

Soil fertility and its significance to crop productivity and sustainability in typical agroecosystem: a summary of long-term fertilizer experiments in China

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Abstract

Aims and background Soil fertility quality index is a useful indicator that helps to improve sustainable land use management and achieve economical yield in agriculture production. The objectives of this study were to evaluate the changes of soil fertility quality between the 1980s and 2000s in different cropping systems and its significance to crop productivity and sustainability.

Methods We collected all published data on crop yields and soil parameters from 58 long-term experiments in three typical double-cropping systems in China, including maize-wheat (M-W), rice-rice (R-R) and rice-wheat (R-W) cropping systems, and selected seven fertilizer treatments in each experiment, including inorganic fertilizer [nitrogen and phosphorus fertilizer (NP), nitrogen

and potassium fertilizer (NK), phosphorus and potassium fertilizer (PK) and balanced mineral fertilizer (NPK)], combined NPK with farmyard manure (NPKM) or crop straw (NPKS), and no fertilizer application (served as control). For comparison, an integrated fertility quality index (IFQI) was used to estimate the variations in soil fertility in different cropping systems. Moreover, the mean production variability index (PVI, %) in each cropping system was calculated to evaluate the stability of crop production.

Results Over cropping systems, the averaged relative yields of PK, NK and NP ranged from 38.0 to 97.4 %, while the mean yields can be increased by 2.4–5.1 % in NPKM, compared to NPK. The mean yields were similar between NPK and NPKS for maize and wheat crops, but the yield was increased by 4.3–10.0 % in NPKS. Among the different treatments, the highest variability of cereal productivity was obtained in NK, PK or Control, while the lowest value was mostly recorded in NPKM or NPKS in these three cropping systems. Relative to the control, the IFQIs in fertilization treatments were increased by 9.4–150.0 %, 6.2–41.5 % and 1.3–17.5 % in M-W, R-W and R-R systems, respectively (except for PK treatment in R-R system). However, changes of IFQI in topsoil differed among fertilizer treatments, and greater increases existed in the treatments receiving organic residues (NPKM and NPKS).
Conclusions The increase in crop yield is exponentially correlated with the increased IFQI over treatments in

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three cropping systems. Over the treatments and systems, production variability among years is shown to be negatively, linearly related to IFQI ($P < 0.001$). Therefore, the high grain yield and low production variability can be simultaneously achieved by increasing soil fertility in all three cropping systems.

Keywords Crop productivity · Long-term fertilizer · Maize · Rice · Soil fertility · Wheat · Yield stability

Introduction

Food security for the large and ever increasing population of China has been an important issue in recent decades (Brown 1995). In the past 49 years, Chinese cereal grain yields have increased 3.5-fold from 1.2 Mg ha⁻¹ in 1961 to 5.4 Mg ha⁻¹ in 2009, and meanwhile total grain production has increased 3.4-fold from 110 to 483 million ton (MT) (FAO 2011). Over the last 10 years, however, annual growth rates of the cereal yields have shown declining or stagnant trends in some regions of China (Fan et al. 2012). Correspondingly, some croplands have undergone human-induced soil degradation (Dawe et al. 2000; Guo et al. 2010; Ju et al. 2009; Ladha et al. 2003; Vitousek et al. 2009; Zhang et al. 2007). It was estimated that the areas of low, medium, and high productivity land account for 41, 30, and 29 % of the total arable area in China, respectively (Wang 2005). The arable lands with poor soil fertility make it difficult to achieve high crop yields. In order to improve the crop productivity and sustainability, it is very important to evaluate the effects of human activities on soil fertility quality in agricultural systems.

Agricultural soil fertility quality is most commonly defined in terms of the ability of a soil to supply nutrients to crops (Watson et al. 2002), and it has been drastically affected by human activities (Bi et al. 2009; Huang et al. 2007; Jiang et al. 2006). Research indicated that soil fertility can be improved by appropriate agricultural practices such as tillage (Hussain et al. 1999; Kong et al. 2006), fertilizer application (Guo et al. 2010), incorporation of crop residues into soil (Bi et al. 2009) and conversion from dryland agriculture to rice paddy production (Dawe et al. 2003). Conversely, inappropriate human activities such as imbalanced inorganic fertilizer application and sewage sludge irrigation negatively affect soil fertility, which in turn, can influence the sustainability of agricultural systems (Stamatiadis et al.

1999; Vitousek et al. 2009). It was estimated that 40 % of agricultural lands were affected by human induced land degradation (Oldeman et al. 1990).

The assessment of soil quality provides a tool to help quantify the combined biological, chemical and physical responses of soil to land use and soil/crop management practices. There are many methods to evaluate soil quality, such as integrated soil quality indexes (Doran and Jones 1996), multi-variable indicator kriging (Nazzareno and Michele 2004) and soil quality dynamics (Larson and Pierce 1994). Integrated soil quality indexes are the most common methods to assess soil quality. It is a measurable soil parameter that affects the capacity of a soil to perform a specified function (Karlen et al. 2006). The indicators, the weights of the indicators and the calculation method of the quality indexes are the most important considerations in soil quality index methods (Wang and Gong 1998).

The change of soil fertility quality may take several years to appear, and it cannot be critically examined with the results of typical short-term experiments (Dawe et al. 2003; Regmi et al. 2002). Long-term experiments (LTEs) provide the best means of studying changes in soil properties and processes over time, and these experiments are important for obtaining information on long-term sustainability of agricultural systems to formulate future strategies for maintaining soil fertility (Rasmussen et al. 1998). Since the 1980s, a great many LTEs have focused on different cropping systems in China. The results of many LTEs suggested that use of organic resources, such as farmyard manure and crop residue, could increase supply of N, P, K, and other nutrients, and improve soil physical properties or soil organic matter in the long term (Bi et al. 2009; Huang et al. 2010; Shen et al. 2004; Shen et al. 2007; Zhang et al. 2009). While these studies provided an insight into soil physical and chemical inventories in major Chinese croplands, we know little about the changes of soil fertility over time and the links between these changes and anthropogenic influences.

Rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are the most important cereal crops in China. In 2009, China accounted for about 29.1 %, 20.0 % and 16.9 % of global rice, maize and wheat production, respectively (China 1950–2010; FAO 2010). Therefore, a better understanding the change of soil fertility as influenced by human activities is important to develop sustainable agriculture management practices for these crops. In this paper, the previous

studies about long-term fertilization on crop yields and soil properties at the plough layer (0–20 cm) were used to estimate the changes of soil fertility quality between the 1980s and 2000s. For analyses, we collected 58 LTEs in three typical double-cropping systems from former published articles, dissertations, and monographs (Appendix S1, S2 and S3).

Materials and methods

Data collected

Since the 1980s, a great many long-term experiments (LTEs) have been established in typical cropping systems in China. Based on the previous formal published articles, dissertations, and monographs, we selected 17, 12 and 29 of the 58 LTEs in maize-wheat (M-W), rice-rice (R-R) and rice-wheat (R-W) cropping systems, respectively. They represent a wide variety of soil types, climatic conditions, and crop management practices (Appendix S1, S2 and S3). The cropping system in most of the places in the South of the Yangtze is double-rice cropping systems and winter fallow. In the Yangtze River Basin, the most popular planting pattern is the systems of rice and winter wheat or other crop. In North China Plain, the annual double crop systems are major adopted by wheat and maize rotation.

There were several treatments in each experiment, and, specifically, we selected seven fertilizer treatments, included those deficient in nitrogen only (PK), deficient in potassium only (NP), deficient in phosphorus only (NK), or balanced in mineral nutrients (NPK), and combined NPK with farmyard manure (NPKM) or crop straw (NPKS). Treatment without fertilizer application served as the control (Control). In each annual cropping cycle, the total amount of N, P, and K applied were uniform across the treatments. Generally, urea for N, superphosphate or ammonium hydrogen phosphate for P, and potassium chloride or potassium sulfate for K were used in these experiments, respectively. The nutrient input from inorganic and organic sources in LTEs were listed in Appendix S1, S2, S3. Urea was applied as the local custom with two or three splits in rice growing season, 40 % as basal fertilizer, 50–60 % as tillering fertilizer and 0–10 % as panicle fertilizer, and it was simply applied as basal fertilizer in maize/wheat growing season in most of the LTEs. The P, K and organic fertilizers were applied as basal fertilizer. Generally, the

basal fertilizer was applied 2 days before crop planting and was well incorporated into the soil by plowing to the topsoil. The top dressing was applied by surface broadcast.

The data of soil properties and grain yields in M-W, R-W and R-R systems were referenced from Appendix S1, S2 and S3, respectively. The mean grain yields were calculated by averaging the seasonal yield over the period of each LTE under a specific treatment. Thereafter, the averaged grain yields were determined by averaging the mean yields over all the LTEs in each cropping system (Table 2). The soil samples were sampled at the plough layer depth of 0–20 cm, and the selected soil properties were determined at the beginning (initial soil) and end of the each LTE, respectively (Appendix S1, S2, S3). The averaged soil properties listed in Table 1 were thus determined by averaging the values over the LTEs for a given cropping system. The physicochemical properties of soil samples were analyzed according to the standard methods recommended by the Chinese Society of Soil Science (Lu 2000). Soil pH was determined with a pH meter (PHS-3C, Leizi, China) in 1:2.5 (soil: water, weight/volume, air-dried soil) suspensions. Soil organic carbon was detected by the potassium dichromate-volumetric method [digested by $K_2Cr_2O_7$ -sulfuric acid (H_2SO_4)], and total nitrogen by the Kjeldahl method [digested by H_2SO_4 and cupric sulfate-sodium sulfate ($CuSO_4-Na_2SO_4$) as the catalyst agent]. Soil total phosphorus and total potassium were determined by the molybdenum (Mo)-antimony (Sb) colorimetric method and flame atomic absorption spectrophotometry, respectively, after wet digestion with sodium hydroxide (NaOH). Soil available nitrogen was determined using a micro-diffusion technique after alkaline hydrolysis. Soil available phosphorus was determined by the Olsen method. Soil available potassium was measured in 1 M ammonium acetate (NH_4OAc) extracts by flame atomic absorption spectrophotometry.

Soil fertility quality evaluations

For evaluation of soil fertility quality, it is desirable to select parameters that are directly related to soil fertility. Because soil fertility assessment is purpose- and site-specific, parameters used by different researchers or in different regions may not be the same (Wang and Gong 1998). In this paper, we selected 8 parameters for soil fertility evaluation, including soil pH, SOM, total and available N, P and K. These parameters were chosen

Table 1 Averaged soil properties in topsoil under different fertilization treatments sampled at the beginning (initial soil) and end of the experiments in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems

Treatments	Sample number	SOC* (g kg ⁻¹)	TN (g kg ⁻¹)	TP (g kg ⁻¹)	TK (g kg ⁻¹)	AN (mg kg ⁻¹)	AP (mg kg ⁻¹)	AK (mg kg ⁻¹)	pH
M-W									
Initial soil	17	6.4	0.70	0.70	19.5	44.6	11.9	81.4	8.1
Control	12	5.8	0.67	1.00	16.2	54.5	5.9	72.8	8.3
NP	9	7.3	0.81	1.21	17.2	76.5	15.2	67.7	8.2
NK	7	6.6	0.71	0.99	17.2	76.9	4.1	91.3	8.4
PK	4	7.3	0.62	1.44	17.2	63.7	27.1	107.2	8.3
NPK	12	6.8	0.86	1.23	17.2	76.6	22.0	84.7	8.1
NPKM	12	9.3	1.08	1.83	17.7	85.6	63.8	119.9	8.0
NPKS	4	10.4	0.68	1.44	18.2	79.1	21.4	98.4	8.1
R-W									
Initial soil	12	14.3	1.47	0.77	24.3	114.1	7.4	88.7	7.0
Control	10	14.9	1.46	0.52	18.3	142.2	3.6	65.7	7.0
NP	4	14.7	1.41	0.74	19.7	148.7	23.1	56.2	6.0
NK	3	15.1	1.57	0.54	20.9	132.8	2.1	82.5	5.8
PK	3	14.4	1.45	0.75	21.4	127.2	36.3	108.0	5.9
NPK	10	16.3	1.65	0.74	18.6	151.6	19.1	93.2	6.8
NPKM	10	17.8	1.78	0.86	19.3	165.6	30.8	102.2	6.8
NPKS	6	18.0	1.81	0.80	21.3	139.5	19.9	82.6	7.4
R-R									
Initial soil	28	16.7	1.75	1.48	14.8	108.0	15.3	66.2	6.1
Control	23	18.1	1.81	0.59	15.1	124.3	14.0	51.6	6.0
NP	8	16.3	1.95	1.12	13.9	125.4	39.6	64.0	6.0
NK	8	16.7	2.07	0.99	14.2	168.0	14.5	93.0	5.8
PK	2	9.3	1.00	–	13.3	66.6	36.1	56.4	5.7
NPK	23	19.6	2.00	0.83	15.6	143.8	28.4	72.0	5.8
NPKM	22	22.3	2.25	0.99	16.1	152.9	42.1	76.7	5.9
NPKS	4	21.3	2.17	0.75	13.0	193.3	23.8	104.3	5.8

* SOC soil organic carbon; TN total nitrogen; TP total phosphorus; TK total potassium; AP available phosphorus; AK available potassium

because the research purpose was focused on soil fertility quality. Nitrogen, P and K show the nutrient status of the soil for plants, and SOC and pH influence the habitat for soil nutrients.

An integrated fertility quality index (IFQI) is a quantifiable indicator of soil fertility that affects the capacity of a soil to perform a specified function, which was established and defined as following.

$$IFQI = \sum_{i=1}^n W_i \times I_i \quad (1)$$

where W_i is the weight coefficient of the i th fertility quality parameter, I_i is the score of the i th parameter to

soil fertility, and n is the number of parameters. The score value of each fertility parameter was calculated by their monitoring value and the standard scoring function (SSF) (Hussan 1997), which is used to calculate the scores for all soil parameters except pH. The SSF is given by “S” function:

$$f(x) = \begin{cases} 0.1 & x \leq x_1 \\ 0.9(x-x_1)/(x_2-x_1) + 0.1 & x_1 \leq x \leq x_2 \\ 1.0 & x \geq x_2 \end{cases} \quad (2)$$

where x is the monitoring value of the parameter, $f(x)$ is the score of the parameter, ranging from 0.1 to 1, and x_1 and x_2 are the lower and the upper threshold values respectively. The values x_1 and x_2 for the parameters

Table 2 Averaged grain yields, yield variability (PVI), and integrated fertility quality index (IFQI) in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems

Treatments	Averaged grain yields (Mg ha ⁻¹)						PVI (%)			IFQI		
	M-W		R-W		R-R		M-W	R-W	R-R	M-W	R-W	R-R
	Maize	Wheat	Rice	Wheat	Early-rice	Late-rice						
Control	2.43±1.14 b	1.42±0.65 b	4.34±0.97 c	1.36±0.75 a	2.82±0.80 d	3.32±0.70 b	28.9	15.0	19.7	0.32	0.65	0.80
NP	5.84±1.25 a	4.91±1.28 a	6.57±0.58 ab	2.81±1.70 a	4.93±0.67 abc	4.60±0.68 a	17.0	14.9	13.7	0.53	0.80	0.81
NK	3.36±2.22 b	2.19±1.49 b	6.47±0.89 ab	1.80±1.63 a	4.46±1.48 bc	4.54±1.18 a	31.3	20.5	17.2	0.35	0.69	0.88
PK	2.98±1.27 b	1.74±0.76 b	5.01±0.54 bc	1.42±1.21 a	3.96±0.82 cd	4.75±1.58 a	28.6	23.2	9.8	0.58	0.84	0.52
NPK	6.75±1.80 a	5.45±1.54 a	6.83±0.69 a	2.85±1.32 a	5.22±0.64 ab	5.34±0.93 a	13.7	14.7	13.8	0.62	0.88	0.89
NPKM	6.89±1.11 a	5.60±0.97 a	7.06±0.65 a	3.04±1.27 a	5.58±0.70 a	5.51±0.97 a	12.0	14.2	12.8	0.80	0.92	0.91
NPKS	6.67±1.59 a	5.49±1.33 a	7.51±0.47 a	2.91±0.41 a	5.59±0.67 a	5.57±1.12 a	14.3	12.6	9.6	0.69	0.83	0.94

are determined by the effect of soil parameters on plant growth in China (Qi et al. 2011; Shen 1990; Sun et al. 1995; Wang and Gong 1998). x_1 is the value under which plant growth is severely limited and x_2 is the value at which plant growth is optimum. The values of x_1 and x_2 are listed in Table 3.

For soil pH, because there is an optimum range, the SSF is:

$$f(x) = \begin{cases} 0.1 & x < x_1, x \geq x_4 \\ 0.9(x-x_1)/(x_2-x_1) + 0.1 & x_1 \leq x \leq x_2 \\ 1.0 & x_2 \leq x \leq x_3 \\ 0.9(x-x_3)/(x_4-x_3) + 0.1 & x_3 \leq x \leq x_4 \end{cases} \quad (3)$$

The values of x_1, x_2, x_3 and x_4 are listed in Table 3.

There are many methods to assign weight coefficient of each index, such as experience, mathematical statistics and models (Wang and Gong 1998). In this paper, parameter weights were assigned by its communality through principal component analysis. The given value and contribution of each principal factor was calculated, and then the communality explained by each parameter based on the load matrix was calculated. The value of the communality indicated the contribution of each soil parameter to soil fertility and, on this basis, parameter weights were assigned (Table 4).

Production variability estimates

The stability index of cereal production is evaluated by the variability of yield over the period of each LTE under a specific fertilizer treatment. The mean production variability was thus estimated for each cropping system by averaging the variability values. The production variability ($PV_i, \%$) for a given cropping system in a given LTE is estimated by using the following equation (Pan et al. 2009).

$$PV_i(\%) = \left\{ \frac{\text{stands deviation of yield}}{\text{mean yield in a period } i} \right. \quad (4)$$

Thereafter, the average of the production variability ($PV_i, \%$) of all the LTEs in each cropping system was used as the estimation of the mean production variability index (PVI, %) for a given cropping system.

$$PVI(\%) = \text{average}(PV_i, i = 1, 2, 3, \dots, n) \quad (5)$$

Here, the cropping system included M-W, R-W and R-R systems, respectively (Appendix S1, S2 and S3).

Table 3 Value of turning point of soil parameters in standard score function Eq. (2) and (3) in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems

y	Soil parameters							
	SOC	TN	AN	TP	AP	TK	AK	pH
M-W								
x ₁	3.5	0.5	30	0.2	3	5	50	4.5
x ₂	11.6	1.2	150	1.0	20	25	150	6.5
x ₃								8.0
x ₄								8.5
R-W								
x ₁	8.7	0.75	50	0.3	3	5	40	4.5
x ₂	17.4	1.5	150	1.0	15	25	150	5.5
x ₃								6.5
x ₄								8.5
R-R								
x ₁	8.7	0.75	50	0.4	3	5	30	4.5
x ₂	20.3	1.5	150	1.0	15	25	150	5.5
x ₃								6.5
x ₄								8.5

* SOC soil organic carbon; TN total nitrogen; TP total phosphorus; TK total potassium; AP available phosphorus; AK available potassium

Results

Soil parameters

Selected soil parameters changed under long-term fertilizer application in M-W, R-W and R-R systems (Table 1). Among the three systems, after the LTEs, the contents of

SOC were increased by 6.2–17.4 %, 24.5–45.3 % and 25.9–62.5 % for NPK, NPKM and NPKS treatments, respectively. However, SOC contents were increased only by 3.1–14.1 % and 0.7–5.6 % for the treatments with unbalanced fertilizer application (NP, NK and PK) in M-W and R-W systems, respectively, and they were not increased for these treatments in R-R system. The contents of TN were increased by 1.4–54.3 % for all the N-applied treatments (except for NP in R-W system and NPKS in M-W system), and the values were generally higher for NPKM in these three systems. Among the three systems, in contrast, TN decreased by 1.4–42.9 % in PK treatments. However, the contents of AN were increased by 11.5–91.9 % for all the treatments among these systems (except for PK in R-R system). The contents of TP were increased by 41.4–161.4 % for all the treatments in M-W system, while they were decreased by 2.6–32.5 % and 24.3–60.1 % for the treatments in R-W and R-R systems, respectively (except for NPKS and NPKM in R-W system). Among the three systems, the contents of AP were increased by 27.7–436.1 % for the P-applied treatments, while they were decreased by 5.2–71.6 % for the NK treatments. The contents of TK were decreased for all the treatments in M-W, R-W and R-R systems (except for NPK and NPKM in R-R system), but the contents of AK generally increased for the K-applied treatments in these systems. There were no clear changes of soil pH for all the treatments in M-W system, but they were decreased by 2.9–17.1 % and 1.6–6.6 % among the treatments in R-W and R-R systems, respectively.

Table 4 Estimated communality and weight value of each soil fertility soil parameters in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems

Soil parameters	M-W		R-W		R-R	
	Communality	Weight	Communality	Weight	Communality	Weight
SOC	0.674	0.110	0.954	0.138	0.959	0.147
TN	0.579	0.094	0.888	0.129	0.954	0.146
AN	0.750	0.122	0.961	0.139	0.991	0.152
TP	0.935	0.152	0.808	0.117	0.259	0.040
AP	0.882	0.144	0.912	0.132	0.932	0.143
TK	0.898	0.146	0.931	0.135	0.746	0.114
AK	0.602	0.098	0.654	0.095	0.889	0.136
pH	0.821	0.134	0.801	0.116	0.784	0.120

Soil fertility assessment

The radar diagram in Fig. 1 is the plot of the linear scores of the major selected soil fertility quality parameters. Lines crossing the axes are the soil treatments. The lines lying at the periphery of the web have better soil fertility quality, and lines towards the origin have low soil quality. Among treatments, long-term combined inorganic/organic fertilizer treated soil (NPKM and NPKS) had the highest linear scores of major soil parameters. In contrast, the linear scores of available soil P and K were relatively lower in the P- and K-omitted treatments in M-W, R-W and R-R systems. Among the three systems, the linear scores of SOC, TN and AN were lower in M-W system compared with rice-based cropping systems.

The overall integrated fertility quality index (IFQI) is contributed by the linear scores of these component parameters and their weight coefficients (Table 2). Relative to the control, the IFQIs for other treatments were increased by 9.4–150.0 %, 6.2–41.5 % and 1.3–17.5 % in M-W, R-W and R-R systems, respectively (except for PK in R-R system). Among treatments, the largest IFQI was obtained in NPKM, followed by NPKS or NPK. However, the relative index for imbalanced fertilization treatments (NP, NK and PK) to NPK was 61.1–99.2 % across the three cropping systems.

Grain yield

Long-term fertilizer application increased generally the mean grain yields across the different LTEs in each cropping system (Table 2). Relative to NPK, however, the imbalanced fertilization treatments (PK, NK and NP) tended to have negative effects on grain yields in

three cropping systems. Among the three systems, the relative mean yields of PK, NK and NP to NPK averaged 38.0–82.4 %, 44.9–85.3 % and 88.3–97.4 %, respectively. Compared with NPK, in contrast, the mean yields can be increased by 2.4–5.1 % for the NPKM treatment. The mean yields were similar between NPK and NPKS for upland crops in M-W and R-W systems, but the yields for NPKS were increased by 4.3–10.0 % for rice crops in R-W and R-R systems.

Production variability

The variability of cereal production varied with treatments for a given cropping system (Table 2). Among the treatments, the highest variability of cereal productivity was obtained in NK, PK or Control, while the lowest value was generally recorded in NPKM or NPKS in these three cropping systems. Among the three systems, the PVIs were increased by 24.6–128.5 % for NK in comparison with NPK. Compared with NPK, however, the increased PVIs for NP and NK treatments were identified only in M-W and R-W systems. Among these systems, the PVIs were decreased by 3.4–12.4 % for NPKM and by 14.3–30.4 % for NPKS (except for NPKS in M-W system).

Discussion

Variations of soil fertility quality in three cropping systems

The apparent separation of soil fertility is mainly attributed to changes in agriculture managements (Ladha et al. 2003). Indeed, the variations of the radar diagrams

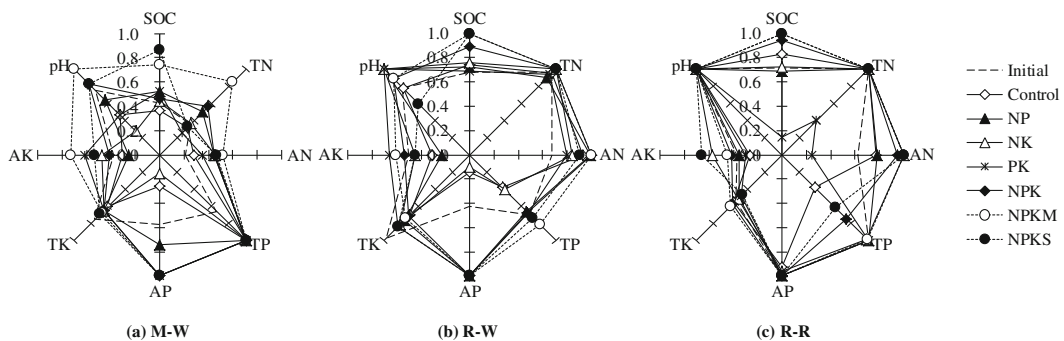


Fig. 1 Radar plot of linear scores of selected soil parameters in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems. Lines crossing the axes are the soil treatments.

The lines lying at the periphery of the web have better soil quality, and lines towards the origin have low soil quality

and the final IFQIs in topsoil differed among systems as well as treatments in this study. Relative to the control, the IFQIs for other treatments were increased by 9.4–150.0 %, 6.2–41.5 % and 1.3–17.5 % in M-W, R-W and R-R systems, respectively (except for PK treatment in R-R system).

One of the reasons for these variations is the differences in the turning point value of soil parameters used in the standard scoring function among systems (Table 3). But more importantly, the big changes of the monitoring values were observed in different treatments for each system in this study, although their standard scoring functions are identical. The parameters of available P and K in soil decreased obviously for P- and K-omitted treatments in all three cropping systems (Table 1). However, the status of SOC and TN were much lower in M-W system. Some reports suggested that conservations of SOC is generally problematic in upland cropping systems because of the consistent aerobic phase in the soil (Dawe et al. 2003). Typically, continuous rice-based cropping systems results in a net accumulation of C and N, even in the absence of organic amendments (Witt et al. 2000). Compared with the initial soils, however, soil pH declined in rice-based cropping systems under the long-term fertilization. Earlier studies showed that nitrification followed by leaching is one of the major processes responsible for soil acidification (Helyar and Porter 1989). In rice-based cropping systems, the large amounts of soil N accumulated would greatly enhance N mineralization and nitrification. In addition, large amounts of unused N fertilizer also can drive soil acidification (Guo et al. 2010). It was reported that high level of soil acidification is a major factor limiting crop production in southern China (Xu et al. 2003). Recently, it was reported that organic material incorporation not only increases crop production, but also could slow the rate of soil acidification in agricultural ecosystems (Huang et al. 2010; Zhang et al. 2009; Zhong et al. 2010). Indeed, soil pH was increased with crop straw returning after long-term experiments in R-W system in this study, which was similar to the reports in some croplands in other countries (e.g. Dolling 1995; Jarvis and Robson 1983).

Effect of soil fertility quality on crop productivity

While the effect of long-term fertilization regimes on crop yield and soil properties in farmland had been frequently studied, the coupling of the productivity

and yield stability of cereals with soil fertility has not previously been discussed. Here, we evaluated the effects of integrated soil fertility quality on crop productivity according to the published data from most of the LTEs in three typical double-cropping systems in China.

During the LTEs, there was a similar change for averaged grain yields among the systems for a given treatments. Statistical results showed that unbalanced inorganic fertilizer application (NP, NK and PK) reduced soil fertility in the long term, and thus decreased the sustainability of crop yields and the fertilization effect. Obviously, the mean yields for PK and NK to NPK were much lower than that for NP to NPK in three cropping systems, particularly for upland crops. Since soil K did not reach to a critical level, the smaller response of yield-increasing to nutrient K is that the soils were well supplied with K. Thus, crop production largely depends on the supply of N and P fertilizers. In contrast, total grain yield remained consistently higher under continuous application of balanced NPK fertilizer with organic amendments in NPKM and NPKS. These results are consistent with the findings in most of the LTEs in other countries (Gami et al. 2001; Manna et al. 2005; Regmi et al. 2002), which may arise from the combined effects of change in climate, cultivars, soil, and management practices (Kucharik and Serbin 2008).

In this study, changes of IFQI in topsoil differed between fertilization treatments with greater increases in treatments receiving organic fertilizer amendments (NPKM and NPKS) (Table 2). Regression analysis showed that the increase in crop yield is positively correlated with the improved IFQI over treatments in all three cropping systems (Fig. 2). Similarly, some results also showed a positive relationship between crop yields and soil quality in a semi-arid inceptisol (Masto et al. 2007). Therefore, increased soil fertility by combined organic and balanced mineral fertilizers application is important for crop production.

Effect of soil fertility quality on crop sustainability

Crop yield stability is used as one of the important criteria to measure the quality of farmland ecological system (Berzsenyi et al. 2000; Tollenaar and Lee 2002). It is generally believed that an appropriate fertilization practice was a key measure to improve soil structure and increase nutrient contents, and thus enhance crop sustainability (Huang et al. 2010; Sun et al. 2003). Previous studies have demonstrated that integrated use of mineral

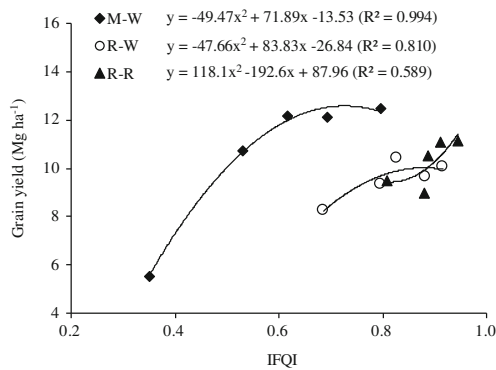


Fig. 2 Relationship between integrated fertility quality index (IFQI) and crop yield in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems

fertilizers were better than their sole application in increasing the stability of crop yields (Hao et al. 2007; Manna et al. 2005). Indeed, the variability of cereal production was obviously lower for NPK treatment as compared to the NP, NK and PK treatments with lower soil fertility in the M-W and R-W systems (Table 2). Consistent with previous studies, the yield stability can be further increased by organic material incorporation compared with most of the mineral fertilizer treatments (Gutser et al. 2005; Li et al. 2009; Manna et al. 2005).

Long-term organic fertilizer application led to obviously higher values of SOC and TN contents and to higher availability of soil P and K, relative to unmanured plots. SOC is one of the key contributors to soil productivity directly through controlling the availability of soil nutrients and indirectly through regulating the soil physical conditions (Reeves 1997). It was observed that crop yield stability was significantly positively correlated with the content of SOC (Manna et al. 2005). Over the treatments and systems, similarly, production variability among years is shown to be negatively related linearly to IFQI in this study (Fig. 3).

Fertilizer management strategy in three cropping systems

To assure the future food security needed in China, we must focus on increasing crop productivity while decreasing production variability. Our present study suggested that enhanced crop productivity and yield stability can be simultaneously obtained by reasonable fertilization and its consequent improvement of integrated soil fertility in intensive cropping systems. Therefore, increasing the recycling of organic materials such as

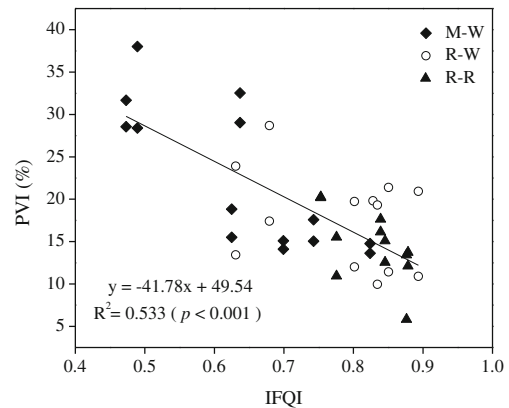


Fig. 3 Relationship between integrated fertility quality index (IFQI) and production variability (PVI) in maize-wheat (M-W), rice-wheat (R-W) and rice-rice (R-R) cropping systems

animal and human excreta, crop straw and stalks, and green manure can be seen as an important step towards saving natural resources as well as stabilizing and optimizing soil quality for crop production.

Moreover, crop production largely depends on the supply of balanced fertilizer application, particularly by N and P fertilizers. Nonetheless, because of the difficulty for farmers to accurately predict fertilizer requirements, excess or inadequate supplement of nutrients are often applied. Thus, we must develop an in-season N management to synchronize N demand and supply in the root zone. As for P and K inputs, they also should be based on nutrient balance through soil nutrients testing (Li et al. 2011). These approach aim to maintain the available of soil P and K at the optimal level for plant growth by fertilizer application management (Zhang et al. 2008). The optimal level is more than the critical concentration of available of soil P and K needed to sustain high crop yield and less than their leaching level. The critical level for crop yield depends on the characteristics of the different plant species and cropping systems, and can be found through long-term fertilizer experiments.

Conclusions

The variation in soil fertility was affected directly by the changes of selected soil parameters in three typical double-cropping systems in China, including maize-wheat, rice-rice and rice-wheat cropping systems. However, variation in the time taken for chemical fertility changes to accumulate, variation in buffer capacity

dealing with acidity, will all affect the rate of change in fertility, and the average yield responses over time. According to our study, changes of integrated soil fertility quality index (IFQI) in topsoil differed between fertilization treatments with greater increases in treatments receiving organic fertilizer amendments, such as farmyard manure or crop straw. The high grain yields and low production variability can be simultaneously achieved by increasing IFQI in intensive cropping systems.

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