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Quantitative Assessment of Soil Health Under Different Planting Patterns and Soil Types*[1]

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ABSTRACT

Soil health assessment is an important step toward understanding the potential effects of agricultural practices on crop yield, quality and human health. The objectives of this study were to select a minimum data set for soil health evaluation from the physical, chemical and biological properties and environmental pollution characteristics of agricultural soil and to develop a soil health diagnosis model for determining the soil health status under different planting patterns and soil types in Chongming Island of Shanghai, China. The results showed that the majority of the farmland soils in Chongming Island were in poor soil health condition, accounting for 48.9% of the survey samples, followed by the medium healthy soil, accounting for 32.2% of the survey samples and mainly distributed in the central and mid-eastern regions of the island. The indicators of pH, total organic carbon, microbial biomass carbon and Cd exerted less influence on soil health, while the soil salinization and nitrate accumulation under a greenhouse cropping pattern and phosphate fertilizer shortage in the paddy field had limited the development of soil health. Dichlorodiphenyltrichloroethanes, hexachlorocyclohexanes and Hg contributed less to soil health index (SHI) and showed no significant difference among paddy field, greenhouse and open-air vegetable/watermelon fields. The difference of the SHI of the three soil types was significant at $P = 0.05$. The paddy soil had the highest SHI values, followed by the gray alluvial soil, and the coastal saline soil was in a poor soil health condition, indicating a need to plant some salt-tolerant crops to effectively improve soil quality.

Key Words: Chongming Island, minimum data set, soil health indexes, soil quality

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INTRODUCTION

Soil is an important natural resource that sustains agricultural productivity, maintains water and air quality, and supports human health and habitation. Soil quality (SQ) integrates three components, including continuous biological productivity, environmental quality, and plant and animal health (Karlen *et al.*, 1997). Because SQ links closely with human health, soil health is also widely mentioned, but in most cases, the meaning of soil health is similar to SQ (Doran and Zeiss, 2000). However, in natural ecosystems, the term "soil health" is not exactly equal to SQ. Considering the time scales, soil health can describe the "potential" and "dynamic" conditions of the soil in a short period, while the SQ can describe the "inner" and "static" conditions of the soil over longer time scales (Carter *et al.*, 1997). The term "soil quality" will generally be associated with a soil's fitness for a specific use (Larson and Pierce, 1994), while soil health is used in a broader sense to indicate the capacity of the soil to function as a vital living system (Doran and Zeiss, 2000). Soil health focuses more on the biotic components of a soil, reflecting the maintenance of soil organisms and their proper functions to regulate nutrient cycling and soil fertility (Anderson, 2003).

As soil health mainly reflects the activity and dynamics of soil based on soil function, it is difficult to define soil health standards. Assessment of soil health can be conducted in a variety of ways according to soil physical, chemical and biological characteristics. The Soil Management Assessment Framework (SMAF), which is widely used in SQ assessment and can comprehensively evaluate the variety of biological, chemical and physical indicators and further quantify SQ, can be used as a soil health evaluation method (Karlen *et al.*,

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2006). The method has been successfully used to analyze crop rotation effects on the SQ in various planting systems (Andrews *et al.*, 2002a; Andrews *et al.*, 2004; Karlen *et al.*, 2006; Wienhold *et al.*, 2006) and to examine the effects of supplemental C management practices on farmland SQ (Andrews *et al.*, 2002b). The SQ is dependent on its inherent properties, resulting from soil type, intended land use, and management goals (Andrews *et al.*, 2004).

Soil microorganisms play a key role in energy flows, nutrient transformations and element cycles in terrestrial environments that are essential for obtaining a healthy soil. The microbial biomass is the essential source and sinks of nutrients for the whole terrestrial ecosystem and is expressed as the mass of carbon immobilized in microbial cells (microbial biomass C). The functionality of microorganisms may be measured by microbial respiration, which is influenced both by the energy sources in the soil and the number of microorganisms. Abnormally high respiration could indicate stress as a result of increased energy requirements (Anderson and Domsch, 1985). Both the microbial biomass C and respiration may vary with management practices, tillage, amendment, contamination or even climate change. While differences might exist in the microbial biomass between different soil types (Schloter *et al.*, 2003), it is necessary to evaluate soil quality by integrating a variety of indicators (Bastida *et al.*, 2008).

Chongming Island is located in the Yangtze estuary (121° 09′–121° 54′ N, 31° 27′–31° 51′ E). The report of a "Master Plan for the Three Islands of Chongming" clarifies the developing goal of Chongming Island. Based on agriculture, the development goal is to promote the transformation from traditional agriculture to ecological agriculture and ultimately to achieve eco-industries. However, the contaminated soil (*e.g.*, heavy metals and pesticides) and inadequate or excessive fertilization in some areas would severely restrict the development of ecological agriculture in Chongming (Sun *et al.*, 2010). How to establish a scientific soil health monitoring system to ensure the quality of crop products from the agricultural environment has become a research focus.

The objectives of this current work were i) to choose a minimum data set (MDS) for soil health assessment based on the physical, chemical and biological properties and environmental pollution and using principal components analysis (PCA) as a data reduction technique, ii) to develop a soil health assessment model to study soil health status and its spatial variations in Chongming Island, China and iii) to study the effects of planting patterns and soil types on soil health so as to provide a basis for decision-making for the development of the Chongming ecological agriculture.

MATERIALS AND METHODS

Study site

Farmers fertilize mainly based on their own experience and purchasing power in China. They believe "high input, high output" and blindly invest a large amount of fertilizer into agricultural fields to ensure high yield (Gao *et al.*, 2006). In Chongming County, for a corn-cauliflower crop rotation field, a greenhouse vegetable crop rotation field, and a greenhouse asparagus field fertilized with urea, compound fertilizer, potassium sulfate and organic animal manure-based fertilizers in 2007–2009, the average annual nutrient inputs were: 525, 1 579 and 1 492 kg ha^{-1} of inorganic and organic nitrogen; 330, 771 and 1 228 kg ha^{-1} of inorganic and organic phosphorus; and 100, 676 and 1 139 kg ha^{-1} of inorganic and organic potassium, respectively, with a nutrient surplus rate of 76%, 57% and 88% for nitrogen, 86%, 70% and 94% for phosphorus, and 6%, 28% and 77% for potassium, respectively (Li *et al.*, 2011). The amount of chemical fertilizer applied to the rice fields in Chongming County contained 382 kg ha^{-1} of nitrogen and 48 kg ha^{-1} of P_2O_5 in the early 21st century, while the application amount of K_2O in the early 21st century was 5.4 times that in the late 1980s (Yang, 2006).

Soil sampling and analyses

The planting systems in Chongming are mainly rice/wheat rotation and vegetable/watermelon rotation, while the management pattern of the latter includes two kinds: greenhouse and open-air planting. Therefore, the three land planting patterns of paddy fields, greenhouse and open-air vegetable/watermelon fields were studied in this work. In addition, to examine the effects of soil types on soil health, three main soil types, paddy soil, gray alluvial soil and coastal saline soil, were analyzed. The soil sampling sites were selected based on a grid of 2 km × 2 km in accordance with crop type, soil type and the layout of the functional areas of Chongming. In each sampling site, approximately 8–10 subsamples of topsoil (0–20 cm) were taken and mixed thoroughly to obtain a bulk sample. A total of 102 samples, 65 samples from the paddy fields, 24 samples from the greenhouse vegetable/watermelon fields and 13 samples from the open-air vegetable/watermelon fields, were collected in

July, 2008. The coordinates of the sample locations were recorded with a portable global positioning system, and the sampling sites are shown in Fig. 1.

Selecting appropriate indicators is the foundation of soil health assessment. A total of 19 indicators were considered, including the physical and chemical properties such as pH, redox (Eh), clay content and electrical conductivity (EC), soil nutrient indicators such as available phosphorus (AP), available potassium (AK), available nitrogen (AN) and nitrate (NO_3^--N), the biological indicators such as total organic carbon (C_{org}), microbial biomass carbon (C_{bio}), metabolic quotient (C_{BR}/C_{bio}, where C_{BR} is the basal respiration without addition of any substrate) and potential respiration quotient (C_{PR}/C_{bio}, where C_{PR} is the potential respiration after the actual addition of glucose to the soil), and soil pollution indicators such as Cd, Cr, As, Pb, Hg, hexachlorocyclohexanes (HCHs) and dichlorodiphenyltrichloroethanes (DDTs). In the physical indicators, considering the relationship between clay content and other physical indicators, such as saturated hydraulic conductivity, non-capillary pores and available water-holding capacity, and the sensitivity of biological indicators to changes in the physical parameters (Bastida *et al.*, 2008), only one physical parameter, *i.e.*, clay content, was used for soil health assessment.

The Eh and pH values of the soil were measured *in situ* using a portable pH instrument (IQ Scientific Instruments, USA). The soil samples were freeze-dried, then ground to pass through a 1.0-mm sieve for the measurements of ions and through a 0.125-mm sieve for the measurement of heavy metals and persistent organic pollutants. Any samples not sieved were dispersed, and the soil particle sizes were determined using a laser grain analyzer (Beckman Coulter LS13320, USA). The soil EC values were measured using a salinity-conductivity-temperature meter (YSI30, USA) in accordance with Lu (2000). After the soil samples were screened with a 60-mesh sieve, the contents of AP, AK and AN were determined using a HCl-H_2SO_4 extraction method, an ammonium acetate extraction-flame spectrophotometer, and a diffusion-absorption method, respectively (Lu, 2000). The nitrates were extracted using KCl (Keeney and Nelson, 1982) and analyzed with a continuous flow analyzer (Alliance Futura, France) with the error within 2%. The C_{org} was determined using a potassium dichromate oxidation-external heating method (Nelson and Sommers, 1982). The C_{bio} was determined using a chloroform fumigation extraction method (Vance *et al.*, 1987; ISO14240-2, 1997). The C_{BR} and C_{PR} were measured after pre-incubation of the moistened soil samples in accordance with ISO14240-1 (1997) and Hofman *et al.* (2003). The soil sample was digested using concentrated HNO_3, HF and $HClO_4$ in a microwave oven, and the solutions were determined using a flame atomic adsorption spectrophotometer (Perkin-Elmer AANALYST 800, USA) for Cr, a graphite stove method for Cd and Pb, and an atomic fluorescence spectrometer (Titan AFS9230, China) for As and Hg (Shi *et al.*, 2009; Sun *et al.*, 2010). The soil samples were extracted with acetone/dichloromethane (1:1, v:v) and then purified, dried and concentrated to 1 mL. The HCHs and DDTs were measured by gas chromatography with a ^{63}Ni electron capture detector (Agilent 7890A, USA) (Shi *et al.*, 2009).

For quality assurance and quality control (QA/QC), blanks and triplicate samples were processed for every 20 samples. The China certified reference material (GBW07309) was used to ensure analysis accuracy of heavy metals, and the relative standard deviations

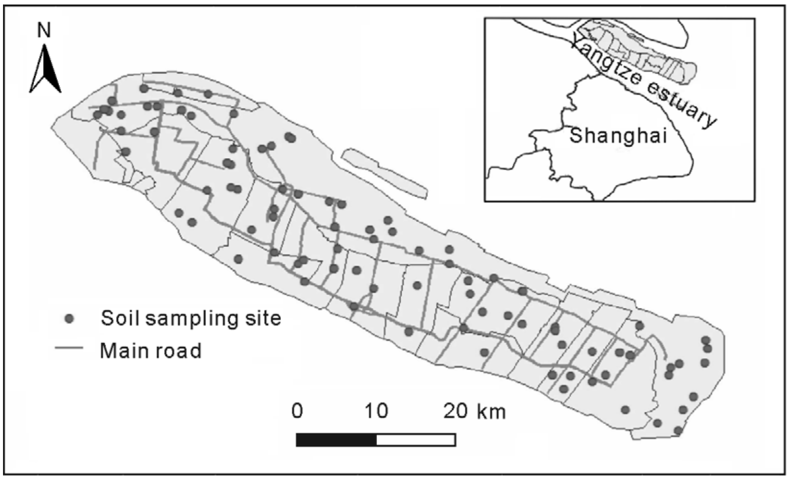

Fig. 1 Locations of agricultural soil samples in Chongming Island, China.

of triplicate samples were less than 10%. The recoveries of spiked organochlorine pesticides were between 64.2% and 89.5%.

Soil health assessment method

The SMAF involves three basic steps: indicator selection, indicator transformation, and integration into an SQ index (Andrews *et al.*, 2004). Since the MDS was proposed to evaluate the SQ (Larson and Pierce, 1991), many MDSs from plot to regional scale were developed to assess the SQ (Glover *et al.*, 2000; Liebig *et al.*, 2001; Andrews *et al.*, 2002a; Zhang *et al.*, 2007; Li *et al.*, 2008). The MDS indicators are chosen based on their testability, repeatability and representation of key variables to control SQ. Until now, the selection of MDS components has relied primarily on expert opinion and statistical methods, but there is no significant difference between expert opinion and PCA methods for the vegetable production systems in Northern California, as reported by Andrews *et al.* (2002a), although the results might not be suitable for other agricultural fields in the world. The selection method should be carefully considered and may vary by site and use.

The MDS indicators can be scored using linear and non-linear scoring techniques (Andrews *et al.*, 2002a). The linear scoring method is based on whether a higher value of indicators is considered “good” or “bad” in terms of soil function. For “more is better” indicators, each observation was divided by the highest observed value, while for “less is better” indicators, each observation was divided by the lowest observed value (Andrews *et al.*, 2002b; Bastida *et al.*, 2008). For the non-linear scoring method, the indicators were scored by the standardized scoring functions constructed using CurveExpert v.1.3 shareware, which can normalize the indicator measurement to a value between 0 and 1.0 (Glover *et al.*, 2000). Three decision functions were developed, *i.e.*, “mid-point optimum”, “more is better” and “less is better”, and had been used to transform the indicators, such as C_{org}, C_{bio}, AP, pH, EC, Zn, *etc.* (Hendrix *et al.*, 1990; Tiessen *et al.*, 1994; Smith and Doran, 1996; Maynard and Hochmuth, 1997). Finally, the numerical values for each soil quality indicator were converted into unitless scores between 0 and 1.

Once transformed, the MDS indicators for each observation were weighted using the PCA results. Each principal component (PC) explained a certain amount of the variation in the total data set. This percentage, divided by the total percentage of all PCs with eigenvectors > 1, provided the weight for the variables under each PC. The weighted, additive soil quality index (SQI) method was used for index integration (Harris *et al.*, 1996; Andrews *et al.*, 2002a). In this study, soil health index (SHI) was calculated using the following formula:

$$\mathrm{SHI} = \sum_{i=1}^{n} W_i S_i \qquad (1)$$

where W_i is the weight of i variable, S_i represents the scored indicator value, and n is the number of indicators in the MDS. Higher SHI scores are assumed to mean better soil health conditions or more high-performance soil functions.

Statistical analyses

The statistical analyses were conducted using SPSS11.5 software package (SPSS Inc., Chicago, USA). The PCA was performed on the observed indicators to select the MDS. Pearson correlation analyses between the indicators were used to examine the redundancy of variables in the MDS. A one-way analysis of variance (ANOVA) on the soil SHI values was employed to compare the statistical differences between the three planting patterns or three soil types, and a general linear model (GLM) univariate analysis was used to compare the difference between the interaction of planting patterns and soil types.

The SHI data for the agricultural fields were mapped using the interpolation method of inverse distance weighting using ArcGIS v.9.3 (ESRI Co., Redlands, USA) for the analysis of spatial variation.

RESULTS AND DISCUSSION

Physical, chemical and microbial properties of agricultural soils

Table I lists the statistics of soil indicators in the paddy field, greenhouse and open-air vegetable/watermelon fields in Chongming Island. Among the soil physical and chemical indicators, for EC in a large spatial variability, the variation coefficients were 82.4%, 202.2% and 151.1% in the paddy field, the greenhouse and the open-air vegetable/watermelon fields, respectively, and the high values for the vegetable/watermelon planting showed that this planting method can cause soil salinization. Among the soil nutrient indicators, the contents of AP, NO_3^--N and AN in the greenhouse and open-air vegetable/watermelon soils were significantly higher than those in the paddy soil, and their variation coefficients were higher in all the soil types, with values of 241.6%, 97.8% and 67.8% in the paddy soil, 96.5%, 97.2% and 101.9% in the greenhouse

TABLE I

Descriptive statistics of soil indicators for soil health assessment in different planting patterns of Chongming Island, China

Indicator	Variable[a)]	Paddy field			Greenhouse vegetable/ watermelon field			Open-air vegetable/ watermelon field		
		n	Mean value	Standard error	n	Mean value	Standard error	n	Mean value	Standard error
Physical and chemical indicators	pH	65	7.36	0.45	23	7.11	0.40	13	7.40	0.27
	Eh (mV)	65	−21.92	25.49	23	−5.90	17.69	13	−23.95	13.21
	Clay (%)	64	13.41	2.09	24	13.77	2.13	13	12.86	1.82
	EC (µS cm^{-1})	62	157.5	129.8	24	329.5	666.1	12	491.6	743.0
Nutrient indicators	AP (mg kg^{-1})	65	5.70	13.77	24	55.19	53.26	13	15.11	26.24
	AK (mg kg^{-1})	65	308.73	146.38	24	433.69	370.73	13	295.73	107.75
	NO_3^--N (mg kg^{-1})	63	93.21	91.19	24	335.96	326.67	13	247.87	314.36
	AN (mg kg^{-1})	65	165.07	111.92	24	491.64	501.04	13	355.23	341.23
Pollutant indicators	Cd (mg kg^{-1})	64	0.17	0.04	23	0.21	0.08	13	0.17	0.06
	Pb (mg kg^{-1})	64	24.41	17.71	23	21.18	2.81	13	19.28	2.72
	Cr (mg kg^{-1})	64	68.14	9.06	23	73.94	7.69	13	67.52	7.44
	As (mg kg^{-1})	65	8.61	3.11	24	12.44	8.29	13	9.15	2.96
	Hg (mg kg^{-1})	65	0.14	0.11	24	0.14	0.11	13	0.23	0.23
	HCHs (mg kg^{-1})	65	6.23	15.54	24	6.52	9.38	13	4.05	4.56
	DDTs (mg kg^{-1})	65	10.67	17.26	24	20.09	29.42	13	7.40	10.67
Biological indicators	C_{org} (g kg^{-1})	65	22.58	7.30	24	23.01	6.28	13	14.26	6.00
	C_{bio} (mg kg^{-1})	65	110	40	24	120	40	13	120	30
	C_{BR}/C_{bio} (mg CO_2-C g^{-1} h^{-1})	63	2.83	1.06	23	2.65	1.17	13	2.82	0.90
	C_{PR}/C_{bio} (mg CO_2-C g^{-1} h^{-1})	63	9.20	4.40	23	9.13	2.97	13	8.88	3.75

[a)] EC = electrical conductivity; AP = available phosphorus; AK = available potassium; AN = available nitrogen; HCHs = hexachlorocyclohexanes; DDTs = dichlorodiphenyltrichloroethanes; C_{org} = total organic carbon; C_{bio} = microbial biomass carbon; C_{BR} = basal respiration without addition of any substrate; C_{PR} = potential respiration after actual addition of glucose to soil.

vegetable/watermelon soil, and 173.7%, 126.8% and 96.1% in the open-air vegetable/watermelon soil, respectively. These large spatial differences were mainly caused by unbalanced fertilization. To promote productivity, the phosphate and nitrogen fertilizers were applied more in the vegetable/watermelon fields than in the paddy fields. The soil pollution and biological indicators had no significant differences in the different planting patterns. Only the HCHs and DDTs showed a relatively greater spatial difference.

MDS for soil health assessment

PCA as a data reduction tool can select the most representative indicators from a data set and has been used to screen the MDS by many authors (Andrews *et al.*, 2002a, b; Shukla *et al.*, 2006). Usually only the PCs with eigenvalues > 1 (Brejda *et al.*, 2000) or that explain ≥ 5% of variability in the soil data (Wander and Bollero, 1999) were selected into the MDS.

We performed a standardized PCA on all the data (untransformed) to extract the MDS from 19 soil indicators for Chongming. Only the PCs with eigenvalues > 1 were examined, and eight PCs were ultimately extracted, the cumulative contribution of which reached 70.54%. Under a PC, the variables with a loading within 20% of the highest factor loading were retained for the MDS. When more than one variable was retained within a PC, correlation analysis was employed to determine whether the variables could be considered redundant and eliminated from the MDS (Andrews *et al.*, 2002a; Sharma *et al.*, 2005). Based on the loading values of the variables, pH, Eh, NO_3^--N, AN, C_{bio}, C_{BR}/C_{bio}, AP, AK, C_{org}, Cd, Cr, HCHs, DDTs, EC and Hg were first selected (Table II). Under each PC, a significant correlation existed between pH and Eh ($r = -0.910$, $P = 0$), NO_3^--N and AN ($r = 0.767$, $P = 0$), C_{bio} and C_{BR}/C_{bio} ($r = -0.571$, $P = 0$), Cd and Cr ($r = 0.481$, $P = 0$), and AP and AK ($r = 0.459$, $P = 0$). Taking into account the absolute high loading values of pH, C_{bio} and AP, these indicators were retained for the MDS. Nitrate as the main form of nitrogen in soil, which could be directly utilized by crops and conveniently determined, was also retained. The content of Cd exceeded the background value for farmland soil in Shanghai; therefore, Cd was retained for the MDS. A correlation analysis was further performed for the MDS indicators to examine if the variables could be redundant. The results showed low correlations between most of the indicators. Therefore, a total of 10 indicators were selected for the MDS, including physical and chemical indicators of pH and EC, nutrition indicators of NO_3^--N and AP, biological

TABLE II

Results of principal components (PC) analysis on soil health index in agriculture lands of Chongming Island, China

Soil indicator[a]	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
pH	−0.940[b]	−0.070	0.049	−0.138	−0.102	−0.035	0.045	0.046
Eh	0.933[c]	−0.011	−0.001	0.173	0.066	0.093	0.004	0.015
Clay content	0.265	−0.114	0.165	0.576	0.077	−0.075	−0.059	−0.114
EC	−0.072	0.086	−0.077	0.026	0.041	−0.020	0.780[b]	0.004
AP	0.035	0.332	−0.082	0.305	0.724[b]	−0.014	−0.001	0.008
AK	0.092	−0.078	−0.083	0.068	0.702[c]	−0.002	0.168	−0.133
NO_3^--N	0.014	0.891[b]	−0.110	0.011	−0.080	0.020	0.052	0.066
AN	0.009	0.894[c]	0.017	0.057	0.080	−0.080	0.065	−0.007
Cd	−0.017	0.228	−0.054	0.651[b]	0.195	0.349	−0.289	0.078
Pb	0.016	0.004	0.158	−0.486	0.043	0.236	−0.216	0.287
Cr	0.218	0.046	0.096	0.744[c]	0.127	0.203	0.072	0.208
As	0.070	0.429	0.022	−0.188	0.042	0.324	0.469	−0.090
Hg	0.045	−0.047	0.107	0.001	−0.016	0.079	0.000	−0.894[b]
HCHs	0.260	−0.154	−0.119	0.300	−0.218	0.701[b]	0.021	0.011
DDTs	−0.055	0.065	0.146	−0.060	0.385	0.735[b]	0.036	−0.099
C_{org}	0.067	−0.118	0.157	−0.029	0.673[b]	0.172	−0.162	0.233
C_{bio}	−0.011	−0.046	−0.861[b]	0.025	0.056	−0.007	0.022	0.200
C_{BR}/C_{bio}	−0.147	−0.080	0.798[c]	0.073	0.068	0.036	−0.176	0.002
C_{PR}/C_{bio}	0.242	−0.143	0.596	0.086	−0.050	0.000	0.381	0.298

[a] See Table I for the descriptions of EC, AP, AK, AN, HCHs, DDTs, C_{org}, C_{bio}, C_{BR} and C_{PR}.

[b] Factor loadings corresponding to the indicators included in the minimum data set.

[c] Factor loadings considered highly weighted.

indicators of C_{org} and C_{bio}, and pollution indicators of Cd, Hg, HCHs and DDTs.

Transforming of each MDS indicator

This study mainly focused on the establishment of soil health indexes that include a pollution index. Based on the characteristics of heavy metals and persistent organic pollutants, the higher the content in the soil, the greater the degradation of SQ (Fu *et al.*, 2011). Heavy metals and persistent organic pollutants pose a potential health risk through food chain (Xu *et al.*, 2009), and greater pollution contributions to adjacent water bodies through surface runoff. Therefore, the effects of these pollution indicators on soil health can be considered as linear and the following formula can be used to transform:

$$S_{ij} = c_{i_{\min}}/c_{ij} \tag{2}$$

where S_{ij} presents the score of i indicator for j observation, $c_{i_{\min}}$ is the minimum observation of i indicator, and c_{ij} is the jth observation of i indicator.

In the MDS, pH, EC, NO_3^--N and AP have a positive impact on the soil health with increased levels before the threshold and are harmful beyond the optimum levels; hence, they can be transformed using the "mid-point optimum" function. The C_{bio} is closely correlated to organic carbon and total nitrogen, indicating that it is an important indicator of soil fertility (Insam *et al.*, 1991; Yao *et al.*, 2000). In general, a high C_{bio} value indicates a better state of soil microorganisms, because they can store more nutrients and also improve nutrient cycling in the system (Stenberg, 1999). The greater C_{org} accumulation, the better soil quality; therefore, these two indicators were transformed using the "more is better" curve. According to the data in the literature (Hussain *et al.*, 1999; Glover *et al.*, 2000; Andrews *et al.*, 2002b), combined with the soil properties and the measured values of the indicators, we determined the standard scoring curves and their parameters for soil health assessment in Chongming (Fig. 2).

Once transformed, the MDS indicators were weighted using the PCA results. The weights of pH, EC, NO_3^--N, AP, C_{org}, C_{bio}, Cd, Hg, HCHs and DDTs were 0.153, 0.090, 0.153, 0.132, 0.132, 0.142, 0.137, 0.087, 0.106 and 0.106, respectively.

Soil health levels of Chongming agricultural soils

According to Eq. 1, the SHI values of different agricultural plots in Chongming were calculated using indicator scores and their weights. Soil indicator scores of 0, 0.5 and 1 represent the upper or lower limit, benchmark and optimal values of functions. The calculated SHI based on those scores are 0, 0.619 and 1.238, respectively. Because the indicator score of 0.5 repre-

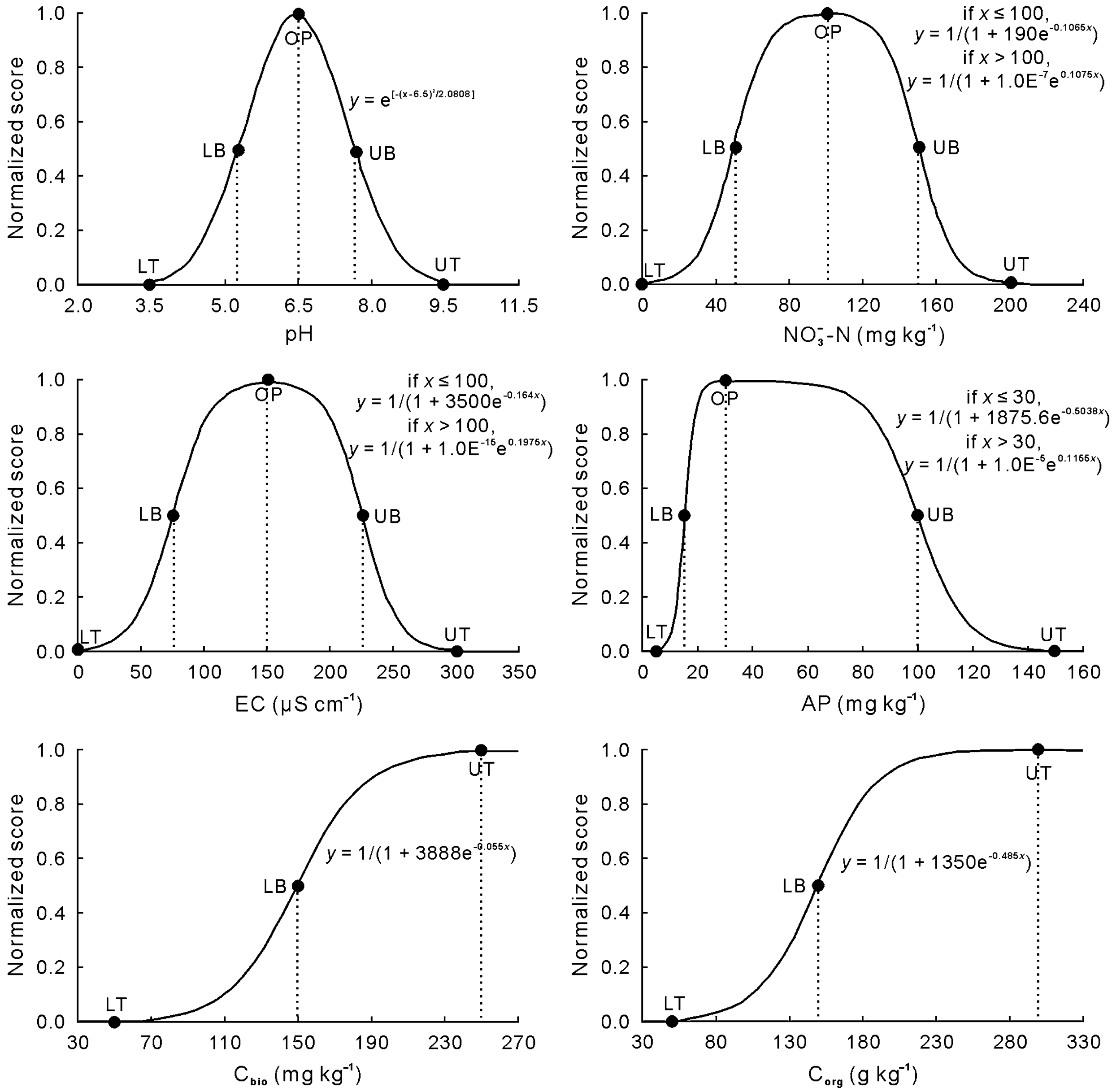

Fig. 2 Standard scoring functions used for transforming soil health indicators in Chongming Island, China. EC = electrical conductivity; AP = available phosphorus; C_{bio} = microbial biomass carbon; C_{org} = total organic carbon; LT = low threshold; LB = low baseline; OP = optimum; UB = upper baseline; UT = upper threshold.

sents soil baseline properties and less than 0.5 shows poor soil quality, the SHI value of 0.619 can be regarded as the reference value or threshold of soil health in Chongming. SHI values less than 0.619 indicate poor soil health conditions, and values between 0.619 and 1.238 can be considered as different levels of health status. If the scores ascend or descend by 30% based on a benchmark score of 0.5, the soil health status can be divided into 5 levels according to the calculated SHI, and the specific grading standards are shown in Table III.

The farmland plots in Chongming were extracted based on high-resolution airborne remote sensing maps in 2008. The spatial variations of SHI for agricultural lands were shown in Fig. 3. According to the soil health rating, 48.9% of the survey samples in Chongming Island were in poor soil health condition, followed by the medium healthy soil, accounting for 32.2% of the survey samples and mainly distributed in the central and mid-eastern regions, and very poor health soil accounted for only 18.9% of the survey samples, mainly distributed in small pieces in the northwest and eastern regions of Chongming. For the farmland in eastern Chongming Island, with the land reclamation *via* newly deposited soil, salinization is serious; while for the soil in the western region, especially in northwest

TABLE III

Grading standards of soil health condition in Chongming Island, China

Discrepant percent based on benchmark	Grading of score	Soil health index (SHI)	Grading of SHI	Soil health condition
−30%	0.35	0.433	$\text{SHI} < 0.433$	Very poor
Benchmark	0.50	0.619	$0.433 \leq \text{SHI} < 0.619$	Poor
30%	0.65	0.804	$0.619 \leq \text{SHI} < 0.804$	Medium
60%	0.80	0.990	$0.804 \leq \text{SHI} < 0.990$	Good
100%	1.00	1.238	$0.990 \leq \text{SHI} \leq 1.238$	Very good

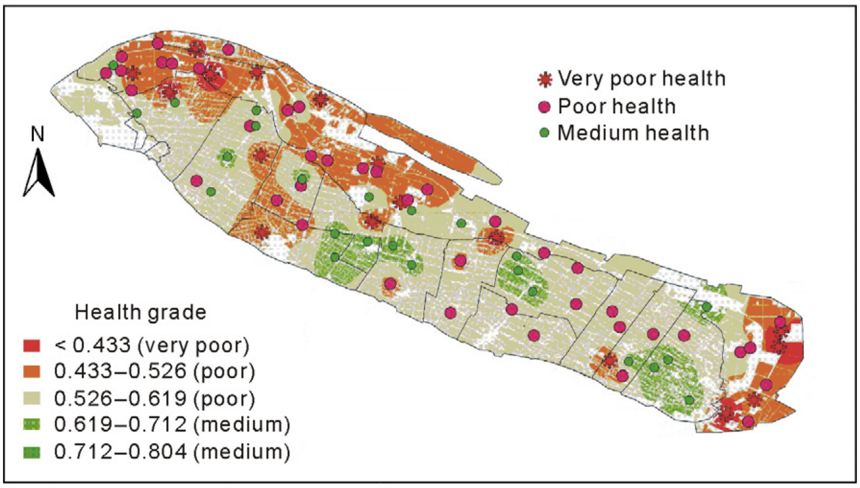

Fig. 3 Spatial distributions of agricultural soil health index in Chongming Island, China.

Chongming, which has experienced more intensive cultivation of farms and long periods of land reclamation, more pollutants have accumulated in the soil, resulting in lower levels of soil health.

Contributions of soil indicators to SHI

Fig. 4 presented the contribution of each indicator to SHI of the paddy field, greenhouse and open-air vegetable/watermelon fields in Chongming. The contributions of most indicators to soil health had no significant difference in the three planting patterns. The C_{org}, C_{bio}, pH and Cd contents offered the largest contribution to the SHI, with the contribution rate always above 10%, suggesting that these indicators were basically within the threshold range and had less influence on soil health. However, the contributions of NO_3^--N, EC and AP under different planting patterns varied greatly. Nitrate is the main component available for crop growth, and EC mainly indicates the amount of salt accumulation in the soil. Both contributed more to the SHI of the paddy field and open-air vegetable/watermelon field than to the greenhouse vegetable/watermelon field, indicating that the soil salinization and nitrate accumulation under the greenhouse cropping pattern had limited soil health level. The contribution of AP to SHI was relatively lower, with the minimum SHI in the paddy field. The reason for this was the phosphate fertilizer shortage in the paddy field according to the measured values. The pollution indicators of DDTs, HCHs and Hg contributed less to the SHI under the three planting patterns, suggesting a

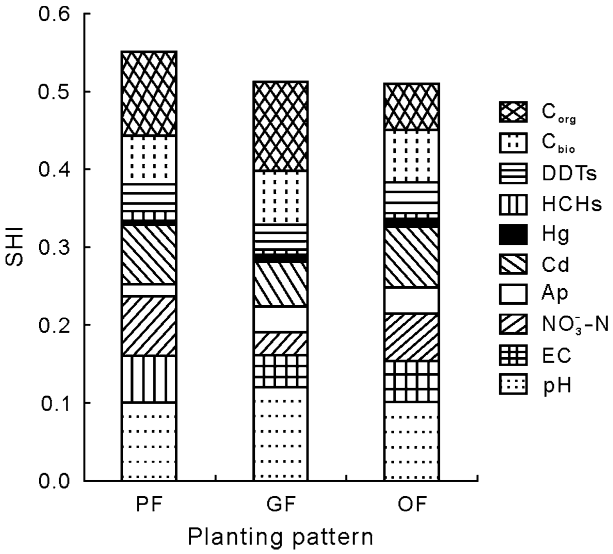

Fig. 4 Contributions of the minimum data set (MDS) indicators to soil health index (SHI) under three planting patterns of paddy field (PF), greenhouse vegetable/watermelon field (GF) and open-air vegetable/watermelon field (OF). The MDS indicators include total organic carbon (C_{org}), microbial biomass carbon (C_{bio}), dichlorodiphenyltrichloroethanes (DDTs), hexachlorocyclohexanes (HCHs), Hg, Cd, available phosphorus (AP), NO_3^--N, electrical conductivity (EC) and pH.

poor soil health status when an increased amount of pollutants had accumulated in the soil.

Effects of planting patterns and soil types on soil health

From the perspective of different planting patterns, the SHI values of the paddy field were the highest, followed by the open-air vegetable/watermelon field, and the SHI values of the greenhouse vegetable/watermelon field were the lowest. The results of ANOVA showed that the SHI values of the different planting patterns had no significant difference ($P > 0.05$). However, the lower SHI values suggested that the greenhouse and open-air intensive cultivation of vegetables and watermelons were not conductive to soil health.

Considered from a perspective of soil type, the SHI values of paddy soil, gray alluvial soil and coastal saline soil were significantly different ($P < 0.05$). The SHI of the paddy soil was the highest, followed by the gray alluvial soil, and the SHI of the coastal saline soil was the lowest. The GLM univariate analysis results showed that the SHI values were significantly different ($P < 0.01$) under the interaction of planting patterns and soil types, showing their significant impact on soil properties and health status, with the soil types providing the larger impact.

In total, 58 soil samples were collected from the Chongming paddy field. Among the three soil types in the paddy field, the gray alluvial soil had no very poor health soil samples. The samples of gray alluvial soil at a medium healthy condition accounted for 46.2%, the mean SHI value of which was higher than those of the paddy soil and the coastal saline soil, suggesting a better health status. Although very poor health samples accounted for 15% of the paddy soil, the medium health soil accounted for 50%, illustrating that the soil health status of the paddy soil was only slightly worse than that of the gray alluvial soil. For the coastal saline soil, very poor and medium health soil samples accounted for 24% and 16%, respectively, and the proportion of poor health soil was significantly increased, showing its worst health status of the three soil types. Therefore, the paddy soil and gray alluvial soil were more suitable for rice cultivation than the coastal saline soil.

For the vegetable/watermelon fields, the mean SHI value of the paddy soil was the highest, followed by the coastal saline soil. There was no very poor health sample in the paddy soil, which was mainly at poor health level. Both the very poor and poor health samples accounted for 37.5% in the gray alluvial soil, and they accounted for 25.0% and 55.0%, respectively, in the coastal saline soil. Therefore, the paddy soil was more suitable for vegetable/watermelon cultivation than the other soil types.

It can be seen from the above analyses that the health status of the coastal saline soil was at a lower level whether planting rice or vegetables/watermelons. For this type of soil, it is necessary to select some salt-tolerant crops to effectively improve soil quality.

CONCLUSIONS

Ten indicators were selected for the MDS for soil health assessment using PCA, including physical and chemical indicators of pH and EC, nutrition indicators of NO_3^--N and AP, biological indicators of C_{org} and C_{bio}, and pollution indicators of Cd, Hg, HCHs and DDTs. The majority of the farmland soil in Chongming Island was at poor health level, accounting for 48.9% of the survey samples, followed by the medium health soil. The very poor health soil accounted for 18.9% of the survey samples, distributed in small pieces in the northwestern and eastern regions of Chongming Island. The indicators of pH, C_{org}, C_{bio} and Cd had less influence on soil health, while NO_3^--N, EC and AP under the three planting patterns varied greatly. Soil salinization and nitrate accumulation under the greenhouse cropping pattern and phosphate fertilizer shortage in the paddy field limited the soil health. The DDTs, HCHs and Hg contributed less to the SHI, and accumulation of those pollutants in the soil reduced the soil health status. The SHI value of the paddy soil was significantly higher than that of the gray alluvial soil, and the coastal saline soil had the lowest SHI level. The health status of the coastal saline soil was at a lower level whether planting rice or vegetables/watermelons.

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