



Changes of yields, soil properties and micronutrients as affected by 17-yr fertilization treatments

Benyin Li ^{1,2}, Mingbao Wei ³, Alin Shen ^{1*}, Jianmin Xu ², Hailin Zhang ⁴ and Fazheng Hao ⁵

¹ Institute of Plant Nutrition, Agricultural Resources and Environmental Science, Henan Academy of Agricultural Sciences, Zhengzhou 450002, China. ² College of Natural Resources and Environment Science, Zhejiang University, Hangzhou 310058, China. ³ Henan Provincial Key Lab of Surface and Interface Science, Zhengzhou University of Light Industry, Zhengzhou 450002 China. ⁴ Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, USA. ⁵ Zhongmu Country Agro-technology Extension Center, Zhengzhou 451450, China.

*e-mail: shenalin_123@126.com, benyinli@foxmail.com

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Abstract

Plant essential and toxic microelement status in soil and crops can be affected by long-term fertilization practices. The main objective of this paper was to investigate the change of micronutrients and Cd in soil and brown rice after 17-yr cropping and fertilization treatments in Southeast China. The long-term fertilization experiment included treatments with different combinations of N, P, K and pig manure with or without straw incorporated. Soil pH, organic matter, available N, P, K and the contents of Cu, Zn, Fe, Mn and Cd in soil and brown rice were determined. Balanced chemical fertilizers (N, P, K) with the application of manure and incorporation of straw resulted in high available soil N, P, K, which produced highest yield of rice grain among the treatments. Manure application increased total Cu, Zn and Cd by 13-23, 5-8 and 138-162% and soil available Cu, Zn and Cd by 89-123, 61-71% and 212-225%, respectively, compared with their initial status. However, no such difference was observed for total soil Fe and Mn contents after 33 rice seasons. The Cu, Zn, Fe, Mn and Cd contents in brown rice were significantly affected by different long-term fertilization practices. The Cd contents in brown rice in three manure-applied treatments were 3 times (0.26-0.28 mg kg⁻¹) as high as that (0.08 mg kg⁻¹) in the control treatment, suggesting long-term application of pig manure from intensive livestock farms could result in Cd contents exceeding the upper limit of the criteria (> 0.2 mg kg⁻¹, National Standard for Food Hygiene). Attention should be paid to potential soil Cd contamination caused by long-term application of pig manure containing heavy metals.

Key words: Long-term fertilization experiment, micronutrients, rice, paddy soil.

Introduction

Rice (*Oryza sativa* L.) is the most predominant crop in Jiangxi Province, China. The soil fertility in this region is fairly poor with low pH, low soil organic matter (OM) and low available P and K levels, largely as the result of local climate and soil parent material. Therefore, reasonable application of fertilizer is necessary for optimum yield. Previous studies have shown that application of farmyard manure or incorporation of straw into the field improved rice grain yield ¹⁻³. However, only a small amount of straw was directly incorporated into soil in Jiangxi Province because of very short turnaround time before the next crop is established and the lack of proper straw placement method which allows rice seedlings to grow normally in straw incorporated paddy fields.

In order to obtain a sustainable high yield, application of required micronutrients with balanced NPK fertilizer is required ⁴⁻⁶, whereas long-term application of chemical fertilizers causes deficiency in soil micronutrients ⁷. Usually, soil receives micronutrients from atmospheric deposition, irrigation water, and phosphate rock fertilizer and farmyard manure ⁸⁻¹¹. However, phosphate rock fertilizer often contains some essential and toxic microelements such as Cu, Zn, Fe, Mn, Pb and Cd ¹². On the other hand, farmyard

manures, especially poultry manure from concentrated feeding operations contains heavy metals such as Co, Cu, Fe, Mn, Zn and Cd, and As and Se, which are supplied in feeds for growth stimulation and disease prevention ^{13,14}. High contents of heavy metals in poultry waste-amended soil could cause environmental concerns as a result of potential contamination of surface and groundwater via runoff and leaching. Therefore, soils receiving repeated applications of poultry litter for several years have exhibited high content of extractable Cu and Zn ^{15,17}. Moore *et al.* ¹⁸ also found that heavy metal contents in runoff from poultry-waste amended soils increased as the litter application rate increased. Therefore, the objectives of this study were to investigate the changes of essential micronutrients and toxic elements in soil and in brown rice due to 17 years of fertilization and cropping.

Materials and Methods

Study site: The samples used in this study were collected from the Ecological Experimental Station of Red Soil, Chinese Academy of Sciences, located at Yingtan, Jiangxi Province, China (28°15'N,

116°55'E). The region has a typical subtropical monsoon climate with an annual precipitation of 1795 mm, annual evaporation of 1318 mm and a mean annual temperature of 17.6°C. Early rice - late rice - fallow rotation is a popular practice in this region. After the late rice is harvested, paddy field is usually fallowed without floodwater layer from November to April. The tested soil was classified as a Haplic Stagnic Anthrosol and derived from quaternary red clay.

Fertilization treatment and sample collection: Eight treatments included a control with no fertilizer (CK), no chemical fertilizer but application of pig manure and all straw returned to the field (SM), fertilizer N (N), fertilizer N plus pig manure with all straw return to field (NSM), fertilizer NP (NP), fertilizer NK (NK), fertilizer NPK (NPK), fertilizer NPK plus pig manure and all straw return to field (NPKSM). They were laid out in a randomized block design with three replications. The size of each plot was 5 m × 6 m.

The amounts of N, P and K applied for every season crop were 230, 29.7 and 69.7 kg ha⁻¹, respectively. All phosphorus (superphosphate), potassium (potassium chloride) and pig manure were applied as basal fertilizers whereas fertilizer N (urea) was added in two splits as both the basal and supplementary fertilizer. Pig manure was applied at the rate of 833.3 kg ha⁻¹ (dry weight) containing N, P and K 22.6, 12.6 and 6.2 g kg⁻¹, respectively. Average contents of Cu, Zn, Fe, Mn and Cd in straw, superphosphate, pig manure, potassium chloride and urea applied in this experiment in 1989-2006 are shown in Table 1.

Rice (*Oryza sativa* L.) in this study was transplanted in April and harvested in July. Rice grain were dried in an electric oven at 60°C for 2 days, husked with JLGJ-45 Rice Hulling Machine (made in Taizhou, China) and ground through a 60 mesh sieve for the analysis of microelements. All plant samples for analysis were placed in plastic bottles. Soil samples (0-15 cm) were air-dried and ground to pass through a 10 mesh sieve for analysis of soil pH, soil OM, available soil N, P and K and Cu, Zn, Fe, Mn and Cd. Part of each soil sample (< 10 mesh) was ground to pass through a 100 mesh sieve for analysis of soil total Cu, Zn, Fe, Mn and Cd.

Chemical analysis: Soil pH was measured in a 1:2.5 soil to water suspension with a combination glass electrode¹⁹. Available N, P and K were determined by extracting 5.0 g soil with 50 ml 2 M KCl, 100 ml 0.5 M NaHCO₃ and 50 ml 1.0 M NH₄OAc, respectively²⁰. Soil organic matter content was determined by the Walkley-Black method²¹.

Available soil Cu, Zn, Fe, Mn, Pb and Cd were extracted by 0.1 M HCl^{22,23}. After 2 h continuous shaking at 25°C, the soil solution was centrifuged and filtered through a 0.45 μm membrane to analyze available soil Cu, Zn, Fe, Mn and Cd contents. A portion of 0.5 g soil was digested with HClO₄-HNO₃-HF for analysis of soil Cu, Zn, Fe, Mn, Pb and Cd. The concentrations of Cu, Zn, Fe

and Mn in the extracts or digests were analyzed by flame atomic absorption spectroscopy (FAAS). Cd was determined using graphic furnace atomic spectroscopy (GFAAS).

All glass wares were soaked in detergent solution at first and then in 10% HNO₃ (v/v) for 24 h. They were cleaned with de-ionized water. All reagents used for micronutrients in this study were of reagents grade. Standard soil reference materials (GBW07401, GBW07402) and plant reference materials (GBW10010, GBW10015) from the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences, were carried through the digestion and analyses as a part of the quality assurance-quality control protocol.

Statistical analysis: The data were subjected to one-way ANOVA using SPSS (Statistic Program for Social Sciences) software package (Version 11.5) (Statistical Graphics Corp., Princeton, NJ). Means and standard errors were calculated for three replicates. Means were compared by the Duncan's multiple range test at a significance level of 0.05. The same letter in a column in the tables represents no significant difference among the treatments.

Results and Discussion

Yield of rice grain and straw: Yields of rice grain and straw in the final year of the study were strongly affected by different fertilization treatments, as shown in Fig. 1. The yields of rice grain in the treatments CK, SM, N and NK were lower than those in the

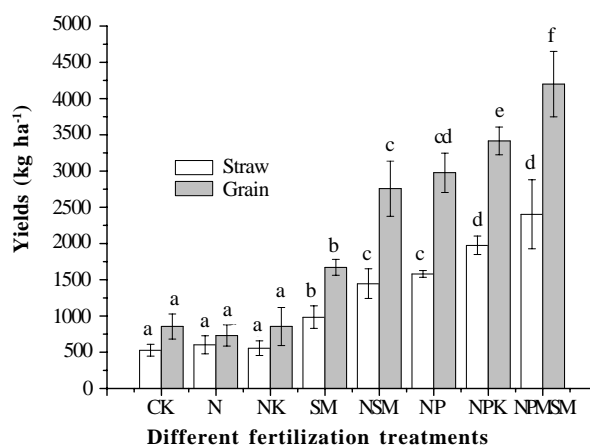


Figure 1. Rice grain and straw yields in 2006 among different long-term fertilization treatments (CK no fertilizer; N application of N alone; NK application of N and K; SM incorporation of straw and application of pig manure; NSM application of N, pig manure and incorporation of straw; NP application of N and P; NPK application of N, P and K fertilizer; NPKSM application of N, P, K fertilizer, pig manure, and incorporation of straw). Histograms with the same letter are not statistically different at $P = 0.05$ by the Duncan's multiple range test.

Table 1. The average contents of Cu, Zn, Fe, Mn and Cd in different types of fertilizers applied during 1989-2006.

	Cu mg kg ⁻¹	Zn mg kg ⁻¹	Fe mg kg ⁻¹	Mn mg kg ⁻¹	Cd mg kg ⁻¹
Straw	3.73	49.6	225	467	0.97
Superphosphate	24.6	78.1	9070	949	0.20
Pig manure	502	563	1416	367	4.65
Potassium chloride	1.71	0.75	16.9	0.20	0.01
Urea	0.23	0.21	0.43	0.02	0.02

NP, NMS, NPK and NPKMS treatments in 2006, and the order of average yield of rice grain was NPKSM>NPK>NP>NSM>SM>NK>N>CK. The highest crop yield was obtained when inorganic fertilizers NPK and pig manure were applied together with all straw returned to the field (NPKSM). This is consistent with previous results, in which a better yield was obtained when inorganic fertilizers and manure were both applied together^{24,25}. It is most likely that the manures improved soil physical properties^{26,27} and provided a stable supply of both macro- and micronutrients²⁸.

The lowest yield was recorded for the treatment with no fertilizer (CK). Applying N or NK only produced lower yields than other fertilized treatments because the available soil P was classified as very low (<0.6 mg kg⁻¹) at the study site. The NP treatment without the application of K resulted in lower yields than the NPK treatment, indicating that application of K fertilizer was necessitated at this location. The yields of straw (Fig.1) demonstrated similar trends to the grain yields, suggesting the biomass of straw is correlated with grain production.

Changes of soil properties after 17-yr cropping and fertilizations:

Compared with the initial soil pH, a decline in soil pH in all treatments was observed after 17 cropping and fertilization treatments (Table 2). This is likely due to serious acid rain in southern China²⁹ or long-term application of chemical fertilizers³⁰ and crop production.

On the other hand there was a dramatic increase in soil OM from the initial level of 5.70 to 13.1-17.2 g kg⁻¹ in the final year. Especially for the SM, NSM and NPKSM treatments, marked increase in soil OM occurred over the CK due to the application of pig manure and incorporation of straw to the field. This is in agreement with other researchers who found application of animal manure significantly increased soil OM³¹.

Available N contents in the CK and N treatments were lower than their initial levels, showing no fertilization or application of N alone decreased available soil N. N fertilizer combined with P and K fertilizer and organic manure could maintain or improve soil available N, especially for the NPKMS treatment, showing application of organic manure played an important role in enhancing soil fertility.

Available P contents decreased from initial 5.60 to 0.28-4.31 mg kg⁻¹ in all treatments in the final year. This showed that a trend of significant decrease was observed due to long-term cropping irrespective of fertilization treatments. According to Lu *et al.*¹⁹, available P content was at very low levels; thus application of P

would dramatically enhance crop yield. However, it is unclear why soil test P was not increased when inorganic and organic P fertilizers were applied.

Available K contents in the CK and N treatments were unchanged, but that of the NK treatment was significantly increased while those of the rest of the treatments were significantly decreased over the initial available K contents. According to suggestion by Hu and Zhou³², available K contents in the NSM, NP and NPK treatments were classified as low levels or deficient, and for the other treatments enough available K contents existed to meet the demand for rice growth.

Essential soil micronutrients and toxic elements: The total soil Cu contents at the start of this experiment were significantly higher than those in the CK, N, NK, NP and NPK treatments in the final year but were lower than those in the SM, NSM and NPKSM treatments in the final year (Table 3). A decrease in total soil Cu contents in the CK, N, NK, NP and NPK treatments over the study period was because the input of Cu from chemical fertilizers was lower than the outputs by rice harvest. In contrast, a significant increase in total soil Cu contents in the SM, NSM and NPKSM treatments in the final year was probably due to the pig manure applied in this experiment containing Cu (Table 1) and to the incorporation of straw to the field returning most of the Cu taken up by the rice to the field (Table 1). Both manure application and straw returning not only slowed down the depletion of soil Cu pool but also served as an additional Cu source.

Similar to total soil Cu contents, a noticeable reduction in total soil Zn contents in the CK, N, NK, NP and NPK treatments in the final year occurred over the initial Zn content. However, a significant increase in total soil Zn contents in the SM, NSM and NPKSM treatments in the final year was observed, compared with their initial total soil Zn content. A significant decrease in total soil Zn contents in the CK, N, NK, NP and NPK treatments was possibly because inputs of Zn via chemical fertilizers was lower than outputs by crop removal in harvest. In contrast, pig manure and straw contained Zn 563 and 49.6 mg kg⁻¹, respectively (Table1), which helped to maintain or increase total soil Zn contents.

The total soil Cd contents in the CK, N, NK, NP and NPK treatments in the final year did not show a significant difference from those of the first year. However, total soil Cd content in the SM, NSM and NPKSM treatments in the final year increased by 108, 115 and 115%, respectively, compared with their initial levels. A slight change between the CK, N, NK, NP and NPK

Table 2. Soil pH, OM content and plant available N, P and K from samples collected from a long-term fertilization experiment (1989-2006).

Treatment	pH (1 mol l ⁻¹ KCl)	OM g kg ⁻¹	Available N	Available P	Available K
			(mg kg ⁻¹)		
Initial status ¹	4.50c ²	5.70d	90.2b	5.60a	106b
CK	4.01ab	13.1c	63.4c	0.56f	109b
N	3.97ab	13.9bc	65.2c	0.37g	101b
NK	3.94ab	14.5bc	84.5b	0.28g	170a
MS	3.97ab	17.2a	77.2bc	1.14e	76.0cd
NMS	3.85a	16.9a	88.2b	0.62f	61.3d
NP	3.97ab	15.2abc	84.5b	2.71d	46.1e
NPK	4.11b	15.2abc	91.9ab	3.16c	56.6d
NPKMS	3.97ab	16.0ab	101a	4.31b	85.9c

¹Initial status: soil properties at the beginning of this experiment; CK no fertilizer; N application of N alone; NK application of N, K; SM incorporation of straw and application of pig manure; NSM application of N, pig manure and incorporation of straw; NP application of N, P; NPK application of N, P, K fertilizer; NPKSM application of N, P, K fertilizer, pig manure, and incorporation of straw. ²Values in a column followed by different letters are statistically different at the level of 0.05.

Table 3. Total concentrations of essential micronutrients and Cd in soil after 17-yr cropping and fertilization treatments.

Treatment	Cu mg kg ⁻¹	Zn mg kg ⁻¹	Fe g kg ⁻¹	Mn mg kg ⁻¹	Cd mg kg ⁻¹
Initial status ¹	24.9c ²	66.2b	3.69a	128a	0.13a
CK	24.0ab	64.1a	3.68a	126a	0.11a
N	23.0a	64.6a	3.58a	118a	0.10a
NK	24.1ab	63.7a	3.59a	124a	0.13a
SM	30.5d	71.2c	3.69a	113a	0.33b
NSM	30.1d	69.3c	3.55a	110a	0.34b
NP	24.3b	62.9a	3.53a	116a	0.21a
NPK	23.7ab	65.4a	3.56a	119a	0.20a
NPKSM	28.1de	70.4c	3.73a	131a	0.31b

¹Initial status: soil properties at the beginning of this experiment; CK no fertilizer; N application of N alone; NK application of N, K; SM incorporation of straw and application of pig manure; NSM application of N, pig manure and incorporation of straw; NP application of N, P; NPK application of N, P, K fertilizer; NPKSM application of N, P, K fertilizer, pig manure, and incorporation of straw. ²Values in a column followed by different letters are statistically different at the level of 0.05.

treatments and initial total soil Cd content was due to chemical fertilizers (urea, potassium fertilizer and superphosphate) containing low contents of Cd (Table 1). Due to continuous application of pig manure containing higher contents of Cd (4.65 mg kg⁻¹) and incorporation of straw to the field, inputs of Cd by pig manure and straw was bigger than outputs by crop removal, which resulted in an increase in total soil Cd concentrations. Moreover, long-term application of P resulted in increase in total soil Cd contents in the NP and NPK treatments compared with the CK because superphosphate contained Cd 0.20 mg kg⁻¹. Jones *et al.*³³ also found long-term phosphorus fertilizer application was a major source of Cd in soil.

The total soil Fe and Mn concentrations of all treatments in the final year did not show a significant difference compared with the initial concentrations (Table 3). It is likely that the contents of soil Fe and Mn are very high; therefore inputs by application of the fertilizers or outputs by crop removal had little effects on total soil Fe and Mn contents.

Available soil microelements: Available soil micronutrients were often affected by tillage and application of fertilizer. As shown in Table 4, the available soil Cu contents in the CK, N, NK, NP and NPK treatments in the final year varied from 1.86 to 2.39 mg kg⁻¹, which were lower than the initial Cu content. This was possibly because available soil Cu was taken up and removed by crops. For instance, the CK treatment did not received any fertilizers, a significant decline in available Cu content occurred due to no replenishment from the external sources. Although urea, potassium chloride and superphosphate applied in this experiment contained small amounts of Cu (Table 1), their application was helpful to slow the rate of Cu depletion from the soil. For example, available Cu contents in the NP and NPK treatments were higher than in the CK treatment after 17-yr cropping and fertilization treatments. In contrast, Cu contents in three manure-applied treatments in the final year were significantly higher than their initial status. This was attributed to the pig manure used in this experiment containing high contents of Cu (502 mg kg⁻¹) and organic matter (56 g kg⁻¹) (Table 1). Han *et al.*³⁴ reported that 25-yr consecutive application of poultry manure also resulted in an increase of available soil Cu in the amended soil.

A decline in available soil Zn in the CK, N, NK, NP and NPK treatments in the final year was observed, compared with the initial level. However, there was a significant increase in available soil Zn for the treatments receiving pig manure and straw in the final

year over that of the first year. It suggests that long-term application of chemical fertilizers such as urea and potassium chloride could not maintain available soil Zn content, although N, K and P fertilizers also supplied Zn as impurities (Table 1). Setia and Sharma⁷ also found that application of chemical fertilizers (urea or P₂O₅ < 40 kg ha⁻¹) alone resulted in available Zn decrease. However, the treatments with application of pig manure and incorporation of straw had higher available soil Zn contents. This was because pig manure and straw not only supplied large amounts of Zn to the field, but also promoted biological and chemical reactions that resulted in the dissolution of non-available Zn in the soil³⁵. Thus, available Zn concentrations in the SM, NSM and NPKSM treatments were significantly higher than those in the other treatments.

As compared with initial available soil Fe content at the start of this experiment, there was a significant increase in available Fe contents in the SM, NSM, NP, NPK and NPKSM treatments and marked decline for the CK, N and NK treatments. Due to the high content of Fe in pig manure and superphosphate used in this experiment (Table 1), significant amounts of Fe were added to the soil through pig manure and superphosphate application, resulting in dramatic increase in available Fe after 17-yr fertilization practices. Urea and potassium chloride used in this experiment contained less Fe (Table 1), so available soil Fe was reduced by continuous crop uptake and removal. As a result of this, available soil Fe in the N and NK treatments was reduced. Setia and Sharma⁷ also reported the application of N and K fertilizer caused a decrease in soil DTPA-Fe. Our study confirms that application of N alone or application of NK can not improve available soil Fe content, while combination P or organic manure application can result in significant increase of soil available Fe^{3,36}.

After 17-yr cropping and fertilization treatment, a decline in available soil Mn content in all treatments in the final year was observed, compared with the initial year. Decrease in available soil Mn content was most likely due to excessive leaching of soluble Mn resulting from flood irrigation during rice cultivation³⁷. The available soil Mn content in the control was greater than in the other treatments except for the N treatment, which was in agreement with the decrease of available soil Mn with continuous cropping and application of various fertilizers⁷.

The soil Cd content in the CK, N, NK, NP and NPK treatments in the final year did not show significant difference over that of the initial year, although extractable soil Cd contents in the P-applied treatments (NP, NPK) were higher than in non-P applied

treatments (CK, N, NK), which suggests long-term application of P fertilizer can result in increase of soil Cd content. However, a significant increase in extractable soil Cd of the final year occurred in the SM, NSM and NPKSM treatments receiving pig manure and straw, compared with that of the initial year.

Essential and toxic microelement contents in brown early rice

in 2006: The Cu contents in brown rice (early rice of 2006) varied from 2.90 to 4.12 mg kg⁻¹ among all treatments (Table 5). There was no significant difference between CK and N, NP and NPK, indicating application of urea or urea combined with fertilizer P did not increase the Cu content in brown rice, but the NK treatment without P led to increase in Cu content in brown rice. Due to higher available soil Cu contents in the manure-applied treatments (Table 4), the SM, NSM and NPKSM treatments had higher content of Cu in brown rice compared with the CK.

The fertilizer-applied treatments (N, NK, SM, NSM, NP, NPK and NPKSM) had significantly higher Zn in the brown rice than the CK treatment (Table 5). It suggests that application of fertilizers promoted the uptake of Zn by brown rice. It was reported that proper levels of N, P and K could enhance the content of Zn in brown rice, our results were in agreement with earlier reports^{38,39}. It appeared Zn contents in brown rice did not positively correlate with total or available soil Zn contents. For instance, available soil Zn contents in the SM, NSM and NPKSM treatments were 1.06-1.48 folds higher than in N, NK, NP and NPK treatments, but no significant difference of Zn contents in brown rice was observed among N, NK, NP, NPK and SM, NSM, NPKSM treatments.

The Fe contents in brown rice of all treatments varied from 6.71 to 13.1 mg kg⁻¹. With the comparison of N and NK treatments, NP and NPK treatments, it was found application of fertilizer K decreased the Fe contents in brown rice. This is possibly because K has antagonistic action for Fe uptake. Abundant K in soil resulted in decrease in Fe content in brown rice³⁸. By comparing CK with N, SM and NSM, and NPK with NPKSM, it is obvious that application of nitrogen improved Fe contents in brown rice, which was in agreement with previous results on enhanced Fe content under application of proper levels of N (< 160 kg ha⁻¹)³⁹.

The Mn contents in brown rice in the CK, N and NK treatments were significantly lower than those in the SM, NP, NPK and NPKSM treatments. However, available soil Mn content in the CK, N and NK treatments was higher than that of SM, NP, NPK and NPKSM treatments. It seemed that the Mn in brown rice was negatively correlated to available Mn in soil, but the mechanism remains to be explored.

The CK, N and NK treatments had lower Cd in brown rice than other treatments and did not show significant difference among CK, N and NK, suggesting Cd in brown rice was not affected by application of urea and potassium chloride. In contrast, the NP and NPK treatments with application of superphosphate had higher Cd than the CK. It was ascribed that long-term application of superphosphate containing Cd (Table 1) led to increase in Cd in brown rice. Especially, due to continuous application of pig manure and return of straw to the soil, significant increase in total and extractable Cd in soil resulted in marked increase (0.26-0.28 mg kg⁻¹) in Cd in brown rice, compared with the 0.08 mg kg⁻¹ of Cd in the CK treatment.

Table 4. Changes of available soil micronutrients and Cd after 17-yr cropping and fertilization treatments.

Treatment	Cu mg kg ⁻¹	Zn mg kg ⁻¹	Fe mg kg ⁻¹	Mn mg kg ⁻¹	Cd mg kg ⁻¹
Initial status ¹	2.59c ²	2.04b	107b	18.4f	0.08a
CK	1.86a	1.55a	91.8a	17.4de	0.08a
N	1.99a	1.59a	83.9a	17.6e	0.08a
NK	1.93a	1.51a	77.9a	16.1cd	0.08a
SM	4.89d	3.29c	151c	16.0cd	0.25b
NSM	5.19d	3.36c	204d	11.5a	0.26b
NP	2.39bc	1.44a	230d	12.0a	0.17a
NPK	2.19b	1.40a	183cd	13.7b	0.16a
NPKSM	5.77e	3.48c	403e	15.5c	0.26b

¹Initial status: soil properties at the beginning of this experiment; CK no fertilizer; N application of N alone; NK application of N and K; SM incorporation of straw and application of pig manure; NSM application of N, pig manure and incorporation of straw; NP application of N and P; NPK application of N, P, K fertilizer; NPKSM application of N, P, K fertilizer, pig manure, and incorporation of straw. ²Values in a column followed by different letters are statistically different at the level of 0.05.

Table 5. Essential and toxic microelement contents in brown rice in early rice in 2006.

Treatment	Cu mg kg ⁻¹	Zn mg kg ⁻¹	Fe mg kg ⁻¹	Mn mg kg ⁻¹	Cd mg kg ⁻¹
CK ¹	3.02c ²	27.9c	11.3ab	15.1c	0.08cd
N	2.99c	31.5ab	13.1a	13.5cd	0.05d
NK	3.85b	30.8ab	8.63d	12.8d	0.07d
SM	3.24b	29.8ab	6.71e	18.2b	0.28a
NSM	4.12a	29.8ab	12.3ab	14.4cd	0.27a
NP	2.99c	30.4ab	12.9a	20.8a	0.14bc
NPK	2.90c	32.3a	10.8c	21.0a	0.17b
NPKSM	3.76b	31.5ab	12.0ab	18.5b	0.26a

¹CK no fertilizer; N application of N alone; NK application of N, K; SM incorporation of straw and application of pig manure; NSM application of N, pig manure and incorporation of straw; NP application of N, P; NPK application of N, P, K fertilizer; NPKSM application of N, P, K fertilizer, pig manure, and incorporation of straw. ²Values in a column followed by different letters are statistically different at the level of 0.05.

Conclusions

Long-term application of NPK and pig manure together with straw return to field produced the highest rice grain yield. Long-term application of pig manure and the return of straw to field significantly increased the total and available soil Cu, Zn and Cd contents. Available soil Fe content also significantly increased with application of P fertilizer or manure. The Cu, Zn, Fe, Mn and Cd contents in brown rice were strongly affected by long-term application of different types of fertilizers, especially for the Cd contents in brown rice. Application of pig manure from intensive livestock farm resulted in significant increase in Cd contents in rice grain, exceeding the upper limit (> 0.20 mg kg⁻¹) of the National Standard for Food Hygiene for Rice Cd content. Attention should be paid when animal manure is continuously applied to crop land.

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