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ORIGINAL PAPER

Soil quality assessment of yellow clayey paddy soils with different productivity

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Abstract Yellow clayey paddy soil is a typical soil with low productivity in southern China. However, a systematic evaluation of soil quality, which is important for improving sustainable land use management and increasing crop yields, has not been carried out for yellow clayey paddy soils. This study adopted two indicator selection methods, Total Data Set (TDS) and Minimum Data Set (MDS), to evaluate soil quality of high (HPPS), medium (MPPS) and low (LPPS) productive yellow clayey paddy soils and aimed to identify the factors limiting the rice productivity. Twenty-six soil parameters including physical, chemical and microbiological properties including phospholipid fatty acid analysis, were determined. Most measured soil parameters showed significant differences ($P \leq 0.05$) between the different productivity paddy soils. Best values were always observed for many soil properties in HPPS, indicating a better nutrient supply and microbiological activity. Those 15 variables having significant differences were selected for principal component analysis, and arbuscular mycorrhizal fungi (AMF), microbial biomass carbon (MBC), available silicon (ASi), available potassium (AK) and total nitrogen (TN) were retained in the refined MDS. After scoring and weighting the selected indicators, a soil quality index (SQI) was calculated using the Integrated Quality Index equation. Based on the TDS method, the mean SQI scores of HPPS, MPPS and LPPS were 0.79, 0.71 and 0.57, respectively. Similarly, HPPS, MPPS and LPPS showed average SQI scores of 0.82, 0.67 and 0.50, respectively, using the MDS method. A significant correlation was observed between SQI and rice yield considering both TDS and MDS methods. Although the TDS method is more accurate, the MDS method can adequately represent the TDS method (r^2=0.85). Low levels of AK and TN were considered as the major constraints limiting the rice productivity for LPPS. All soil samples collected were rich in available P, Zn and Si, but deficient in available K, which may be the major constraint for the studied regions.

Keywords Minimum data set · PLFA · Soil quality evaluation · Soil quality index · Yellow clayey paddy soil

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Introduction

Soil quality integrates soil physical, chemical and microbiological attributes and is often defined as "the capacity of the soil to function within ecosystem boundaries to sustain biological productivity, to maintain environment quality and to promote plant and animal health" (Doran and Parkin 1994). Maintaining soil quality is essential for ensuring a sustainable environment and biosphere (Arshad and Martin 2002). However, soil quality has declined significantly worldwide, especially in developing countries (Barrios and Trejo 2003; Krowntree and Fox 2008). Food security remains a priority in China, but it has been challenged by climate change, increasing population and other anthropogenic factors (Khan et al. 2009). Paddy soils are the most important arable soil types in southern China and the area under cultivation has continued to increase in recent years. Unfortunately, about one-third of these soils belong to low-yield soil types (Xiao 1981). Yellow clayey paddy soil is considered as one primary soil of low productivity, and covers about 1.3 million ha across southern China with an important contribution to the national

food supply. A better knowledge and comprehensive evaluation of soil quality are crucial to designing sustainable agricultural management, improving crop production and developing appropriate soil conservation measures (McGrath and Zhang 2003; Tesfahunegn et al. 2011). Therefore, evaluating soil quality status and revealing the differences concerning yellow clayey paddy soil with different productivity are rather critical for developing sustainable land use management and improving grain yield.

Unfortunately, challenges remain in assessing soil quality because no established standards exist and soils vary widely, both spatially and temporally (Stocking 2003). Soil quality depends on the interactions of physical, chemical and biological characteristics and a proper assessment of soil quality requires measurement of a high number of parameters (Marzaioli et al. 2010). Specialists have agreed to search for a minimum data set (MDS) to reduce the cost of soil quality assessment (Rezaei et al. 2006). The MDS with proper indicators can reduce the need for determining a large number of indicators (Andrews et al. 2002) and should adequately represent the total data set (Qi et al. 2009). Though soil biological indicators have been increasingly used to evaluate soil quality (Bhardwaj et al. 2011), numerous studies mainly focused on soil physical and chemical properties (Bastida et al. 2008; Qi et al. 2009; Tesfahunegn et al. 2011; Li et al. 2013; Yao et al. 2013). Bastida et al. (2008) pointed out that the structural and functional relationships of soil microbial communities are considered as probable future indicators for soil quality. Moreover phospholipid fatty acid (PLFA) analysis has been increasingly used to study the composition and of the abundance of soil microbial groups (Puglisi et al. 2005; Ramsey et al. 2006; Moeskops et al. 2010; Romaniuk et al. 2011, 2012).

Numerous studies have evaluated soil quality using different indicators, but only a few established SQI have been set up (Bastida et al. 2008), and some have little biological significance (Li et al. 2013).

Soil organic matter (SOM) content of paddy soils increased during recent two decades, and it can play a important role in maintaining the yields of cereals (Pan et al. 2009). Conversely, soil pH, and the contents of Olsen-P and available K decreased in large area of paddy soils in southern China. Qi et al. (2009) has evaluated soil quality indices in agricultural soils of the region and established an MDS for the cultivated soil layer considering topography, obstacle horizon depth, drainage modulus, and contents of SOM, available P and available Fe. Li et al. (2013) also established an MDS including available N, P and K, SOM and sand and there was significant correlation between SQI and crop yield. However, little attention has been paid on evaluating soil quality of low productivity yellow clayey paddy soils. Therefore, it is necessary to evaluate soil quality for yellow clayey paddy soils. In this paper, several physical, chemical and biological properties were determined, with the aim to evaluate soil quality by (1) an MDS with proper indicators and (2) an SQI using both Total Data Set (TDS) and MDS methods. In addition, we aimed to identify the constraints limiting the rice productivity.

Materials and methods

Study area

Soil sample sites were collected in a large area of yellow clayey paddy soils, with similar cropping systems and productivity levels in eastern Hubei and Zhejiang provinces, southern China. In general, Hubei is characterized by a subtropical monsoon climate with a mean annual temperature of 21.0 °C and an annual rainfall of 1,117 mm during the rice growth season (from March to November). Similarly, the subtropical monsoon climate also prevails in Zhejiang, and the mean annual temperature and precipitation are 21.1 °C and 1,154 mm, respectively. The natural conditions were considered similar, although Hubei and Zhejiang were located in Huang–Huai–Hai plain temperate zone and Central East Subtropical zone, respectively (Pan et al. 2009). All studied fields had yellow clayey paddy soil were cropped with a double rice system and the major clay minerals are hydrous mica and kaolinite. Fertilizer types were $CO(NH_2)_2$, $Ca(H_2PO_4)_2$, and KCl for N, P and K, respectively.

Soil sampling

Soil sampling was accomplished in three steps. Firstly, the distribution of the yellow clayey paddy soils was determined based on rural surveys and information provided by the local agricultural department. Secondly, yellow clayey paddy fields were divided into soils with high (≥13,500 kg ha^{-1}), medium (10,500–13,500 kg ha^{-1}) and low (≤10,500 kg ha^{-1}) yields according to the average annual rice yield over the last 10 years. Thirdly, soil samples were collected from 0 to 20 cm soil plow layer before the transplanting of early rice (February–March).

Ten cores (5.0 cm diameter) were collected randomly and well mixed to form a composite sample. Overall, 81 composite soil samples were collected, with 27 samples from each of the high, medium and low yield paddy soils. Considering the analytical costs, we selected 36 soil samples for soil biological analysis. These 36 samples were collected from four typical locations, Wucheng (119°28′E, 29°02′N), Jinyun (120°02′E, 28°41′N), Yunmeng (113°45′E, 31°09′N) and Xiaochang (113°52′E, 31°17′N). In each location, we collected three samples representative of each productivity class of paddy soils. The samples were immediately transported to the laboratory, and one sub-sample was air-dried at room temperature for physical and chemical analysis, one sub-sample was stored

at 4 °C for biochemical analysis and the last sub-sample was freeze-dried prior to being stored at −18 °C for PLFA analysis.

Soil analysis

Physical and chemical characteristics

Soil texture and bulk density (BD) were determined by Bouyoucos hydrometer (Gee and Bauder 1986) and the core method (Blake and Hartge 1986), respectively. Soil aggregate stability (SAS) was measured using the wet sieving method (Beare and Bruce 1993), and available phosphorus (AP) by the method of Olsen and Sommers (1982). SOM, pH (soil/water 1:2.5), available silicon (ASi; citric acid extraction), total nitrogen (TN), alkali-hydrolyzable nitrogen (AN), and available potassium (AK), available zinc (AZn) and cation exchange capacity (CEC) were determined following the procedures described by Page et al. (1982).

Enzyme activities and microbial C and N

Urease, β-glucosidase, acid phosphatase and dehydrogenase activities were measured according to Alef and Nannipieri (1995). Microbial biomass carbon (MBC) and nitrogen (MBN) were analyzed using the chloroform fumigation–extraction and the fumigation–incubation method according to Vance et al. (1987) and Shen et al. (1984), respectively.

Microbial community structure

Microbial community structure was determined by PLFA analysis following the procedure described by Wu et al. (2009), and concentrations of PLFAs were calculated and expressed in units of nmol g^{-1} and mol%.

The fatty acids *i*C15:0, *a*C15:0, *i*C16:0, *i*C17:0 *a*C17:0 were used as biomarkers for Gram-positive bacteria (G+) and C16:1ω7c, C18:1ω7c, *cy*C17:0 for Gram-negative bacteria (G−) (Kozdroj and van Elsas 2001; Moeskops et al. 2010). The sum of G+, G−, C:15, C17:0 and *cy*C19:0ω11,12c was assumed to represent the total bacterial community, and the sum of 10*Me*C16:0 and 10*Me*C18:0 was regarded as indicator of actinomycetes. The fatty acids C18:2ω6,9c and C16:1ω5c were biomarkers for fungi and arbuscular mycorrhizal fungi (AMF), respectively.

Soil quality assessment

Indicator selection

For the TDS method, 26 physical, chemical and biological properties were considered.

In the case of MDS, principal component analysis (PCA) was used because of its ability to group related soil properties into a small set of independent factors and to reduce redundant information of the original data set (Yao et al. 2013). Nonparametric statistics (Kruskal–Wallis χ^2) were conducted to identify indicators with significant treatment differences, and only variables having significant differences ($P \leq 0.05$) were chosen for PCA (Andrews et al. 2002; Andrews and Carroll 2001). During the PCA process, the biological data columns of soil samples not analyzed for their biological properties were kept blank. We assumed principal components (PCs) with high eigenvalues and variables with high factor loading best represent soil properties, and only examined the PCs with eigenvalues ≥1 (Brejda et al. 2000). Within each PC, the factor loading of each variable represents its contribution to the PC. Highly weighted factors were those with absolute values within 10 % of the highest weight of the loading factor. When more than one variable was retained in a PC, each was considered important and was considered in the MDS if the two considered values were not correlated ($r < 0.60$) (Andrews et al. 2002). Among well-correlated variables within a PC, the variable with the highest correlation sum was selected for the MDS (Andrews and Carroll 2001).

Indicators scoring

Because of different indicator units, a standard scoring function (SSF) was used to score soil indicators in the TDS and MDS methods and to normalize indicator observations to a value between 0 and 1.0 (Andrews et al. 2002). Three types of indicators were divided according to their soil quality function, which were described by three SSF equations as follows:

$$\mathrm{SSF1}: f(x) = \begin{cases} = 0.1 & x < L \\ = 0.1 + \dfrac{0.9 \times (x - L)}{(U - L)} & L \leq x \leq U \\ = 1.0 & x > U \end{cases} \quad (1)$$

$$\mathrm{SSF2}: f(x) = \begin{cases} = 1.0 & x < L \\ = 0.1 + \dfrac{0.9 \times (U - x)}{(U - L)} & L \leq x \leq U \\ = 1.0 & x > U \end{cases} \quad (2)$$

$$\mathrm{SSF3}: f(x) = \begin{cases} = 0.1 & x < L_1, x > U_2 \\ = 0.1 + \dfrac{0.9 \times (x - L_1)}{(U_1 - L_1)} & L_1 \leq x < U_1 \\ = 1.0 & U_1 \leq x \leq L_2 \\ = 0.1 + \dfrac{0.9 \times (U_2 - x)}{(U_2 - L_2)} & L_2 < x \leq U_2 \end{cases} \quad (3)$$

In these three equations, x is the monitoring value of the indicator; $f(x)$ is the score of indicators ranging between 0.1 and 1; and L and U are the lower and the upper threshold values of the indicator, respectively. The indicators without a

certain threshold value were scored and normalized using a linear scoring function described by Liebig et al. (2001).

Weight assignment

Based on the TDS method, the PCA was conducted with all observations of measured soil properties, and the weight for each TDS indicator was calculated by its communality, which was equal to the ratio of its communality divided by the sum of communalities of all TDS indicators (Shukla et al. 2006). For the MDS method, MDS variables selected by PCA results were subjected to another PCA, and the weight of each MDS indicator was also assigned by its communality, which is similar to the TDS (Shukla et al. 2006; Li et al. 2013).

Developing the soil quality index

After the selected indicators were scored and weighted, soil quality index (SQI) was calculated using the following equation described by Doran and Parkin (1994):

$$\mathrm{SQI} = \sum_{i-1}^{n} W_i \times S_i, \quad (4)$$

where W is the PC weighting factor and S is the indicator score. We assumed that the higher index scores indicated better soil quality or strong performance of soil functions.

Statistical analysis

Data were subjected to statistical analysis using SPSS 18.0 and Canoco for Windows (version 4.5). One-way analysis of variance (ANOVA) was used to test all the parameters and separation of means was subjected to Tukey's honestly significant difference test. Correlation analysis was conducted using the Pearson product moment correlation test (two-tailed) to identify relationships between the measured properties.

Results

Evaluation of soil quality using soil characteristics

Physical and chemical properties

Table 1 showed that no significant difference was found for sand, silt and clay contents between the yellow clayey paddy soils with different productivity, although comparatively lower sand (36.1 %) and higher silt contents (41.2 %) were observed in the high productivity paddy soils (HPPS). Generally, all tested samples were loamy sand soils. The highest BD was observed in the low productivity paddy soils (LPPS) (1.32 Mg m^{-3}), which was higher than that of in the HPPS (1.19 Mg m^{-3}), but not significantly different compared with the medium productivity paddy soils (MPPS) (1.24 Mg m^{-3}). The lowest values of SAS were observed in LPPS (Table 1).

In Table 2, we summarized the statistics of soil chemical properties and showed that the HPPS had the highest pH values. Significantly lower SOM, TN and AN contents were observed in LPPS compared with the HPPS and MPPS. The HPPS contained the highest values for AK, CEC and ASi, which were significantly higher than those for the LPPS, but not significantly different compared with those of the MPPS. Also, no significant differences were found for AP and AZn between the paddy soils of different productivity.

Soil enzyme activities and microbial biomass C, N

Table 3 showed that no significant differences among soil enzyme activities except for dehydrogenase activity, which was 1.8 times higher in HPPS than in the LPPS, but no significant difference was observed between the HPPS and MPPS. The MBN contents of HPPS and MPPS were significantly increased by 1.2 times and 0.94 times, respectively, compared with the LPPS value. The HPPS had the highest MBC value, which was 1.1 times higher than the LPPS, but not significantly different compared with the MPPS.

PLFA analysis

The total PLFA ranged from 34.59 to 77.03 nmol g^{-1} and was significantly higher in HPPS than in LPPS, whereas the MPPS had values not significantly different compared to HPPS and LPPS (Fig. 1a). No significant differences were found among G+, total bacteria and fungi when data were expressed as nmol g^{-1} (Fig. 1a). The concentrations of actinomycetes in the HPPS and the MPPS were significantly higher than that in LPPS, increasing by 78.9 % and 68.4 %, respectively. The concentrations of G−and AMF in the HPPS were increased by 75.0 % and 94.0 %, respectively, compared with the LPPS.

There were no significant differences in G+, G−, total bacteria, actinomycetes, fungi and AMF among HPPS, MPPS and LPPS, when data were expressed mol% (Fig. 1b).

Based on the PLFA data, the PCA was conducted with 35 PLFAs expressed as nmol g^{-1}. The PC1 and PC2 accounted for 62.6 % and 14.3 % of the total variation, respectively; HPPS, MPPS and LPPS were well separated by the PC scores either in Hubei or Zhejiang province (Fig. 2a). PC loadings of each PLFA are shown in Fig. 2b. The amounts of saturated fatty acids (14:0, 15:0, 16:0, 17:0, a 14:0, a 15:0, a 16:0), monounsaturated fatty acids (16:1w5c, 16:1w7c, 16:1w9c, 17:1w8c) and polyunsaturated fatty acids of 18:2w6,9c and 18:3w6c(6,9,12) increased in HPPS, whereas those of the saturated fatty acid i16:0, monounsaturated fatty acids 16:1w11c and 20:1w9c, and the hydroxylated fatty acid 16:1 2 OH increased in MPPS.

Table 1 Descriptive statistics of the physical properties for HPPS, MPPS and LPPS (mean±standard deviation and range of variation)

Soil parameters	HPPS (n=27)		MPPS (n=27)		LPPS (n=27)	
	Mean	Range	Mean	Range	Mean	Range
Sand (%)	36.1±3.32 a	32.9–40.2	38.0±4.62 a	31.8–42.8	38.3±6.06 a	33.9–46.9
Silt (%)	41.2±6.08 a	32.5–46.5	38.6±1.56 a	36.4–39.9	38.2±7.18 a	27.8–43.0
Clay (%)	22.7±3.49 a	19.6–27.3	23.4±6.12 a	17.3–31.9	23.5±3.32 a	19.1–26.7
Bulk density (Mg m^{-3})	1.19±0.08 b	1.06–1.28	1.24±0.10 ab	1.09–1.44	1.32±0.12 a	1.11–1.52
Soil aggregate stability (%)	44.0±1.53 a	42.9–46.1	41.1±4.74 a	37.4–48.0	27.0±5.29 b	22.2–34.5

For the same property, different letters indicate significant differences (P<0.05)

HPPS high productive paddy soils, *MPPS* medium productive paddy soils, *LPPS* low productive paddy soils. n is the number of representative sampling points used for soil analysis in each productive paddy soils

Stepwise multiple regression analysis

Stepwise multiple regression analysis showed that SAS was the most important physical factor, markedly affecting (P< 0.05) all microbial groups with the exception of fungi (Table 4). Both G+and TB were significantly correlated with soil ASi (P< 0.05) and MBC(P< 0.01); G−was correlated (P< 0.01) with MBN. Both AMF and actinomycetes were correlated (P< 0.01) with SOM and MBN; MBC was significantly correlated with (P< 0.01) actinomycetes, and a significant correlation (P< 0.01) was found between AMF and CEC.

Soil quality evaluation

Indicator selection

The nonparametric test of means of soil parameters revealed that of 26 soil variables, soil texture (sand, silt and clay), AP and AZn, β-glucosidase, acid phosphatase, and urease activities, G^+, total bacteria and fungi, did not show significant differences among HPPS, MPPS and LPPS (P>0.05). Therefore, these 11 variables were dropped, and the remaining 15 variables with significant differences were selected for PCA (Table 5); this analysis grouped soil parameters into four main PCs with eigenvalues≥1. The communalities of the four extracted PCs explained 82.5 % to 99.8 % of the variance of soil parameters, which indicates that the extracted components well represented the soil variables. Finally, soil parameters were grouped into four main PCs with eigenvalues ≥1 which explained 93.84 % of the variance of data.

The major weighted variables of those analyzed by PC, defined as those within 10 % of the highest weight of eigenvectors, were SAS, MBN, MBC, G−, actinomycetes and AMF in PC1, TN and AN in PC2, Si in PC3, and K in PC4, and are presented in bold in Table 5.

Generally, the major weighted variables in PC1 were correlated, and AMF was chosen as the most representative of the PC1 group to be used in the MDS because of its highest weight of factor loading (Table 5) and correlation sum (Table 6). Because the PC1 explained such a large percentage of the data

Table 2 Descriptive statistics of the chemical properties for HPPS, MPPS and LPPS (mean±standard deviation and range of variation)

Soil parameters	HPPS (n=27)		MPPS (n=27)		LPPS (n=27)	
	Mean	Range	Mean	Range	Mean	Range
pH	5.80±0.68 a	4.80–7.50	5.36±0.62 b	4.50–6.90	5.35±0.71 b	3.90–6.70
SOM (g kg^{-1})	29.8±6.47 a	19.7–44.3	28.9±6.54 a	19.4–41.8	23.7±6.44 b	5.90–37.4
Total N (g kg^{-1})	1.57±0.52 a	0.81–2.70	1.56±0.37 a	0.78–2.44	1.24±0.42 b	0.29–2.22
AN (mg kg^{-1})	128±35.5 a	62.4–202	130±5.10 a	76.8–220	103±9.60 b	20.5–164
Available P (mg kg^{-1})	13.3±6.24 a	6.10–28.5	14.0±8.08 a	3.10–37.3	11.0±5.81 a	1.40–23.4
Available K (mg kg^{-1})	97.2±22.4 a	56.1–145	87.0±7.50 ab	21.3–178	75.7±24.9 b	24.0–138
CEC (cmol kg^{-1})	15.6±6.49 a	4.50–25.9	11.6±0.57ab	2.30–27.6	10.7±5.82 b	2.70–22.6
Available Si (mg kg^{-1})	111±52.3 a	23.5–230	84.1±0.90 ab	21.9–247	76.1±37.6 b	24.0–181
Available Zn (mg kg^{-1})	5.08±2.34 a	1.86–11.4	5.07±3.52 a	1.01–15.5	4.22±2.22 a	0.30–10.9

For the same property, different letters indicate significant differences (P<0.05)

SOM soil organic matter, *AN* alkali-hydrolyzable N, *CEC* cation exchange capacity, *HPPS* high productive paddy soils, *MPPS* medium productive paddy soils, *LPPS* low productive paddy soils. n is the number of representative sampling points used for soil analysis in each productive paddy soils

Table 3 Description of soil biochemical properties for HPPS, MPPS and LPPS (mean±standard deviation and range of variation)

Soil parameters	HPPS (n=12)		MPPS (n=12)		LPPS (n=12)	
	Mean	Range	Mean	Range	Mean	Range
MBN (mg kg^{-1})	47.6±11.2 a	34.2–59.7	41.8±8.0 a	33.1–50.6	21.6±7.73 b	13.8–31.5
MBC (mg kg^{-1})	649±15.2 a	479–734	493±33.6 ab	316–619	311±157 b	189–529
Urease (μmol NH_3 g^{-1})	1.03±0.29 a	0.80–1.46	1.17±0.38 a	0.67–1.51	0.74±0.22 a	0.43–0.94
Acid phosphatase(μg PNP g^{-1})	625±4.32 a	589–669	642±104 a	559–793	550±106 a	421–666
β-Glucosidase (μg PNP g^{-1})	102±6.28 a	82.5–122	92.1±19.4 a	72.3–116.7	70.1±16.4 a	47.5–85.9
Dehydrogenase (μg TPF g^{-1})	124±9.50 a	103–167	65.6±13.7 ab	51.5–80.7	44.5±2.86 b	30.5–59.8

For the same property, different letters indicate significant differences (P<0.05)

MBN microbial biomass N, *MBC* microbial biomass C, *HPPS* high productive paddy soils, *MPPS* medium productive paddy soils, *LPPS* low productive paddy soils. n is the number of measured soils used for soil analysis in each productive paddy soils

variation (50 %), we also select the parameter with the lowest correlation sum, MBC, to represent the variation within this group (Table 6). Additionally, MBC is a simple and inexpensive test, and it has been regarded as a good indicator of soil quality assessment by Chilima et al. (2002). Two important variables for PC2, TN and AN, were correlated (r>0.60); TN was selected for the MDS because of its higher weight of factor loading. Both PC3 and PC4 only showed one variable with high weighting, respectively, and thus available Si and K were also included in the MDS. Therefore, the refined MDS included the following parameters: AMF, MBC, TN, ASi and AK. All the measured soil parameters were included in the TDS method.

Indicator scoring and weight assignment

To normalize the selected parameters, the SSF1 was used for SAS, SOM, TN, AN, AP, AK, AZn, ASi and CEC; SSF2 was used for BD and sand; and SSF3 was used for silt, clay and pH. Meanwhile, the threshold values for quantitative soil quality indicators were used according to Qi et al. (2009) and Li et al. (2013). The remaining microbial and biological properties were considered as "higher is better". For urease activity, the highest value received a score of 1, and the other values were divided by the highest value to normalize them. The same procedure was carried out for MBN, MBC, the other enzymatic activities and soil microbial group.

All measured parameters of the TDS method and the MDS variables were subjected to another PCA and their communalities and weights are shown in Table 7. The weights of TDS variables were relatively even, and AMF and MBC received the highest weight of all MDS indicators, suggesting that these two soil properties probably played a more important role in soil quality evaluation than the others.

Developing the soil quality index

After the selected indicators were scored and weighted, the SQI was calculated using the Integrated Quality Index equation (Eq. 4). The SQI values calculated by the TDS method ranged from 0.48 to 0.88, and the mean SQI values of HPPS, MPPS and LPPS were 0.79±0.04, 0.71±0.05 and 0.59±0.05, respectively (Fig. 3). The SQI values calculated by the MDS method ranged from 0.32 to 0.93, and the HPPS, MPPS and LPPS showed average SQI values of 0.82±0.07, 0.67±0.09 and 0.50±0.08, respectively (Fig. 3). Significant differences were observed for SQI values among the different productive yellow clayey paddy soils, which can be ranked as HPPS>MPPS>LPPS using both TDS and MDS methods (Fig. 3).

Correlation analysis showed that soil quality indices calculated using both TDS and MDS methods were significantly correlated with rice yields (Fig. 4a and b). The TDS method was more accurate than MDS method because of its higher coefficient of determination. Also, a significant correlation was observed between SQI_{TDS} and SQI_{MDS} values (Fig. 5), indicating that evaluating soil quality using the MDS method can adequately represent the TDS approach.

Discussion

Soil quality is important for sustainable agriculture (Warkentin 1995). According to our soil quality evaluation, paddy soils can be ranked as HPPS>MPPS>LPPS on the basis of both TDS and MDS methods, suggesting that there were some constraints limiting soil quality in MPPS and in particular in LPPS compared to HPPS.

Evaluation of soil quality status using physical and chemical properties

Soil physical properties strongly influence soil function and determine potential land uses (Fernández-Ugalde et al. 2009). BD has often been used as a physical indicator for soil quality evaluation (Andrews et al. 2002; Bhardwaj et al. 2011). HPPS had lower BD, which indicated that high bulk density in LPPS

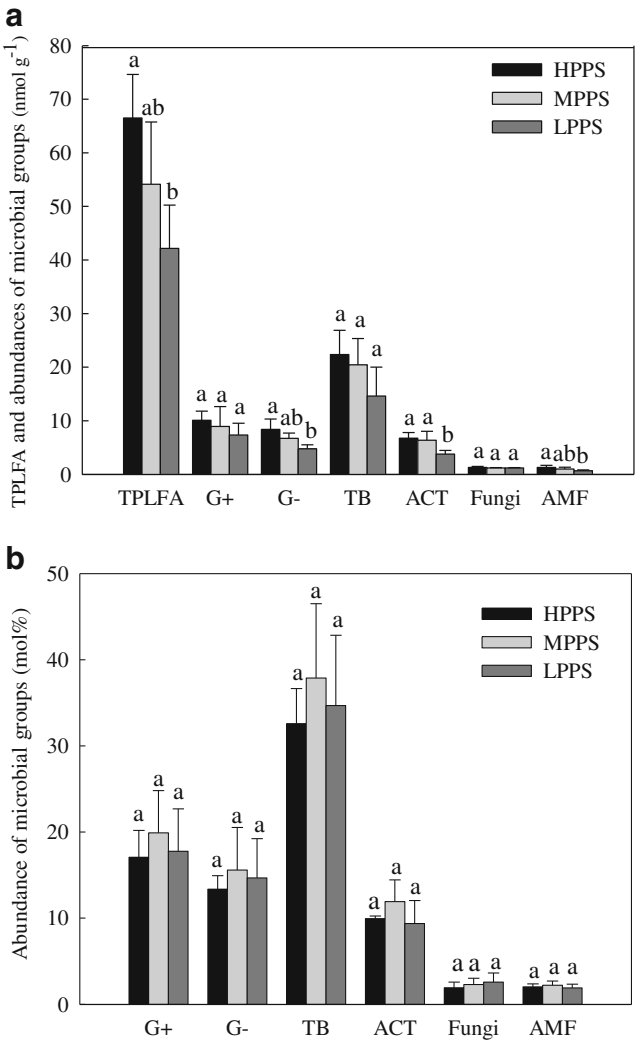

Fig. 1 Total PLFA (*TPLFA*) and abundance of gram-positive bacteria (*G+*), gram-negative bacteria (*G−*), total bacteria (*TB*), actinomycetes (*ACT*), fungi and AMF expressed in nmol g^{-1} (**a**) and mol% (**b**). *Vertical bars* represent the SE ($n=12$); columns with different letters indicated significant differences ($P<0.05$) between HPPS, MPPS and LPPS. *HPPS* high productive paddy soils, *MPPS* medium productive paddy soils, *LPPS* low productive paddy soils

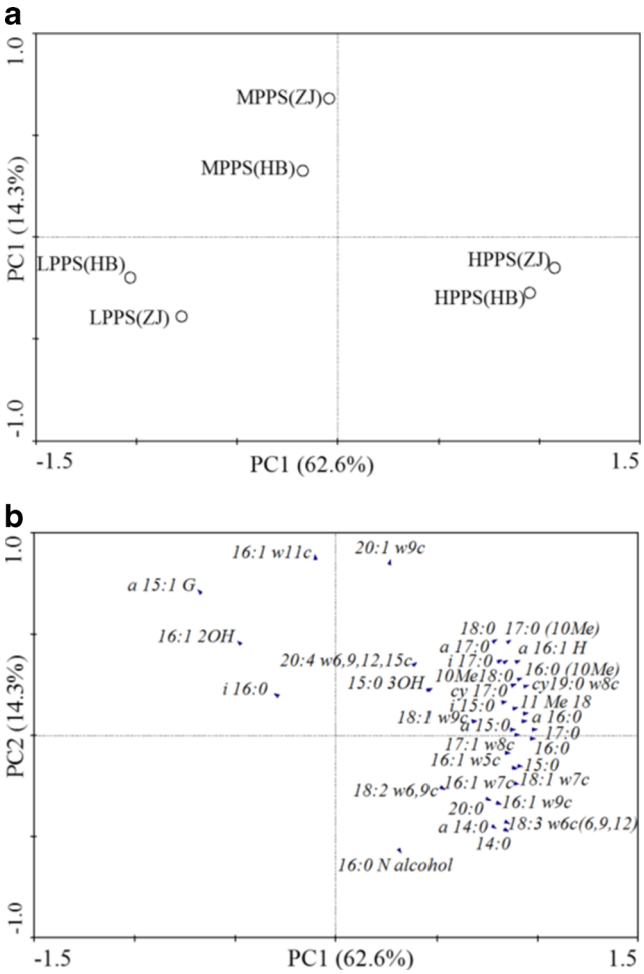

Fig. 2 Plot of first two principal components (PC1 and PC2) grouped in HPPS, MPPS and LPPS of Hubie (*HB*) and Zhejiang (*ZJ*) provinces (Fig. 3a) and plot of first two principal components (PC1 and PC2) among 35 PLFAs from the collected paddy soils. *HPPS* high productive paddy soils, *MPPS* medium productive paddy soils, *LPPS* low productive paddy soils

may be unfavorable to crop growth through affecting circulation of air, water and plant nutrients (Doran et al. 2002) and soil penetration by the root system (Tesfahunegn et al. 2011). SAS is considered one of the most important indicators of soil degradation, and is defined as the resistance of the soil against external destructive effects (Saygın et al. 2012). The lowest SAS value was observed in LPPS, and this was probably due to lower SOM levels, which is in agreement with the findings of Tesfahunegn et al. (2011).

Appropriate values of soil pH and SOM contents are fundamental for soil fertility (Lal 2004; Manlay et al. 2007). In general, a value of 7.0 for soil pH is regarded as optimum for nutrient cycling (Smith and Doran 1996) and availability of soil nutrients (Brady 1974). However, the pH values of HPPS, MPPS and LPPS were all lower than 7.0. HPPS had the highest pH value, which was closed to 7.0. Therefore, the availability of the immobile nutrient P may be increased during the crop growing in the HPPS, although no significant difference was found for AP between the paddy soils of different productivity. LPPS had the lowest SOM contents indicating worse soil fertility and irrational land use management. Improving the quantity of SOM in these soils should be a future management practice.

Noble et al. (2000) noted that a potential risk exists for chemical degradation of acid paddy soils with low CEC levels. The LPPS has the lowest CEC value, which indicates a potential chemical degradation for LPPS. Some sustainable measures should be taken to improve CEC values of LPPS.

About two-thirds of the region's paddy soils in south China are deficient in K, and the over-exploitation has exacerbated this problem (Sheldrick et al. 2003). Usually, soils with K concentrations ≤150 mg kg^{-1} are K-deficient. The average AK value of our studied yellow clayey paddy soils was below the critical

Table 4 Stepwise regressions between the selected microbial groups (dependents variable *Y*) and the other determined properties (independents variable *X*)

Dependents (*Y*)	Variables related (*X*)					
	Physical properties	R^2	Chemical properties	R^2	Biochemical properties	R^2
Gram-positive	SAS	0.57**	ASi	0.44*	MBC	0.66**
Gram-negative	SAS	0.54*	NS		MBN	0.74**
Total bacteria	SAS	0.59**	ASi	0.37*	MBC	0.59**
Fungi	NS[a]		NS		NS	
AMF	SAS	0.83**	SOM, CEC	0.78**	MBN	0.69**
Actinomycetes	SAS	0.74**	SOM	0.52**	MBN, MBC	0.89**

No variable was detected by stepwise regression analysis to be correlated with a corresponding microbial property

*P< 0.05; **P<0.01

value, even for HPPS (Table 2). Therefore, soil AK can be considered a constraint for yellow clayey soils, especially for LPPS. Increasing K application on a national basis is suggested as being an effective measure for improving rice yield and this fertilization practice should be investigated in further studies.

Silicon is a beneficial element for rice and Si deficiency in soil is now recognized as a factor potentially limiting rice production (Liang et al. 2007). Our results showed that the contents of soil ASi for HPPS, MPPS, and LPPS were all above the critical value of 60 mg Si kg^{-1} reported by Ma and Takahashi (2002). although significant differences were observed in the different productivity paddy soils. Conversely, the concentrations of soil AP and AZn in HPPS, MPPS and LPPS are all above the threshold values of 10 mg kg^{-1} (Kamprath and Watson 1980) and 1.0 mg kg^{-1} (Zhu and Liu 1981), respectively. This suggests that P and Zn are not factors limiting the productivity of yellow clayey paddy soils.

Soil microbial properties

Soil enzyme activities have been suggested as suitable indicators for evaluating soil quality, because of their rapid

Table 5 Results from the principal components analysis (PCA) of statistically significant variables

Soil quality attribute	Principal component, PC[a]				Communalities
	1	2	3	4	
Eigenvalues	7.64	2.99	2.33	1.12	n.a.
% of variance	50.91	19.94	15.53	7.46	n.a.
Cumulative percent	50.91	70.85	86.38	93.84	n.a.
Eigenvectors/Factor loading					
Soil parameter					
Bulk density (BD)	−0.668	−0.177	0.685	0.208	0.990
Soil aggregate stability (SAS)	**0.948**	0.068	−0.139	−0.171	0.953
Soil organic matter (SOM)	0.759	0.455	0.242	−0.056	0.844
pH	0.601	−0.579	0.484	0.011	0.930
Total N, TN	0.349	**0.913**	0.033	0.100	0.966
Alkali-hydrolyzable N (AN)	0.161	**0.911**	−0.270	0.137	0.947
Available K (AK)	0.063	−0.253	−0.540	**0.796**	0.993
Cation exchange capacity (CEC)	0.768	−0.442	0.318	0.283	0.966
Available Si (ASi)	−0.210	0.400	**0.778**	0.416	0.983
Microbial biomass N (MBN)	**0.880**	−0.217	−0.173	−0.172	0.881
Microbial biomass C (MBC)	**0.898**	−0.262	−0.295	0.188	0.998
Dehydrogenase activity	0.662	0.275	0.553	−0.076	0.825
Gram-negative bacteria (G−)	**0.903**	−0.027	0.188	−0.106	0.863
Actinomycetes	**0.903**	0.302	−0.112	0.209	0.962
Arbuscular mycorrhizal fungi (AMF)	**0.957**	−0.219	0.086	0.043	0.974

n.a. not applicable

[a] Data presented in bold indicate highly weighted properties

Table 6 Correlation coefficients and correlation sums for highly weighted variables under principal components (PCs) with multiple high factor loadings

PC1 variables	SAS	MBN	MBC	Gram-negative	Actinomycetes	AMF
Correlation coefficients						
SAS	1.000	0.759	0.855	0.734	0.857	0.913
MBN	0.759	1.000	0.577	0.860	0.896	0.829
MBC	0.855	0.577	1.000	0.569	0.677	0.925
Gram-negative	0.734	0.860	0.569	1.000	0.795	0.856
Actinomycetes	0.857	0.896	0.677	0.795	1.000	0.857
AMF	0.913	0.829	0.925	0.856	0.857	1.000
Correlation sums[a]	5.118	4.921	4.603	4.814	5.082	5.380
PC2 variables	Total N	AN				
Correlation coefficients						
Total N	1.000	0.628				
AN	0.628	1.000				

SAS soil aggregate stability, *MBN* microbial biomass N, *MBC* microbial biomass C, *AMF* arbuscular mycorrhizal fungi, *AN* alkali-hydrolyzable N

[a] The correlation sum is the sum of the absolute value of correlation coefficients for each variable

response and high sensitivity to soil management changes (García-Ruiz et al. 2009; Huang et al. 2013). Dehydrogenase activity is used as an indicator of soil microbiological activity and plays an important role in the initial oxidation of organic matter (Bastida et al. 2006; Nannipieri et al. 2012). The HPPS showed the highest enzyme activities, probably due to the highest fertility and microbial activity of these soils.

Soil microbial biomass is considered one of the most sensitive indicators of changes in soil quality (Stenberg 1999). Higher soil MBC and MBN values were observed in HPPS than in the other paddy soils. Garcia-Gil et al. (2000) showed that highest MBN and MBC values were found in the most fertile soils. Microbial activity, microbial biomass and enzyme activities of soils are correlated to SOM contents (Chaer et al. 2009). Soil microbial properties were all significantly correlated with MBC ($P<0.05$) but not always with SOM. Therefore, soil MBC may be an accurate indicator for assessing soil quality (Chilima et al. 2002).

Concentrations of PLFA markers of selected microbial groups (e.g., actinomycetes, total bacteria and fungi) were significantly increased by organic management, and decreased by contamination of paddy soils (Li et al. 2006; Moeskops et al. 2010). AMF have been considered indictors of fertility of soils subjected to sustainable agricultural management because of their susceptibility to disturbance (Bending et al. 2004). Significantly lower abundances of G −, actinomycetes and AMF were observed in LPPS, and these data also suggest the use of proper agricultural managements to improve fertility of LPPS. AMF abundance was significantly correlated with most soil properties including soil nutrient status, thus confirming results by Lauber et al. (2008). AMF may have enhanced the uptake of immobile soil

Table 7 Estimated communality and weight value of each soil quality indicator in TDS and MDS methods

Indicator	TDS		MDS		Indicator	TDS		MDS	
	COM	Weight	COM	Weight		COM	Weight	COM	Weight
BD	0.998	0.040			CEC	0.998	0.040		
Sand	0.993	0.039			MBN	0.989	0.039		
Silt	0.998	0.040			MBC	1.000	0.040	0.971	0.250
Clay	0.972	0.039			ACP	0.934	0.037		
SAS	0.995	0.039			Urease	0.974	0.039		
pH	0.991	0.039			β-Glucosidase	0.932	0.037		
SOM	0.997	0.040			Dehydrogenase	0.999	0.040		
TN	1.000	0.040	0.755	0.194	G+	0.963	0.038		
AN	0.995	0.039			G−	0.999	0.040		
AP	0.969	0.038			Total bacteria	0.984	0.039		
AK	0.972	0.039	0.573	0.147	Fungi	0.771	0.031		
ASi	0.999	0.040	0.712	0.183	Actinomycetes	0.994	0.039		
AZn	0.783	0.031			AMF	0.992	0.039	0.875	0.225

COM communality of each indicator, *BD* bulk density, *SAS* soil aggregate stability, *SOM* soil organic matter, *TN* total N, *AN* alkali-hydrolyzable N, *AP* available P, *AK* is available K, *ASi* available Si, *AZn* available Zn, *CEC* cation exchange capacity, *MBN* microbial biomass N, *MBC* microbial biomass C, *ACP* acid phosphatase, *G+* gram-positive bacteria, *G−* gram-negative bacteria, *AMF* arbuscular mycorrhizal fungi

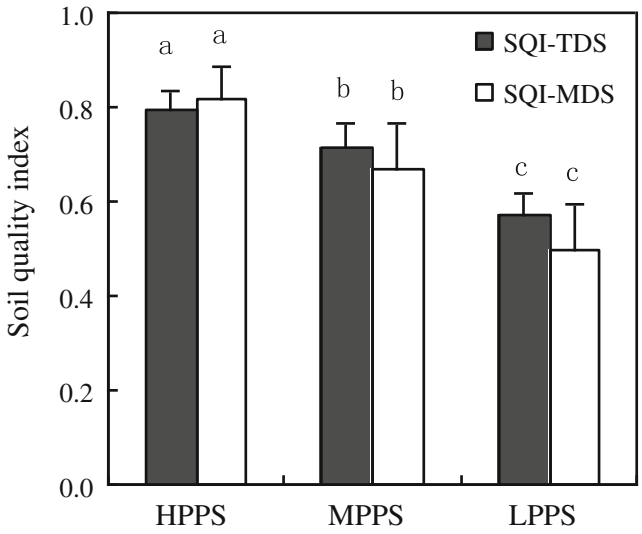

Fig. 3 Mean values of soil quality index for HPPS, MPPS and LPPS based on TDS method (*filled bars*) and MDS method (*empty bars*). *HPPS* high productive paddy soils, *MPPS* medium productive paddy soils, *LPPS* low productive paddy soils

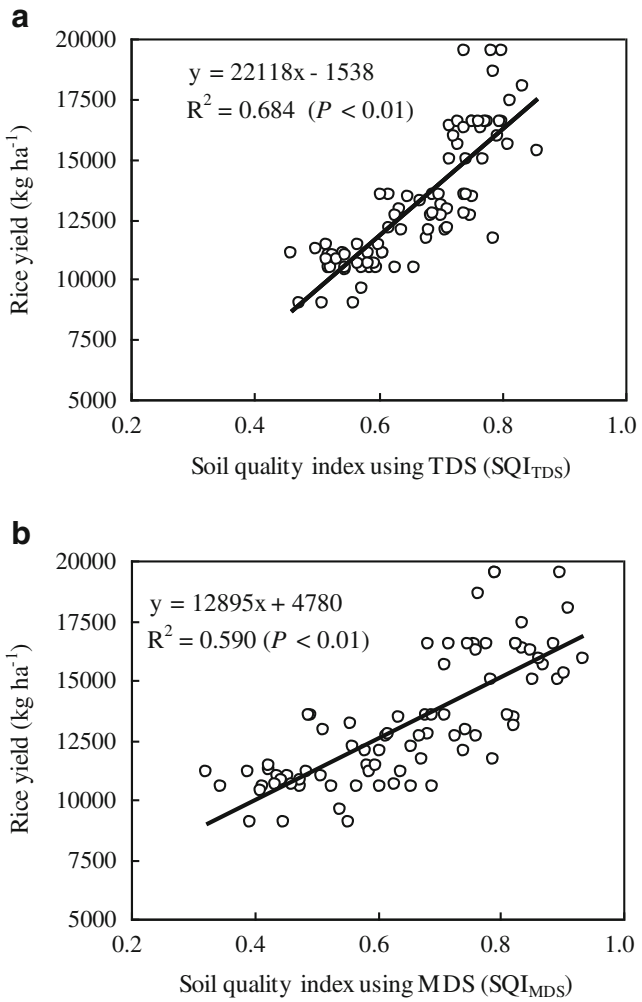

Fig. 4 Correlation between soil quality index and rice yield of 81 paddy fields using the TDS method (**a**) and MDS method (**b**)

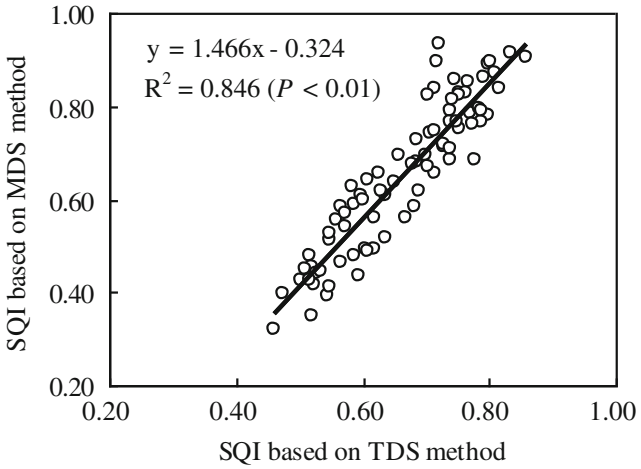

Fig. 5 Correlation of soil quality index between TDS and MDS methods

nutrients in HPPS (Jakobsen 1999). Generally, AMF are considered to be a suitable indicator for soil quality assessment, and the relative abundance was selected for the MDS according to the PCA results.

Soil quality index

SQI is considered as the primary indicator of sustainable land management (Mohanty et al. 2007). Based on the MDS method and the relative SQI values, the paddy soils are ranked as HPPS>MPPS>LPPS. The same rank order was observed by SQI values of the TDS method. Therefore, there were constraints limiting the rice productivity in MPPS and LPPS. Comparing these soils with HPPS, lower values of TN and AK were probably the primary factors limiting the productivity particularly for LPPS. Probably the low content of AK was the main factor limiting the productivity in MPPS. Some effective management approaches such as biochar amendment may be conducted for improving the productivity of the LPPS.

The significant correlation between SQI_{MDS} and rice yield indicated that soil parameters selected for MDS had a biological significance, and can be used to evaluate soil as a rice production medium. Similar findings were observed by Li et al. (2013). In addition, we have found that the MDS method can adequately represent the TDS method, although the TDS method was more accurate, in accordance with Qi et al. (2009).

Conclusion

Twenty-six soil properties including physical, chemical and microbiological properties were determined. Fifteen of the properties showed significant differences between HPPS, MPPS and LPPS, and were selected for PCA. Only MBC, AMF, TN, ASi and K were considered in the MDS based on

the PCA results. The SQI values were calculated using the Integrated Quality, and the paddy soils could be ranked as HPPS>MPPS>LPPS using either the TDS or the MDS method. HPPS were characterized by low bulk density, adequate nutrients supply, favorable physical–chemical properties and good abundances of microbial groups. Low levels of TN and AK were considered to be the primary constraints limiting the rice productivity in LPPS. The contents of soil AP, AZn and ASi were sufficient for plant nutrition whereas that of AK was deficient in the studied paddy fields, even in HPPS. Significant correlations were observed between SQI values and rice yield when these values were calculated by using both the TDS and the MDS methods. Although the TDS method was more accurate, the MDS method can adequately represent the TDS method for soil quality assessment of yellow clayey paddy soil. Based on our results, the application of K and other sustainable management practices eliminating the constraints limiting rice productivity should be conducted to increase rice yield, especially in the LPPS.

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