Entisols and Aridisols (Lyu Chen 2016).

Experimental layout

The experiment was conducted as a randomized complete block design in a factorial arrangement with 3 replications during 2011–2015. Experimental treatments consisted of the following different soil tillage systems: 1) conventional tillage, CT (plowing + disc + leveling + furrowing + seed cultivation), 2) minimum tillage, MT (disc + furrowing + seed cultivation) and 3) no-tillage, NT (seed cultivation) that were considered as the first factor; and three management practices of plant residues: 1) without residues (control, 0%), 2) retaining 1,500 kg ha^{-1} (30%), and 3) retaining 3,000 kg ha^{-1} (60 %) of residues as a the second factor. In total, we had nine treatments. Plant residues were applied on the soil surface after harvesting them in September every year in plots of size 2 × 4 m. In no-tillage system, a disk or cyclotiller was used and seed cultivation were carried out at a single stage. In the conventional system, soil tillage was carried out by moldboard plough. Crop rotation was wheat-canola-wheat-tomato. Wheat is a predominant plant that is cultivated annually in this area. Tomato and canola are also cultivated, therefore, these crops were included in the rotation.

Sampling and analysis

At the end of the rotation, in October 2015, soil samples were taken from the center of plats at 0–30 cm depth. For chemical analysis, soil samples were air-dried and passed through a 2-mm sieve. In addition, undisturbed samples were obtained to determine the structure and moisture characteristics (by pressure plates). A set of 23 physical, chemical and biological characteristics (Table 1) affecting soil quality were measured based on standard methods. Chemical parameters such as pH and electrical conductivity (EC) were measured using pH meter and EC-meter, respectively (Maynard *et al*. 2007). Soil organic carbon was determined by wet digestion (Olsen 1954), available phosphorus – by sodium bicarbonate extraction and Spectrophotometer apparatus at a wavelength of 660 nm (Page 1982), available potassium – by ammonium acetate extraction and flame-photometer (Pieri 1992), total nitrogen – by the Kjeldahl method (Pieri 1992), micronutrients (Fe, Mn, Zn, and Cu) – by DTPA extraction (Qi *et al*. 2009), active carbon – by potassium permanganate oxidation (Qin and Zhao 2000). Sodium adsorption ratio (SAR) was calculated based on the amount of soluble sodium (Na^+), total calcium and magnesium in the saturated extract (Maynard *et al*. 2007). Basal respiration was determined according to the method of Vance *et al*. (1987). Soil texture was determined by the hydrometer method (Reynolds *et al*. 2009), mean weight diameter of aggregates (MWD) – by wet sieve method (Reynolds and Topp 2008), whereas the percentage of aggregates larger than 2 mm (WSA) (Seybold *et al*. 2001) and the soil structure stability index (SI) (Shahab *et al*. 2013) was calculated based on Equation (1).

$$\mathrm{SI} = \frac{1.72OC}{(Silt+Clay)} \times 100 \quad (1)$$

Aggregate sustainability index (AS) was calculated based on Equation 2 (Shahab *et al*. 2018).

$$\mathrm{AS} = \frac{(M_{soil} - wp25 - M_{sand})}{(M_{soil} - M_{sand})} \times 100 \quad (2)$$

where M_{soil} is the dry weight of the soil, *wp25* is the weight of the aggregates smaller than 0.25 mm, and M_{sand} is the weight of particle between 2 and 0.05 mm.

Bulk density (Sharma 1996), macroporosity (AC) were determined by subtracting the saturated water content from moisture content at pressure head 1 KP (Shukla *et al*. 2006), plant available water (PAW) – by subtracting the moisture content at pressure heads 33 and 1,500 kPa, relative field capacity (RFC) – by dividing the moisture content at pressure 33 kPa (θ_{FC}) to saturated moisture content (Sun *et al*. 2003) (Equation 3) and S_{gi} index (slope of water retention curve at inflection point) – based on Dexter's (Torbert *et al*. 2008) formula (Equation 4).

$$RFC = \frac{\theta FC}{\theta s} \tag{3}$$

$$S_{gi} = \frac{d(\theta gi)}{d(\ln hi)} = \left| -n(\theta_{gs} - \theta_{gr}) \left[1 + \frac{1}{m}\right]^{-(m+1)} \right| \quad m = 1\text{-}(1/n) \tag{4}$$

where θ_{gs} and θ_{gr} are gravimetric saturated and residue soil water contents (g g^{-1}), respectively; θ_i and h_i are water content and matric potential at the inflection point of the retention curve, respectively; and *n* and *m* are parameters of Van Genouchten retention curve.

Table 1. Averages of parameters of soil characteristics in different treatments

Soil properties	Minimum tillage			No-tillage			Conventional tillage		
Plant residue (%)	0	30	60	0	30	60	0	30	60
MWD (mm)	2.17	2.70	2.99	2.57	2.71	2.62	1.59	1.89	2.50
WSA (%)	44.03	56.72	71.62	60.67	57.16	61.59	33.88	34.10	66.45
PAW (m^3 m^{-3})	0.19	0.15	0.19	0.24	0.20	0.24	0.19	0.20	0.19
RFC	0.95	0.88	0.88	0.95	0.93	0.92	0.91	0.84	0.88
AC (m^3 m^{-3})	0.021	0.050	0.050	0.020	0.029	0.034	0.036	0.068	0.048
S_{gi}	0.062	0.058	0.058	0.062	0.062	0.065	0.058	0.061	0.063
SI (%)	1.76	2.09	2.88	1.73	1.75	1.90	1.21	1.36	1.50
BD (g cm^{-3})	1.54	1.49	1.47	1.61	1.61	1.50	1.50	1.47	1.57
N	0.42	0.44	0.44	0.39	0.39	0.43	0.43	0.44	0.41
AS (%)	17.21	48.70	33.97	21.41	23.97	24.77	18.71	14.53	19.17
pH	7.40	7.43	7.40	7.33	7.57	7.40	7.49	7.63	7.70
EC (ds m^{-1})	2.20	2.50	2.30	2.30	2.20	2.50	2.20	2.50	2.40
SAR	4.73	4.43	4.47	4.03	3.33	3.39	5.56	4.52	5.82
OC (%)	0.56	0.77	1.03	0.67	0.66	0.71	0.43	0.48	0.54
Active C (mg kg^{-1})	11.58	10.55	10.86	11.69	12.13	11.51	13.29	12.85	12.81
TN (mg kg^{-1})	634.6	618.3	646.3	774.6	665	868	987	798	780.5
K (mg kg^{-1})	98.88	94.97	112.9	235.62	150.77	174.6	257.82	137.07	175.25
P (mg kg^{-1})	15.37	13.43	10.59	23.45	21.89	18.79	40.14	27.58	31.50

Soil properties	Minimum tillage			No-tillage			Conventional tillage		
Fe (mg kg^{-1})	4.32	4.88	4.19	2.80	2.67	3.22	2.97	3.05	2.91
Cu (mg kg^{-1})	5.20	5.10	6.20	5.40	5.20	32.98	5.50	6.40	5.80
Mn (mg kg^{-1})	5.20	24.72	27.14	29.56	25.53	32.98	32.73	36.92	30.25
Zn (mg kg^{-1})	3.2	1.6	1.7	9.9	9.6	9.4	4.0	4.3	3.4
MR (mg CO_2/g. day)	0.0067	0.0074	0.0074	0.0092	0.0088	0.012	0.012	0.0079	0.0084

MWD – mean weight diameter of aggregates; WSA – water stable aggregates; PAW – plant available water capacity; RFC – relative field capacity; AC – aeration porosity; S_{gi} – slope of retention curve at inflection point; SI – soil structure stability index; BD – bulk density; n – total porosity; AS – aggregate stability index; EC – electrical conductivity; SAR – sodium adsorption ratio; OC – organic carbon; Active C – active carbon; TN – total nitrogen; diameter. The underlined variables mean that they had the higher loading value; MR – microbial respiration.

Determination of the soil quality indices

In this study, 23 physicochemical properties of soil that have been introduced in literature as affecting soil quality were considered as TDS (Castro *et al*. 1998, Chen *et al*. 2013, Dexter 2004, Doran and Jones 1996, Gholoubi 2018, Govaerts *et al*. 2006, Gugino *et al*. 2009, Lal *et al*. 1990, Vance *et al*. 1987). Principal components analysis (PCA) was used to select the minimum data set (MDS). Based on the MDS procedure, only the PCs with eigenvalues ≥1 were considered for the MDS (Jarecki and Lal 2003, Lal *et al*. 1990, Walkley and Black 1934). Within each PC, highly weighted indicators were defined as those with absolute values within 10% of the highest weighted loading. When more than one variable was retained in a PC, each of them was considered important and was retained in the MDS if they were not correlated ($r < 0.60$) (Walkley and Black 1934).

Fuzzy membership functions were used to unify the units of effective characteristics on the general soil quality index (Lal *et al*. 1990, Vance *et al*. 1987). Therefore, the highest and lowest range of desired characteristic values had a membership value of one and zero, respectively (Lal *et al*. 1990). Using Equations 5 and 6, the range of each characteristic values in two sets of TDS and MDS was scored.

$$S_i = 0.1 + ((X_i - B_i) / (A_i - B_i)) \times 0.9 \tag{5}$$

$$S_i = 1 - ((X_i - B_i) / (A_i - B_i)) \times 0.9 \tag{6}$$

where S_i is variable score, X_i is variable value, A_i is the the maximum observed value of the variable, and B_i is the minimum observed value of the variable.

Equation 5 is used for the soil characteristics that the high values of them have a positive effect on the soil and plant growth (more is better: in this situation the higher the value of the indicator, the higher the score until a maximum level is attained), and Equation 6 is used for characteristic that the low values of them have a favorable effect on the soil and plant growth (less is better: the scoring curve, in this case, gives higher scores to lower values of the indicator) (Wang and Gong 1998). Communality (COM) and weighted values of each characteristic were determined by factor analysis (FA) for TDS and MDS (Doran and Parkin 1994, White 2006). To calculate the weighting of each characteristic, its communality was divided by total communality of all characteristics (Lal *et al*. 1990). To express quantitative soil quality, two models, including the IQI (Bremner and Mulvaney 1982) and NQI (Gholoubi *et al*. 2018, Yao *et al*. 2013) were calculated.

$$IQI = \sum_{i=1}^{n} W_i N_i \tag{7}$$

where W_i is the weighting assigned to each soil characteristic, N_i is the value assigned to each characteristic, and n is the number of characteristics.

$$\mathrm{NQI} = \sqrt{\frac{P_{avc}^2 + P_{min}^2}{2} \times \frac{n-1}{n}} \tag{8}$$

P_{avc} is the average of selected properties, P_{min} is the minimum score among the selected characteristic, and n is the number of soil characteristics measured. The total data set and minimum data set were used to calculate the IQI and NQI, thus, four soil quality indices including IQI_{TDS}, IQI_{MDS}, NQI_{TDS}, and NQI_{MDS} were obtained and the soil quality status was classified according to its effect on plant growth for soil quality assessment (Lal *et al*. 1990).

RESULTS AND DISCUSSION

The results of the principal component analysis (PCA) method for determining the MDS are shown in Table 2. Principal components (PCs) with an eigenvalue ≥1 were chosen for MDS (Yoder 1936). Accordingly, the initial six PCs were selected (Table 2). These 6 PCs with eigenvalues greater than one, explained 83.68% of the variance. The first PC, with 26.09% of variance, was higher than other PCs. PC2, PC3, PC4, PC5, and PC6 characterized with 16.49, 12.88, 11.75, 32.8, 15.8% of variance, respectively, so it can be concluded that the lower PCs have a lesser role in explaining the variation among soil properties (Zangi Abadi 2016).

Table 2. The selected minimum data set (MDS) using principal component analysis (PCA)

Variables	PC1	PC2	PC3	PC4	PC5	PC6
Eigen value	6.00	3.79	2.96	2.70	1.91	1.87
Variance portion (%)	26.09	16.49	12.88	11.75	8.32	8.15
Cumulative variance (%)	26.09	42.58	55.46	67.21	75.53	83.68
Eigen vector variables						
K	0.291	-0.005	0.042	-0.152	0.307	-0.108
P	0.226	-0.022	0.206	-0.362	-0.114	-0.278
TN	0.305	0.057	-0.119	-0.129	-0.005	0.225
Cu	0.059	0.024	**-<u>0.536</u>**	0.134	-0.228	-0.033
Mn	0.215	0.083	-0.209	0.216	-0.138	-0.068
Fe	-0.257	0.025	-0.291	0.144	0.009	0.110
Zn	0.166	-0.160	-0.059	0.255	0.489	0.074
OC	0.310	0.113	0.108	0.109	-0.059	-0.060
Active C	-0.275	-0.062	0.077	-0.128	0.039	0.133
pH	-0.228	0.053	0.373	0.028	-0.155	0.073
EC	0.173	0.017	-0.233	**-<u>0.537</u>**	-0.006	-0.077
BD	0.001	-<u>0.419</u>	0.120	0.049	-0.254	0.206
MWD	0.234	-0.244	0.282	0.187	-0.143	-0.065
N	-0.001	0.419	-0.120	-0.049	0.254	-0.206
SI	0.311	0.157	0.111	-0.074	-0.083	-0.032
MR	0.186	0.152	-0.088	0.105	0.254	0.592
SAR	0.042	0.249	0.070	-0.321	-0.104	0.465
WSA	0.248	-0.049	0.323	0.191	0.010	0.171
AS	0.215	0.172	-0.077	0.353	-0.319	-0.188
S_{gi}	-0.008	-0.177	0.113	0.097	0.465	-0.243
PAW	0.243	-0.248	-0.073	0.042	-0.052	0.153
AC	-0.093	0.421	0.172	0.129	0.024	0.008
RFC	0.105	**-<u>0.422</u>**	-0.156	-0.115	-0.017	-0.025

EC – electrical conductivity; SAR – sodium adsorption ratio; OC – organic carbon; Active C – active carbon; TN – total nitrogen; MR – microbial respiration; MWD – mean weight diameter of aggregates diameter; WSA – water stable aggregates; PAW – plant available water capacity; RFC – relative field capacity; AC – aeration porosity; SI – soil structure stability index; BD – bulk density; n – total porosity; AS –aggregate stability index. The underlined variables mean that they had the higher loading value.

To reduce repetitive information, Pearson correlation coefficients between the variables were determined and parameters that had a high correlation with each other were removed and only one of them was selected (Andrews *et al*. 2002). In PC1, the SI variable had the highest loading value (0.311). The absolute loading value of K, TN, and OC was 10% less than the highest value (Table 2). Therefore, in PC1, variables SI, K, TN, and OC have the high loading value, but due to the high correlation between these characteristics (SI and OC, SI and K, SI and TN, TN and K – Table 3), SI was selected in the first PC as MDS. Similarly, the variables RFC, Cu, EC, Zn, S_{gi}, and microbial respiration were selected as MDS on PC2, PC3, PC4, PC5, and PC6, respectively (Table 4). Therefore, through the PCA method, the number of considered variables was reduced.

Table 3. Pearson correlation between main soil characteristics

	TN	OC	K	BD	n	AC	SI	RFC
TN	1	0.73^{**}	0.69^{**}	-0.11^{ns}	0.42^{ns}	0.25^{ns}	0.80^{**}	0.17^{ns}
OC	-	1	0.72^{**}	-0.31^{ns}	0.42^{ns}	0.45^{ns}	0.92^{**}	0.50^{ns}
K	-	-	1	-0.34^{ns}	$0.^{28ns}$	0.30^{ns}	0.74^{**}	0.39^{ns}
BD	-	-	-	1	-0.61^{*}	0.61^{*}	0.56^{*}	0.44^{ns}
N	-	-	-	-	1	0.61^{*}	0.30^{ns}	0.52^{ns}
AC	-	-	-	-	-	1	0.19^{ns}	0.98^{**}
SI	-	-	-	-	-	-	-	0.24^{ns}
RFC	-	-	-	-	-	-		1

** significant at $p < 0.01$; * significant at $p < 0.05$; ns (non-significant)

Table 4. Weighted TDS and MDS variables based on communality

Parameter	TDS		MDS		Parameter	TDS		MDS	
	weight	COM	weight	COM		weight	COM	weight	COM
K	**0.047**	**0.908**			MWD	0.039	0.749		
P	**0.045**	**0.868**			n	0.047	0.912	0.163	0.921
TN	**0.047**	**0.902**			**SI**	**0.049**	**0.952**	**0.149**	**0.722**
Cu	**0.043**	**0.828**	**0.105**	**0.508**	**CO_2**	**0.047**	**0.904**	**0.156**	**0.756**
Mn	**0.033**	**0.634**			SAR	0.037	0.721		
Fe	**0.042**	**0.800**			WSA	0.045	0.867		
Zn	**0.044**	**0.840**	**0.166**	**0.807**	AS	0.049	0.943		
OC	**0.047**	**0.906**			**S_{gi}**	**0.030**	**0.578**	**0.133**	**0.649**
Active C	**0.037**	**0.707**			PAW	0.041	0.788		
pH	**0.042**	**0.816**			AC	0.047	0.903		
EC	**0.047**	**0.898**	0.131	0.638	RFC	0.047	0.910	0.161	0.782
BD	**0.047**	**0.912**							

Effect of tillage systems and plant residues on soil quality indices

The results of the analysis of variance showed that the effect of soil tillage, plant residues and their interaction on soil quality indices were significant ($p < 0.01$). A comparison of means showed that the values of IQI_{TDS} and NQI_{TDS} indices in NT and MT treatments were significantly greater than that of CT treatment. Further, these indices of soil quality for the conservation tillage treatments (MT and NT) showed no significant difference (Table 5). Also, the differences between IQI_{MDS} in the three tillage treatments were significantly different. A similar trend was found for NQI_{MDS} so that the order of IQI_{MDS} and NQI_{MDS} was found to be MT > NT > CT. According to Tables 5 and 6, it can be concluded that IQI_{TDS} value in MT, IQI_{MDS} in NT, and NQI_{TDS} in NT and MT treatments were classified as low-quality grade (III) (Lal *et al*. 1990), while IQI_{TDS} in NT, and CT; IQI_{MDS} in MT, and CT; NQI_{TDS} in CT; and NQI_{MDS} in CT, MT, and NT treatments were classified as very low-quality grade (IV).

Table 5. Effect of different tillage treatments on soil quality

Soil quality models	Conventional tillage	No tillage	Minimum tillage
IQI_{TDS}	0.44^{b}	0.54^{a}	0.56^{a}
IQI_{MDS}	0.43^{c}	0.60^{a}	0.50^{b}
NQI_{TDS}	0.32^{b}	0.41^{a}	0.40^{a}
NQI_{MDS}	0.32^{c}	0.46^{a}	0.38^{b}

Similar letters in each row are not significant ($p < 0.05$).

The comparison of the means of plant residue indicated that the values of IQI_{TDS}, IQI_{MDS} and NQI_{TDS} showed no significant differences in treatments including that of 1,500 kg ha^{-1} and no residues (control), while the addition of 3,000 kg ha^{-1} plant residues significantly increased these soil quality indicators compared to 0 (control) and 1,500 kg ha^{-1} (Table 7). The value of NQI_{MDS} in NT treatment was the highest and its difference with MT was significant, but it had no significant difference with control. In treatments including 0 and 1,500 kg ha^{-1} plant residues, IQI_{TDS} and IQI_{MDS} indices were classified in very low-quality grade (IV, Table 6), but the addition of 3,000 kg ha^{-1} of plant residues resulted in the increase in the values of IQI_{TDS} and IQI_{MDS} so that their class changed to low-quality grade (III) (Lal *et al.* 1990). Also, the addition of 1,500 and 3,000 kg ha^{-1} plant residue resulted in NQI_{TDS} being low in the quality grade (III). Besides, NQI_{MDS} for the three rates of plant residue had very low quality (IV).

Table 6. The grade of soil quality indicators (Qi *et al.*, 2009)

Grade	NQI_{MDS}	NQI_{TDS}	IQI_{MDS}	IQI_{TDS}
I	>0.80	<0.55	<0.78	<0.76
II	0.70–0.80	0.45–0.55	0.68–0.78	0.66–0.76
III	0.60–0.70	0.35–0.45	0.58–0.68	0.56–0.66
IV	>0.60	>0.35	>0.58	>0.56

Table 7. The effect of plant residues on soil quality indicators

Soil quality models	0	1,500 kg ha^{-1}	3,000 kg ha^{-1}
IQI_{TDS}	0.47^{b}	0.50^{b}	0.57^{a}
IQI_{MDS}	0.51^{ab}	0.46^{b}	0.56^{a}
NQI_{TDS}	0.34^{b}	0.36^{b}	0.42^{a}
NQI_{MDS}	0.39^{ab}	0.35^{b}	0.43^{a}

Similar letters in each row are not significant ($p < 0.05$).

The interaction effect of the different tillage systems and plant residues rates (Fig. 1 and 2) showed that the combination of no-residue and the addition of 1,500 kg ha^{-1} treatments resulted in IQI_{TDS} and IQI_{MDS} indicative of very low soil quality grade. However, the addition of 3,000 kg ha^{-1} residues improved the soil quality to grade (III). In addition, minimum tillage and the addition of 1,500 and 3,000 kg ha^{-1} of plant residue slightly improved the soil quality to grade (III), while other treatments were classified in very low-quality grade (IV) (Lal *et al*. 1990). These results indicated that a combination of minimum tillage and plant residue less than 3,000 kg ha^{-1} did not affect soil quality indicators, while 3,000 increased the soil quality from grade IV to III. In conventional tillage, increasing the plant residue caused a non-significant effect on soil quality. In the no-tillage system, the addition of plant residues had no significant effect on IQI_{TDS}, but in the minimum tillage system, the IQI_{TDS} value increased significantly with the addition of plant residues.

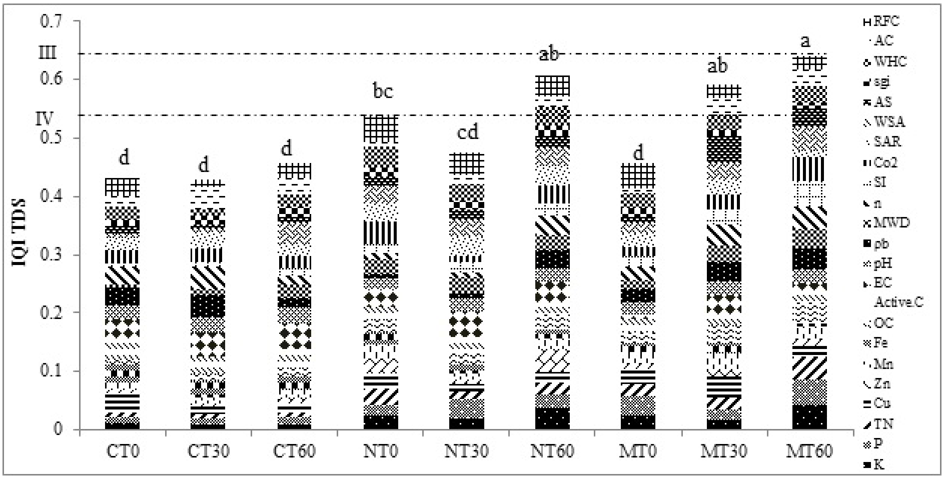

Fig. 1. The effect of tillage and addition of plant residues on IQI_{TDS}

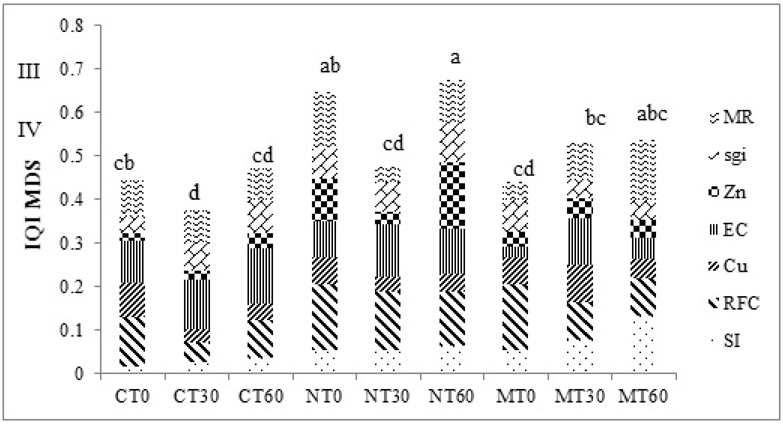

Fig. 2. The effect of tillage and addition of plant residues on IQI_{MDS}

Similar letters in columns are not significant at $p < 0.01$; CT – conventional tillage; NT – no-tillage; MT – minimum tillage; 0, 30 and 60 represent 0, 1,500 and 3,000 kg ha^{-1} of plant residues, respectively; IV – very low quality; and III – low quality.

Limiting factors of soil quality in conventional tillage (control system) were P, TN, Zn, OC, MWD, SI, WSI, and S_{gi}, while those in conventional tillage with 1,500 kg ha^{-1} plant residue were K, TN, Zn, Mn, SI, WSA, AS and PAW. Also, limiting factors of soil quality in conventional tillage with 3,000 kg ha^{-1} of plant residues were K, TN, and Zn, and in no-tillage with 0% plant residue, BD and *n* (soil porosity), whereas in no-tillage with 1,500 kg ha^{-1} plant residue were Zn, BD and *n* were limiting factors for soil quality. Furthermore, limiting factors of soil quality in minimum tillage with 0% plant residue were Zn and AC; in MT with 1,500 kg ha^{-1} plant residue S_{gi} index and in 3,000 kg ha^{-1} plant residue Fe, and S_{gi} indices were limiting factors for soil quality which were determined by IQI_{TDS}.

The interaction effect between tillage systems and plant residues revealed that IQI_{MDS} in CT and MT treatments which received plant residues did not change significantly compared to the control, while in the NT system, application of 1,500 kg ha^{-1} of plant residues significantly decreased the IQI_{MDS} in relation to the control and where 3,000 kg ha^{-1} of residues were applied. In addition, according to Qi *et al*. classification, NT0 and NT + 3,000 kg ha^{-1}, IQI_{MDS} had low soil quality, while other treatments were classified as very low-quality grade (IV) (Lal *et al*. 1990). Limiting factors for IQI_{MDS} in CT treatments at all three rates of plant residues were SI and Zn. Limiting factors for soil quality in the no-tillage system with 1,500 kg ha^{-1} of plant residues included Cu, Zn, and MR. The minimum tillage treatments at three rates of plant residues were classified as very low-quality grade (IV). The limiting factor for IQI_{MDS} in MT treatments with no plant residues was Zn.

The results of the comparison of means (Table 5) showed that the values of NQI_{TDS} showed no significant difference between the minimum and no-tillage treatments, but it had the highest value in no-tillage treatment. According to Qi *et al.*, the soil quality in conventional tillage was classified as very low-quality grade (IV) and minimum and no-tillage were classified as low-quality grade (III) (Table 6) (Lal *et al*. 1990). Further, the NQI_{TDS} values obtained in treatments including the control and with 1,500 kg ha^{-1} of plant residues were not significantly different, while NQI_{TDS} was significantly increased with the addition of 3,000 kg ha^{-1}of plant residues compared to the control and the treatment with 1,500 kg ha^{-1} (Table 7). According to Qi *et al*. (Table 6) ranking, treatments containing no plant residues were classified as very low-quality grade (IV) and 1,500 and 3,000 kg ha^{-1} of plant residues were classified as low-quality grade (III) (Lal *et al*. 1990).

The interaction effects of tillage systems and plant residues for NQI_{TDS} showed that soil quality in conventional tillage treatments including the three rates of plant residues, no-tillage containing 1,500 kg ha^{-1} of plant residues and minimum tillage with no plant residues were classified as of very low quality (IV), while soil quality in no-tillage with no plant residues, minimum tillage containing 1,500 and 3,000 kg ha^{-1} of plant residues were rated a grade higher and classified as low-quality grade (III) and only no-tillage with 3,000 kg ha^{-1} of plant residues was classified as medium quality grade (II). In the conventional tillage, increasing the plant residues led to a non-significant increase in NQI_{TDS}. In the no-tillage system, the addition of 3,000 kg ha^{-1} of plant residues resulted in a significant increase in NQI_{TDS} compared to the control and 1,500 kg ha^{-1} of plant residues and no significant difference was found between 0 and 1,500 kg ha^{-1} of plant residues ($p < 0.05$). In the minimum tillage system, NQI_{TDS} significantly increased with the increase in the plant residues compared to the control. However, adding 1,500 and 3,000 kg ha^{-1} of plant residues had no significant difference (Fig. 3). The results of IQI_{TDS} and NQI_{TDS} showed that the soil quality obtained by the NQI_{TDS} method in no-tillage treatment with 3,000 kg ha^{-1} of plant residues was classified at medium grade (II), while from the IQI_{TDS} method, it was classified at low-quality grade (III). Therefore, it can be concluded that in most applications both IQI_{TDS} and NQI_{TDS} methods represented the same results in terms of statistical analysis.

The results of the comparison of means for IQI_{TDS} (Table 5) showed that there was a significant difference between the three soil tillage treatments, and the soil quality obtained based on IQI_{MDS} showed the highest value in no-tillage system. In addition, plant residues had no significant effect on values of soil quality (Table 7). According to Qi *et al.* (Table 6), all soil tillage and plant residue treatments are classified at very low-quality grade (IV) (Lal *et al*. 1990).

The interaction effects of tillage practices and plant residues indicated that in CT and MT systems, the addition of the plant residues had no significant effect on NQI_{MDS}. Here, all soil treatments were classified as very low-quality grade (IV) and their values in all treatments were less than 0.6 (Fig. 4). In no-tillage treatments, increasing the residues from 0 to 1,500 kg ha^{-1} resulted in significant decrease in $NQI_{MDS,}$ but when the rate of plant residues was increased to 3,000 kg ha^{-1}, the NQI_{MDS} increased significantly in relation to the rate of 1,500 kg ha^{-1}. However, its difference compared to the control was not significant. According to these results, plant residues had more significant effect on soil quality indicators than the tillage systems.

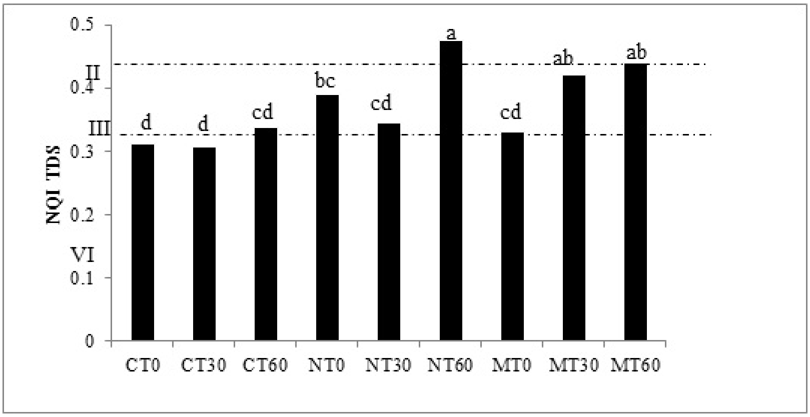

Fig. 3. Effect of tillage and plant residues on NQI_{TDS}

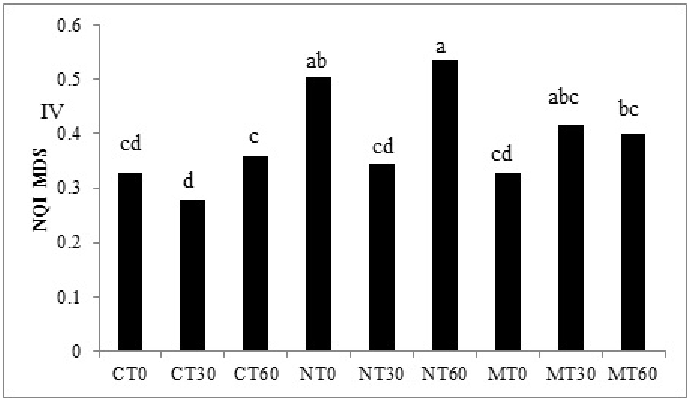

Fig. 4. Effect of tillage and plant residues on NQI_{TDS}

Similar letters in columns are not significant at $p < 0.01$; CT – conventional tillage; NT – no-tillage; MT – minimum tillage; 0, 30 and 60 represent 0, 1,500 and 3,000 kg ha^{-1} of plant residues, respectively; (IV – very low quality).

To examine the use of MDS rather than TDS, the correlation between soil quality indicators in the two data sets was determined. As shown in Fig. 5, there were significant correlations between IQI and NQI indices derived from the MDS and TDS. The correlation coefficients between IQI_{TDS} and IQI_{MDS} were 0.69, and 0.76 for NQI_{TDS} and NQI_{MDS} ($p < 0.01$). Therefore, using MDS instead of TDS, the IQI and NQI can be accurately calculated. Generally, all data sets are not considered for soil quality indices in MDS, and this reduces MDS responsiveness to soil quality assessment. Because of using all the data sets, the TDS method is more accurate than MDS to calculate soil quality indicators. However, because MDS uses soil data set with fewer parameters, it is more economical.

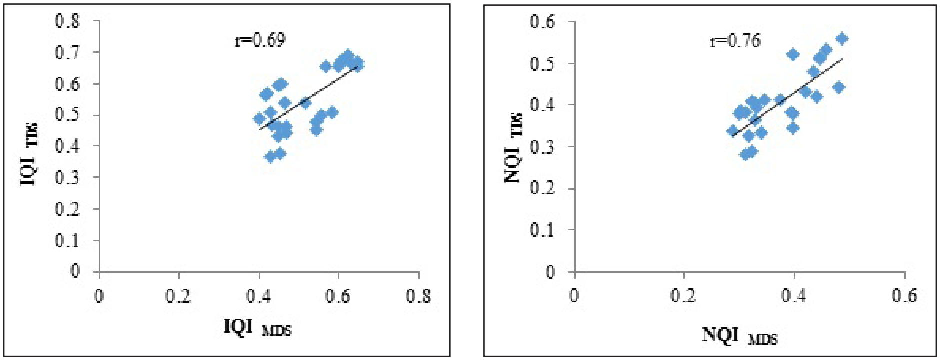

Fig. 5. Correlation between MDS and TDS for determining IQI (left) and NQI (right)

CONCLUSIONS

The results of this study showed that the soil quality in minimum and no-tillage systems was better than conventional tillage with the addition of plant residues which only slightly improved soil quality. According to the results of NQI and IQI, the no-tillage and minimum tillage systems with the addition of 3,000 kg ha^{-1} of plant residues had a positive effect on better soil quality. All the other treatments resulted in low soil quality. The limiting factors for soil quality in conventional tillage were low values of macro and micronutrients and soil structure indicators, while in conservational tillage micronutrients and especially Zn were the limiting factors for soil quality. The correlation coefficients between NQI_{TDS} with NQI_{MDS} (r = 0.76) and IQI_{TDS} with IQI_{MDS} (r = 0.69) were slightly high but not statistically different, therefore, it indicates MDS as a reliable, fast and suitable economical solution that can be useful to select the effective soil quality indicators and consequently to calculate the soil quality indices.

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