



Lower soil chemical quality of pomelo orchards compared with that of paddy and vegetable fields in acidic red soil hilly regions of southern China

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Abstract

Purpose Sustainable land management is considered an effective measure to ensure national food security by matching improved soil quality with enhanced crop productivity. The objectives of the present study were to evaluate soil quality status among paddy fields, vegetable fields, and pomelo orchards managed by continuous cropping systems, to establish a minimum data set (MDS) and recommend fertilization strategies to enhance productivity in acidic red soil hilly regions.

Materials and methods The soil quality index (SQI) was calculated using the total data set (TDS) and MDS as indicator selection methods. A total of 51, 32, 44 soil samples (0–20 cm) were collected from different cropping systems in paddy fields, vegetable fields, and pomelo orchards, respectively. Eleven soil properties (geographical indicator (altitude) and 10 chemical parameters) were measured to evaluate soil quality of acidic red soil hilly regions in Pinghe County, Fujian province, southern China.

Results and discussion The results showed significant differences in soil quality indicators between paddy fields, vegetable fields, and pomelo orchards, and altitude, total N, hydrolysable nitrogen (Avail-N), exchangeable calcium (Avail-Ca), and available zinc (Avail-Zn) were adopted as indicators in the MDS using principal component analysis (PCA). After scoring and weighting the selected indicators, the mean SQI scores of paddy field, vegetable field, and pomelo orchard soils were 0.267, 0.282, and 0.236 for TDS, respectively, and the SQI scores were 0.233, 0.256, and 0.166 for MDS. A significant positive correlation was observed between SQI and crop yield using both the TDS and MDS methods, indicating that the MDS method adequately represents the TDS method ($R^2 = 0.6839$) for evaluation of the effects of farming production practices on soil quality. Overall, the unbalanced soil quality indicators, including rich in total N, organic matter and Avail-P, and deficient in Avail-N, Avail-K, Avail-Ca, Avail-Mg, Avail-Zn, and Avail-B, were implicated as the main limiting factors for crop production in the studied regions.

Conclusions Compared with paddy and vegetable fields, the lower total N and Avail-N status at higher altitudes were considered as the major factors limiting pomelo productivity. Therefore, there is a great potential for increasing pomelo productivity by improving soil quality with integrated nutrient management in acidic red soil hilly regions.

Keywords Cropping system · Minimum data set · Soil quality evaluation · Soil quality index · Total data set

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1 Introduction

Food security remains an important development issue in China, and it has been challenged by population growth, agricultural land reduction, soil degradation, and environmental pollution (Gong 2011; Chen et al. 2014; Zhang et al. 2016). Ferralsols (Food and Agriculture Organization, FAO), oxisols (United States Department of Agriculture, USDA), and/or red soil and lateritic red soil (Chinese Soil Taxonomic Classification) are a typical low productivity agricultural soils, which cover approximately 11.8% of the land areas in China and are distributed mainly in the southern regions (Bouwman 1990; Liu et al. 2014a; Xu et al. 2017). In recent decades, due to the increasing market demands for fruit and vegetable products and higher economic returns, the red soil regions have undergone remarkable changes in land use, particularly in changing paddy fields or reclaiming of barren hills for growing fruit and vegetables (Lin et al. 2012; Liu et al. 2016). Although individual attributes are often interdependent, the process of land-use change has led to diverse land management practices with different methods of cultivation, fertilization, and irrigation, which significantly affect soil quality. Hence, it is important to evaluate the soil quality under different cropping systems in acidic red soil regions to meet the challenges of matching food security with sustainable land management.

Cereal, vegetable, and fruit crops are the major planting patterns of traditional agricultural production systems. Citrus is the leading fruit crop grown worldwide, with production and consumption showing a trend of rapid growth in China. The most famous citrus area for pomelo production is Pinghe County in Fujian Province. In Pinghe, the main paddy planting patterns involve rotation of early and late rice varieties of conventional cultivars (Shanyou 63, Mancang 515, etc.). The main vegetable planting patterns are field and greenhouse cultivation of leaf vegetables (Chinese cabbage, lettuce, etc.) and Solanum vegetables (sweet pepper, eggplant, etc.). The main fruit planting pattern is citrus with pomelo, with the well-known “the town of Chinese pomelo,” and the special typical of “‘Guanximiyou’ pomelo” varieties having been planted for more than 500 years (Li et al. 2015). With the aim of increased economic benefits, the balance of conventional planting patterns in rice, vegetable, and pomelo cropping systems has been eroded, and pomelo production has now become the major industry in this county. However, intensive agriculture productions of crops, including cereal, vegetable, and fruit, are generally considered a high nutrient input and high environmental risk system, mainly due to the low nutrient utilization efficiency and low soil health associated with damaging adverse practices associated with fertilization, pesticide, and irrigation (Chen et al. 2014; Wan et al. 2017; Wang et al. 2018). Recently, pomelo fruit quality displayed a downward trend, with lower fruit quality often associated with low soil fertility

and unbalanced tree nutrients (Li et al. 2015). Adequate nutrient management depends on knowledge of soil fertility. However, the effects of land-use changes on soil fertility under different cropping systems of paddy, vegetables, and fruit have not yet been reported. Therefore, it is extremely important to elucidate soil quality status and to identify limiting factors and recommended fertilization practices to achieve sustainable agriculture production in this region.

Previous studies showed that a comprehensive knowledge of agricultural soil quality is of vital importance in determining soil function, promoting plant growth and animal health, predicting the productivity of agricultural ecosystems, and providing policy recommendations and improvement measures to achieve sustainable land-use management (Karlen et al. 2001, 2003; Qi et al. 2009; Bhardwaj et al. 2011; Liu et al. 2014b). Soil quality index (SQI) is the most commonly used evaluation method, with quantitative flexibility that reflects management-induced land-use changes in soil conditions (Andrews and Carroll 2001; Andrews et al. 2002). Furthermore, SQI is widely accepted as an effective tool for assessing the soil quality based on its advantages in integrating systematic complexity effects to evaluate relationships between site-specific soil indicators and crop productivity under natural and farmed conditions (Liu et al. 2014c). Unfortunately, unfixed evaluation standards or indicators remain challenges in assessing soil quality, due to the dependence of soil quality on the interactions of physical, chemical and biological characteristics in diverse environments. Thus, it is necessary to measure a large number of soil parameters for precise evaluation of soil fertility (Marzaioli et al. 2010; Liu et al. 2014b,c). Most researchers establish a minimum data set (MDS) consisting of selected indicators to represent the total data set (TDS), through the use of principal component analysis (PCA). The method reduces the number of indicators that must be measured for a precise evaluation of soil quality, therefore reducing the cost of soil quality assessment (Rezaei et al. 2006; Yao et al. 2013). Therefore, it is critical to establish the MDS to evaluate soil quality for special soil regions or conditions, such as acidic red soil hilly regions using the SQI method.

However, little is known about the regional soil quality assessment under conventional farming practices, and especially for acidic red soil hilly regions with different continuous cropping systems. To evaluate the impacts of different agricultural practices on soil quality in paddy field, vegetable field, and pomelo orchard conditions, we determined the altitude, soil pH, organic matter, and mineral element content in soils and crop yields in Pinghe County, Fujian Province, southern China. The aims of this study were to (i) determine the soil nutrient status in paddy field, vegetable field, and pomelo orchard conditions; (ii) establish an MDS of acidic red soil quality under long-term agricultural practices; and (iii) evaluate the SQI, based on altitude and soil chemistry indicators, using both the TDS and MDS methods.

2 Materials and methods

2.1 Study area

Pinghe ($24^{\circ} 02'–24^{\circ} 35' N$, $116^{\circ} 54'–117^{\circ} 31' E$) is located in the acidic red soil hilly region in southern China (Fig. 1). The altitude ranges from 10 m in Xiaoxi town to 1545 m in Daxi town, while the annual mean temperature and precipitation are $23.58^{\circ} C$ and 165.2 mm, respectively, which are representative of a subtropical oceanic monsoon climate that is beneficial for agricultural crop production. It is the most developed agricultural county for pomelo production in China, with $1337 km^2$ woodlands, $295 km^2$ garden land, and $246 km^2$ arable land. In this study area, the landform is mainly mountainous and the hills where the pomelo orchards are located on terraced. The main soil types are red soil and red paddy soil, the parent material of which are ferralsols or oxisols based on FAO (IUSS Working Group WRB 2014) or USDA (Soil Survey Staff 2014). These soils are traditionally associated with agricultural activities favoring the production of three cropping systems: paddy field, vegetable field, and pomelo orchard. These three typical planting areas selected for soil sampling were distributed in Pinghe (Fig. 1).

2.2 Climate data collection

The climate data (monthly mean air temperature and precipitation) in the study area during the period from 2012 to 2016 were collected from the Pinghe Statistical Yearbook 2013–2017. These data are presented in Fig. 2.

2.3 Sampling, processing, and analysis

Soil sample collection was conducted in November and December 2015 from the 0–20 cm of soil tillage depth. Each soil sample was a composite of five sub-samples taken in a single field or orchard. Finally, 127 composite samples (paddy fields, 51; vegetable fields, 32; and pomelo orchards, 44) were selected for this study. Most of the soil samples were from fields that were continuously planted for 10 years with different cropping systems; the vegetable fields were planted with sweet pepper and cabbage at the time of collection. To avoid fertilization and edge effects, all samples were collected from the center of each field or orchard after harvesting and before planting the next crop. A handheld global positioning system (GPS) was employed to record the information for geographic location on spatial distribution (altitude, latitude, and longitude) of each sample (Fig. 1).

After air drying, the soil samples were gently ground and then passed through sieves (0.15 mm and 0.85 mm) and properly stored for later analysis. Soil chemical properties (pH; organic matter; total nitrogen (N); available nutrients including the macro-nutrients N, phosphorus (P), and potassium (K); the medium nutrients calcium (Ca) and magnesium (Mg); and the micronutrients zinc (Zn) and boron (B)) were then measured according to the method described by Li et al. (2015). Briefly, soil pH was estimated in 1:2.5 soil to water mixture using a pH meter. Organic matter was determined using K_2CrO_7 oxidation with the heated oil bath method. Total N was determined by sulfuric acid digestion and measured using an AA3 digital colorimeter (Bran+Luebbe, Hamburg, Germany). Available N (Avail-N) of hydrolysable N was

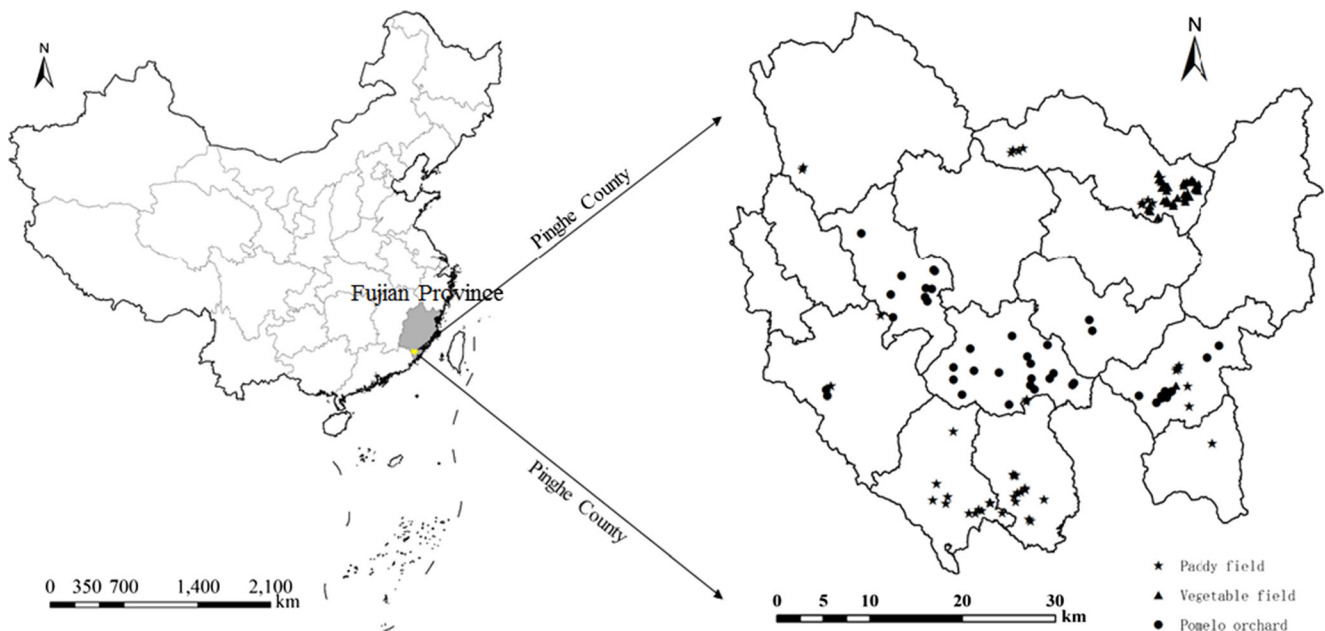
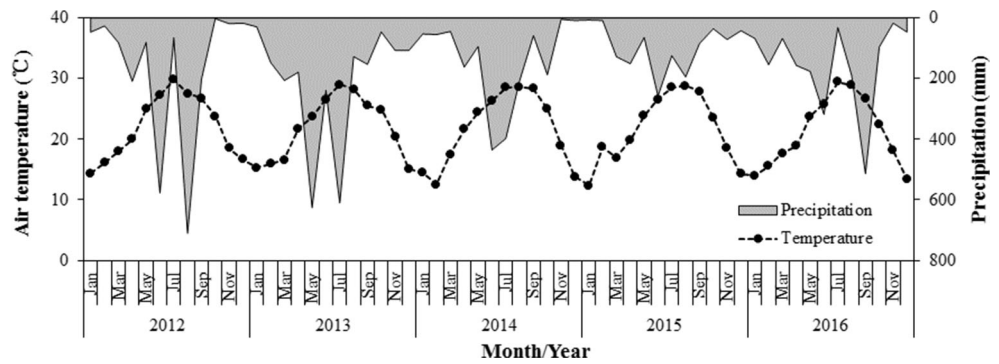


Fig. 1 Soil map of Pinghe County (yellow region) with sample sites in three cropping systems in the paddy field (black star), vegetable field (black triangle), and pomelo orchard (black circle). Maps were created using the ArcGis 10.2 software

Fig. 2 The mean monthly air temperature and precipitation in Pinghe County during the period from 2012 to 2016



measured using the alkaline hydrolysis diffusion method. Available P (Avail-P) was determined by NaHCO₃ extraction using the ascorbic acid reduction method and measured using a SpectraMax M4 spectrophotometer (Molecular Devices, CA, USA). Available K (Avail-K), exchangeable Ca (Avail-Ca), and exchangeable Mg (Avail-Mg) were extracted using the ammonium acetate method, while available Zn (Avail-Zn) was extracted using diethylene triamine pentaacetic acid (DTPA) and assayed by atomic absorption spectrophotometry (SpectrAA-220FS, Varian, CA, USA). Water soluble B (Avail-B) was extracted with hot water and measured using the curcumin method. These measurement methods were validated using the certified standard reference materials GBW(E)070045 (State Administration for Market Regulation of China). Finally, 1270 measurements were obtained.

Crop yields of rice, vegetable, and pomelo were recorded according to the farmers’ survey of the average annual yield over the previous 3 years. Rice grain yield was based on air-dried weight, and edible yields of vegetable and pomelo were based on fresh weight.

2.4 Soil quality evaluation method

2.4.1 Indicator selection

A total of 1397 measurements of 11 soil properties (geographical indicator (altitude) and 10 chemical parameters: pH value, organic matter, total N, and Avail-N, Avail-P, Avail-K, Avail-Ca, Avail-Mg, Avail-Zn, and Avail-B) were evaluated using the TDS method. Altitude was included because it plays an important role in influencing the farm management practices of fertilization, irrigation, and pesticide, which affect the soil quality. The PCA method was used as a data reduction tool to select the most representative indicators for MDS from the list of indicators of TDS (Yao et al. 2013; Liu et al. 2014a, b, c). According to Brejda et al. (2000) and Rezaei et al. (2006), only the principal components (PCs) with high eigenvalues (≥ 1) and the highly weighted indicators within 10% of the highest weight loading were selected in each PC for the

MDS. Moreover, optimum indicators in a PC were selected using the multiple regression method described by Andrews and Carroll (2001) and Andrews et al. (2002).

2.4.2 Indicator scoring

The standard scoring function (SSF) method was employed to score soil indicators both in the TDS and MDS methods. These indicator scores were transformed and normalized to a value between 0 and 1.0 to correct for different indicator units. Soil quality indicators were divided into the upper limit, lower limit, peak limit, and descriptive function (Karlen et al. 1994, 2001, 2003; Qi et al. 2009; Liu et al. 2014b, c). In this study, due to these indicators near the upper limit, the following SSF equation was selected:

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

where x is the value of a single indicator, $f(x)$ is the score of a given indicator, and L and U are the lower and the upper threshold values of the indicator. In addition, indicators of altitude were defined without a specific threshold value based on a “lower is better” definition with the highest altitude receiving a score of 1. This is mainly due to the fact that low altitude is not only favorable to agricultural practices but also controls soil erosion and is relative beneficial for agricultural production (Tan and Wang, 2016). Details of the scoring and normalization methods are described by Karlen et al. (1994, 2003) and Liebig et al. (2001).

2.4.3 Weight assignment

The weight assignment for the assessment of soil properties usually requires the two-step PCA for TDS and MDS methods through a communality of each indicator. This was performed according to the methods described by Shukla et al. (2006) and Qi et al. (2009).

2.4.4 Calculation of soil quality index

After all indicators selected using both the TDS and MDS methods were scored and weighted, SQI was calculated using the following integrated quality index (IQI) equation method (Doran and Parkin 1994; Karlen et al. 2001) as follows:

$$\text{SQI} = \sum_{i=0}^n W_i \times S_i \quad (2)$$

where W_i is the assigned weighting factor of each indicator, S_i is either the linear or nonlinear indicator score, and n is the number of indicators in the refined TDS and MDS. Higher SQI values indicated higher soil quality or better soil functions.

2.5 Statistical analysis

Data were subjected to PCA and statistical analysis to assess the differences between the measured properties using SPSS Statistics 17.0 (IBM, NY, USA) and plotted using SigmaPlot 12.5 (Systat Software Inc., CA, USA). Means and correlation analysis results were compared among treatments using the least significant difference (LSD) test with $P < 0.05$ considered to indicate statistical significance.

3 Results

3.1 Agricultural situation in Pinghe

In this study area, obvious differences in inter-annual and inter-month climate data were observed. The mean air temperature and precipitation of annual agricultural production from 2012 to 2016 were 21.7 °C and 1865 mm, respectively. The monthly mean air temperature and precipitation ranged from 14.1–29.0 °C and 32.2–275.4 mm, respectively (Fig. 2). The monthly mean air temperature also showed a similar seasonal pattern for years, with low variation and ranging from 21.3 to 22.0 °C and peaking in July. The frequency and intensity of the mean annual precipitation varied, and the annual fluctuation of the intensity ranged from 1168.2 mm in 2015 to 2577.8 mm in 2013, which was higher than of the fluctuation in the frequency and mainly concentrated in the period from May to August.

There were significant differences in the planting areas of different cropping systems, with increased areas for vegetable and pomelo, whereas the areas of paddy cropping decreased gradually. In 2016, the planting areas of paddy, vegetable, and pomelo were 0.9×10^4 ha, 2.3×10^4 ha, and 4.9×10^4 ha, and the trends of the total yield for different cropping systems (paddy, vegetable, and pomelo: 2.3%, 34.1%, and 63.6%, respectively) were consistent with those of the planting area (Fig. 3). The distribution of different cropping systems along the altitudes was significantly different in the hilly region

(Fig. 4). The altitude of pomelo orchards ranged from 55 to 701 m, with an average value of 345 m, average values that were significantly higher than those of paddy fields (137 m), which in turn were significantly higher than those of vegetable fields (33 m).

3.2 Soil chemical properties

Overall, the characteristics of soil nutrients showed co-existing change trends of deficiency and excess in this study (Table 1). The soil pH of all the total 127 samples from the different cropping soils (paddy field, vegetable field, and pomelo orchard) ranged from 3.5 to 5.0, with almost 100% of soils being lower than the optimum range of 5.0–6.5 for crop growth, and followed by 99.2%, 88.2%, 87.4%, 81.1%, 66.9%, and 55.9% in Avail-Ca, Avail-B, Avail-Zn, Avail-Mg, Avail-N, and Avail-K, respectively. However, the soil Avail-P was much more than the optimum range of 15 to 80 mg kg⁻¹ and 50.4% of soils were super-optimum, followed by organic matter (23.6%), total N (10.2%), Avail-B (0.8%), and Avail-Mg (0.8%). Box-plot summaries of the soil indicators showed that there were significant differences between the cropping systems (Fig. 4). The total N and Avail-N of pomelo orchards was significantly lower than that of paddy and vegetable fields. Furthermore, the Avail-Zn of paddy fields was significantly lower than that of vegetable fields and pomelo orchards. However, the highest yields and average values were found in pomelo orchards.

3.3 Evaluation of soil quality for indicator selection

In total, 11 soil quality indicators were selected for PCA, which revealed four main PC groups with eigenvalues ≥ 1 , with the cumulative values accounting for 66.79% in the TDS method (Table 2). The communalities of all indicators were explained from 61.1% (Avail-B) to 81.5% (total N), indicating that the extracted PCs reflected the soil properties well (Table 4). The major weighted variables in each PC defined as the indicators within 10% of the highest weight of eigenvectors or factor loading were selected as follows: total N and Avail-N in PC1, pH value, Avail-Ca and Avail-Mg in PC2, altitude in PC3, and Avail-Zn in PC4 (Table 2).

Second, the major weighted variables in each PC should be correlated by multiple regression method for the MDS method, particularly in PC with multivariate indicators. Based on the highest weight of eigenvector (Table 2) and the highest weight of correlation sum (Table 3), the optimized indicators of total N and Avail-N in PC1 and Avail-Ca in PC2 were selected in the MDS. Moreover, altitude in PC3 and Avail-Zn in PC4 were identified as two undisputed indicators with high weighting in the MDS (Tables 2 and 3). Finally, the refined MDS consisted of the following indicators: total N, Avail-N, Avail-Ca, altitude, and Avail-Zn.

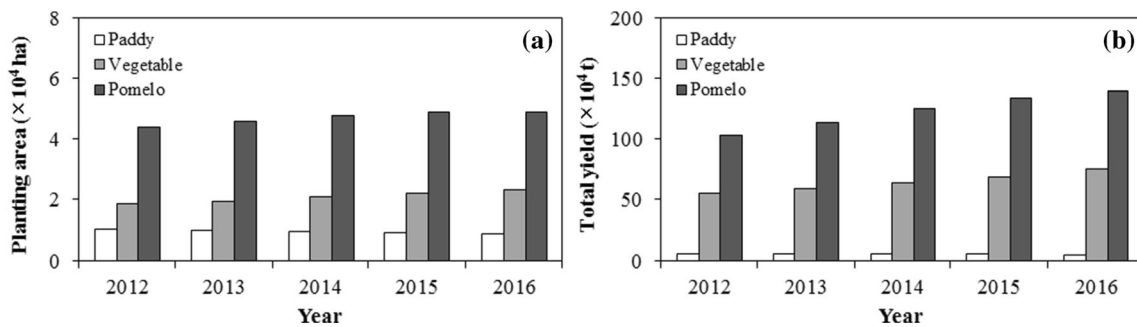


Fig. 3 The planting area (a) and total yield (b) of different cropping systems in the paddy field, vegetable field, and pomelo orchard in Pinghe County during 2012–2016

3.4 Evaluation of soil quality for indicator scoring and weight assignment

In addition to altitude defined using the “lower is better” method, the SSF equation (Eq. 1) was used for all soil quality indicators in TDS and selected indicators in MDS, with the lower (L) and the upper (U) threshold values of SSF representing optimum ranges based on the classification

standard of paddy and citrus in Table 1. Five representative indicators in MDS were then subjected to further PCA to determine their communalities and weights (Table 4). Generally, the Avail-K (0.058) and Avail-Ca (0.097) have the lowest weight in TDS and MDS indicators, while the weight of other indicators was relatively even, indicating that these soil properties play important roles in soil quality evaluation.

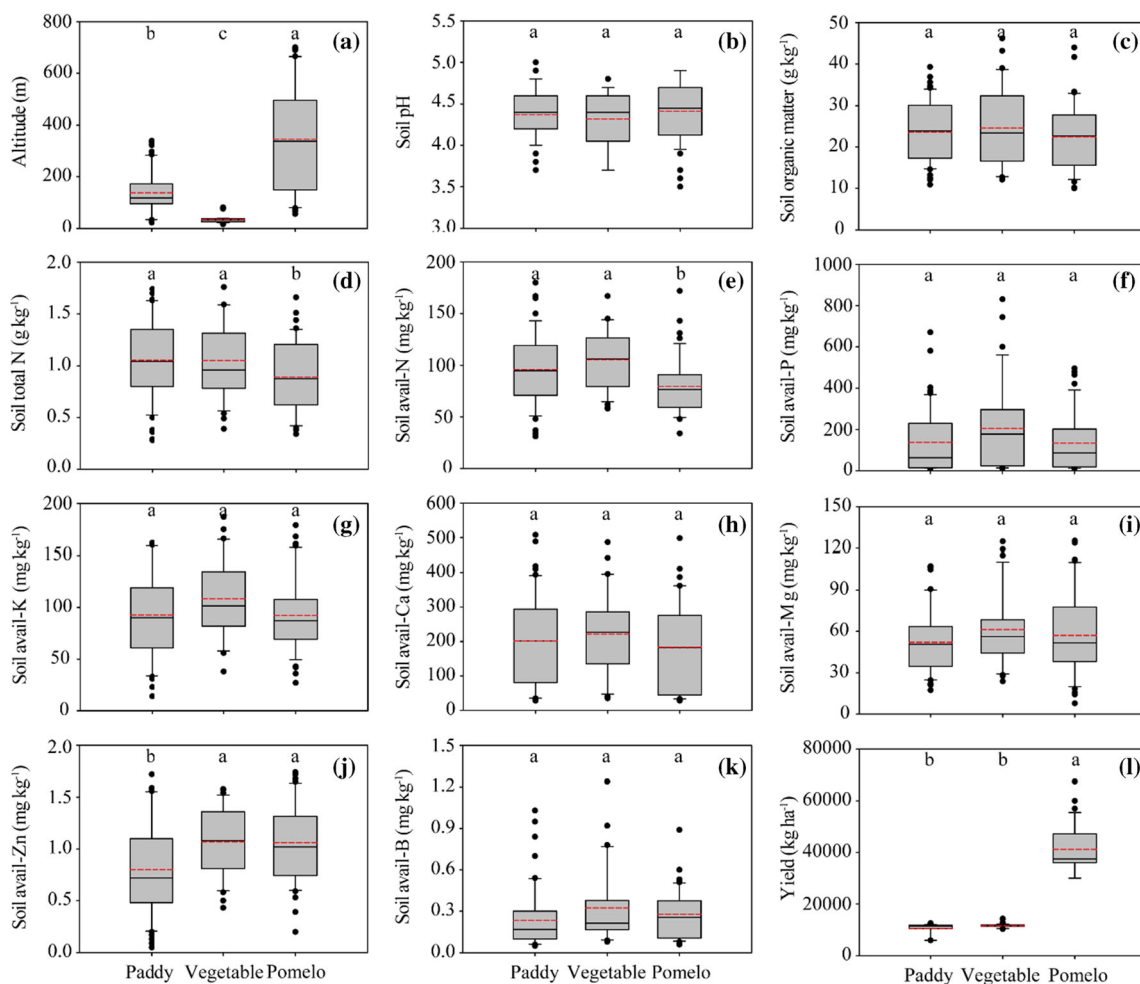


Fig. 4 The distribution of altitude (a), soil chemical properties (b–k) and yields (l) of different cropping systems in the paddy field, vegetable field and pomelo orchard in Pinghe County. The red dotted line represents the average value

Table 1 Soil chemical properties under different cropping systems in a paddy field, vegetable field, and pomelo orchard in Pinghe County

Cropping system	Avail-nutrient	Samples	Data range	Average	Coefficient of variation (%)	Optimum range	Classification percent (%)		
							Sub-optimum	Optimum	Super-optimum
Paddy field	pH value	51	3.7–5.0	4.4 ± 0.3	7.2	5.0–6.5	100.0	0.0	0.0
	Organic matter (g kg ⁻¹)	51	10.9–39.3	23.6 ± 7.3	30.9	15–30	9.8	64.7	25.5
	Total N (g kg ⁻¹)	51	0.3–1.7	1.1 ± 0.4	36.0	0.7–1.5	21.6	64.7	13.7
	Avail-N (mg kg ⁻¹)	51	31.0–180.0	96.0 ± 34.4	35.8	100–200	66.7	33.3	0.0
	Avail-P (mg kg ⁻¹)	51	10.2–670.4	137.9 ± 158.8	115.2	15–80	25.5	31.4	43.1
	Avail-K (mg kg ⁻¹)	51	14.0–162.0	92.6 ± 41.7	45.0	100–200	58.8	41.2	0.0
	Avail-Ca (mg kg ⁻¹)	51	28.1–507.6	201.3 ± 130.1	64.6	500–2000	98.0	2.0	0.0
	Avail-Mg (mg kg ⁻¹)	51	17.4–107.4	52.2 ± 24.0	45.9	80–125	86.3	13.7	0.0
	Avail-Zn (mg kg ⁻¹)	51	0.1–1.7	0.8 ± 0.4	55.9	1.5–5.0	90.2	9.8	0.0
	Avail-B (mg kg ⁻¹)	51	0.1–1.0	0.2 ± 0.2	94.8	0.5–1.0	88.2	11.8	0.0
	pH value	32	3.7–4.8	4.3 ± 0.3	7.9	5.0–6.5	100.0	0.0	0.0
	Organic matter (g kg ⁻¹)	32	12.1–46.2	24.6 ± 9.4	38.2	15–30	15.6	53.1	31.3
	Total N (g kg ⁻¹)	32	0.4–1.8	1.0 ± 0.4	33.7	0.7–1.5	21.9	65.6	12.5
	Avail-N (mg kg ⁻¹)	32	58.0–167.0	105.1 ± 29.5	28.1	100–200	43.8	56.3	0.0
Avail-P (mg kg ⁻¹)	32	11.2–830.9	205.0 ± 214.5	104.7	15–80	15.6	25.0	59.4	
Avail-K (mg kg ⁻¹)	32	38.0–187.0	108.5 ± 37.8	34.8	100–200	40.6	59.4	0.0	
Avail-Ca (mg kg ⁻¹)	32	35.2–486.5	221.2 ± 116.6	52.7	500–2000	100.0	0.0	0.0	
Avail-Mg (mg kg ⁻¹)	32	23.8–124.9	61.2 ± 26.2	42.8	80–125	78.1	21.9	0.0	
Avail-Zn (mg kg ⁻¹)	32	0.4–1.6	1.1 ± 0.3	30.2	1.5–5.0	93.8	6.3	0.0	
Avail-B (mg kg ⁻¹)	32	0.1–1.2	0.3 ± 0.3	83.2	0.5–1.0	84.4	12.5	3.1	
Pomelo orchard	pH value	44	3.5–4.9	4.4 ± 0.4	8.2	5.0–6.5	100.0	0.0	0.0
	Organic matter (g kg ⁻¹)	44	10.0–44.0	22.5 ± 8.1	36.2	15–30	18.2	65.9	15.9
	Total N (g kg ⁻¹)	44	0.3–1.7	0.9 ± 0.3	38.2	0.7–1.5	36.4	59.1	4.5
	Avail-N (mg kg ⁻¹)	44	34.0–172.0	79.7 ± 28.2	35.3	100–200	84.1	15.9	0.0
	Avail-P (mg kg ⁻¹)	44	10.7–497.0	133.9 ± 142.7	106.6	15–80	15.9	31.8	52.3
	Avail-K (mg kg ⁻¹)	44	27.0–179.0	92.2 ± 34.7	37.7	100–200	63.6	36.4	0.0
	Avail-Ca (mg kg ⁻¹)	44	28.0–498.0	183.7 ± 126.1	68.6	500–2000	100.0	0.0	0.0
	Avail-Mg (mg kg ⁻¹)	44	7.8–125.4	57.0 ± 30.1	52.8	80–125	77.3	20.5	2.3
	Avail-Zn (mg kg ⁻¹)	44	0.2–1.7	1.1 ± 0.4	36.4	1.5–5.0	86.4	13.6	0.0
	Avail-B (mg kg ⁻¹)	44	0.1–0.9	0.3 ± 0.2	64.3	0.5–1.0	90.9	9.1	0.0
	pH value	127	3.5–5.0	4.4 ± 0.3	7.7	5.0–6.5	100.0	0.0	0.0
	Organic matter (g kg ⁻¹)	127	10.0–46.2	23.5 ± 8.1	34.6	15–30	14.2	62.2	23.6
	Total N (g kg ⁻¹)	127	0.3–1.8	1.0 ± 0.4	36.7	0.7–1.5	26.8	63.0	10.2
	Avail-N (mg kg ⁻¹)	127	31.0–180.0	92.6 ± 32.5	35.1	100–200	66.9	33.1	0.0
Avail-P (mg kg ⁻¹)	127	10.2–830.9	153.4 ± 170.8	111.4	15–80	19.7	29.9	50.4	
Avail-K (mg kg ⁻¹)	127	14.0–187.0	96.4 ± 38.8	40.2	100–200	55.9	44.1	0.0	
Avail-Ca (mg kg ⁻¹)	127	28.0–507.6	200.2 ± 125.3	62.6	500–2000	99.2	0.8	0.0	
Avail-Mg (mg kg ⁻¹)	127	7.8–125.4	56.1 ± 26.8	47.8	80–125	81.1	18.1	0.8	
Avail-Zn (mg kg ⁻¹)	127	0.1–1.7	1.1 ± 0.4	43.4	1.5–5.0	87.4	12.6	0.0	
Avail-B (mg kg ⁻¹)	127	0.1–1.2	0.3 ± 0.2	81.9	0.5–1.0	88.2	11.0	0.8	

Optimum ranges refer to the classification standard of paddy and citrus (Qi et al. 2009; Li et al. 2015), with the lower (L) and the upper (U) threshold values for the SSF equation

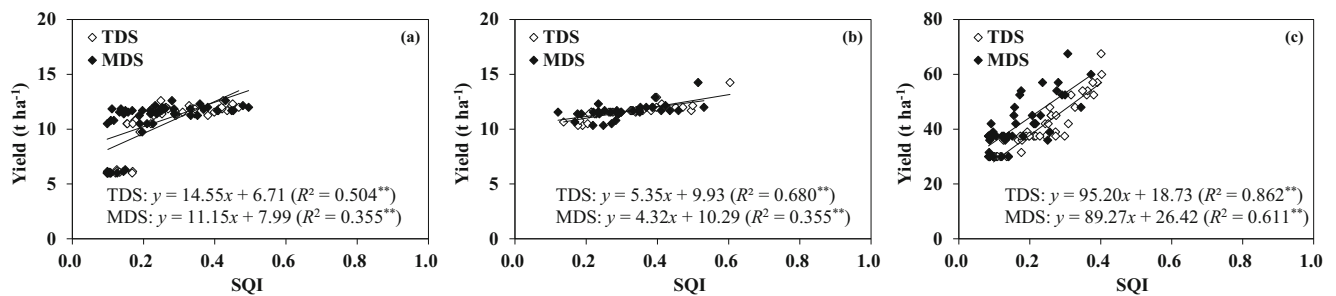


Fig. 6 Correlation between SQI and yields of different cropping systems in paddy field (a), vegetable field (b), and pomelo orchard (c) using the TDS and MDS methods

one most effective soil quality indicators of soil carbon stocks and element cycles in a soil-plant system (Tan and Wang 2016). Guo et al. (2010a) reported out that altitude is negatively correlated with seed mass, and also significantly influences the plant allometry between reproductive and vegetative mass (Guo et al. 2012). In addition, higher altitude is accompanied by lower temperature, which reduces the net primary production and the litter input and decomposition in plants (Bu et al. 2012), through effects on soil microbial activity (Xu et al. 2014). In the current study, a significant difference was detected in the influence of altitude among the different crop system soils (Fig. 4), indicating that altitude is a factor limiting the productivity of acidic red soil hilly regions. The value of altitude was significantly higher in pomelo production soil (Fig. 4), probably due to mandatory government policy for basic farmland protection and competitive farmer's practice for economic benefits. The higher altitude of fruit orchard may produce negative effects on pomelo production, such as delayed fruit coloration, decreased sugar to acid ratio, and reduced market benefit. In addition, higher altitude also influenced the crop planting practice with the implementation of hard irrigation and fertilization. Generally, an area can be divided into many different regions of soil quality based on soil heterogeneity and crop productivity (Liu et al. 2014a, b, c). The region investigated in this study can be separated into

two distinct regions for water and soil conservation and agricultural production: (1) the low altitude and relatively higher-quality flat region and (2) the high altitude and relatively lower-quality hilly region.

Soil chemical properties are affected by soil structure and farming practices. Appropriate soil organic matter content is fundamental to soil quality (Manlay et al. 2007). In the last two decades, the soil organic matter content has gradually increased as a result of human activity, playing an essential role in improving soil quality and maintaining crop yield (Pan et al. 2009). This is mainly due to the increasingly active participation by farmers (Mowo et al. 2006; Zhang et al. 2016). Changed land-use from natural hilly land to reclaimed fruit orchards usually improves soil quality, and fertilization (organic and chemical) results in increased organic matter and nutrient content (Huang et al. 2007). The present study showed that the pomelo orchards had the lowest soil organic matter contents (Table 1, Fig. 4), suggesting that improving the quantity of soil organic matter for high soil fertility and high yield in orchards should be a focus of future management practices. In this study area, the soil total N and Avail-N of pomelo were significantly lower than that of paddy and vegetable fields, and the soil Avail-Zn of pomelo and vegetable was significantly higher than that of paddy fields (Fig. 4). These results indicate that different planting systems significantly change soil chemical properties, and lower levels of soil N are considered the most important limiting factor for pomelo orchards.

In general, although continuous intensive production practices can significantly improve soil fertility, the result of increasing total environmental risks cannot be ignored. To obtain a high yield, farmers often adopt heavy and imbalanced application of chemical fertilizers, especially N, P, and K fertilizers, while neglecting the application of micronutrients, leading to micronutrient deficiency (Cakmak 2008) and soil acidification (Guo et al. 2010a). In accordance with our results, previous studies showed that Zn is an essential micronutrient for plant nutrition, and Zn deficiency is the most widespread micronutrient disorder in paddy fields (Rehman et al. 2012; Guo et al. 2016). These results suggest that, in addition to order micronutrients, the application of Zn

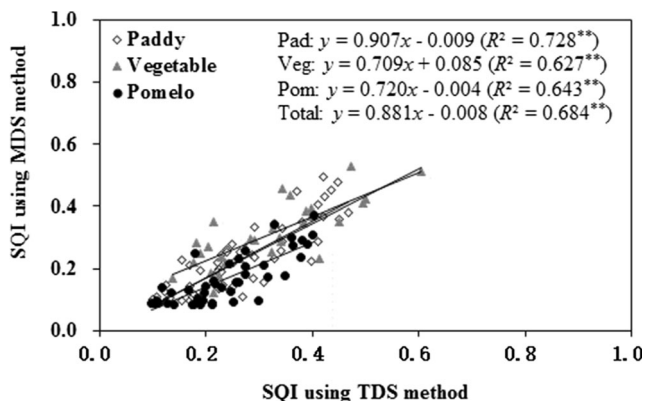


Fig. 7 Linear relationship of soil quality index (SQI) on the MDS indicator method with the TDS indicator method

fertilizer should be a priority for rice production in this region. Soil pH is considered to be a critical indicator of soil quality. Acidic soils (pH < 5) are unfavorable for crop production because the environment induces variation in nutrient cycling of N and P, bioavailability of the microelements, Ca and Mg, and excessive solubility of Al and Mn (Myaer 1998; Kemmitt et al. 2005). These conditions significantly affect plant growth and nutrient uptake in rice, vegetable (Fageria and Baligar 1999), and citrus (Long et al. 2017) crops. Fortunately, the soil pH in Pinghe is still below 5.0 (Table 1; Fig. 4). As a result of the integrated effects of soil characteristics and climate environment, acidic soils are rich in Avail-P and poor in Avail-K, Avail-Ca, Avail-Mg, Avail-Zn, and Avail-B in this region, which is consistent with the findings of Li et al. (2015). Due to the lack of Ca and Mg in the soil, fruit cracking and leaf chlorosis are frequently observed during the maturity period in pomelo production (Li et al. 2015). This suggests the application of alkaline fertilizer containing Ca and Mg will play multiple roles in regulating soil acidification to improve soil and fruit quality.

4.2 Evaluation of soil chemical quality in acidic red soil hilly regions

Quantifying soil quality requires an MDS, which is an important approach to the reduction of the number of soil indicators. This strategy improves the targeted determination of soil properties, which reduces the cost and time required for testing, and provide a single index that increases the precision of the assessment (Andrews et al. 2002; Rezaei et al. 2006; Yao et al. 2013). In the present study, the MDS of soil properties was established for different cropping systems (paddy field, vegetable field, and pomelo orchard) based on the PCA results. Table 2 shows that soil pH, Avail-Ca, and Avail-Mg were loaded on the PC2. Avail-Ca was optimally selected in the MDS because of its intermediate eigenvector and strong correlation with soil pH and Avail-Mg based on multiple regression analysis, which was performed to verify how well indicators selected for the MDS reflect soil quality (Andrews et al. 2002; Rezaei et al. 2006). However, there were slight differences in the loading factor values for soil pH (0.663), Avail-Ca (0.659), and Avail-Mg (0.626), indicating an almost equally important role in soil quality assessment. Finally, the MDS of typical indicators was established as total N, Avail-N, Avail-Ca, altitude, and Avail-Zn, with fewer indicators in the MDS (5) than in the TDS (11). Compared with the TDS method, the Avail-N has the highest weight and the Avail-Ca has the lowest weight in the MDS method (Table 4). However, a significant positive correlation was found between SQIs calculated using the TDS and MDS methods (Fig. 7), demonstrating that soil quality

assessment using the MDS method is highly representative of the assessment using the TDS method in this study. Inclusion of micronutrients, such as Avail-Ca and Avail-Zn, would provide farmers with a concept of balanced soil nutrients; this is not focused only on N, P, and K. Furthermore, our list also includes altitude, which was not identified in evaluations of any other MDS methods. This suggests that altitude properties are included in the assessments of the soil quality in hilly and mountainous areas.

In China, the SQI is consistent with four grades based on the classification standard of the regional type and soil quality characteristics (ISMAPRC 1996; Qi et al. 2009), which is the criterion for calculating SQI using the TDS method. Our results showed that average SQI in paddy-vegetable-pomelo cropping systems was 0.26, far lower than 0.56 of the fourth grade, which severely limits plant growth. The value implies that the soil quality status in Pinghe County is very low, which is consistent with the result reported by Li et al. (2015). There were significant differences in the SQI values calculated for paddy, vegetable, and pomelo soil using both of the TDS and MDS methods, indicating marked variation in the soil quality for these three agriculture ecosystems in this particular region. The soil quality in different crop systems may also be affected by low water and soil conservation and high nutrient runoff due to the differences in attitude distribution and adequate rainfall capacity. Moreover, there is a significant positive correlation between crop yield and soil quality, and the slope and correlation coefficient (R^2) of pomelo were obviously higher than those of paddy and vegetable fields (Fig. 6), indicating pomelo orchards have a huge potential for increasing production by soil fertility management.

Physical properties of soil also strongly influence soil function and determine potential land-use (Fernández-Ugalde et al. 2009; Qi et al. 2009), and the physical quality of soil is also considered a critical factor in evaluating the total quality of agroecosystems because of the significant effects on the chemical and biological processes in soil (Liu et al. 2014a, b, c). Similar to the physical and chemical properties, the biochemical properties of soil, such as soil biology and enzyme activities, have also been widely adopted as indicators for soil quality assessment (Bastida et al. 2008; Liu et al. 2014a, b, c). Soil biochemical properties play an essential role in controlling soil nutrient release and availability, improving the richness of soil quality indicators, enhancing sensitivity to environmental changes, and indicating the consequences of land management on plant growth and maintenance of soil fertility (Bandick and Dick 1999; Romaniuk et al. 2012; Li et al. 2013). The results of our study provide a practical basis and initial strategy for selection of the optimized and targeted indicators for soil quality assessment in acidic red soil hilly regions, although the newly identified indicators require further evaluation.

5 Conclusions

To evaluate soil quality in acidic red soil hilly regions, 11 soil properties (altitude and 10 chemical parameters) were determined and selected for PCA. The altitude, total N, Avail-N, Avail-Ca, and Avail-Zn were considered in the MDS. SQI values were calculated and the soil quality was ranked as vegetable > paddy > pomelo using both the TDS and MDS methods. Significant positive correlations were observed between SQI and annual crop yields, indicating the selected indicators in MDS are a suitable and convincing method for soil quality assessment. Our results suggest that lower levels of total N and Avail-N with higher altitude are the major factors limiting pomelo crop production, and integrated nutrient management including soil application of Ca and Mg fertilizers and foliar application of trace element fertilizers is required to improve soil quality and crop yield. Taken together, our findings indicate that long-term intensive farming practices in different cropping systems significantly affect the soil nutrient status, thereby affecting soil quality. Therefore, farmers in this area should focus on specific limiting factors in soil fertility-building management to improve pomelo productivity.

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