Expl Agric. (2017), volume 53 (4), pp. 497–511 © *Cambridge University Press 2016*
doi:10.1017/S0014479716000521

SOIL QUALITY INDICATORS AND CROP YIELD UNDER LONG-TERM TILLAGE SYSTEMS

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(*Accepted 26 July 2016; First published online 31 August 2016*)

SUMMARY

Soil quality indicators (SQI) can be used as a synthetic tool for the assessment of the sustainability of agricultural systems. In this study, we developed SQI using minimum data set (MDS) and determined the response of SQI to long-term tillage systems. Field pea (*Pisum sativum* L.) and spring wheat (*Triticum aestivum* L.) were grown in alternate years at northwestern China, and soil attributes and crop productivity were measured 6 years after the initiation of the experiment. The MDS used to develop the SQI included soil physical (aggregate, bulk density, capillary porosity, field capacity), chemical (soil organic matter, total nitrogen, available phosphorus, available potassium) and biological (microbial count, microbial biomass, and the activities of catalase, urease, alkaline phosphatase, and invertase) properties. All the property variables were measured in each of the 0–5, 5–10 and 10–30 cm depths and those variables that contributed significantly to the SQI were selected to be included in the MDS. Amongst the measured variables, bulk density and microbial counts occurred in the MDS of all the three depths, suggesting that these two properties are highly affected by the tillage treatments. In the long-term field experiment, the no-till with stubble covering the soil surface treatment received the greatest SQI score and achieved the highest crop yield. Soil quality under tillage systems can be assessed adequately using MDS measured at the top soil (0–5 cm) layer in rainfed agro-ecosystems.

INTRODUCTION

Soil quality is defined as ‘the capacity of soil to function effectively at present and in the future or as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health’ (Doran and Parkin, 1994). This definition of soil quality covers a wide range of functions. However, it is unlikely that a particular soil is able to provide all these functions successfully. Some of those functions occur in natural ecosystems whilst the others are the result of human modification. Soil quality depends on the extent to which a soil fulfils the role it is destined for (Singer and Ewing, 2000). Within the framework of agricultural production, high soil quality equates to the

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maintenance of high productivity without causing significant soil degradation or environmental consequences.

Soil quality is a combination of soil physical, chemical and biological properties that are able to readily change in response to variations in soil management (Brejda *et al.*, 2000a). A wide range of indicators are available for the assessment of soil quality, but the interpretation of the indicators is often difficult. Therefore, it is essential to elaborate numerical indices that can be used as synthetic tools to integrate information about soil quality functions deriving from individual parameters. Integrated soil quality indices based on a combination of soil properties provide a better indication of soil quality than individual parameters. These selected properties are grouped into a minimum data set (MDS), and such a collection of selected indicators may have the features of measuring soil state and function from plot to regional scale (Doran and Parkin, 1994; Karlen *et al.*, 1997; Liebig *et al.*, 2001). The concept of MDS of soil quality indicators is widely accepted, but many different methods have been suggested to calculate indices from an MDS (Karlen *et al.*, 1997; Liebig *et al.*, 2001; Wienhold *et al.*, 2004; Zornoza *et al.*, 2008). Generally, the development of a soil quality index (SQI) starts with the establishment of a valid and precise MDS. The different indicators to be included in the MDS are usually expressed by numerical scales which are normalized using the scoring functions of linear and non-linear regressions. The integration of non-dimensional indicators (obtained by normalization) into quality indices is possible through many procedures based on multiplicative (Pierce *et al.*, 1983; Singh *et al.*, 1992), simple additive (Andrews and Carroll, 2001) or weighted additive (Karlen *et al.*, 1998).

A well-developed SQI can be used to improve soil management especially in those fragile agro-ecosystems such as the semi-arid areas of the western Loess Plateau of China. In many arid and semi-arid areas on the planet, serious soil erosion often occurs, largely due to the use of intensive tillage. In the western Loess Plateau of China, seedbed is typically prepared using three ploughs and two harrows during the period from post-harvest in the fall to the sowing time the following spring. This tillage system is believed to capture and store precipitation in the soil and maximize precipitation use in this ecoregion where precipitation is low and extremely variable. Furthermore, nearly all crop residues are removed from the field at harvest for animal feed or fuel for heating or cooking. The soil surface is left bare for the 7–8 months after harvest in the late summer until early spring (April) the following year. In this region, there is only one crop each year, which coincides with the part of the wet season in July to September. These practices have been shown to exacerbate the degradation of soils, promote erosion and reduce production potential. Thus, management practices must provide protection against the degradation of these soils. Conservation tillage has been shown to play an important role in minimizing soil erosion and improving soil quality. For example, Cai *et al.* (2008) found that no-till promoted water stability of soil aggregates and stubble retention improved soil organic matter (SOM). The use of conservation tillage improved soil water condition (Enfors *et al.*, 2011; Van Wie *et al.*, 2013). Zhang *et al.* (2011) and Niu *et al.* (2016) reported that no-till with stubble retention improved soil physical properties compared to conventional tillage in a 7-year study.

The aim of the study was to develop a SQI by selecting the best soil quality assessment indicators. The assessment was performed using a long-term field experiment conducted at the semi-arid Loess Plateau of northwest China where different tillage systems were evaluated. For this purpose, soils from the different tillage treatments were sampled and the physical, chemical and biological parameters were determined. The MDS was established by selecting and integrating soil quality indicators together according to the methods described by previous researchers (Doran and Parkin, 1994; Larson and Pierce, 1994). Also, to better characterize the soil under investigations, we considered some other parameters and the impact of human activities on the ecosystems in the analysis. Using multivariate statistical analyses and soil quality indices, different soil quality classes were determined for the different tillage/stubble management systems.

MATERIALS AND METHODS

Site description

A long-term conservation tillage experiment was established in 2001 at Dingxi Experimental Station of Gansu Agricultural University (35°28′N, 104°44′E, 1971 m a.s.l.). The station is located in the heart of the semi-arid Loess Plateau of China. Long-term annual precipitation averages 391 mm, with about 54% occurring between July and September. Daily maximum temperatures are up to 38 °C in July, whilst minimum temperatures can be −22 °C in January. The soil was a Huangmian which is aligning with a Calcaric Cambisols in the FAO soil map of the world. The site had a long history of continuous cropping using conventional tillage system. Field pea (*Pisum sativum* L.) and spring wheat (*Triticum aestivum* L.) were grown in alternate years in the experiment since the start of the experiment in 2001 after a previous flax (*Linum usitatissimum* L.) crop.

Experimental design and treatments

The experiment had a fully phased factorial design, with six tillage treatments (Table 1), two rotation phases and replicated four times (blocks). Spring wheat (cv. Dingxi No. 35) and field pea (cv. Yannong) were sown in rotation with each of the two phases present in each year. There were 48 plots in total (6 tillage treatments x 2 phases x 4 replicates). Further details of the experimental design and plot management are described in Niu *et al.* (2016).

Soil properties and crop measurements

After 6 years of experiment rotation, soil physical, chemical and biological properties were determined. Soil bulk density and capillary porosity, non-capillary porosity, field capacity and saturation capacity were determined (Nanjing Institute of Soil Science, 1978). Soil aggregates were measured by wet sieved method (Yang and Wander, 1998).

For those measurements, soil samples were taken from the 0–5, 5–10 and 10–30 cm depths after crop was harvested. The three depths were chosen with the consideration

Table 1. Treatments and their description in the long-term conservation tillage experiment.

Treatments		
Name	Abbreviation	Description
Conventional tillage with stubble removed	T	Fields were ploughed three times and harrowed twice after harvesting using animal power. The first ploughing was in August immediately after harvesting, the second and third ploughing were in late August and September, respectively. The depths of the three plough were 20, 10 and 5 cm, respectively. The field was harrowed after the last cultivation in September and again in October before the ground was frozen. This is the typical conventional tillage practice in the Dingxi region. The crops were sown by a small seeder (5–6 rows in 1.2 m width), drawn by a 13.4 kW (18 HP) tractor and designed by China Agricultural University, allowing fertilizers to be placed below the seed-rows, followed by concave rubber press wheels in one operation.
No-till with stubble removed	NT	No-till throughout the life of the experiment. The straw was removed from the field and used as fuel or feed. The crops were sown exactly as for the T treatment.
Conventional tillage with stubble incorporated	TS	Fields were ploughed and harrowed exactly as for the T treatment described above, but with straw incorporated at the first ploughing. All the straw from the previous crop was returned to the original plot immediately after threshing and then incorporated into the soil. The crops were sown exactly as for the T treatment.
No-till with stubble cover	NTS	No-till throughout the life of the experiment. The ground was covered with the straw of previous crops from August until the following March. All the straw from previous crops was returned to the original plot immediately after threshing. The crops were sown exactly as for the T treatment.
Conventional tillage with plastic film mulch	TP	Plots were cultivated three times and harrowed twice before the plastic film (0.05 mm thick) was laid out in October. All stubble was removed before cultivation. The crops were sown by the locally designed traditional seeder, drawn by animal power, which was designed to form a ridge, lay the plastic film, sow the seeds and apply fertilizers in one operation.
No-till with plastic film mulch	NTP	All stubble was removed before plastic film (0.5 mm thick) was laid out in October. The crops were sown exactly as for the TP treatment. The removal of straw allowed plastic film mulch to layout.

that the impacts of tillage systems on the main soil quality indicators are most likely on the surface layers. Five cores (25 mm diameter) were collected from each plot and bulked into one sample per plot at each depth. After mixing using a portable soil mixer, the soil samples were dried and sieved through 2 mm size. Soil organic carbon (Walkley and Black, 1934), total N (Bao, 2000), Olsen P (Olsen *et al.*, 1954) and soil available K (Jackson, 1973) were determined.

Soil biological properties, such as soil catalase activity and urease activity (Yan, 1988), alkaline phosphates activity (Zhao and Jiang, 1986), invertase activities (Guan, 1986) and soil microbial propagules (colony forming units, CFUs) were also measured (Li *et al.*, 1996). Crop grain yield, straw and chaff weights were obtained when crop was harvest. More details on soil properties and crop yield measurements are given in Niu *et al.* (2016).

Soil quality indicators assessment

In the assessment of soil quality indicators, the three steps were followed: (i) select an MDS of indicators that contributed most to soil quality, (ii) score the MDS indicators based on their performance of soil function and (iii) integrate the indicator scores into a comparative index.

Representative MDS (Andrews *et al.*, 2002b; Doran and Parkin, 1994) includes only those soil properties that have a significant treatment difference. Significant variables ($P < 0.05$) were chosen for the next step in MDS formation through principal component analysis (PCA) (Andrews *et al.*, 2002a, 2002b; Shukla *et al.*, 2004). Principal components (PC) for a data set are defined as linear combinations of variables that account for maximum variance within the set by describing vectors of closest fit to the n observation in p-dimensional space, subject to being orthogonal to one another. The PC receiving high eigen values and variables with high factor loading were assumed to be variables that best represented system attributes. Therefore, only the PCs with eigen values ≥ 1 (Brejda *et al.*, 2000b) and those that explained at least 5% of the variation in the data (Wander and Bollero, 1999) were examined. Within each PC, only highly weighted factors were retained for MDS. Highly weighted factor loadings were defined as having absolute values within 10% of the highest factor loading. When more than one factor was retained under a single PC, multivariate correlation coefficients were employed to determine if the variables could be considered redundant and therefore eliminated from the MDS (Andrews *et al.*, 2002b). Well-correlated variables were considered redundant and only one of them was considered for the MDS, with the others being eliminated from the data set. If the highly weighted variables were not correlated, each was considered important and was retained in the MDS.

After the MDS indicators were determined, every observation of each MDS indicator was transformed using a linear scoring method. Indicators were arranged in order depending on whether a higher value was considered 'good' or 'bad' in terms of soil function, which were assigned applying 'more is better' or 'less is better'. The 'more is better' indicators and the 'less is better' indicators were calculated, respectively, by the ascending and descending functions. Equations #1 below defines a 'more is better' scoring curve for positive slopes, and Equation #2 defines the 'less is better' curve for negative slopes. In these equations, numerical values for each soil quality indicator were converted into unit-less scores ranging from 0 to 1.

$$F(X_i) = {}^{(X_{ij} - X_{imim})}\!\big/\!_{(X_{imax} - X_{imim})}, \tag{1}$$

$$F(X_i) = {}^{(X_{imax} - X_{ij})}\!\big/\!_{(X_{imax} - X_{imim})}, \tag{2}$$

where $F(X_i)$ is the score for the subscripted variable, and X_{ij} is the value of the soil indicator that was selected for the soil quality; X_{imax} and X_{imim} are the maximum and minimum value of the i soil indicator.

Once observation of each MDS indicator was transformed, the MDS variables for each observation were weighted. There are many ways to assign the weights for each indicator. This includes experience, mathematical statistics or models (Wang, 1994). In this study, PCA was used to determine the weights for each indicator (Equation #3).

$$W_i = C_i / \sum_{i=1}^{n} (C_i), \tag{3}$$

where W_i is the weighting factor derived from the PCA; C_i is the communality of i soil quality indicator andnis the number of soil indicators included in the index.

Finally, we summed up the weighted MDS variables scores for each observation using equation #4 below, then the SQI was obtained. Here, the assumption is that higher index scores meant better soil quality or greater performance of soil function, which in this study was to sustain crop yields.

$$\mathrm{SQI} = \sum_{i=1}^{n} F(X_i) \times W_i. \tag{4}$$

Data analysis

Analysis of variance (ANOVA) was performed to determine the effects of different tillage systems on soil properties and soil quality. All statistical analyses of data were carried out through the SPSS package (SPSS Software, 13.0, SPSS Institute Ltd, USA). Significances were declared at $P < 0.05$.

RESULTS

Selection of soil quality indicators

Tillage systems had a different influence on the different soil properties. Taking into account soil and climatic conditions for the specific agro-ecological zone, 16 soil property indicators were used in the index development, namely soil bulk density, total porosity, capillary porosity, non-capillary porosity, aggregates, field capacity, saturation capacity, SOM, total nitrogen, available phosphorus, available potassium, microbial biomass, catalase activities, urease activities, alkaline phosphatase activities and invertase activities. The most sensitive indicators out of the 16 assessment indicators were selected using PCA and these selected indicators were used to evaluate the treatment effect in different soil depths. In the PCA of 16 variables at the 0–5 cm soil depth, five PCs had eigen value >1 and explained 79.2% of the variance in the data (Table 2). Highly weighted variables under PC1 included total nitrogen, available potassium and invertase activity. A correlation matrix for the highly weighted variables under different PCs was run separately for each depth (Table 3). Only variables with the highest correlation sum were included in the MDS. Amongst the three variables in PC1, total nitrogen was chosen for the MDS because of its highest correlation sum. Available potassium ($r = 0.746^{**}$) and invertase activity ($r = 0.635^{**}$) were highly correlation with total nitrogen and hence they were dropped. In PC2, bulk density and total porosity were highly weighted. Bulk

Table 2. Principal component analysis (PCA) of soil quality indicators at 0–5 and 5–10 cm soil depth.

Component	0–5 cm component					5–10 cm component				
PC'S	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
Eigen value	6.44	2.8	1.33	1.08	1.02	4.33	3.44	1.7	1.43	1.04
% of variance	40.27	17.48	8.33	6.74	6.39	27.08	21.5	10.64	8.95	6.47
Cumulative % of variable	40.27	57.75	66.07	72.81	79.2	27.08	48.58	59.22	68.16	74.63
Variable										
Bulk density	0.612	0.754	0.146	0.026	0.119	0.886	−0.291	−0.158	0.215	0.184
Total porosity	0.612	0.754	0.146	0.026	0.119	0.886	−0.291	−0.158	0.215	0.184
Capillary porosity	0.031	0.347	0.847	0.103	0.305	0.397	−0.213	−0.554	0.547	0.176
Non-capillary porosity	0.651	0.626	−0.325	−0.024	−0.053	0.765	−0.186	0.292	−0.215	0.083
Aggregates	0.675	−0.151	−0.125	−0.135	−0.121	0.438	0.532	0.264	0.015	0.249
Field capacity	0.408	−0.039	−0.49	0.489	0.53	−0.181	0.337	0.037	−0.364	0.771
Saturation capacity	0.441	0.349	−0.271	−0.591	0.173	0.649	−0.445	0.276	0.087	−0.255
Soil organic matter	0.749	−0.063	0.117	0.328	−0.381	0.423	0.738	0.083	0.161	0.062
Total N	0.836	−0.066	−0.087	0.162	−0.324	0.478	0.448	0.353	0.028	−0.175
Available P	0.688	−0.129	0.034	0.302	0.09	0.663	0.262	−0.109	−0.436	0.063
Available K	0.766	−0.049	0.2	−0.088	−0.361	0.54	0.572	0.142	−0.086	−0.296
Microbial biomass	0.292	−0.73	0.216	−0.04	0.273	0.003	0.708	0.188	0.242	−0.068
Catalase activities	0.628	−0.31	0.116	0.037	−0.075	−0.22	−0.087	0.646	0.404	0.129
Urease activities	0.669	−0.335	0.112	−0.465	0.12	−0.356	0.702	−0.142	0.304	−0.006
Alkaline P activities	0.728	−0.404	0.029	−0.052	0.231	−0.006	0.581	−0.437	0.331	−0.023
Invertase activities	0.823	−0.269	−0.017	−0.063	0.193	0.246	0.339	−0.535	−0.453	−0.247

density was chosen for the MDS and total porosity was dropped because total porosity was calculated by bulk density. Microbial counts were retained under MDS because it was no significantly correlated with bulk density. In PC3, capillary porosity was eliminated because of highly correlated with bulk density ($r = 0.417^{*}$). Under PC4 and PC5, saturation capacity and field capacity were highly weighted variables and both of them were retained in MDS because of their relative importance in dryland agriculture.

In the PCA of 16 variable at the 5–10 cm depth, five PCs had eigen value >1 and explained 74.6% of the variance in the data (Table 2). Highly weighted variables under PC1 included bulk density and total porosity. Bulk density was chosen for the MDS and total porosity was dropped. In PC2, SOM, microbial count and urease activity were highly weighted. Microbial count was chosen for the MDS because of its highest correlation sum. SOM plays an important role in maintaining soil quality of erodible environment and was considered under MDS. The urease activity was dropped because it was highly correlated with microbial counts ($r = 0.441^{**}$). Under PC3, PC4 and PC5, catalase activity, capillary porosity and field capacity were highly weighted variables. Capillary porosity was eliminated because it was highly correlated

Table 3. Correlation matrix for highly weighted variables under PC's at 0–5, 5–10 and 10–30 cm soil depth.

0–5 cm component				5–10 cm component				10–30cm component		
PC1 variable	Total N	Available K	Invertase	PC1 variable	Bulk density	Total porosity		PC1 variable	Bulk density	Total porosity
Total N	1	0.746**	0.635**	Bulk density	1	−1		Bulk density	1	−1
Available K	0.746**	1	0.491	Total porosity	−1	1		Total porosity	−1	1
Invertase	0.635**	0.491	1							
Correlation sums	2.381	2.237	2.126							
PC2 variable	Bulk density	Total porosity	Microbial counts	PC2 variable	SOM	Microbial counts	Urease	PC2 variable	No-capillary porosity	
Bulk density	1	−1	0.267	SOM	1	0.567	0.378**	No-capillary porosity	1	
Total porosity	−1	1	−0.267	Microbial counts	0.567**	1	0.441**			
Microbial counts	0.267	−0.267	1	Urease	0.378**	0.441**	1			
Correlation sums	2.267	2.267	1.534	Correlation sums	1.945	2.008	1.819			

Table 4. Principal component analysis (PCA) of soil quality indicators at 10–30 and 0–30 cm depth.

Component PC'S	10–30 cm component						0–30 cm component			
	PC1	PC2	PC3	PC4	PC5	PC6	PC1	PC2	PC3	PC4
Eigen value	3.79	2.92	1.84	1.53	1.34	1.19	6.17	3.25	1.57	1.18
% of variance	23.69	18.24	11.51	9.59	8.38	7.43	38.55	20.31	9.82	7.39
Cumulative %	23.69	41.93	53.43	63.02	71.4	78.83	38.55	58.86	68.68	76.08
Variable										
Bulk density	0.928	−0.1	0.173	−0.175	−0.139	−0.135	0.699	−0.673	0.194	−0.037
Total porosity	0.928	−0.1	0.173	−0.175	−0.139	−0.135	0.699	−0.673	0.194	−0.037
Capillary porosity	0.721	−0.212	−0.453	−0.156	−0.228	−0.105	0.261	−0.471	0.742	0.176
Non-capillary porosity	0.489	0.094	0.739	−0.071	0.052	−0.091	0.727	−0.537	−0.267	−0.169
Aggregates	0.229	0.658	0.332	0.457	−0.027	−0.066	0.732	0.227	−0.36	0.17
Field capacity	0.384	0.144	−0.642	0.257	−0.361	−0.092	0.319	0.337	0.071	0.271
Saturation capacity	0.722	−0.076	−0.226	0.33	0.341	0.22	0.59	−0.581	−0.102	0.326
Soil organic matter	0.22	0.68	0.112	0.017	−0.328	0.323	0.785	0.373	−0.039	−0.287
Total N	0.31	0.362	−0.106	−0.189	0.458	0.329	0.79	0.188	−0.229	−0.122
Available P	−0.056	0.291	0.379	−0.552	−0.307	0.107	0.805	0.049	−0.035	−0.207
Available K	−0.02	0.557	−0.238	0.129	−0.372	0.478	0.741	0.307	−0.089	−0.376
Microbial biomass	−0.151	0.808	0.083	0.167	0.018	−0.19	0.332	0.724	0.061	0.209
Catalase activities	0.314	−0.228	0.312	0.753	0.03	−0.102	0.29	−0.135	−0.514	0.707
Urease activities	0.507	−0.056	−0.023	−0.183	0.366	0.47	0.427	0.478	0.353	0.143
Alkaline P activities	0.246	0.57	−0.305	−0.252	0.083	−0.551	0.498	0.49	0.518	0.255
Invertase activities	−0.02	0.602	−0.187	−0.098	0.555	−0.219	0.74	0.221	0.075	0.039

with bulk density ($r = 0.616^{**}$). Field capacity and catalase activity was retained in MDS.

In the PCA of 16 variable at the 10–30 cm depth, six PCs had eigen value >1 and explained 78.8% of the variance in the data (Table 4). Highly weighted variables under PC1 included bulk density and total porosity. Bulk density was chosen for the MDS and total porosity was dropped. In PC2, PC3, PC4, PC5 and PC6, no-capillary porosity, microbial counts, catalase, invertase and alkaline phosphatase activity were highly weighted variables. No-capillary porosity, microbial count and catalase activity were retained under MDS. These soil properties have been reported as the early and sensitive indicators of changes in soil quality because they manifest themselves over shorter timescales and are central to the ecological function of a soil (Bandick and Dick, 1999; Karlen *et al.*, 1994). Alkaline phosphatase ($r = -0.395^{*}$) and invertase activities ($r = -0.\ 453^{**}$) were eliminated from the MDS because of its high correlation with microbial counts.

In the PCA of 16 variable at the 0–30 cm depth, four PCs had eigen value >1 and explained 76.1% of the variance in the data (Table 4). Highly weighted variables under PC1 included no-capillary porosity, aggregates, SOM, total N, available phosphatase, available potassium and invertase activity. Amongst the seven variables in PC1, SOM was chosen for the MDS because of its highest correlation

Table 5. Correlation matrix for highly weighted variables under PC's at 0–30 cm soil depth.

	No-capillary porosity	Aggregates	SOM	Total N	Available P	Available K	Invertase activity
PC1 variable							
No-capillary porosity	1	0.426**	0.408**	0.501**	0.587**	0.439**	0.374*
Aggregates	0.426**	1	0.681**	0.688**	0.544**	0.512**	0.513**
SOM	0.408*	0.681**	1	0.691**	0.663**	0.789**	0.514**
Total N	0.501**	0.688**	0.691**	1	0.526**	0.710**	0.560**
Available P	0.587**	0.544**	0.663**	0.526**	1,.00	0.580**	0.689**
Available K	0.439**	0.512**	0.789**	0.710**	0.580**	1	0.513**
Invertase activity	0.374*	0.513**	0.514**	0.560**	0.689**	0.513**	1
Correlation sums	3.735	4.364	4.746	4.676	4.589	4.543	4.163
PC2 variable	Bulk density	Total porosity	Microbial counts				
Bulk density	1	−1	0.224				
Total porosity	−1	1	−0.214				
Microbial counts	0.214	−0.224	1				
Correlation sums	2.224	2.214	1.438				

sum. Water-stable soil aggregates play an important role in maintaining soil quality of erodible environment and was considered under MDS. The other variables were highly correlated with SOM and hence they were dropped (Table 5). In PC2, bulk density was chosen for the MDS because of its highest correlation sum, and total porosity was dropped. The microbial count was retained. In PC3 and PC4, capillary porosity and catalase were highly weighted variables. Capillary porosity was eliminated from the MDS because of its high correlation with bulk density ($r = -0.641^{**}$). Catalase activity was retained as a biochemical soil property.

Calculation of indicators weights

Having finalized the MDS indicators, numerical values for each soil quality indicator were converted into unit-less scores ranging from 0 to 1. The indicators retained in the MDS were considered 'good' in an increasing order except bulk density, and they were scored with Equation #1, as 'more is better'. Excessively high soil bulk density was considered 'poor', and it was scored with Equation #2, as 'less is better'. Once transformed, the MDS variables for each observation were weighted using PCA results (Supplementary Table S1, available online at http://dx.doi.org/10.1017/S0014479716000521).

Assessment of soil quality

The SQI calculated for the different tillage systems in the 0–5 cm depth decreased in the following order: 0.647 (NTS) > 0.558 (TS) > 0.516 (NTP) > 0.462 (NT) > 0.440 (TP) > 0.369 (T) (Supplementary Table S2). The SQI calculated for the different tillage systems in the 5–10 cm depth decreased in the following order: 0.493 (NTS) > 0.484 (TS) > 0.471 (NTP) > 0.414 (NT) > 0.377 (T) >0.374 (TP). The SQI calculated for the different tillage systems in the 10–30 cm depth decreased in the following order: 0.301 (NTS) > 0.278 (NT) > 0.265 (NTP) > 0 .252 (TS) > 0.215

(T) > 0.194 (TP). The SQI calculated for the different tillage systems in the 0–30 cm depth decreased in the following order: 0.527 (NTS) > 0.432 (TS) > 0 .419 (NTP) > 0.396 (NT) > 0.307 (T) > 0.303 (TP). These results clearly showed that the tillage systems had a significant impact on soil quality as shown by the SQI. The residue retention treatment significantly increased the soil quality in the top (0–5 and 5–10 cm) soil, whilst minimum tillage significantly increased the soil quality in the deeper soil layers (10–30 cm).

The soil quality indices were correlated with crop productivity under different tillage and stubble management treatments. Correlation analysis amongst SQI of different soil depths and grain yields showed that grain yield had a significant ($P < 0.01$) positive correlation with SQI in the 0–5 cm depth (Supplementary Table S3). Also, grain yield was significantly ($P < 0.05$) correlated with SQI in the 0–30 cm depth. However, there was no correlation amongst grain yield and SQI in the 5–10 or 10–30 cm depths.

DISCUSSION

Selection of soil depth for soil quality assessment

Tillage systems have a different effect on soil properties in different soil depths. Previous studies on conservation tillage have concentrated on single soil property evaluations related to different soil depths, such as changes in bulk density (Ferreras *et al.*, 2000; Unger and Jones, 1998), SOM (Chan and Heenan, 2005) and nutrients available to plants (Tracy *et al.*, 1990). Less attention has been paid to a comprehensive assessment of soil quality changes in different soil layers. The present study showed that grain yield had a positive correlation with SQI in the 0–5 cm ($P < 0.01$) and 0–30 cm ($P < 0.05$) soil depths, indicating that soil quality assessment in relation to cropping treatments should be conducted in the soil (0–5 cm) or tilth (0–30 cm) soil layers. Soil properties in the 0–5 cm depth can be considered as the early and sensitive indicators of management-induced changes in soil, whilst those in the 5–30 cm depth may have a strong effect on crop growth and grain yield. Therefore, under the experimental conditions, an effective soil quality assessment is in the depth of 0–5 and 0–30 cm for the typical soil in the Loess Plateau.

Selection of soil quality indicators

Selection of an MDS for soil quality evaluation took into account general soil and climatic conditions for the specific agro-ecological zone and their interaction. Most soil quality indicators suggested by previous researchers (Doran and Parkin, 1994; Karlen and Stott, 1994; Larson and Pierce, 1994; Singer and Ewing, 2000) were included in the list of variables assessed in the present study. Also, our list also included some other properties like saturation capacity and soil enzyme activities, but excluded some others like earthworm (Glover *et al.*, 2000), pH and soil texture (Doran and Parkin, 1994). These excluded ones are not applicable for the present agro-ecological zone, or are of no relevance to our soil quality comparison on a small regional scale. Inclusion of more biological soil properties such as soil enzyme activity helped improve the understanding of the specific soil systems. Andrews *et al.* (2002b) reported that choice amongst well-correlated variables could be based on the practicability of the variables. Options to retain or drop a variable from the final MDS may depend on various factors, such as the ease of sampling, cost of estimation, and logic and interpretability. Following these principles, we determined the final MDS for the various soil depths. In the 0–5 cm depth, the MDS consisted of total nitrogen, bulk density, microbial counts, capillary porosity, field capacity and saturation capacity. The final MDS in the 5–10 cm consisted of bulk density, field capacity, SOM, microbial counts and catalase activity. The final MDS in the 10–30 cm consisted of bulk density, no-capillary porosity, microbial counts and catalase activity. Two common indicators appeared in the MDSs of the three soil layers are bulk density and microbial counts, suggesting that these two properties play a key role in affecting the quality of the particular soil.

Soil quality assessment

Accurate assessment of soil quality requires a systematic method for measuring and interpreting soil properties that adequately serve as soil quality indicators. It is well known that individual soil properties may not be an adequate measure of soil quality. Integrated soil quality indicators based on a combination of soil properties can better reflect the status of soil quality than individual parameters. To select a representative MDS only those soil properties that showed significant treatment effect were chosen, which was determined by PCA. Based on the soil quality evaluation, the SQI was developed using the relative value of each of the selected soil properties and their weights.

In all of soil depths, the highest SQI occurred under NTS, which was also the treatment with highest and most stable yield. The results, in line with numerous studies in temperate regions, demonstrated that decreasing tillage intensity or increasing amount of crop residues retained on the soil surface leads to improved soil quality (Halvorson *et al.*, 2002; Lal *et al.*, 1994; Soon *et al.*, 2001). No-till or minimum tillage with crop residues covering soil surface offer the best opportunity to increase C sequestration, soil microbial biomass and nutrient cycling (Salinas-Garcia, 2001). In contrast, the T and TP treatments had the lowest SQI value mainly because of the human disturbance and the absence of residue retention. Soil inversion and pulverization by repeated tillage accelerates decomposition of organic matter thus affecting soil physical, chemical and biological properties (Cannell and Hawes, 1994). Care must be taken when looking at the SQI values of TS and NT, which were higher than the other three treatments but lower than NTS treatment. Improvement in soil quality depends mainly on the modification of soil properties through various means such as tillage reduction, residue retention or the combination of both. In rainfed agro-ecosystems of the loess plateau, these two management practices have been proven to be better than either practice used alone to elevate soil nutrient levels and improve soil quality. The lower SQI of the NTP treatment, as compared with NTS, indicated that soil degradation is associated with the removal of crop residues and the mulch of plastic film. The latter practice has been considered an innovative technique in boosting crop yield in arid and semi-arid areas (Gan *et al.*, 2013), but it may disturb soil eco-environment, leading to decreased soil aggregates and reduced microbial biomass. Accelerated decomposition of SOM due to plastic film leads to the reduction of SOM (Li *et al.*, 2003).

CONCLUSION

Considering the SQI for soil depths, the present study indicated that soil quality assessment should be done in the top soil (0–5 cm) layer. Different sets of indicators were found for MDSs of soil layers, but bulk density and microbial counts appeared in all MDSs, suggesting that these two indicators are closely related to the tillage systems tested. The greatest SQI score and the highest crop yield occurred with the no-till and stubble covering treatments, indicating that no-till with stubble retention is the most effective option for improving soil quality and increasing crop productivity in the semi-arid Loess Plateau of northwest China.

Acknowledgments. The project was supported by the National Natural Science Foundation of China (No. 31171513, No. 41461067 and No. 31560379), Natural Science Foundation of Gansu Province (145RJZA208) and the Fundamental Research Funds for the Gansu Provincial Universities (037041014, 035041049). Special thanks to all postgraduate and undergraduates students from Gansu Agricultural University who were involved in the project for different periods of time.

SUPPLEMENTARY MATERIAL

For supplementary material for this article, please visit http://dx.doi.org/10.1017/S0014479716000521.

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