



Soil quality assessment of paddy fields (in Northern Iran) with different productivities: establishing the critical limits of minimum data set indicators

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Abstract

The aim of this study was to assess soil quality and identify main indicators and their critical limits as a function of relative rice yield in northern Iran. In present study, 60 topsoil (0–30 cm) samples were collected and 18 physical, chemical, and biological soil attributes were measured and analyzed. Based on the mean rice yield obtained from sampling sites, paddy fields were divided into fields with low ($< 4.5 \text{ t ha}^{-1}$) and high ($\geq 4.5 \text{ t ha}^{-1}$) productivity. Using the principal component analysis (PCA), among 18 soil indicators, 4 indicators were selected as the minimum dataset (MDS) including soil organic carbon (OC), urease activity, bulk density (BD), and available Zn (AZn). The upper and lower limits of MDS indicators and soil quality index (SQI) were defined using scatterplot. The results showed that the mean SQI of high productivity fields (0.95) was significantly higher than that in low productivity fields (0.77). The upper and lower limits for soil OC were 3.5 and 1.0 ($\text{g } 100 \text{ g}^{-1}$), urease activity 84 and 43 ($\mu\text{g NH}_4 \text{ g soil}^{-1} 2 \text{ h}^{-1}$), BD 1.84 and 1.60 (g cm^{-3}), and AZn 2.0 and 0.6 (mg kg^{-1}), respectively. The soil quality assessment using SQI accounted for 52% of the rice yield variation. Thus, management practices and mitigation of soil limiting factors should be comprehensively investigated to ensure sustainable rice production in the paddy fields of northern Iran.

Keywords Critical limit · Minimum dataset · Paddy soil · Rice yield · Soil properties · Soil quality index

Introduction

Rice (*Oryza sativa* L.) is considered as one of the main food products around the world other than wheat and corn. Over half of the world's people, especially in Southwest Asia, China, and India, depend on rice as the main meal to survive (Fahad et al. 2019). In general, 90% of rice is produced

and consumed in Asia (Arouna et al. 2021). In Iran, 80% of rice produced belongs to Guilan and Mazandaran provinces. However, the rice productivity is still low and decreasing due to the loss of optimal soil conditions and weaknesses of management practices. The continuous soil compaction necessary for waterlogging impacts the soil system. In particular, it destroys soil aggregates stability, increase bulk density and thereby reduce soil hydraulic conductivity (Zhao et al. 2015; Zheng et al. 2021). Soil gleization of paddy fields is one of the main causes of land degradation and a major challenge to national food security (Liu et al. 2015). Gleyed paddy soils show reduced conditions as a result of extended waterlogging or poor drainage. Weak air circulation and toxicity of reduced substances have been determined to be the major limiting factors (Pan 1996).

With regard to an increase in land use pressure, soil quality assessment is necessary to achieve sustainable management and soil degradation control (Abdelrahman and Tahoun 2019; Jahany and Rezapour 2020; Rezapour et al. 2021). Soil quality is a concept that also goes beyond crop yield. However, identifying situations that allow the

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establishment of relationships between soil quality and crop yields parameters, such as grain yields are important, mainly from farmer's perspective (Mendes et al. 2021). Since crop yield is considered as a plant biological factor which directly responds to soil properties it was proposed as the main criterion for soil quality assessment (Li et al. 2019). Using crop yield as the main criterion reduces the possible effects of other factors that are not related directly to soil quality. Therefore, crop yield can be taken into account as a field factor for assessment that considers farmers' satisfaction (Lopes et al. 2013).

Assessing soil quality and identifying main indicators and critical limits are very essential to the maintenance of soil natural functions and crop yield, especially in paddy fields (Biswas et al. 2017). Given the complexities of crop yield response to critical limits, the best thing that might be done is to establish these limits for the main soil indicators based on local crop yield (Bai et al. 2018). The specific conditions of crop yield (low to high) can be beneficial for preparing a guideline for interpretation of individual main soil indicator (Lopes et al. 2013). Therefore, a reliable and accurate assessment of soil quality and the detection of limiting indicators based on crop yield can lead to economic crop production along with improved soil quality. Many previous studies have either provided crop yield data or analyzed the relationship between soil quality index (SQI) and yield in paddy fields in different areas (Rezaee et al. 2020; Dengiz 2020; Liu et al. 2014), but the critical limits of soil quality indicators have not been established in paddy field conditions.

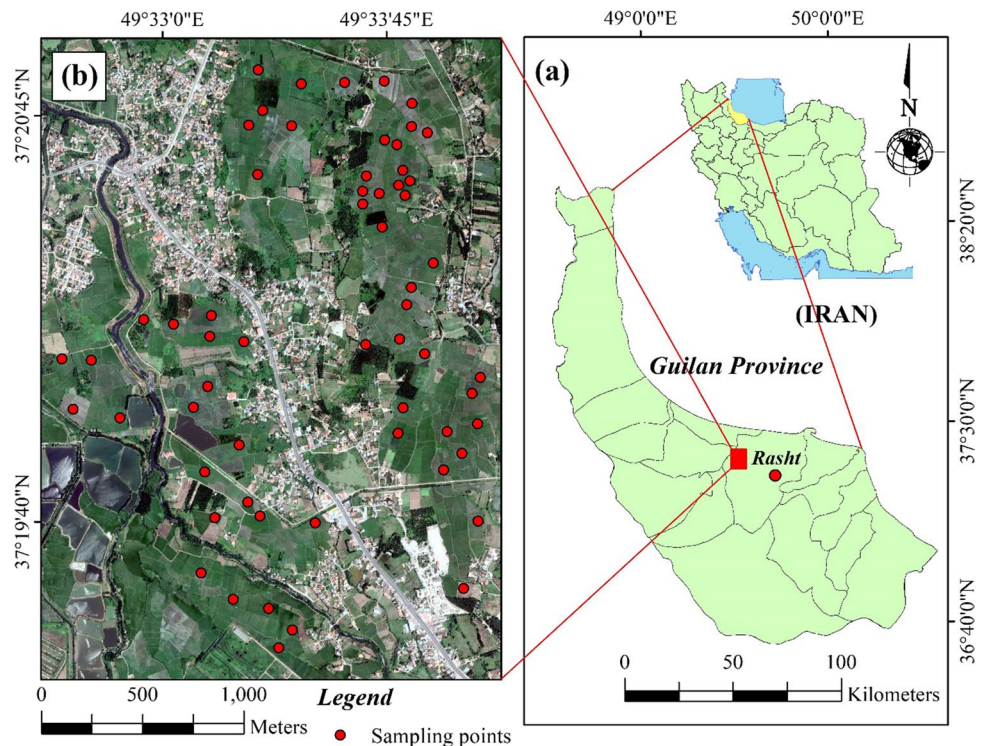
About 200,000 hectares of paddy fields are located in Guilan province, northern Iran) Rezaee et al. 2020(. Improving the productivity of these lands, which is important for ensuring national food security, is faced with many challenges. The systematic assessment of soil quality can help productivity improvement. However, soil quality assessment based on the establishing the critical limits of indicators in the real field conditions is limited in the northern Iran. We hypothesized that exceeding tillage, unbalanced fertilization, puddling, and waterlogging might have negative effects on different physical, chemical, and biological properties of soil quality and crop yield in the study area. The main objectives of this study were to (a) establish the minimum dataset (MDS) consisting of main soil variables and (b) identify upper and lower critical limits of the soil quality indicators based on the local crop yields under field condition.

Materials and methods

Study area, soil sampling, and analysis

The present study was carried out in the Pirbazar region (central areas of Guilan province, northern Iran) located between $49^{\circ}32'40''$ E to $49^{\circ}34'20''$ E and $37^{\circ}19'20''$ N to $37^{\circ}20'55''$ N (Fig. 1). In the study area, the mean annual temperature is 16.8°C and the mean annual precipitation is 1246 mm. Soil temperature and moisture regimes are thermic and udic, respectively. Aquept is the predominant soil

Fig. 1 Location of the study area in Guilan province and Iran (a), and geographic locations of sampling points (b)



group and low land (slope < 1%) is the major physiographic unit in the study area and paddy fields are the major land use. Land preparation practices including plowing, puddling, harrowing, and leveling are annually performed 7 to 30 days before transplanting in early spring. Based on farmers' surveys, conventional fertilization focused on mineral fertilizers for N, P, and K. Once tillage were conducted before each cropping season, and the N, P, and K fertilizers were usually applied totally as basic fertilizer during soil tillage across the whole study area. The sampling sites have similar climate conditions, cropping systems, and agricultural management (i.e., fertilization, tillage).

Sixty sampling sites in paddy fields with almost the same agricultural practices and crop management were randomly collected. Based on the recorded mean rice yield of the three years (2015 to 2017), the chosen paddy fields had been divided into low (< 4.5 t ha⁻¹) and high (≥ 4.5 t ha⁻¹) productivity, which have been cultivated for about 30 years. A sampling quadrat (with regular shape, 10 × 10 m) was established in each sampling site. Soil samples were taken from four corners of square and mixed to form a composite sample. The composite soil samples were taken from a depth of 0 to 30 cm, 7–14 days after rice harvest. It was assumed that the soil stabilizes within 7–14 days after rice harvest due to the fading of the rhizosphere effect (Majumder et al. 2008). A total of 60 composite soil samples were collected, and the LP (low productivity) and HP (high productivity) paddy fields had representative soil samples of 34 and 26, respectively.

A portion of the soil sample was air-dried to analyze the physical and chemical soil properties and the rest of it was kept at 4 °C to measure biological soil properties. Some physical, chemical and biological soil properties were measured using the following standard methods: clay content (Gee and Bauder 1986); mean weight diameter (MWD) of soil aggregates by wet-sieve-method (Kemper and Rosenau 1986); soil bulk density (BD) by core method (Grossman and Reinsch 2002); soil pH by a pH meter in soil/distilled water extract (1:2.5) (McLean 1982); electrical conductivity by an EC meter in soil/distilled water extract (1:2.5) (Rhoades 1982); soil organic carbon (OC) by wet oxidation method (Nelson and Sommers 1982); total nitrogen (TN) by Kjeldahl digestion method (Bremner 1960); available phosphorus (AP) by sodium bicarbonate extraction and subsequent colorimetric analysis (Olsen et al. 1954); available potassium (AK) by flame photometer after extraction with ammonium acetate (Knudsen et al. 1982); available copper (ACu), available zinc (AZn), and available iron (AFe) by ICP after extracting with DTPA (Lindsay and Norvell 1978); soluble calcium (Ca) and magnesium (Mg) using EDTA complexometric titration method (Richards 1954); active C (AC) by KMnO₄ oxidation procedure, microbial biomass carbon (MBC) using the chloroform

fumigation–incubation method and urease activity by the phenol-hypochlorite assay method (Vance et al. 1987). Microbial carbon ratio (MCR) was also calculated based on MBC and soil OC.

SQI assessment

Selecting the MDS

Soil quality was assessed by selecting the representative soil indicators. The Pearson correlation of soil indicators and rice yield was used to identify dependent variables. Soil indicators with a significant relationship to rice yield were selected for the standardized principal component analysis (PCA) (Li et al. 2019).

In order to reduce the number of studied variables and provide independent components, PCA was employed to define the indicators that play the greatest role in explaining changes in soil properties. The reduction of the number of components was obtained using the eigenvalue-one criterion, also known as Kaiser criterion (Kaiser 1960), and the Scree test (Cattell 1966). Thus, according to the method of Andrews et al. (2002) and Govaerts et al. (2006), the principal components (PCs) with eigenvalues ≥ 1 have only been taken into account. After selecting the PCs, within each PC, only factors with the highest weight (i.e., those having absolute values within 10% of the highest factor loading) were retained for the MDS. If more than one indicator was preserved within a PC, variables with higher correlation coefficients and lower weight are removed.

Indicator scoring

After minimum dataset determination, each indicator applied a scoring function for transformation and standardized between 0 and 1. For each indicator that improves soil quality with increasing or decreasing their value, “more is better” (Eq. 1) and “less is better” (Eq. 2) functions were used, respectively. The “optimal range” function (Eq. 3) was used for indicators that have an increasingly positive relationship with soil quality to the optimum level beyond which soil quality decreases.

$$M(X) = \begin{cases} 0.1 & x < x_1 \\ 0.9 \times \frac{x-x_1}{x_2-x_1} + 0.1 & x_1 \leq x \leq x_2 \\ 1 & x > x_2 \end{cases} \quad (1)$$

$$L(X) = \begin{cases} 1 & x < x_1 \\ 1 - 0.9 \times \frac{x-x_1}{x_2-x_1} & x_1 \leq x \leq x_2 \\ 0.1 & x > x_2 \end{cases} \quad (2)$$

$$R(X) = \begin{cases} 0.1 & x < x_1 \\ 0.9 \times \frac{x-x_1}{r_1-x_1} + 0.1 & x_1 \leq x < r_1 \\ 1 & r_1 \leq x \leq r_2 \\ 1 - 0.9 \times \frac{x-r_2}{x_2-r_2} & r_2 < x \leq r_2 \\ 0.1 & x > x_2 \end{cases} \quad (3)$$

where x_1 and x_2 are the lower and upper threshold value of indicator, respectively; r_1 and r_2 are the lower and upper value of optimal range, respectively; x is the indicator value; M , L , and R are more is better, low is better, and optimal range scoring functions, respectively; (X) is the score between 0.1 and 1.

Calculating soil quality index

After choosing the MDS indicators, the weight of each indicator has been allocated using the PCA results, and was equal to the percentage of variance explained by each PC (full value for uncorrelated variable, divided between variables for correlated variables) standardized to the unit (Armenise et al. 2013). Then, the soil quality index (SQI) was calculated as follow (Eq. 4) (Li et al. 2013):

$$SQI = \sum_{i=1}^n wi \times si \quad (4)$$

where wi is the indicator weight; si is the indicator score, and n is the number of indicators.

Determining critical limits

For each soil quality indicator, critical limits are defined according to favorable threshold value needed for optimum soil functioning and quality maintenance for agriculture production. The relative yield (RY) was described as 100 times the yield of a site divided by the yield of a site that generated the highest yield with sufficient but not exceeding inputs (Eq. 5) (Biswas et al. 2017; Lopes et al. 2013):

$$RY = \frac{\text{Yield of each sampling site}}{\text{Maximum yield obtainable}} \times 100 \quad (5)$$

The critical limit of a soil quality indicator is the optimal range of its value required for soil functions and maintenance of its health for sustainable crop production. The regression lines between the selected main indicators in MDS and RY were created for determining the critical limits. In the regression equation, relative yield, (Y)=80 and 40 were taken and the corresponding values of indicator “ X ” represent its upper and lower critical limits, respectively. The values of key indicators higher than RY of 80% were considered adequate, assuming

Table 1 Descriptive statistics of measured soil properties and rice yield for HP and LP fields

Type	Soil indicator	Unit	LP (n=34)		HP (n=26)	
			Mean	Range	Mean	Range
Physical properties	Clay	g 100 g ⁻¹	23.65	14.5–38.00	22.25	8.50–39.50
	BD	g cm ⁻³	1.69	1.60–1.85	1.59	1.52–1.67
	MWD	mm	2.21	1.48–2.68	2.58	1.97–2.94
Chemical properties	pH		7.30	6.75–7.57	7.20	6.60–7.63
	EC	dS m ⁻¹	0.92	0.28–4.64	0.75	0.31–2.72
	OC	g 100 g ⁻¹	2.67	1.17–3.73	3.55	2.56–4.68
	AC	mg 100 g ⁻¹	32.57	9.76–97.15	33.82	22.66–55.16
	TN	g 100 g ⁻¹	0.17	0.11–0.29	0.21	0.16–0.28
	AP	mg kg ⁻¹	10.71	0.2–21.64	15.20	0.30–33.68
	AK	mg kg ⁻¹	139.23	54.00–432.00	184.88	50.00–400.00
	ACu	mg kg ⁻¹	5.40	1.66–10.31	4.90	2.46–7.40
	AFe	mg kg ⁻¹	28.96	6.63–59.10	54.54	6.63–105.20
Microbiological properties	AZn	mg kg ⁻¹	1.64	0.80–2.14	1.98	1.52–2.51
	Ca	mg kg ⁻¹	151.36	16.03–368.74	101.12	16.03–240.48
	Mg	mg kg ⁻¹	95.85	9.73–321.02	91.29	9.73–243.20
	MBC	mg 100 g ⁻¹	65.96	6.87–251.01	72.59	8.51–413.10
	MCR	g 100 g ⁻¹	2.01	0.15–10.73	3.25	0.18–11.77
Yield	Urease	μg NH ₄ g soil ⁻¹ 2 h ⁻¹	59.19	27.50–105.00	82.74	61.49–105.00
		t ha ⁻¹	3.71	2.20–4.43	5.17	4.64–5.93

BD bulk density, *MWD* mean weight diameter, *EC* electrical conductivity, *OC* organic carbon, *AC* active carbon, *TN* total nitrogen, *AP* available phosphorus, *AK* available potassium, *ACu* available copper, *AFe* available iron, *AZn* available zinc, *Ca* soluble calcium, *Mg* soluble magnesium, *MBC* microbial biomass carbon, *MCR* microbial carbon ratio, *LP* low productivity, *HP* high productivity

Table 2 Correlation coefficients between soil quality attributes and rice yield

Soil quality indicator	Yield	Soil quality indicator	Yield
Clay	−0.270*	AK	0.335**
BD	−0.342**	ACu	−0.146
MWD	0.451**	AFe	0.604**
pH	−0.052	AZn	0.454**
EC	−0.389**	Ca	0.084
OC	0.485**	Mg	−0.047
AC	−0.019	MCR	0.333**
TN	0.528**	MBC	0.230
AP	0.193	Urease	0.607**

* and ** indicate significance at probability of 5% and 1% level, respectively

that RY of 80% corresponds to the production of maximum economic efficiency. Values of key indicators corresponds to RY of 40 and 80% were defined as moderate, the values lower than RY of 40% were classified as low (Lopes et al. 2013).

Statistical analysis

Correlation relationships between the soil quality attributes were done using Pearson correlation coefficient. PCA was performed to determine the best soil quality indicators. Hotelling's *t*-squared test was used to investigate the particular difference among soil quality attributes and an unpaired *t*-test was performed to define the effect of soil quality on rice yield. Statistical analyses were done using SPSS 18.0.

Results

Soil attributes of two productivity levels

Eighteen physical, chemical, and biological soil properties were measured as soil quality indicators (Table 1). Higher values of MWD and lower values of bulk density were observed in HP paddy fields. The levels of organic carbon, active C, total N, available P, available K, available Fe, and available Zn were higher in HP than in LP paddy fields. The MBC, MCR, and urease activity were higher in HP than in LP paddy fields, by 10.0%, 61.7%, and 39.8%, respectively. The rice yield of HP was 0.39 times higher than that in LP paddy fields.

Table 3 KMO and Bartlett's test for measured soil properties

Kaiser–Meyer–Olkin measure of sampling adequacy	0.665
Bartlett's test of sphericity	Approximate chi-square 190.578
	Degree of freedom 55
	Significance 0.000

Table 4 Principal components analysis of the statistically significant soil quality indicators

PCs	PC1	PC2	PC3
Eigen value	4.700 ^a	3.922	2.055
Percentage of variance	36.37	22.83	13.34
Cumulative variance percentage	36.37	59.20	72.54
Eigen vectors			
Clay	−0.101	0.245	−0.158
BD	0.254	0.324	0.041
MWD	−0.269	0.225	−0.047
EC	−0.145	0.128	0.189
OC	−0.300^c	0.189	−0.150
TN	−0.284^b	0.087	−0.260
AK	0.254	−0.142	−0.268
AFe	0.175	−0.149	0.139
AZn	0.172	−0.285	−0.367
MCR	0.283	−0.090	0.121
Urease	−0.271	0.085	0.180

^aItalicized eigen values correspond to the PCs examined for the index

^bBold values under each component were highly weighted

^cBold-italicized values were selected in MDS

The results of Hotelling's *t*-squared test showed a significant difference between the low and high productivity fields in total measured soil properties ($p \leq 0.01$). Thus, the portion of the yield difference in selected paddy fields can be attributed to variations in soil properties.

Soil quality assessment

Using the Pearson correlation coefficients between soil properties and rice yields (Table 2), some soil properties including clay content, BD, MWD, EC, OC, TN, AK, AFe, AZn, MCR, and urease activity showed a significant relationship ($p \leq 0.05$) with rice yield. Therefore, these parameters were used for the next step in PCA and the other studied soil characteristics were excluded from subsequent analyses.

Kaiser–Meyer–Olkin (KMO) is a statistical measure to determine how suited data is for factor analysis and to examine the strength of the partial correlation between the variables. KMO values closer to 1.0 are considered ideal and values more than 0.6 are good enough for PCA. A significant Bartlett's (BTS) test ($p < 0.05$) shows the correlation between the variables and the suitability of PCA. The KMO

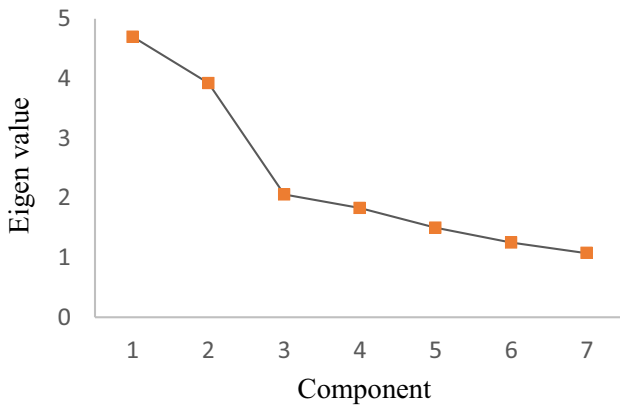


Fig. 2 Scree plot for the 7 PCs

test statistic of 0.665 and the significant ($p < 0.001$) BTS showed that PCA is appropriate in this study (Table 3).

According to the results obtained from PCA, the seven PCs received eigenvalue ≥ 1 (Table 4). Based on the Kaiser criterion; keeping any component with an eigenvalue ≥ 1 (Kaiser 1960), a large number of components remain for interpretation. While, Norman and Streiner (2008) suggest it may not be appropriate to use a criterion in cases where the eigenvalues are close to 1. Hence, according to the Scree plot (Fig. 2) and cutoff at PC3, the first three PCs were considered which explains more than 70% of the total variance; 36.37, 22.83, and 13.34%, respectively. The variables within 10% of the highest factor loading in PC1 were soil OC, TN, MCR and urease activity. Pearson correlation results were used to minimize the redundancy within each PC (Biswas et al. 2017) (Table 5). The high weight variables in the PC1 (OC, TN and MCR) were all significantly correlated. Therefore, OC with the highest factor loading was chosen. Consequently, OC and urease activity were retained for the MDS in PC1. Because only one highly weighted variable was observed in PC2 and PC3 (BD and AZn, respectively), these properties were selected as MDS. Finally, MDS included the following indicators: soil OC, urease activity, BD, and AZn.

After MDS determination, weights (Table 6) were allocated to the MDS indicators using the PCA results (Table 4). Specifically, the full weight, equal to 0.364, was assigned both to OC and urease, as they were not correlated

in PC1. BD and AZn were the only variables selected from PC2 and PC3, respectively. Therefore, these parameters received the full weight equal to 0.228 and 0.133, respectively. Then these weights should be standardized. MDS indicators were scored from 0 to 1 using linear scoring functions. The scoring functions were established in accordance with the relationship between indicators and soil quality. More is better functions were utilized for OC and urease activity. Less is better and optimum functions were utilized for BD and AZn, respectively (Cherubin et al. 2016; Qi et al. 2009). Finally, the SQI was computed as follows:

$$SQI = \frac{0.364 \cdot S_{OC} + 0.364 \cdot S_{Urease} + 0.228 \cdot S_{BD} + 0.133 \cdot S_{AZn}}{1.089} \quad (6)$$

$$= 0.334 \cdot S_{OC} + 0.334 \cdot S_{Urease} + 0.209 \cdot S_{BD} + 0.121 \cdot S_{AZn}$$

Soil quality indices changed from 0.31 to 0.98 in paddy fields. The mean SQI score in high productivity fields (0.95 ± 0.05) was significantly ($p < 0.05$) greater than that in low productivity fields (0.77 ± 0.05) (Fig. 3a). In high and low productivity paddy fields, the scores of MDS indicators were 0.318 and 0.277 for OC, 0.312 and 0.267 for urease activity, 0.203 and 0.152 for BD and 0.128 and 0.091 for AZn, respectively.

Critical limits of MDS indicators and SQI

The upper and lower limits of different MDS indicators and SQI related to relative rice yield were defined using scatterplot. The linear regression equations for the relative yield of rice as a function of each MDS indicators and SQI were shown in Fig. 4. The refined MDS indicators included soil OC, urease activity, BD, and AZn. The upper and lower limits for soil OC were 3.5 and 1.0 g 100 g⁻¹, respectively. The upper and lower limit of urease activity were 84 and 43 μg NH₄ g soil⁻¹ 2 h⁻¹ for achieving 80% and 40% of relative yield, respectively. The critical limits for BD were 1.84 and 1.60 g cm⁻³ for getting 40% and 80% of maximum yield, respectively. The upper and lower limits of AZn were 2.0 and 0.6 mg kg⁻¹, respectively. Finally, the critical limits for SQI were determined as a function of relative rice yield. The regression relationship obtained can explain 52% of the variations in rice yield. The lower and upper critical limits of SQI related to 40% and 80% of relative rice yield were 0.43 and 0.93, respectively (Fig. 4).

Table 5 Correlations matrix for the highly weighted variables under the first three PCs (only the significant correlations are shown)

	OC	TN	MCR	Urease activity	BD	AZn
OC	1	0.66**	0.44**	-	-0.39**	-
TN		1	0.36**	0.31**	-0.31**	-
MCR			1	-	-	-
Urease activity				1	-	-
BD					1	-
AZn						1

**indicates significance at probability of 1% level

Table 6 Commuality and weight of soil quality indicators of MDS

MDS indicator	Commuality	Weights
OC	0.78	0.334
Urease	0.78	0.334
BD	0.65	0.209
AZn	0.43	0.121

Discussion

Healthy and economic crop production in agriculture are highly dependent on soil quality. Soil quality is a comprehensive concept and includes a set of physical, chemical, and biological soil properties. Awareness about the variation of soil properties and their interactions with crops in agriculture can basically lead to the effectiveness of inputs and increase crop production yield (Virgilio et al. 2007). Crop yield is discussed here as an appropriate integrator of the SQI as a result of it is one of the main concerns of farmers (Bai et al. 2018). Regarding the effect of soil properties on soil quality, 18 physical, chemical, and biological soil properties were measured (Table 1). These properties have been introduced as soil quality indicators in the literature review (Dengiz 2020; Li et al. 2019; Biswas et al. 2017; Bhaduri and Purakayastha 2014) because each of them affects the soil productivity. Lima et al. (2013) found that soil biological properties are the most sensitive indicator that leads to differences in the soil quality in rice production systems. The physical properties of soil strongly affect the amount of water, air and nutrients needed for plant growth (Beylich et al. 2010; Bonanomi et al. 2011). Contrary to physical and biological properties, changes in chemical indicators at two levels of yield showed no clear trend. This may be due to differences in fertilizer application by farmers. In this way, one of our hypotheses related to the unbalanced application of fertilizer is justified.

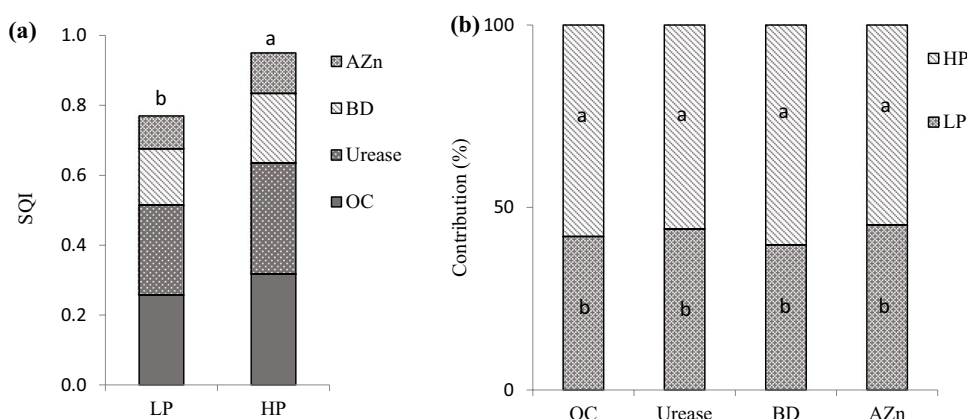
After obtaining the SQI, there is a need to maintain soil function at desired levels (Lopes et al. 2013; Biswas et al. 2017). Furthermore, the critical limits equal to 40% and 80% of RY were considered as the normal objectives of soil

quality indicators. Therefore, these specific critical limits may be found out concretely through suitable soil and crop management practices (Biswas et al. 2017). This interpretation framework was also used to establish critical limits for SQI in India (Biswas et al. 2017), China (Mei et al. 2019; Tian et al. 2020) and Brazil (Mendes et al. 2021).

Soil OC, urease activity, BD, and AZn were the soil limiting factors in the studied paddy fields. Dengiz (2020) reported that clay, OC, and total nitrogen of the soils are the major factors for soil quality assessment of paddy soils. Soil OC has been extensively introduced as one of the main indicators affecting soil quality. The important role of organic matter was known in numerous soil functions such as nutrient cycling, buffering capacity, aggregate stability, and water infiltration. Organic matter is also the main source of feed for microorganisms (Carter 2002), and thus has a significant effect on enzymatic activity in soil. OC plays a key role in crop production because it has significant effects on soil biological, chemical, and physical properties, e.g., root growth, water retention and availability, gas flow intensity, soil conservation, and nitrogen supplying and transformation. Therefore, OC is the most key indicator affecting soil quality and it is highly variable due to different agricultural management systems (Rezaee et al. 2020). In previous studies on agricultural soil quality, soil OC has also been identified as a main indicator (Li et al. 2019; Biswas et al. 2017; Mei et al. 2019). The optimum amount of OC obtained in this study for 80% RY was 34.7 g kg^{-1} . Biswas et al. (2017) reported lower amounts of organic carbon (7.7 g kg^{-1}) under a long term rice-rice system in subtropical Alfisols in India. Since the 1980s, soil organic matter has been one of the most important limiting factor with an average of 7.9 g kg^{-1} (Tian et al. 2020). Currently, this average has increased due to organic products and crop residue additions to agricultural soils. This issue alongside long-term waterlogged condition which restricts organic matter decomposition rate can explain higher amounts of OC average in paddy fields of Guilan province (Table 1).

Among the measured biological soil parameters, urease activity appeared as a main soil quality indicator due to

Fig. 3 Soil quality index (SQI) results of low (LP) and high (HP) productivity paddy fields with the individual contribution of each MDS indicators (a). Different lowercase letters represent values that are significantly different ($p \leq 0.05$) between different productivity levels (b). OC, organic carbon; BD, bulk density; AZn, available zinc



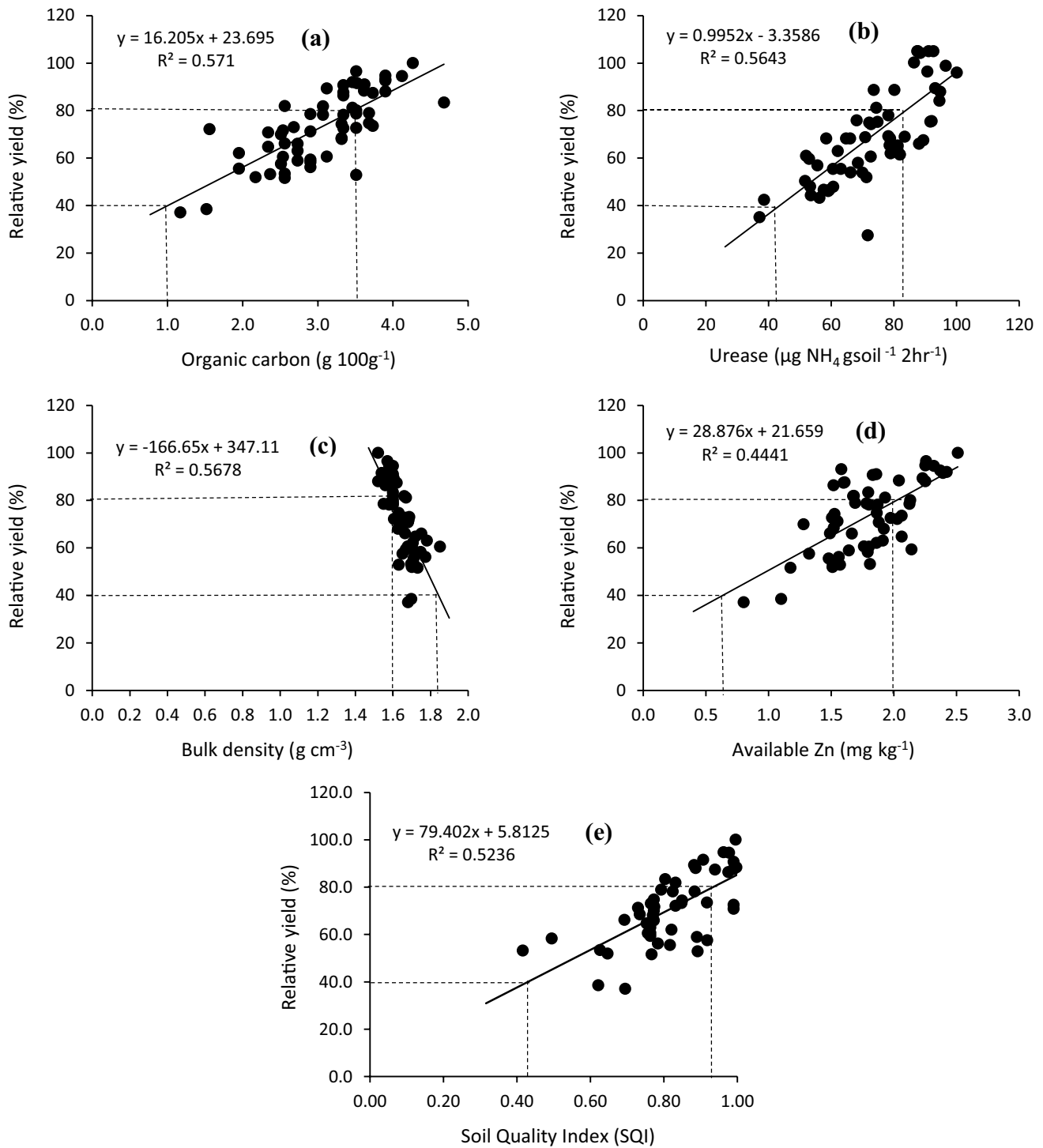


Fig. 4 Critical limits of MDS indicators: organic carbon (a), urease (b), bulk density (c), available Zn (d), and soil quality index (e)

its role in catalyzing numerous biochemical reactions and greatly involvement in N cycle (Mazzei et al. 2020; Finkenbein et al. 2013). Urease activity appearance in MDS is well justified with higher rate of urea application in the studied paddy fields as a main fertilizer material of nitrogen source applied by local farmers. Urease activity was significantly

affected by different management methods (Bandick et al. 1994), and can also be used as a proper indicator of soil quality. In the present study, more urease activity in HP paddy fields is probably due to higher content of total N and available P. The lower limit of urease activity obtained in this study ($43 \mu\text{g NH}_4 \text{g soil}^{-1} 2 \text{ h}^{-1}$) is almost similar to the amount

reported ($31 \mu\text{g NH}_4 \text{ g soil}^{-1} 2 \text{ h}^{-1}$) by Basak et al (2016) from the comprised treatment of chemical fertilizers (NPK) and farm yard manure (FYM) in rice-based cropping system. Biswas et al (2017) also categorized a lower limit of $24 (\mu\text{g NH}_4 \text{ g soil}^{-1} 2 \text{ h}^{-1})$ under a long-term rice-rice system.

BD is known as one of the main soil physical properties due to its important role in maintenance of physical stability and help by controlling available water, aeration, biological activity, and consequently crop production (Choudhary et al. 2018; Shan et al. 2019). The upper and lower limits of BD obtained in this study (1.84 g cm^{-3} and 1.60 g cm^{-3}) were greater than the amounts reported (1.2 g cm^{-3} and 1.6 g cm^{-3}) by Biswas et al (2017), respectively. The lower limit of $1.59 (\text{g cm}^{-3})$ in Inceptisols under a long-term rice-rice cropping system has been reported by Shahid et al. (2013). Pishnamaz Amoli et al. (2021) reported that in the paddy soils, the small number of macropores and the high number of micropores were found, and the soil BD would increase as a result of puddling. Puddling destroys aggregates and increases BD (Janssen and Lennartz 2007) and affects to soil physical properties, such as water retention, BD, and soil permeability (Supriyadi et al. 2017). It seems that higher values of critical limits for BD in this study area related to intensive puddling conducted by local farmers.

Zinc is a micronutrient element that plays some vital roles in many physiological functions of plants. Rice is a very sensitive crop to zinc deficiency and therefore zinc can be a limiting factor in rice growth (Rose et al. 2013). Thus, AZn as a main indicator plays a substantial role in maintenance of soil quality, especially in paddy fields (Shahid et al. 2013; Biswas et al. 2017). In some studies, available zinc has been considered as a MDS indicator affecting soil quality (Bhaduri and Purakayastha 2014; Hamidi Nehrani et al. 2020). Because it provides key informations for assessing soil functions such as the availability of micronutrients and crop production (Li et al. 2019; Kawakami and Bhullar 2020). The lower and upper limits of AZn for 40% and 80% of relative yield were 0.6 and 2.0 mg kg^{-1} , respectively. A similar lower limit value of AZn (1.2 mg kg^{-1}) in Inceptisols under a long term rice-rice cropping system has been reported in the other studies (Biswas et al. 2017; Shahid et al. 2013). Wei et al. (2007) reported that soil available Zn status for rice in the alluvial soil was deficient, low, sufficient, and excessive when its value was < 1 , $1-2$, $2-7.5$, and $> 7.5 \text{ mg kg}^{-1}$, respectively. Rice grown in flooded conditions is generally more sensitive to Zn availability than rice grown in the highlands or irrigated with alternate wetting and drying systems (Coffin and Slaton 2020). In this study, paddy fields are located in lowlands. Due to the accumulation of sediments and calcium carbonate, heavy metals are adsorbed on the sediments and consequently heavy metal availability is reduced. High pH values (Table 1) could be due to the calcareous parent material.

The contribution of soil OC, urease activity, BD, and AZn in SQI of HP is significantly higher than LP paddy fields (Fig. 3b). Therefore, these act as the main soil limiting factors in paddy fields. The upper (0.93) and lower (0.43) critical limits of SQI obviously indicate that there is a considerable potential for increased rice production in LP paddy fields. The soil quality assessment using SQI only explained 52% of the variation of crop yields in the study area. Similar results have been obtained in previous studies. Rezaee et al. (2020) evaluated the soil quality in paddy fields of northern Iran and found that the SQI explained 50% of the variation in rice yield. Li et al (2019) found that the SQI was able to explain 39% of the variation in wheat yield of farmland fields in China. Mei et al. (2019) also reported that the soil quality of topsoil layer could explain approximately 47% of maize yield variation. The results showed that only about half of the rice yield variation in this study controlled by soil quality and possibly other factors such as management practices should be considered.

Determining the critical limits of the main soil quality indicator and SQI as a function of relative rice yield is very important to improve management practices for sustainable rice productivity. Since crop yield is considered as a plant biological factor for a direct response to soil properties and minimizes the impact of factors that are not directly related to soil quality, therefore, crop yield has been suggested as the primary soil quality indicator (Li et al. 2019). Because SQI is obtained from integration of main physical, chemical, and biological indicators, determining critical limits of these indicators has an advantage over determining critical limits of a single index in relation to rice productivity. The results showed that these main soil quality indicators play a significant role in influencing different soil functions and its functional purpose to produce appropriate rice yield. The development of this interpretive framework reinforces the importance of long-term field experiments, whereby it is possible to improve soil quality by implementing optimum management practices.

Conclusion

The soil properties were evaluated in high (HP) and low (LP) productivity paddy fields based on SQI. The key indicators, including soil OC, urease activity, BD, and AZn, were identified as the soil limiting factors. According to the critical limits of key indicators, more organic amendments and proper soil structure (low BD) were required to improve rice yield in the study area. The mean SQI of HP paddy fields (0.95) was significantly higher than LP paddy fields (0.77). Significant correlation between SQI and rice yield confirms that SQI can be used as an effective and practical tool to evaluate the interrelationships of soil quality indicators and

crop production in rice paddy fields. The soil quality assessment explained approximately half (52%) of rice yield variation in the study area. This result reveals that management practices and mitigation of soil limiting factors should be comprehensively investigated to maintain and improve soil quality to ensure sustainable rice production in the paddy fields of northern Iran. Although the results presented here are based on 18 soil properties related to soil quality, considering more soil characteristics especially biological and biochemical ones are recommended. Repeating the analysis in the similar edaphic and climatic area will increase the reliability of results.

Author contribution Samira Hemmati: methodology, software, data curation, writing—original draft. Nafiseh Yaghmaeian: data curation, writing—review and editing, methodology, software. Mohammad Bagher Farhangi: methodology, data curation, writing—review and editing, software. Atefeh Sabouri: data curation, writing—review and editing, software.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate Not applicable.

Consent to publish Not applicable.

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