https://doi.org/10.17221/365/2019-PSE

Integrated soil fertility and yield trend in response to long-term fertilisation under the Chinese double rice-cropping systems

Xiuxia Yang[1,2], *Hui Yan*[1], *Xiaohui Wang*[3], *Qingyin Shang*[2]*

[1]*College of Land Resources and Environment, Jiangxi Agricultural University, Nanchang, P.R. China*
[2]*Ministry of Education and Jiangxi Key Laboratory of Crop Physiology, Ecology and Genetic Breeding, Jiangxi Agricultural University, Nanchang, P.R. China*
[3]*Nanchang Garden Science and Technology Research Institute, Nanchang, P.R. China*
**Corresponding author: qyshang@jxau.edu.cn*

Citation: Yang X.X., Yan H., Wang X.H., Shang Q.Y. (2020): Integrated soil fertility and yield trend in response to long-term fertilisation under the Chinese double rice-cropping systems. Plant Soil Environ., 66: 22–32.

Abstract: Soil fertility is fundamental in determining crop productivity and sustainability in farming systems. A long-term fertiliser experiment in Chinese double rice-cropping systems initiated in 2011 was used in this study to gain an insight into a complete estimating of soil fertility. The six fertiliser treatments included mineral fertiliser (NP, NK, and NPK), combined NPK with farmyard manure (NPKM) or crop straw (NPKS), and no fertiliser application as a control. Results showed that grain yield averaged 5.5–13.0 t/ha/year, and significant increasing trends were observed in the phosphorus-applied plots (NP, NPK, NPKM, and NPKS), but the treatments without phosphorus applied (control and NK) resulted in declining trends in both early- and late-rice yields. After long-term rice cultivation, the contents of total and available phosphorus significantly declined in phosphorus-deficient plots compared to other treatments. Regression analysis showed that the improvement in grain yields was positively correlated with the increased soil fertility over treatments. Relative to the NPK treatment, the NPKM treatment greatly enhanced soil fertility from 0.50 to 0.78, and particularly dramatically increased the content of available soil phosphorus. Therefore, the high grain yield and soil fertility can be simultaneously achieved by long-term balanced fertiliser applications in Chinese double rice-cropping systems.

Keywords: *Oryza sativa* L.; rice production; climate change; nutrition; soil quality

Rice (*Oryza sativa* L.) is the predominant staple food crop for nearly 50% of the world's population, mainly in Asia (Kusano et al. 2015). Over the past decade, however, annual growth rates of the grain yields have shown declining or stagnant trends in these regions (Fan et al. 2012). At the same time, inappropriate human activities and continuous cropping negatively affect soil fertility (Vitousek et al. 2009, Guo et al. 2010). A better understanding of soil fertility variation as influenced by human activities is urgent in order to improve rice production, provide early warning of adverse trends and offer a valuable base against which subsequent and future measurements can be evaluated.

Many researchers have indicated that soil fertility can be improved through appropriate agricultural practices such as fertiliser and lime application (Bora et al. 2018), incorporation of crop residues (Moreno-Cornejo et al. 2017), and conversion from upland agriculture to rice paddy production (Dawe et al. 2003). However, the change of soil fertility may take several years to appear, and it cannot be critically examined with the results of typical short-term experiments (Regmi et al. 2002, Dawe et al. 2003). 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 the long-term sustain-

Supported by the National Natural Science Foundation of China, Grant No. 31601833, and by the National Key R&D Program of China, Project No. 2017YFD0301605.

https://doi.org/10.17221/365/2019-PSE

ability 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. These results suggested long-term fertilisation lead to soil parameters, such as soil organic carbon, soil available nitrogen (N), phosphorus (P) and potassium (K), and pH in different status (Bi et al. 2009, Li et al. 2018). Though many soil parameters were analysed individually in many croplands, crop production is generally affected by soil parameters functioning together as integrated soil fertility.

An integrated fertility index (IFI) is a measurable soil property that affects the capacity of a soil to perform a specified function (Karlen et al. 2006), which provides a better indication for soil fertility than individual properties. The indicators, the weights of the indicators, and the calculation method of the fertility index are the most important considerations in IFI methods (Wang and Gong 1998). As a matter of fact, IFI has been frequently used to class the soil grades in many counties of China (Sun et al. 2003, Liang et al. 2010, Chen et al. 2016, Zhang et al. 2018). Nevertheless, we know little about the changes in soil fertility over time and the links between soil fertility changes and agricultural practices.

In this study, we present field monitoring and multi-year data analyses from a double rice-cropping system under various long-term fertiliser management regimes during 2011–2018. The objectives of this study were to: (1) determine the effects of long-term fertilisation on rice yields and integrated soil fertility quality; (2) identify the causes of yield trends over time.

MATERIAL AND METHODS

Experiment site. Our long-term field experiment was conducted at the experimental station of Jiangxi Agricultural University in Nanchang City, Jiangxi province, China (28°45'34''N, 115°49'42''E), where the cropping regime is dominated by double rice-cropping systems. The paddy soil is classified as stagnic anthrosols that developed from Quaternary red clay, with a clay (< 0.001 mm) content of 255.0 g/kg in the topsoil (0–200 mm). The region is characterized by a subtropical humid monsoonal climate, with an annual average air temperature of 17.5 °C, precipitation of 1587 mm, and a frost-free period of 282 days. The detailed climate information during the experimental period is shown in Table 1.

Fertilisation treatments and management. A randomized block experiment was established with six different fertiliser treatments and three replicates. Each field plot was 5.4 m × 10.0 m. The six fertiliser treatments were grouped as either imbalanced/balanced mineral fertiliser treatments or combined mineral/organic fertiliser regimes. Specifically, the six fertiliser treatments included 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 fertiliser application served as the control. In the two cropping cycles, the total amount of N, P, and K applied were uniform across the treatments, with the splitting ratio varying between the two crops (Table 1). Urea for N, calcium superphosphate for P, and potassium chloride for K was used throughout the experiments. Urea was applied with two splits for the early-rice season, 40% as basal fertiliser and 60% as tillering fertiliser, and three splits for the late-rice season, 40% as basal fertiliser, 50% as tillering fertiliser and 10% as panicle fertiliser. The P and K fertilisers were applied as basal fertilisers before rice transplanting. The basal fertiliser, applied 2 days before rice transplanting, was well incorporated into the soil by plowing to 10–20 cm depth and the top-dressing was surface broadcasted.

Table 1. Means and ranges of monthly rainfall, maximum and minimum temperatures, and their time trends during rice growing seasons from 2011 to 2018

	Early-rice				Late-rice			
	mean	range	trend (°C/year)	R^2	mean	range	trend (°C/year)	R^2
Rainfall (mm)	218.2	199.3–230.5	–15.77*	0.38	105.8	71.8–140.5	–0.27	0.07
T_{max} (°C)	29.5	22.7–32.3	0.23*	0.40	28.8	32.3–23.1	0.04	0.10
T_{min} (°C)	20.1	17.9–24.6	–0.02	0.01	19.7	14.7–23.7	–0.09	0.16

T_{max} and T_{min} – mean monthly maximum and minimum temperatures during rice growing seasons, respectively. *$P < 0.05$

https://doi.org/10.17221/365/2019-PSE

The plots under control, NP, NK, and NPK treatments were fallowed in winter, and all rice straws including the early and late rice, were harvested and removed out of the field. In the NPKM and NPKS plots, green manure (Chinese milk vetch) grown in the winter season was harvested and *in situ* ploughed into the soil before the early-rice transplanting. In addition, the harvested crop straw of early or late rice was incorporated, *in situ*, at full rate to a depth of 100–150 mm just before late-rice transplanting or after harvesting for the NPKS plots, respectively (Table 2). The N, P and K contents averaged 2.59, 0.10 and 1.44% in incorporated Chinese milk vetch and 0.93, 0.08 and 1.83% in crop straw, respectively. In the NPKM plots, 7.5 t/ha of pig manure was applied before rice transplanting. The amount of organic carbon (C), N, P, and K averaged 8.7, 0.50, 0.22, and 0.33% in pig manure in the NPKM plots. Pig manure had a finer texture and more complex ingredients, including protein, fat, organic acid, cellulose, hemicellulose and inorganic salts. Pig manure contained more nitrogen and a lower C:N ratio (14:1), and is generally easily broken down by microorganisms, releasing nutrients that can be absorbed and used by crops.

Between 2011 and 2018, for the early-rice crop, rice seedlings were transplanted by hand in late April and harvested in mid-July, for the late-rice crop, rice seedlings were transplanted in late July and harvested in mid-October. The rice cultivars were selected by the local main push breed, and updated every five years. Herbicides and pesticides were applied during the growth period as needed. The interval between the two rice-cropping seasons was about 3–5 days.

Soil and crop sampling and analyses. The soil samples were collected from each plot using an auger (inner diameter of 3.0 cm) at the plough-layer depth of 0–200 mm from 2011 to 2018. Each sample weighed about 1 kg and was a composite of six subsamples taken randomly from within a plot. The soil samples collected in April 2011 were thoroughly composited as one sample to analyse the initial soil properties. After the samples were air-dried at room temperature and ground sufficiently to pass through a 2 mm sieve, visible plant detritus and any fragments were removed from the soil samples. A subsample was subsequently ground in a porcelain mortar to pass through a 0.15 mm sieve and used for analysis.

Soil organic carbon (SOC); total nitrogen (TN); pH; total phosphorus (TP); total potassium (TK); available nitrogen (AN); available phosphorus (AP), and available potassium (AK) in our soil samples were determined for 2011 and 2018. The analytical methods were SOC (CNS elementabv l analyzer method); TN (micro-Kjeldahl digestion method); TP (molybdenum method); TK (flame photometer method); AN (alkali solution diffusion absorption method); AP (Olsen-P method); AK (1 mol/L NH_4OAc-extraction and flame photometer method), and pH (1:2.5, soil/H_2O). All soil properties analyses were determined using Chinese Soil Society guidelines (Lu 2000).

Grain yields were measured at physiological maturity by hand-harvesting two 2-m-long rows per plot. Grain yields of the rice were determined at harvest by oven drying to a constant weight at approximately 70 °C.

Soil fertility quality evaluations. The integrated fertility index could be used to understand the change

Table 2. Fertiliser application (N:P:K, kg/ha) regime treatments in double rice-cropping fields at the long-term experimental station from 2011–2018

Treatment	Early rice season				Late rice season		
	mineral fertiliser	Chinese milk vetch grown[a]	pig manure[b]	rice straw[c]	mineral fertilizer	pig manure	rice straw
Control	0:0:0	0:0:0	0:0:0	0:0:0	0:0:0	0:0:0	0:0:0
NP	150:39:0	0:0:0	0:0:0	0:0:0	180:26:0	0:0:0	0:0:0
NK	150:0:112	0:0:0	0:0:0	0:0:0	180:0:150	0:0:0	0:0:0
NPK	150:39:112	0:0:0	0:0:0	0:0:0	180:26:125	0:0:0	0:0:0
NPKM	150:39:112	57:2.6:32	38:20:25	0:0:0	180:26:125	38:20:25	0:0:0
NPKS	100:26:75	52:2.2:30	0:0:0	36:3.5:72	120:18:83	0:0:0	32:3.1:63

[a]Chinese milk vetch grown in the previous winter season was harvested as green manure and incorporated into the soil, fresh weight with the water content of 88–91%; [b]pig manure, dry weight; [c]crop straw of rice harvested from double rice growing seasons, dry weight; NP, NK, and NPK – mineral fertiliser, NPKM – NPK with farmyard manure; NPKS – NPK with crop straw; control – no fertiliser

https://doi.org/10.17221/365/2019-PSE

of soil fertility level in double rice-cropping systems under different fertilisation. According to Shang et al. (2014), the eight kinds of soil nutrient parameters, including pH, SOC, TN, TP, TK, AN, AP, and AK, were taken as the original variables (soil nutrient indexes) to evaluate the IFI.

It was established and defined as the following:

$$\text{IFI} = \sum_{i=1}^{n} \text{W}_\text{i} \times \text{I}_\text{i}$$

where: n, W_i and I_i – numbers of parameters, the weight coefficient and score of the i^{th} fertility quality parameter. The value of the 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

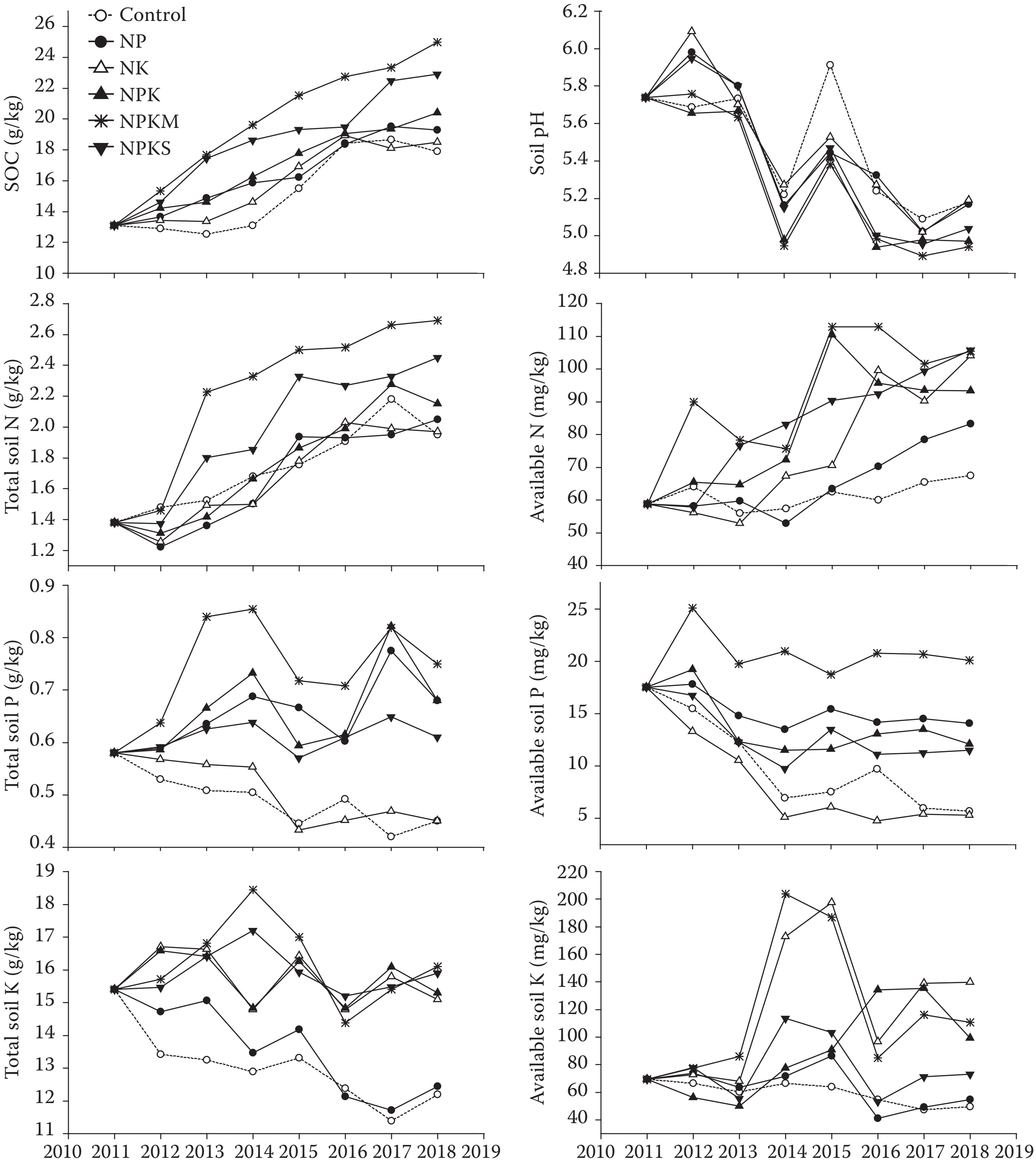

Figure 1. Dynamics of topsoil properties (0–200 mm) as affected by long-term fertilisation in double rice-cropping systems. The values in the figure are the means of three replicates; SOC – soil organic carbon; NP, NK, and NPK – mineral fertiliser, NPKM – NPK with farmyard manure; NPKS – NPK with crop straw; control – no fertiliser

https://doi.org/10.17221/365/2019-PSE

Table 3. Value of turning point of soil parameters in standard score function Equation (2) in double rice-cropping systems

Critical threshold	Soil organic carbon	Total nitrogen	Available nitrogen	Total phosphorus	Available phosphorus	Total potassium	Available potassium
L	8.7	0.75	50	0.4	5	5	30
U	20.3	1.5	150	1.0	15	25	150

U – value at which plant growth is optimum; L – value under which plant growth is severely limited

parameters except pH. The monitoring values were listed in Figure 1. The SSF is given by "S" function:

$$f(x) = \begin{cases} 0.1 & x \leq \mathrm{L} \\ 0.9\,(x - \mathrm{L})/(\mathrm{U} - \mathrm{L}) + 0.1 & \mathrm{L} \leq x \leq \mathrm{U} \\ 1.0 & x \geq \mathrm{U} \end{cases} \quad (2)$$

where: x and f(x) – monitoring value of the parameter and the score of the parameter, ranging from 0.1 to 1. U and L for the parameters are the lower and the upper threshold values. The values U and L are determined by the effect of soil nutrient indexes on plant growth (Shang et al. 2014). U is the value at which plant growth is optimum, and L is the value under which plant growth is severely limited. The values of U and L 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 4.5, 5.5, 6.5 and 8.5, respectively.

In this paper, parameter weights were assigned by its communality through principal component analysis, according to Shang et al. (2014). The given value and contribution of each principal factor was calculated, and then the commonality explained by each parameter based on the load matrix was calculated. The value of the commonality indicated the contribution of each soil parameter to soil fertility, and, on this basis, parameter weights were assigned (Table 4).

Data analysis. Differences in grain yields, topsoil properties (0–200 mm), and integrated fertility index among treatments were examined by the Tukey's multiple range test at the 5% level of significance. Statistical analyses were carried out using JMP, ver. 5.1 (SAS Institute, Cary, USA).

RESULTS

Double rice-crop yields and their trends. Grain yields of early-rice showed declining time trends in the phosphorus-omitted plots (control and NK), and the latter was statistically significant (Figure 2). In contrast, significant increasing time trends were observed in the phosphorus-applied plots (NP, NPK, NPKM, and NPKS). Grain yields of late-rice showed similar time trends as an early-rice crop (Figure 3). Over the 8 years, long-term fertilisation significantly increased mean grain yields compared to the unfertilised control (except NK) ($P < 0.05$, Figure 4). Over the two crop seasons, relative to NPK, the mean yields were dramatically reduced by 70.9% and 51.3% in NK treatments, respectively. In contrast, the mean yields in NPKM treatment can be increased by 5.5% for early-rice and 11.1% for late-rice, but differences were not statistically significant. The mean yields were similar between NPK and NPKS for the double-rice crops.

Correlations between rice yield and weather parameters. The linear regression analyses revealed no large differences in mean maximum and minimum temperatures during the study period, with the exception of the mean maximum temperature in early-rice cropping season, which increased significantly

Table 4. Estimated communality and weight value of each soil fertility parameter in double rice-cropping systems

	Soil organic carbon	Total nitrogen	Available nitrogen	Total phosphorus	Available phosphorus	Total potassium	Available potassium	pH
Communality	0.959	0.954	0.991	0.259	0.932	0.746	0.889	0.784
Weight	0.147	0.146	0.152	0.040	0.143	0.114	0.136	0.120

https://doi.org/10.17221/365/2019-PSE

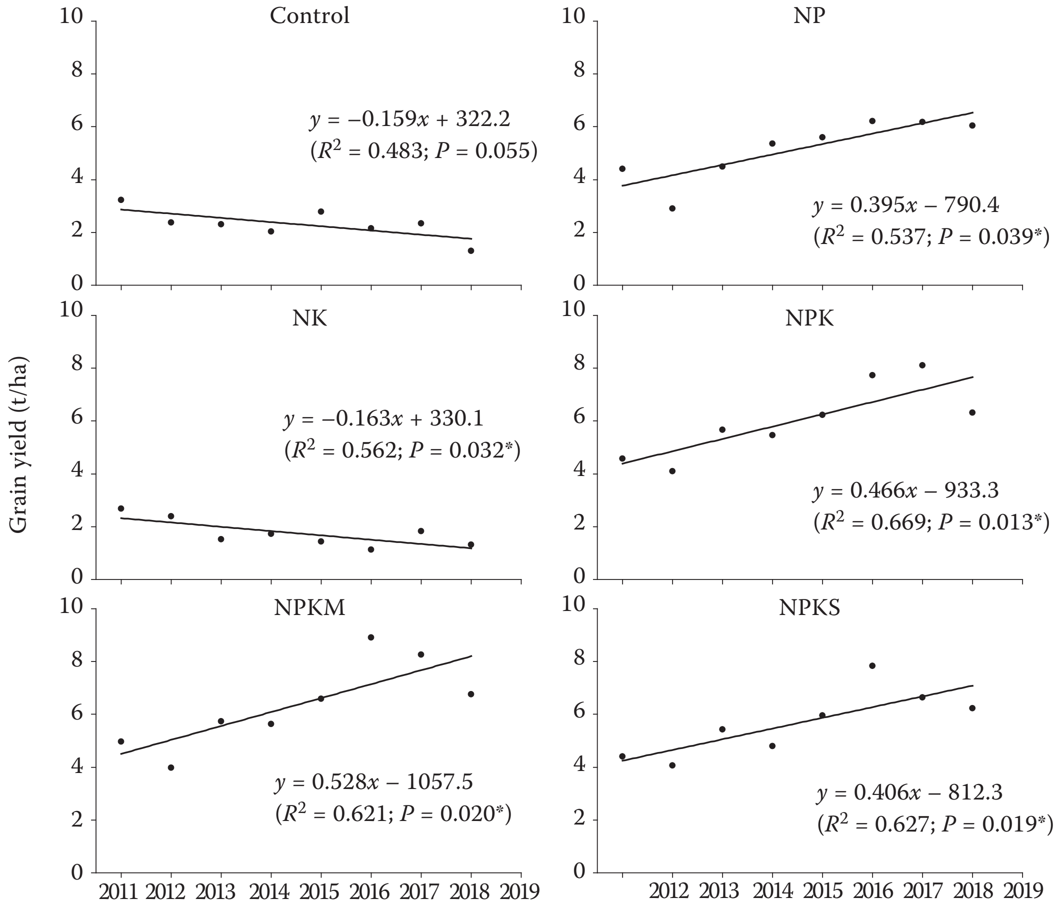

Figure 2. Trends in grain yield of early-rice as affected by long-term fertilisation from 2011 to 2018. The values in the figure are the means of three replicates. *$P < 0.05$; NP, NK, and NPK – mineral fertiliser, NPKM – NPK with farmyard manure; NPKS – NPK with crop straw; control – no fertiliser

($P < 0.05$, Table 1). Rainfall trended to substantially lower values during the early-rice growing period ($P < 0.05$), but no significant change was observed in the late-rice cropping season (Table 1).

Pairwise correlation analyses showed that rice yields in the control treatment were not significantly correlated with any weather parameter for the early- and late-rice crops (Table 5). In both the early- and late-rice seasons, the maximum temperature was significantly and positively correlated with minimum temperature, whereas significant negative relationships were found between the maximum temperature of the late-rice season and rainfall.

Soil fertility parameters. Long-term continuous rice cropping led to a great increase in the content of

Table 5. Pairwise correlations between rice yield in the control treatment and weather parameters during rice growing seasons

	Early rice season				Late rice season			
	yield	rainfall	T_{max}	T_{min}	yield	rainfall	T_{max}	T_{min}
Yield	1	0.05	0.21	–0.38	1	0.01	0.18	–0.34
Rainfall		1	–0.35	–0.33		1	–0.56**	–0.19
T_{max}			1	0.69***			1	0.78***
T_{min}				1				1

T_{max} and T_{min} – mean monthly maximum and minimum temperatures during rice growing seasons, respectively. **$P < 0.01$; ***$P < 0.001$

https://doi.org/10.17221/365/2019-PSE

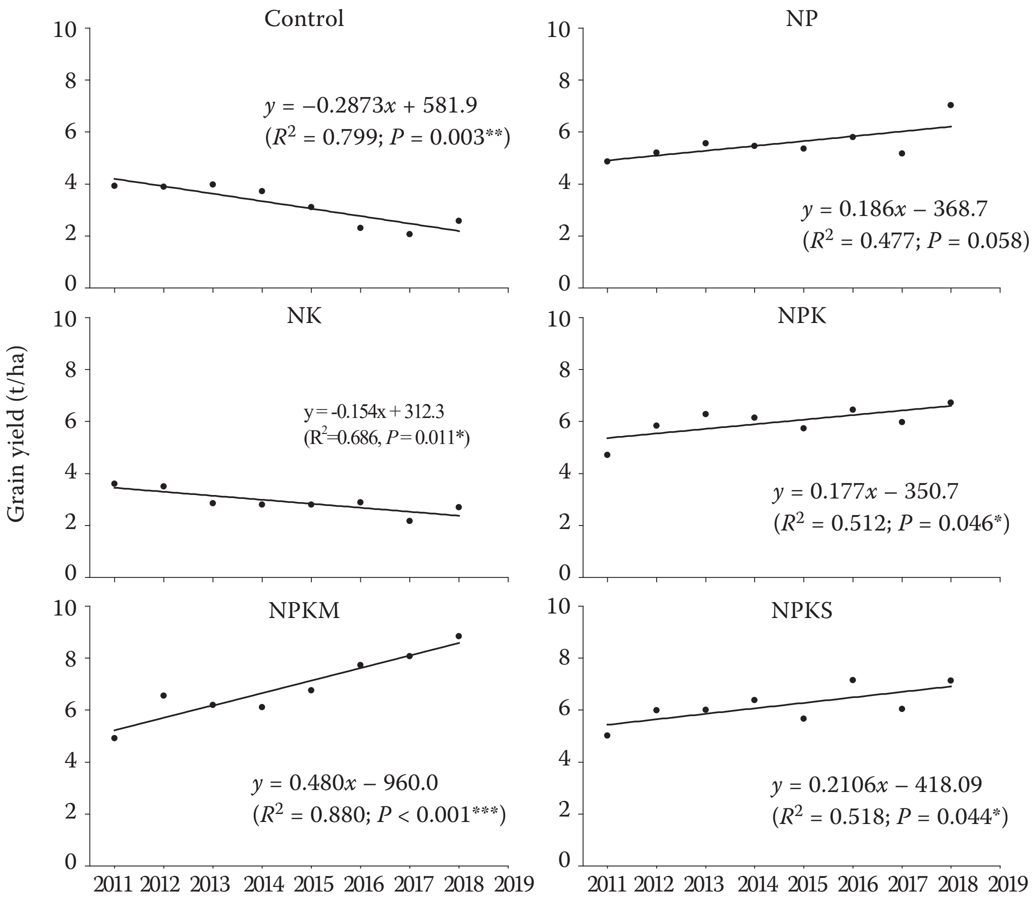

Figure 3. Trends in grain yield of late-rice as affected by long-term fertilisation from 2011 to 2018. The values in the figure are the means of three replicates. *P < 0.05; **P < 0.01; ***P < 0.001; NP, NK, and NPK – mineral fertiliser, NPKM – NPK with farmyard manure; NPKS – NPK with crop straw; control – no fertiliser

SOC for the various treatments (Figure 1). Similar to SOC, TN increased by 64.2–128.7% for all the treatments after the long-term experiment. In particular, the contents of SOC and TN were significantly higher in NPKM treatment than in control treatment, but differences were not statistically significant, among other treatments. In addition, the contents of AN were improved for all treatments after the long-term experiment, but there were no significant differences among these treatments. The contents of TP were increased in phosphorus-applied plots (NP, NPK, NPKM and NPKS), but they tended to decline for the

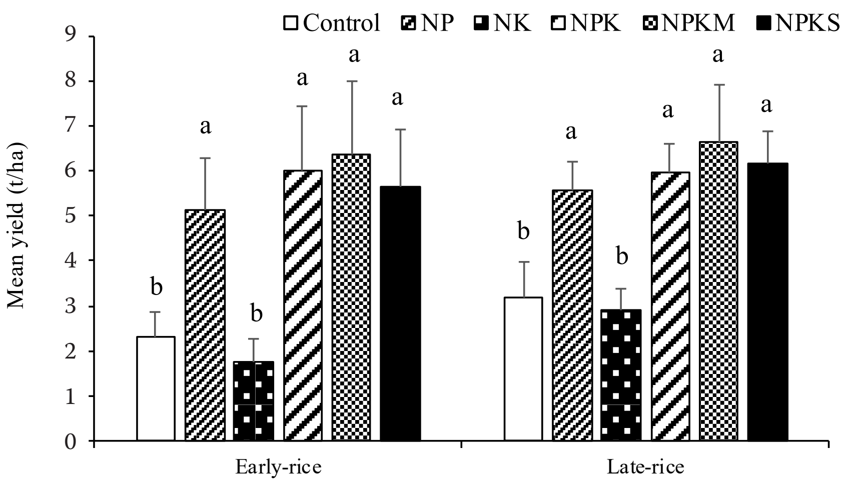

Figure 4. Mean grain yields of early- and late-rice as affected by long-term fertilisation from 2011 to 2018. Different letters indicate analysis of variance in variables mean among different treatments by the Tukey's multiple range test (P < 0.05)

https://doi.org/10.17221/365/2019-PSE

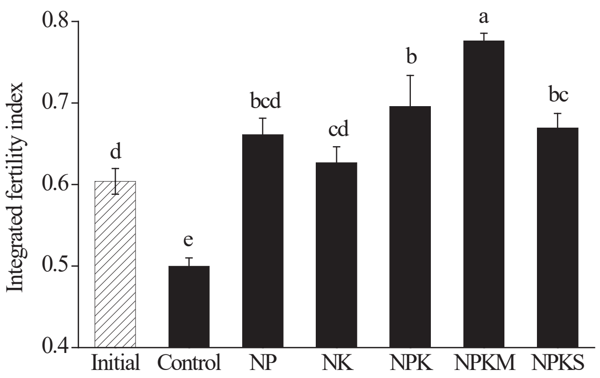

Figure 5. Integrated fertility index initial in 2011 and after the long-term fertilisation experiments in double-rice cropping systems. Different letters indicate analysis of variance in variables mean among different treatments by the Tukey's multiple range test ($P < 0.05$); NP, NK, and NPK – mineral fertiliser, NPKM – NPK with farmyard manure; NPKS – NPK with crop straw; control – no fertiliser

treatments without phosphorus applied (control and NK). The contents of TP were substantially higher in phosphorus-applied plots (except NPKS) compared with the phosphorus-omitted plots. Long-term rice cropping led to a decline in the content of AP for the various treatments, except NPKM. However, the contents of AP were substantially higher in phosphorus-applied plots compared with the phosphorus-omitted plots. The contents of TK were decreased by 19.9% for the potassium-deficient plots as compared to the initial, but they were improved by 4.0% in the combined mineral/organic fertiliser plots (NPKM and NPKS). Similarly, the contents of AK were reduced by 20.9–28.8% in potassium-omitted plots (control and NP), but they were increased by 5.3–101.6% in all the potassium-applied plots (NK, NPK, NPKM and NPKS). The content of AK was greatly higher in NK treatment than in plots without potassium application. Long-term continuous cropping led to a slight decline in the level of soil pH for all the plots, especially in the combined mineral/organic fertiliser plots (NPKM and NPKS), though these differences were not significant. As long-term cultivation progressed, similar to the pH declined in all treatments from 2011 to 2018.

Integrated fertility index. Long-term continuous rice cropping led to a significant decline in IFI for control treatment, while the IFIs were increased by 3.7–28.5% for other treatments relative to the initial (Figure 5). After the long-term experiment, compared to the unfertilised control, the IFIs were significantly increased by mineral fertiliser applied (NP, NK, and NPK) and combined mineral/organic fertiliser applied (NPKM and NPKS). However, compared to the NPK treatment, the values of IFI were obviously reduced by 9.9% under the NK treatment. Although the IFI in NPK treatment was numerically greater than that in the NPKS treatment, differences were not statistically significant; but the combined mineral/organic fertiliser application in NPKM treatment gave a significantly higher IFI after the long-term experiment.

DISCUSSION

Effect of long-term mineral fertiliser application on soil fertility. Many studies have concluded that long-term trends in crop yield are mainly attributable to the combined effects of changes in climate, soil, cultivars, and fertilisation (Ladha et al. 2003, Kucharik and Serbin 2008). Welch et al. (2010) showed that diurnal temperature variation must be considered when investigating the impacts of climate change on irrigated rice-cropping systems. In this light, some studies have reported an increase in both mean maximum and minimum temperatures during the past two decades in southern China (Bi et al. 2009, Huang et al. 2010) and suggested that a warming trend is occurring. However, our results indicated that no appreciable changes in most of the weather variables occurred during the period of study (Table 1). This observation may be attributed, at least in part, to the unique location of the typical hilly agricultural area used for this study. Based on correlation analyses, rice yield trends in this study were not associated with any changes in climatic factors (Table 5). This finding is consistent with other studies using intensive rice-cropping systems (Regmi et al. 2002, Bi et al. 2009). However, all plots were significantly affected by fertiliser application in all the years. These results suggest that fertiliser application is the major factor determining rice yield and soil quality, and the effect of different cultivars on yield is rather limited.

Generally, fertiliser application had a significant effect on rice growth, particularly in single-rice systems with low soil fertility (Bhandari et al. 2002, Shen et al. 2004). In the present study, the mean rice yield was higher in the fertilisation plots than control, except NK plots (Figures 2 and 3). After the long-term experiment, the decline of soil AK in potassium-deficient plots (NP) did not lead to a decrease in grain yield in our long-term experiment. One possibility is that

https://doi.org/10.17221/365/2019-PSE

the content of AK did not reach a critical level, or perhaps the irrigation water supplied a fairly large amount of potassium that helped buffer potassium deficiency (Dobermann et al. 1998, Bhandari et al. 2002). However, unlike the NP and NPK plots, rice yield in NK plots showed significant and negative trends for the early- and late-rice crops. This observation may be attributed to the severe depletion of available phosphorus in the paddy soil. The change of soil nutrients indicates that imbalanced fertilisation application had a tremendous effect on soil fertility. Consistent with previous studies, the contents of AP showed a significant decline in phosphorus-deficient plots after long-term rice cultivation (Shen et al. 2004). In particular, the contents of AP averaged only 5.5 mg/kg in phosphorus-deficient plots in this study. Analysis of soil fertility quality by IFI also suggested that soil fertility was significantly declined in NK treatment compared with NPK, whereas no significant difference between NP and NPK. As a result, it appears that soil phosphorus deficiency is an important factor limiting increased yields in double rice-cropping systems. Therefore, P fertiliser supplement is essential in South China since the soil is generally P deficit.

Effect of long-term organic fertiliser application on soil quality. Regression analysis showed that the increase in grain yields was positively correlated with the improved IFI over treatments in double rice-cropping systems (Figure 6). Similarly, some results also showed a positive relationship between crop yields and soil quality in a semi-arid inceptisol (Masto et al. 2007). These suggested that crop productivity could be enhanced by reasonable fertilisation and its

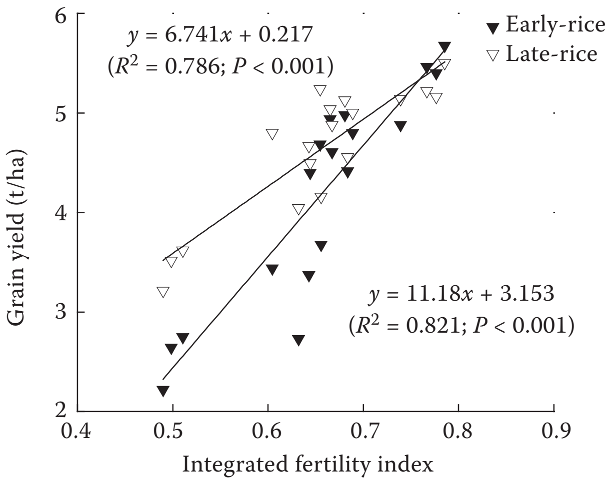

Figure 6. Relationship between integrated fertility index and grain yield in double-rice cropping systems

consequent improvement of integrated soil fertility in intensive rice-cropping systems. In the present study, changes of IFI in topsoil differed among treatments with greater increases in receiving organic fertiliser amendments in NPKM plots (Figure 5). Several reasons may be given for the increase in SOC in this study. First, grain yield averaged 5.5–13.0 t/ha/year in our study, generally higher than that of annual rice-upland rotation systems or upland cropping systems (Huang et al. 2010). This suggests that greater topsoil SOC density is a consequence of increased crop residue maintained into soils due to higher crop net primary production. Second, it could be attributed to surface waterlogging primarily dominated in double rice-cropping systems, where the decomposition rate of SOC was slower than upland

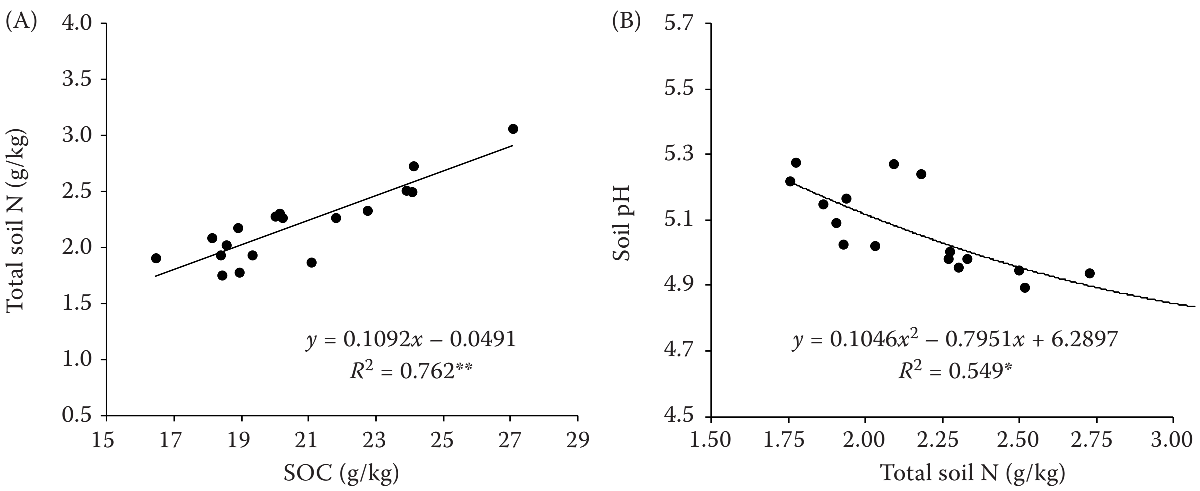

Figure 7. Correlation of total soil nitrogen (N) with soil organic carbon (SOC) content (A) and soil pH (B) during the long-term fertiliser experiment. *$P < 0.05$; **$P < 0.01$

https://doi.org/10.17221/365/2019-PSE

systems. Furthermore, silt and clay contents in paddy fields are higher than those in upland soils, which lead to larger SOC accumulation (Liu et al. 2006). In addition, the content of TN was positively correlated with SOC over-treatments ($P < 0.001$, Figure 7), which was consistent with previous estimates in upland red soil (Zhang et al. 2009). In addition, relative to the NPK treatment, the long-term combined mineral/organic fertiliser amendments in NPKM treatment greatly enhanced soil fertility quality, that might be attributed to the dramatically increased content of soil available phosphorus (Figure 1).

Some studies have suggested that the application of cropping residues could slow the rates of soil acidification in agricultural ecosystems (Huang et al. 2010, Zhong et al. 2010). However, soil pH was slightly lower in NPKM and NPKS treatments compared with other treatments in our study. That may be due to several reasons. First, it was related to the varied agricultural activity in a specific location. Kirchmann and Witter (1989) showed that the decomposition rate of crop straw was generally lower under anaerobic conditions. As a result, the accumulation of crop residues can result in permanent soil acidification in intensive rice-cropping systems because the excess H^+ ions remain in the soil. Second, the growth of leguminous species generally has a major role in soil acidification (Vieira et al. 2008). Burle et al. (1997) suggested that legume-based systems contain larger amounts of nitrogen in their aboveground parts than do non-legume systems, along with larger amounts of soil organic nitrogen. However, the larger amounts of soil organic nitrogen accumulated would greatly enhance nitrogen mineralization and nitrification. Earlier reports suggest that nitrification followed by leaching is one of the major processes responsible for soil acidification in legume-based cropping systems (Helyar and Porter 1989, Dai et al. 2017). In the present study, we found a significant negative relationship between nitrogen accumulation (TN) and soil pH ($P < 0.01$, Figure 7). Since the fields with a high content of soil N in intensive rice-cropping systems, optimal nutrient-management strategies based on soil parameters have become one of the most urgent requirements for sustainable agriculture. We suggest that the application of farmyard manure and Chinese milk vetch as a complement to a recommended dose of NPK should be encouraged to inhibit soil acidification in intensive rice-cropping systems.

REFERENCES

Bhandari A.L., Ladha J.K., Pathak H., Padre A.T., Dawe D., Gupta R.K. (2002): Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Science Society of America Journal, 66: 162–170.

Bi L.D., Zhang B., Liu G.R., Li Z.Z., Liu Y.R., Ye C., Yu X.C., Lai T., Zhang J.G., Yin J.M., Liang Y. (2009): Long-term effects of organic amendments on the rice yields for double rice cropping systems in subtropical China. Agriculture, Ecosystems and Environment, 129: 534–541.

Bora R., Pandey P.C., Singh D.K., Yadav S.K., Chilwal A. (2018): Assessment of soil fertility status under long term balance fertilizer application on rice (*Oryza sativa* L.). International Journal of Chemical Studies, 6: 1696–1699.

Burle M.L., Mielniczuk J., Focchi S. (1997): Effect of cropping systems on soil chemical characteristics, with emphasis on soil acidification. Plant and Soil, 190: 309–316.

Chen X., Zhao Y., Chai G., Zhang Z., Zhang Y., Shi X. (2016): Integrated soil fertility and yield response to long-term different fertilization in purple soil. Transactions of the Chinese Society of Agricultural Engineering, 32: 139–144.

Dai Z.M., Zhang X.J., Tang C., Muhammad N., Wu J.J., Brookes P.C., Xu J.M. (2017): Potential role of biochars in decreasing soil acidification – A critical review. Science of The Total Environment, 581–582: 601–611.

Dawe D., Dobermann A., Ladha J.K., Yadav R.L., Bao L., Gupta R.K., Lal P., Panaullah G., Sariam O., Singh Y., Swarup A., Zhen Q.X. (2003): Do organic amendments improve yield trends and profitability in intensive rice systems? Field Crops Research, 83: 191–213.

Dobermann A., Cassman K.G., Mamaril C.P., Sheehy J.E. (1998): Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. Field Crops Research, 56: 113–138.

Fan M.S., Shen J.B., Yuan L.X., Jiang R.F., Chen X.P., Davies W.J., Zhang F.S. (2012): Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. Journal of Experimental Botany, 63: 13–24.

Guo J.H., Liu X.J., Zhang Y., Shen J.L., Han W.X., Zhang W.F., Christie P., Goulding K.W.T., Vitousek P.M., Zhang F.S. (2010): Significant acidification in major Chinese croplands. Science, 327: 1008–1010

Helyar K.R., Porter W.M. (1989): Soil acidification its measurement and the processes involved. In: Robson A.D. (ed.): Soil Acidity and Plant Growth. Sydney, Academic Press, 61–10.

Huang S., Zhang W.J., Yu X.C., Huang Q.R. (2010): Effects of long-term fertilization on corn productivity and its sustainability in an Ultisol of southern China. Agriculture, Ecosystems and Environment, 138: 44–50.

Hussan I. (1997): Tillage effects on soil properties and crop production in southern Illinois. [Ph.D. Thesis] Urbana, Library University of Illinois.

https://doi.org/10.17221/365/2019-PSE

Karlen D.L., Hurley E.G., Andrews S.S., Cambardella C.A., Meek D.W., Duffy M.D., Mallarino A.P. (2006): Crop rotation effects on soil quality in the northern corn/soybean belt locations. Agronomy Journal, 98: 484–495.

Kirchmann H., Witter E. (1989): Ammonia volatilization during aerobic and anaerobic manure decomposition. Plant and Soil, 115: 35–41.

Kucharik C.J., Serbin S.P. (2008): Impacts of recent climate change on Wisconsin corn and soybean yield trends. Environmental Research Letters, 3: 034003.

Kusano M., Yang Z., Okazaki Y., Nakabayashi R., Fukushima A., Saito K. (2015): Using metabolomic approaches to explore chemical diversity in rice. Molecular Plant, 8: 58–67.

Ladha J.K., Dawe D., Pathak H., Padre A.T., Yadav R.L., Singh B., Singh Y., Singh P., Kundu A.L., Sakal R., Ram N., Regmi A.P., Gami S.K., Bhandari A.L., Amin R., Yadav C.R., Bhattarai E.M., Das S., Aggarwal H.P., Gupta R.K., Hobbs P.R. (2003): How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Research, 81: 159–180.

Li J., Wen Y.C., Li X.H., Li Y.T., Yang X.D., Lin Z., Song Z.Z., Cooper J.M., Zhao B.Q. (2018): Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. Soil and Tillage Research, 175: 281–290.

Liang J., Wang X.A., Yu Z.D., Dong Z.M., Wang J.C. (2010): Effects of vegetation succession on soil fertility within farming-plantation ecotone in Ziwuling Mountains of the Loess Plateau in China. Agricultural Sciences in China, 9: 1481–1491.

Liu Q.H., Shi X.Z., Weindorf D.C., Yu D.S., Zhao Y.C., Sun W.X., Wang H.J. (2006): Soil organic carbon storage of paddy soils in China using the 1:1,000,000 soil database and their implications for C sequestration. Global Biogeochemical Cycles, 20.

Lu R.K. (2000): Analytical Methods for Soil and Agricultural Chemistry. Beijing, Agricultural Science and Technology Press, 106–310. (In Chinese)

Masto R.E., Chhonkar P.K., Singh D., Patra A.K. (2007): Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. Agriculture, Ecosystems and Environment, 118: 130–142.

Moreno-Cornejo J., Caballero-Lajarín A., Faz Á., Zornoza R. (2017): Pepper crop residues and chemical fertilizers effect on soil fertility, yield and nutritional status in a crop of *Brassica oleracea*. Journal of Soil Science and Plant Nutrition, 17: 648–661.

Rasmussen P.E., Goulding K.W.T., Brown J.R., Grace P.R., Janzen H.H., Körschens M. (1998): Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science, 282: 893–896.

Regmi A.P., Ladha J.K., Pathak H., Pasuquin E., Bueno C., Dawe D., Hobbs P.R., Joshy D., Maskey S.L., Pandey S.P. (2002): Yield and soil fertility trends in a 20-year rice-rice-wheat experiment in Nepal. Soil Science Society of America Journal, 66: 857–867.

Shang Q.Y., Ling N., Feng X.M., Yang X.X., Wu P.P., Zou J.W., Shen Q.R., Guo S.W. (2014): Soil fertility and its significance to crop productivity and sustainability in typical agroecosystem: a summary of long-term fertilizer experiments in China. Plant and Soil, 381: 13–23.

Shen J., Li R., Zhang F., Fan J., Tang C., Rengel Z. (2004): Crop yields, soil fertility and phosphorus fractions in response to long-term fertilization under the rice monoculture system on a calcareous soil. Field Crops Research, 86: 225–238.

Sun B., Zhou S.L., Zhao Q.G. (2003): Evaluation of spatial and temporal changes of soil quality based on geostatistical analysis in the hill region of subtropical China. Geoderma, 115: 85–99.

Vieira F.C.B., Bayer C., Mielniczuk J., Zanatta J., Bissani C.A. (2008): Long-term acidification of a Brazilian Acrisol as affected by no till cropping systems and nitrogen fertiliser. Australian Journal of Soil Research, 46: 17–26.

Vitousek P.M., Naylor R., Crews T., David M.B., Drinkwater L.E., Holland E., Johnes P.J., Katzenberger J., Martinelli L.A., Matson P.A., Nziguheba G., Ojima D., Palm C.A., Robertson G.P., Sanchez P.A., Townsend A.R., Zhang F.S. (2009): Nutrient imbalances in agricultural development. Science, 324: 1519–1520.

Wang X.J., Gong Z.T. (1998): Assessment and analysis of soil quality changes after eleven years of reclamation in subtropical China. Geoderma, 81: 339–355.

Welch J.R., Vincent J.R., Auffhammer M., Moya P.F., Dobermann A., Dawe D. (2010): Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proceedings of the National Academy of Sciences of the United States of America, 107: 14562–14567.

Zhang J., Han L., Ji Y., Duan M., Cai G., Wu J., Zhu W., Gao G., Peng Y., Zhou Y. (2018): Study of soil nutrients, physical and biological characteristics of paddy fields after lifting measures: A case study of China's Ganjiang region. Journal of Environmental Biology, 39: 432–439.

Zhang W.J., Xu M.G., Wang B.R., Wang X.J. (2009): Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern China. Nutrient Cycling in Agroecosystems, 84: 59–69.

Zhong W., Gu T., Wang W., Zhang B., Lin X., Huang Q., Shen W. (2010): The effects of mineral fertilizer and organic manure on soil microbial community and diversity. Plant and Soil, 326: 511–522.

Received: June 27, 2019
Accepted: December 19, 2019
Published online: January 9, 2020