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SUSTAINABLE ENVIRONMENTAL MANAGEMENT

Using a modified soil quality index to evaluate densely tilled soils with different yields in Northeast China

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Abstract
Northeastern China has long-term densely tilled soils that supply approximately 20% of the annual total national grains. There are very few reports on the agricultural soil quality subjecting to the predatory tillage. Here, the soil quality index (SQI) of a brunisolic soil was calculated using the minimum data set (MDS) and integrated quality index (IQI). The topsoil layer was divided into plow layer (11.9 ± 1.9 cm) and plow pan (11.4 ± 2.6 cm) in fields of high yields (HYB), medium yields (MYB), and low yields (LYB). Our results showed that the MDS of the topsoil layer only contained chemical indicators. The bulk density (BD), as one of the most important soil quality indicators, was found of no significant differences in the topsoil layers. In different layers (i.e., the topsoil layer, plow layer, and plow pan), the value of SQI presented a consistent tendency of HYB > MYB > LYB ($p < 0.05$). The correlation between SQI and yield was higher in the plow layer (0.60) and plow pan (0.63) than the topsoil layer (0.47). This further verified the reasonability of using soil stratification for SQI calculation. Our findings indicate the potential of using soil quality assessments to examine soil productivity (e.g., fertilizer deficiency) in crop lands with soil stratification.

Keywords Densely tilled soil · Soil properties · Minimum data set · Soil quality index · Critical limit

Introduction

Soil quality is vital for humans because it not only affects the production of food but also the diversity and function of ecosystems (Askari and Holden 2014; Nakajima et al. 2015). With the rapid growth of the land and population, agricultural sustainability has been considered essential for economic development. Agricultural sustainability ensures continuous food supply, which is usually fragile in developing countries. For example, Northeastern China (approximately 20% of the total national grain supply) uses predatory tillage practices (less rotation and no-till, and excess use in inorganic fertilizers), which results in negative effects on soil quality. Plow pan has been thickening and the contradictions occur between water and fertilizer (Liu et al. 2010; You et al. 2017).

Soil quality cannot be directly measured, but it can be reflected by evaluating the physical, chemical, and biological properties of soil (Bhardwaj et al. 2011; Obade and Lal 2016). The physical and chemical properties of soil are widely used (Rojas et al. 2016; Xia et al. 2015). Soil biological properties are mostly used for minor artificially destructive ecosystems, such as forests and grasslands (Parisi et al. 2005; Ritz et al. 2009). Different conceptual frameworks have been developed for soil quality evaluation, from visual approaches (Karlen et al. 2003) to analytical methods (Askari and Holden 2014). The soil quality index (SQI) is the most commonly employed method because of its simplicity and quantitative flexibility (Andrews et al. 2002; Bhardwaj et al. 2011; Hammac et al. 2016). The minimum data set (MDS) has been developed to identify the smallest number of measurable soil properties. Using MDS, fewer soil properties are applied

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to calculate SQI, making the calculation process simpler (Andrews and Carroll 2001; Rezaei et al. 2006). Based on this, the SQI can be calculated through several systematic approaches, such as summing (Cambardella et al. 2004), multiplying (Amirinejad et al. 2011), and averaging (Svoray et al. 2015). However, these approaches do not compare the contribution of each indicator to the SQI. The integrated quality index (IQI) provides a more meaningful SQI by assigning weight and standardizing scores to each indicator in the MDS (Andrews et al. 2002; Doran and Parkin 1994; Hammac et al. 2016).

Many studies have been conducted to evaluate the soil quality of cropland using the SQI in recent decades (Mishra et al. 2017; Ngo-Mbogba et al. 2015), especially for reduced tillage (Raiesi and Kabiri 2016), fertilizer application (Choudhary et al. 2018), and residue incorporation (Das et al. 2016). A few studies have been carried out under farmers' management conditions (Liu et al. 2014; Ngo-Mbogba et al. 2015). Soil profiles have been considered as a whole (Askari and Holden 2015; Karlen et al. 2013); however, field practices always cause physical disturbances, such as moving the plow pan to the top of the soil layer. The plow pan is mainly caused by long-term mechanical crushing and clay-particle deposition (Bertolino et al. 2010; Floyd 1984). Therefore, ignoring the stratification of soil profiles might result in errors when assessing soil qualities.

Liaoning Province, as one of the major commodity grain production bases in China, plays a decisive role in the nation's grain supply. The brunisolic soil region is account for approximately half of the total area (14,800 ha) in Liaoning Province, Northeast China. Finding a way to increase crop yields in this area is crucial to national food security, but it is still a serious problem challenge. We believed that increasing or at least maintaining soil quality (SQ) to meet crop production goals is a necessary condition to meet this challenge. Previous studies have mainly focused on the effects of tillage and freeze-thaw cycles on soil properties (Piao et al. 2016; Wang et al. 2017; You et al. 2017). However, soil quality assessments have not been reported in this area. The objectives of this study were to (1) establish a MDS for the topsoil layer, (2) assess the soil quality of high (HYB), medium (MYB), and low (LYB) yield fields, and (3) establish a reasonable soil quality evaluation method for the brunisolic soil region. In the evaluation of soil quality, crop yield can be used to verify the rationality of SQI. If the SQI and crop yield are closely related, it can confirm that the selected soil indicators are reasonable in calculating the SQI (Armenise et al. 2013; Liu et al. 2018). We hypothesized that (1) there might be significant differences in the SQI of HYB, MYB, and LYB; and (2) soil stratification might have an important impact on soil quality evaluation.

Materials and methods

Site description and experimental setup

This study was performed in Tieling County, Liaoning Province, Northeast China (41.98–42.55° N, 123.47–124.55° E, 63 m a.s.l.). This region has a semi-humid monsoon continental climate. The annual mean temperature and precipitation (2001–2015) were 6.3 °C and 675 mm, respectively. The soil type of the experimental field is brunisolic soil, which is developed from loess parent materials (Piao et al., 2017). The texture of the 0–20 cm soil layer is divided into 64.7% sand (2–0.05 mm), 18.9% silt (0.05–0.002 mm), and 16.4% clay (< 0.002 mm). The bulk density of the topsoil layer (0–30 cm) was 1.32 g cm^{-3}.

The crop-planting pattern is one harvest per year, and all water requirements for crops are provided by precipitation. Based on a local survey, 25 maize fields were selected as sampling plots. The distance between these plots ranged from 0.1 to 10 km. Three replications (36 m^2) were vertically arranged at 5-m intervals between plots. Rotary tillage, ridging, and compacting were conducted uniformly by the cooperative. Further, 200 kg N ha^{-1}, 70 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1} were applied during the seed sowing stage.

Soil sampling and analysis

Three soil profiles were dug in the flat location of each sampling plot in October 2015. The plow pan was assessed by soil compactness measurements (SC900, Field Scout, USA). As shown in Fig. 1, compactness of a typical soil profile commonly increased at a depth of 10–12 cm and was increased or maintained at a high level. It was marked as the plow pan; the thickness of which was 11.4 ± 2.6 cm, ranging between 7.5 and 15.0 cm. The plow layer was defined as the surface soil above the plow pan; the thickness of which was 11.9 ± 1.9 cm. Accordingly, the entire plow layer and plow pan were considered as the topsoil layer. For each layer, 3–5 soil cores were well mixed to form a composite sample and immediately transported to the laboratory in the Shenyang Agricultural University. Table 1 summarizes the analytical methods which were used to determine the soil physical and chemical indicators.

Mean yield and relative yield of maize

With three replications, a rectangle of 7.2-m wide (six rows) and 10-m long was chosen as the yield measurement area in October 2015. The grains were separated from the air-dried cob manually. Maize yield was standardized to 13% moisture content of grains, which was measured with a grain moisture-measuring device (PM-8188-A, KETT, Japan). According to yield measurements of the 25 sampling plots, 7 HYB (>

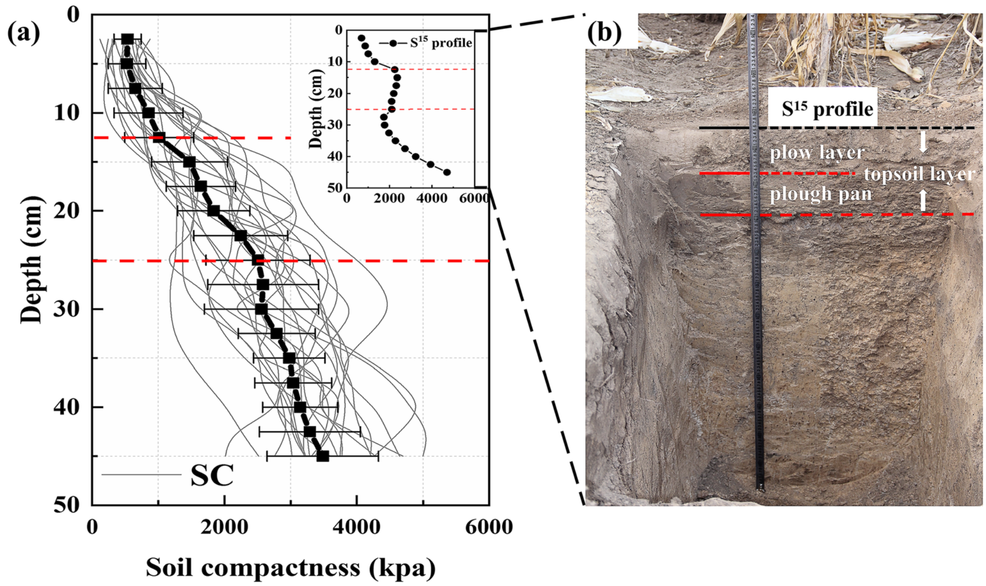

Fig. 1 Soil compactness of the 25 maize fields (**a**) and the real scene of a typical stratified soil profile (**b**). The mean soil compactness was shown in thick black solid line. The inset represents the compactness value of the typical stratified soil profile

9 t ha^{-1}), 10 MYB (6–9 t ha^{-1}), and 8 LYB (< 6 t ha^{-1}) were differentiated ($p < 0.01$).

The relative yield (RY) is defined as the percent of yield of each sampling plot to the highest yield of the sampling plots (Biswas et al. 2017):

$$RY(\%) = \frac{\text{yield of each sampling plot}}{\text{maximum yield of the sampling plot}} \times 100 \quad (1)$$

Calculation of soil quality index

The SQI was determined by the following three steps (Andrews et al. 2002). First, the one-way analysis of variance (ANOVA) was used to test all the parameters, and only those with differences of $p \leq 0.05$ were used to standardize the principal component analysis (PCA). The PCs with the eigenvalue of ≥ 1 were then examined (Rezaei et al. 2006). Within each PC, the highly weighted variables (i.e., the absolute values within 10% of the highest weight) were retained to form the initial MDS. These variables in the MDS were selected if they were not correlated; otherwise, the variable with the highest correlation sum (or highest factor loading) was considered. Second, the weight of each variable in the MDS was calculated by its communality (Shukla et al. 2006). Furthermore, the soil indicator scores were normalized to a value between 0 and 1.0 by the standard scoring function (SSF) (Andrews et al. 2002; Liu et al. 2018). Finally, the SQI was calculated using the integrated quality index (IQI) equation (Doran and Parkin 1994):

Table 1 Analytical protocols for different indicators of soil physical and chemical properties selected in this study

Properties	Indicators	Protocols	Reference
Physical	BD	Core method	Blake and Hartage (1986)
	SC	Compactness meter	Taylor and Brar. (1991)
	TPO	Calculated from BD	Vasu et al. (2016)
	FC	Gravimetric method	Flint and Flint (2002)
	WSA	Wet sieving method	Yoder (1936)
Chemical	AN	Alkaline hydrolysis diffusion	Cornforth and Walmsley (1971)
	AP	Sodium bicarbonate Olsen method	Nafiu (2006)
	AK	Flame photometric method	Motsara and Roy (2008)
	TN	Kjeldahl	Bremner (1960)
	TPH	Digestion, spectrophotometer detection	Olsen et al. (1982)
	TK	Digestion, flame photometer detection	Lu et al. 2000)
	SOM	Dichromate wet combustion	Nelson and Sommers (1982)
	pH	Soil paste (soil:H2O = 1:2.5)	Lu et al. (2000)

BD, bulk density; *SC*, soil compaction; *TPO*, total porosity; *FC*, field capacity; *WSA*: water stable aggregates; *AN*, available nitrogen; *AP*, available phosphorus; *AK*, available potassium; *TN*, total nitrogen; *TPH*, total phosphorus; *TK*, total potassium; *SOM*, soil organic matter

$$\mathrm{SQI} = \sum_{i=1}^{n} W_i \times S_i \quad (2)$$

where W_i is the assigned weight of each indicator, S_i is the indicator score, and n is the number of indicators in the refined MDS.

Critical limits according to the relative yield

The critical limit of a soil quality indicator is its desirable range required for normal functioning soil (Biswas et al. 2017; Lopes et al. 2013). Regressions were developed between the identified key indicators in MDS and relative yield (RY). The values of key indicators higher than 80% of RY were considered adequate. The values of key indicators corresponding to 40–80% of RY were defined as moderate. The values lower than 40% of RY were classified as inferior.

Statistical analyses

All data were statistically analyzed using SPSS 18.0 (SPSS Inc., Chicago, USA). The one-way ANOVA was performed to test the differences between soil indicators and the SQI of different fields. The mean values were compared by least significant difference (LSD). The indicators in MDS were selected by the PCA. The regression analysis was conducted to determine the relationship between SQI and maize yield, as well as the relative yields and key soil indicators.

Results

Soil physical and chemical properties

To verify the effects of soil stratification, the characteristics of the topsoil layer (non-stratification), plow layer, and plow pan (stratification) were presented independently (Table 2). In the topsoil layer, the SC of HYB was significantly lower than that of MYB and LYB. There were no significant differences with respect to other soil physical indicators between different yield plots. In the plow layer, the BD, SC, and TPO of HYB were significantly different from those of LYB. Furthermore, the BD and SC of MYB were also higher than those of LYB. In the plow pan, several physical indicators of HYB were significantly different from those of MYB (BD, SC, and WSA) and LYB (BD, SC, and TPO). In addition, there were significant differences in BD, SC, TPO, and WSA between MYB and LYB.

In the topsoil layer, some chemical indicators of HYB were significantly higher than those of MYB (AN, AK, and TPH) and LYB (AN, TN, TPH, and SOM) (Table 3). Furthermore, the AN and SOM of MYB were higher than those of LYB. In the plow layer, there were significant differences in the AN and AK between HYB and MYB. In addition, the AN of HYB and SOM of MYB were higher than those of LYB. In the plow pan, a few chemical indicators of HYB were higher than those of MYB (AP, TPH, and SOM) and LYB (AN, AP, AK, and TN). Moreover, the AN and AK of MYB were higher than those of LYB.

Indicator selection for MDS

Table 4 presents the PCA of statistically significant physical and chemical indicators of soil. In this step, the number of PCs was acquired for the topsoil layer, plow layer, and plow pan. Both the topsoil layer and plow layer had three PCs, whereas, the plow pan had five PCs. Even with the same number of PCs, the soil indicators in each PC were different from one another. Overall, the PCs for different layers explained approximately 77.1% (topsoil layer), 80.5% (plow layer), and 82.2% (plow pan) of variations in the soil properties. The highly weighted (i.e., high factor loading) variables are shown in bold (Table 4), which were used to reduce the redundancy of variables in each PC.

In the topsoil layer, AN, TN, and SOM were selected to represent PC1, PC2, and PC3 (Table 5). When the correlation sums were the same, the indicators with lower factor

Table 2 Physical properties for the topsoil layer, plow layer, and plow pan in the 25 maize fields

Indicators	Topsoil layer			Plow layer			Plow pan		
	HYB (n = 7)	MYB (n = 10)	LYB (n = 8)	HYB (n = 7)	MYB (n = 10)	LYB (n = 8)	HYB (n = 7)	MYB (n = 10)	LYB (n = 8)
BD (g cm^{-3})	1.35 ± 0.04a	1.34 ± 0.07a	1.33 ± 0.06a	1.29 ± 0.07a	1.24 ± 0.12a	1.18 ± 0.09b	1.41 ± 0.05c	1.44 ± 0.06b	1.47 ± 0.06a
SC (Mpa)	1.52 ± 0_38b	1.85 ± 0.36a	1.84 ± 0.26a	1.09 ± 033a	1.17 ± 0.40a	0.76 ± 0.28b	1.93 ± 0.37c	2.53 ± 0.60b	2.93 ± 0.47a
TPO (%)	48.93 ± 1.72a	49.48 ± 2.81a	49.88 ± 2.09a	51.47 ± 2.78b	53.24 ± 4.70ab	55.36 ± 3.46a	46.97 ± 2.12a	45.72 ± 2.19a	44.40 ± 244b
FC (%)	17.46 ± 1.46a	17.19 ± 1.87a	16.84 ± 1.17a	18.69 ± 1.60a	18.33 ± 2.09a	18.17 ± 1.21a	16.24 ± 1.97a	16.05 ± 2.33a	15.51 ± 1.96a
WSA (%)	16.23 ± 3.64a	15.05 ± 2.44a	14.92 + 2.50a	21.46 ± 6.72a	21.25 ± 4.98a	19.55 ± 4.04a	11.00 ± 3.23a	8.84 ± 1.67b	10.30 ± 3.14a

Data shown are mean ± standard deviation of three replicates. Values for the same property with different letters indicate significant differences at $p \leq 0.05$

Table 3 Chemical properties for topsoil layer, plow layer and plow pan in the 25 maize fields

Indicators	Topsoil layer			Plow layer			Plow pan		
	BYE (n = 7)	MYB (n = 10)	LYS (n = 8)	HIS (n = 7)	MIS (n = 10)	LYS (n = 8)	HYS (n = 7)	MYB (n = 10)	LYS (n = 8)
AN (mg kg^{-1})	103.00 ± 7.01a	94.28 ± 8.00b	88.12 ± 7.89c	119.21 ± 13.50a	104.51 ± 16.11b	97.23 ± 13.96b	86.79 ± 3.99a	84.04 ± 5.88a	79.00 ± 6.81b
AP (mg kg^{-1})	15.05 ± 4.04a	14.06 ± 3.70a	14.01a ± 3.08a	25.70 ± 8.02a	24.19 ± 7.27a	24.26 ± 6.19a	4.39 ± 0.50a	3.93 ± 0.72b	3.76 ± 0.58b
AK (mg kg^{-1})	181.42 ± 37.31a	166.01 ± 18.94b	170.05 ± 18.66ab	222.96 ± 72.31a	192.66 ± 27.06b	211.70 ± 38.98ab	139.88 ± 10.45a	139.37 ± 11.44a	128.40 ± 10.07b
TN (g kg^{-1})	1.09 ± 0.07a	1.03 ± 0.07ab	1.01 ± 0.08b	1.21 ± 0.10a	1.19 ± 0.11a	1.18 ± 0.14a	0.92 ± 0.10a	0.87 ± 0.10ab	0.85 ± 0.10b
TPH (g kg^{-1})	0.42 ± 0.05a	0.39 ± 0.04b	0.39 ± 0.04b	0.52 ± 0.09a	0.50 ± 0.07a	0.49 ± 0.07a	0.32 ± 0.04a	0.29 ± 0.04b	0.30 ± 0.03ab
TK (g kg^{-1})	21.12 ± 1.69a	20.68 ± 1.73a	21.27 ± 1.00a	20.30 ± 2.96a	18.90 ± 2.91a	19.60 ± 1.10a	21.94 ± 2.00a	22.46 ± 1.77a	22.95 ± 1.71a
SOM (g kg^{-1})	14.08 ± 1.99a	14.21 ± 2.11a	13.07 ± 1.01b	15.90 ± 3.88ab	16.74 ± 4.22a	14.16 ± 2.00b	12.27 ± 0.76a	11.68 ± 0.91b	11.98 ± 0.91ab
pH	5.56 ± 0.20a	5.57 ± 0.15a	5.60 ± 0.17a	5.01 ± 0.21a	4.90 ± 0.12a	5.02 ± 0.28a	6.10 ± 0.30a	6.25 ± 0.26a	6.18 ± 0.24a

Data shown are mean ± standard deviation of three replicates. Values for the same property with different letters indicate significant differences at $p \leq 0.05$

Table 4 Results of principal component analysis with statistically significant soil physical and chemical indicators

Statistical parameters	PC1			PC2			PC3			PC4			PC5		
	Topsoil layer	Plow layer	Plow pan	Topsoil layer	Plow layer	Plow pan	Topsoil layer	Plow layer	Plow pan	Topsoil layer	Plow layer	Plow pan	Topsoil layer	Plow layer	Plow pan
Eigenvalues	1.37	2.34	2.54	1.35	1.31	1.70	1.14	1.18	1.48	–	–	1.28	–	–	1.22
% of variance	27.34	38.97	25.35	26.92	21.81	17.00	22.76	19.69	14.78	–	–	12.80	–	–	12.24
Cumulative	27.34	38.97	25.35	54.31	60.78	42.35	77.07	80.47	57.13	–	–	69.93	–	–	82.16
Eigenvalues/factor loading															
BD	–	*0.920*	*− 0.948*	–	− 0.315	− 0.052	–	0.065	− 0.049	–	–	− 0.201	–	–	− 0.070
SC	0.411	*0.860*	0.186	–	0.396	− 0.083	0.344	− 0.138	− 0.083	–	–	*0.891*	–	–	− 0.088
TPO	–	*− 0.920*	*0.948*	–	0.315	0.052	–	− 0.065	0.049	–	–	0.201	–	–	0.070
WSA	–	–	− 0.096	–	–	0.082	–	–	0.013	–	–	− 0.112	–	–	*0.938*
AN	*0.818*	− 0.120	0.050	0.219	− 0.325	0.350	− 0.214	*0.742*	*0.797*	–	–	− 0.154	–	–	− 0.206
AP	–	–	0.069	–	–	− 0.104	–	–	*0.883*	–	–	0.027	–	–	0.176
AK	*− 0.780*	0.124	*0.862*	0.105	0.294	− 0.193	− 0.288	*0.804*	− 0.106	–	–	− 0.478	–	–	− 0.013
TN	0.176	–	0.243	*0.797*	–	*0.818*	− 0.220	–	0.083	–	–	− 0.144	–	–	− 0.080
TPH	− 0.039	–	− 0.250	*0.777*	–	*0.771*	0.363	–	0.014	–	–	0.060	–	–	0.220
SOM	0.058	− 0.230	− 0.014	0.015	*0.868*	*0.796*	*0.873*	0.019	0.427	–	–	0.338	–	–	0.445

Values in italic indicated the highly weighted variables

Table 5 Correlation coefficients and correlation sums for highly weighted variables under principal components (PC) with multiple high factor loadings

		Topsoil layer			Plow layer				Plow pan			
PC1 variables	Correlation coefficients		AN	AK		BD	SC	TPO		BD	TPO	AK
		AN	1	− 0.36**	BD	1	− 0.99**	− 1.00**	BD	1	− 1.00**	0.53**
		AK	− 0.36**	1	SC	− 0.99**	1	0.47**	TPO	− 1.00**	1	− 0.53**
					TPO	− 1.00**	0.47**	1	AK	0.53**	− 0.53**	1
	Correlation sums		1.36	1.36		2.99	2.46	2.47		2.53	0.53	2.06
PC2 variables	Correlation coefficients		TN	TPH	–	–	–	–		TN	TPH	SOM
		TN	1	0.33**	–	–	–	–	TN	1	0.36**	0.39**
		TPH	0.33**	1	–	–	–	–	TPH	0.36**	1	0.35**
					–	–	–	–	SOM	0.39**	0.35**	1
	Correlation sums		1.33	1.33	–	–	–	–		1.75	1.17	1.71
PC3 variables	Correlation coefficients		–	–		AN	AK	–		AN	AP	–
		–	–	–	AN	1	0.16	–	AN	1	0.34**	–
		–	–	–	AK	0.16	1	–	AP	0.34**	1	–
	Correlation sums		–	–		1.16	1.16	–	–	1.34	1.34	–

* Correlation is significant at the 0.05 level

** Correlation is significant at the 0.01 level

loading were ignored (e.g., AK for PC1, TPH for PC2). In the plow layer, the BD and SOM were selected to represent PC1 and PC2. Both the AK and AN were retained in PC3, as they were not correlated. In the plow pan, BD, TN, and AP were selected to represent PC1, PC2, and PC3. As there was only one variable, the SC and WSA were selected for PC4 and PC5. For the topsoil layer, the SOM, AN, and TN were retained in the MDS. There were four MDS indicators, viz., BD, SOM, AK, and AN, for the plow layer. As for the plow pan, five MDS indicators, viz., BD, SC, WSA, AP, and TN, were retained.

Soil quality assessment

It is noteworthy that the MDS for the topsoil layer (non-stratification) only included chemical indicators, while both physical and chemical indicators were contained in the MDS for the plow layer and plow pan (Table 6). Although the role was smaller compared with that in the topsoil layer, the weight of chemical indicators (SOM, AK, and AN) accounted for 69.7% of all indicators in the plow layer. As for the plow pan, 63.0% of the weight of all indicators was occupied by physical indicators (BD, SC, and WSA). Specifically, the BD presented the highest weight in both the plow layer (0.303) and plow pan (0.220).

Figure 2 presents the SQI of the topsoil layer, plow layer, and plow pan. Irrespective of non-stratification (topsoil layer) or stratification (plow layer and plow pan), the SQI of different fields exhibited a similar trend (HYB > MYB > LYB). The differences between HYB, MYB, and LYB were significant for each soil layer ($p < 0.05$).

Figure 3 shows the correlation between SQI and maize yield. Positive relationships between the SQI and yield were observed for the topsoil layer ($Y = 0.02X + 0.32$, $p < 0.001$),

Table 6 Communality and weight of soil quality indicators in MDS

MDS indicators	Communality			Weight		
	Topsoil layer	Plow layer	Plow pan	Topsoil layer	Plow layer	Plow pan
BD	–	0.948	0.949	–	0.303	0.220
SC	–	–	0.851	–	–	0.200
WSA	–	–	0.908	–	–	0.210
AN	0.762	0.627	–	0.340	0.200	–
AP	–	–	0.827	–	–	0.190
AK	–	0.748	–	–	0.239	–
TN	0.715	–	0.763	0.320	–	0.180
SOM	0.766	0.806	–	0.340	0.258	–

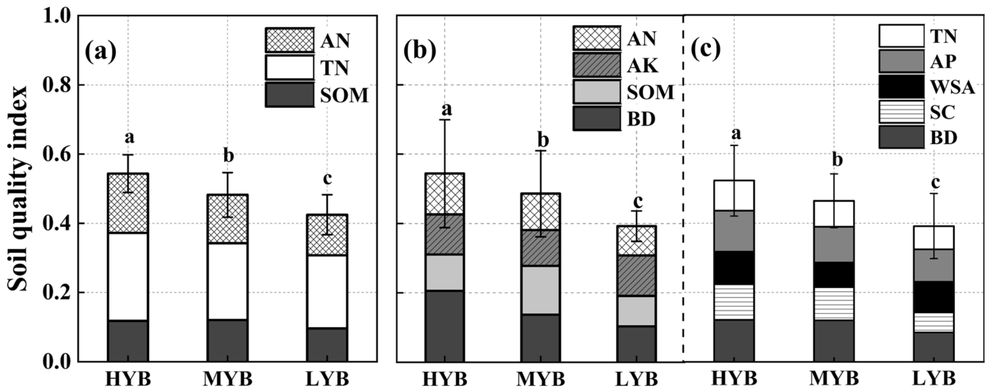

Fig. 2 Mean soil quality index (SQI) of different yields (HYB, MYB, and LYB) for topsoil layer (**a**), plow layer (**b**), and plow pan (**c**). Error bars denote the standard deviation of overall index values in each soil layer. Different lowercase letters denote a significant difference at $p \le 0.05$

plow layer (Y = 0.04X + 0.15, $p < 0.001$), and plow pan (Y = 0.03X + 0.20, $p < 0.001$). Furthermore, the correlation coefficient of the plow layer (0.60) and plow pan (0.63) was higher than that of the topsoil layer (0.47). This indicated that stratification (plow layer and plow pan) was more plausible than non-stratification (topsoil layer) in this study. Therefore, only the critical limits for plow layer and plow pan were explored in the following sections.

Critical limit of the soil quality indicator

In the plow layer, there were positive correlations ($p < 0.05$) between the AN, AK, SOM, BD, and RY (Fig. 4a–d). In the plow pan, there were also positive correlations between the AP, TN, WSA, and RY ($p < 0.05$). However, negative correlations between the BD, SC, and RY were observed in the plow pan (Fig. 4e–i). The range of key indicators (adequate, moderate, and inferior) is summarized in Table 7. In the plow layer, the lower (40% of RY) and upper (80% of RY) critical limits of AN, AK, and SOM were 96.67–118.67 mg kg^{-1}, 186.98–223.38 mg kg^{-1}, and 14.84–17.24 g kg^{-1}, respectively. In the plow pan, the lower and upper critical limits of SC, WSA, AP, and TN were 2911.94–2018.74 kpa, 8.77%–11.57%, 3.73–4.33 mg kg^{-1}, and 843.01–920.21 mg kg^{-1}, respectively. It is important to note that the BD had opposite effects in the plow layer and plow pan. The upper and lower critical limits of BD were 1.16–1.28 g cm^{-3} for the plow layer and 1.46–1.41 g cm^{-3} for the plow pan.

Discussion

Characteristic of key indicators in the topsoil layer

In this study, five physical and eight chemical indicators were used to reflect the soil properties of HYB, MYB, and LYB (Tables 2 and 3). Specifically, the soil properties of the plow layer and plow pan (i.e., stratification of the topsoil layer) were analyzed. There were obvious differences in the soil characteristics of HYB, MYB, and LYB. For example, six indicators (SC, AN, AK, TN, TPH, and SOM) in the topsoil layer were significantly different between these fields. There were also 6–8 indicators (BD, SC, TPO, WSA, AN, AK, AP, TN, TPH, and SOM) that had significant differences in the plow layer and plow pan. Among these indicators, BD, AP, AK, TN, and SOM have been frequently used in previous studies (Askari and Holden 2015; Bhardwaj et al. 2011). Other indicators such as SC, WSA, AN, and TK have been used to make the soil quality assessments more comprehensive (Aziz et al. 2013; Sofi et al. 2016).

Our results also showed that the indicators with significant differences ($p < 0.05$) were distinct in the plow layer and plow

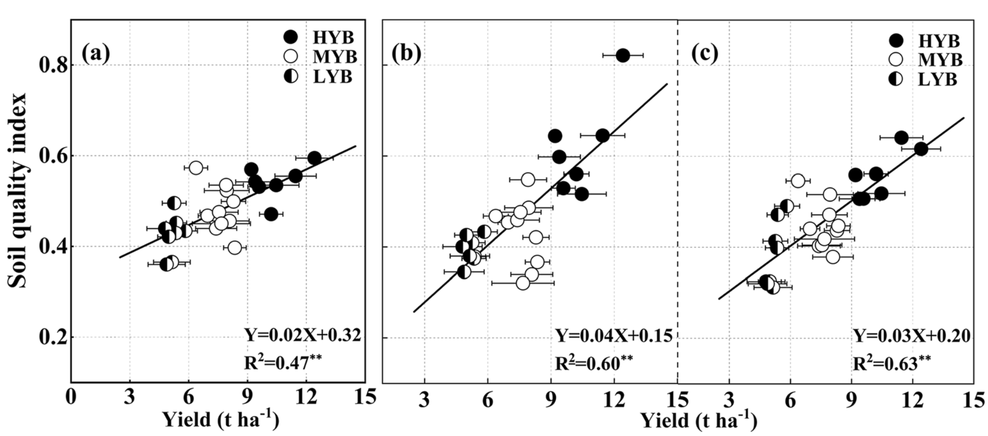

Fig. 3 Correlations between soil quality index (SQI) and crop yield for topsoil layer (**a**), plow layer (**b**), and plow pan (**c**)

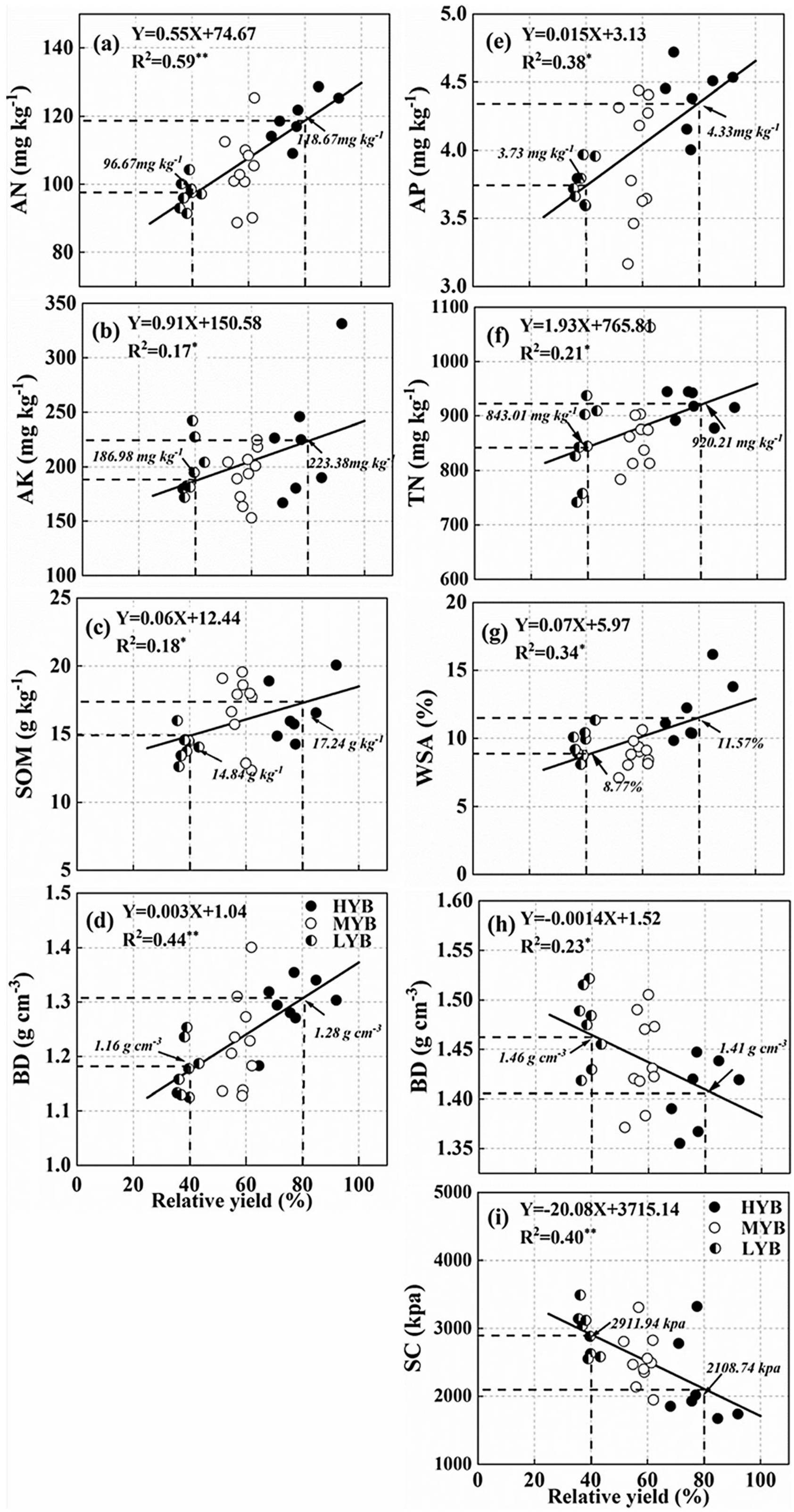

Fig. 4 Critical limits of soil quality indicators of plow layer (**a**–**d**) and plow pan (**e**–**i**)

pan (Tables 4 and 5). This indicated that the plow layer and plow pan had significantly different soil characteristics. The plow layer had three principal components (PCs), whereas, there were five PCs for the plow pan. Furthermore, the components of the MDS were different for the plow layer (BD, SOM, AK, and AN) and plow pan (BD, SC, WSA, AP, and

Table 7 Critical limits of soil quality indicators for plow layer and plow pan

Soil layer	Indicators in MDS	Classification by the relative yield (RY) of maize		
		Inferior	Moderate	Adequate
Plow layer	BD (g cm^{-3})	< 1.16	1.16–1.28	> 1.28
	AN (mg kg^{-1})	< 96.67	96.67–118.67	> 118.67
	AK (mg kg^{-1})	< 186.98	186.98–223.38	> 223.38
	SOM (g kg^{-1})	< 14.84	14.84–17.24	> 17.24
Plow pan	BD (g cm^{-3})	> 1.46	1.41–1.46	< 1.41
	SC (kpa)	> 2911.94	2018.74–2911.94	< 2018.74
	WSA (%)	< 8.77	8.77–11.57	> 11.57
	AP (mg kg^{-1})	< 3.73	3.73–4.33	> 4.33
	TN (mg kg^{-1})	< 843.01	843.01–920.21	> 920.21

Classifications are as follows: inferior (values of indicator were lower than RY of 40%), moderate (values of indicators were corresponding to RY of 40% to 80%), and adequate (values of indicators were higher than RY of 80%)

TN). However, the MDS of the topsoil layer contained only chemical indicators (SOM, AN, and TN). The BD is considered one of the most important soil quality indicators (Chaudhari et al. 2013; Liu et al. 2018). Surprisingly, there were no significant differences in the BD in the topsoil layer. This might be attributed to non-stratification of the plow layer and the plow pan, which weakens some physical characteristics of the topsoil layer.

Influences of soil stratification on soil quality assessments

We found that the soil chemical indicators accounted for 69.7% and 37.0% of all MDS indicators in the plow layer and plow pan (Table 6). With non-stratification, the soil chemical indicators (AN, TN, and SOM) accounted for 100% of the quality variations in the topsoil layer. Several studies have also demonstrated that the soil chemical indicators are the key indicators in soil quality assessments (Sione et al. 2017; Xia et al. 2015). Moreover, the kind of key chemical indicators varies with management intensity, crop selection, and soil type (Hammac et al. 2016; Obade and Lal 2014; Xia et al. 2015). As shown in Fig. 2, the soil physical indicators (BD, SC, and WSA) were also the key indicators of the plow layer and plow pan. Furthermore, the BD was the most important indicator (highest weights) in both the layers. This observation is consistent with the results of several studies, which suggested that the BD significantly influenced the SQI at the surface soil layer (Askari and Holden 2015; Obade and Lal 2016). Studies have also indicated that the BD is not an important soil quality indicator for barren soils (Liu et al. 2014). Overall, the SQI of different yield fields had a consistent tendency of HYB > MYB > LYB ($p < 0.05$).

To verify the rationality of calculating the SQI, the correlations between SQI and yield were fixed (Fig. 3). Apparently, the plow layer and plow pan had higher correlation coefficients (0.60–0.63) than non-stratification of the topsoil layer (0.47). The strong correlations suggested that soil stratification (plow layer and plow pan) might be a promising method to evaluate soil quality for brunisolic soil in Northeast China. The possible reason is that the plow pan of this area had moved up and became thicker because of long-term shallow tillage. In turn, the plow pan would form a barrier that prevented root penetration, air circulation, and the capacity of water and nutrient preservation (Bertolino et al. 2010; Chaudhari et al. 2013). Furthermore, previous studies commonly calculated the SQI of the 0–30 cm topsoil layer without stratification (Bhardwaj et al. 2011; Hammac et al. 2016). Although some studies have provided more attention to subsoil layers (Mishra et al. 2017; Obade and Lal 2014), and the plow pan is not used as the criterion of soil stratification. It is noteworthy that further studies are required to better define the SQI by including more physical, chemical, and biological indicators (Liu et al. 2015; Mishra et al. 2017).

Implications for field management in brunisolic soil region

After obtaining the SQI and its components for HYB, MYB, and LYB, there is a need to maintain soil structure and function at desired levels (Lopes et al. 2013; Biswas et al. 2017). As soil stratification has a greater correlation with SQI and yield, key indicators of the plow layer and plow pan were considered in this study (Fig. 4). Furthermore, the critical limits equivalent to 40% and 80% of RY were treated as the normal targets of soil quality indicators (Table 7). Therefore, these specific critical limits can be realized concretely through appropriate soil and crop management practices (Biswas et al. 2017).

The major constraints in increasing the productivity of this area are lower fertilizer contents and poor BD condition. In both the plow layer and plow pan, the key soil chemical indicators should be improved for low yield fields. More types of fertilizers (AN, AK, and SOM) are needed for the plow layer. This is probably because maize mainly absorbs water and nutrients by lateral roots (Peng et al. 2012; Yang et al. 2015). In addition, the critical limits of AN (96.67–118.67 mg kg^{-1}) and AK (186.98–223.38 mg kg^{-1}) were higher than the normal requirements of maize (AN: 70 mg kg^{-1}, AK: 110 mg kg^{-1}), while the SOM (14.84–17.24 g kg^{-1}) was close only to the fourth level threshold (15–20 g kg^{-1}) of this region (Xu et al. 2010). This indicated that brunisolic soil had become barren gradually. In the plow pan, the soil physical indicators (BD, SC, and WSA) played a central role in soil quality improvements. Furthermore, the BD of the plow pan had opposite effects (negative relationship) compared with that of the plow layer. That is, a relative solid soil plow layer would be beneficial for root anti-lodging, water conductivity improvement, and nutrient accumulation for regional root growth (Nosalewicz and Lipiec 2014; Pulido et al. 2017). In the plow pan, loose soil (lower BD) was required for the penetration of deep roots (Bian et al. 2016; Tesfahunegn et al. 2011). The implication of this study is that we should consider the stratification of soil profiles during soil quality assessments.

Conclusions

Using the SQI as a tool, the properties of brunisolic soil were evaluated in high (HYB), medium (MYB), and low (LYB) yield fields. Three physical (BD, SC, and WSA) and five chemical (AN, AP, AK, TN, and SOM) indicators were selected from 13 indicators, which were used to construct the MDS. The soil chemical indicators accounted for 69.7% and 37.0% of all the MDS indicators in the plow layer and the plow pan. Compared with that of the plow layer and plow pan, the MDS of the topsoil layer contained only chemical indicators (SOM, AN, and TN). Irrespective to soil stratification, the SQI of different yield fields had a consistent tendency of HYB > MYB > LYB ($p < 0.05$). However, the correlations between SQI and yield were higher for the plow layer and plow pan (0.60–0.63) than that of the topsoil layer (0.47). This further confirmed that the stratification of the plow layer and plow pan was more reasonable in calculating the SQI. According to the critical limits of identified key indicators, more fertilizers (AN, AK, and SOM) are needed for the plow layer. Furthermore, the soil structure of relatively high BD in the plow layer and lower BD in plow pan are required for high yield fields. Overall, reasonable fertilization combined with subsoil-tillage should be encouraged in this area.

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