Effects of long-term chemical fertilization on trends of rice yield and nutrient use efficiency under double rice cultivation in subtropical China

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ABSTRACT

A long-term (33 years) experiments were conducted to investigate the effect of chemical fertilization on rice yield, yield trends, soil properties, agronomic efficiency of applied nutrients and nutrient balance for the double rice cropping systems in subtropical China. The treatments were different combinations of N, P and K fertilizers (N, NP, NK and NPK), double dose of recommended NPK (2NPK) and no fertilizer control (control). Compared with no fertilizer control, all fertilization treatments had no significant effects on soil pH and SOC contents ($P > 0.05$), but generally increased nutrients content when corresponding elements were applied. The impact of fertilizers on grain yields was 2NPK > NPK > NP > NK > N, and application of P fertilizer not only increased the rice yield, but improved yield stability. The trend of agronomic use efficiency of applied P was significantly positive ($P < 0.05$) only for the first rice crop, suggesting that P fertilizer played a less important role in the second rice season than in the first rice season. The study indicated that the current local fertilizer recommendations should be optimized for the consideration of differences in indigenous nutrient supplies in different rice seasons.

Keywords: long-term experiment; paddy field; nutrient balance; soil properties; *Oryza sativa*

Rice (*Oryza sativa* L.) is the main staple food for more than 50% of the world's population (Childs 2004) and the world rice production must increase by 1.15% annually to meet the demand of ever-increasing population (Rosegrant et al. 1997). To meet those challenges, long-term experiments (LTEs) are extremely valuable in understanding decade-scale transformations in grain yield and soil properties. Long-term rice yield and yield trend were reported many times in double- and triple-rice and rice-wheat cropping systems in Asian countries. Generally, rice yield in the long-term experiments remained stable when recommended doses of N, P and K were applied (Dawe et al. 2000, Ladha et al. 2003, Bi et al. 2009). Where yield declines occurred, the major causes were attributable to inappropriate fertilizer managements (Dobermann et al. 2000, Ladha et al. 2003), prolonged soil wetness (Dawe et al. 2000), delay in sowing (Regmi et al. 2002), and increased night-time temperature associated with global warming (Peng et al. 2004).

To maximize crop yield, Chinese farmers often apply a higher amount of fertilizers than the minimum required for crop growth (Peng et al. 2002). Therefore, nutrient use efficiency is relatively low in rice systems because of the rapid losses of nutrients, especially N, through leaching, surface runoff and gaseous volatilization (Vlek and Byrnes 1986, Zhu and Chen 2002). Available

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evidence reported by Wang et al. (2001) showed that mean agronomic efficiency of N in farmer's field was only 6.4 kg grain/kg N in Zhejiang province. Direct evidence of nutrient use efficiency from long-term experiments in paddy field will enlighten our understanding of nutrient cycling and sustainable fertilizer management.

Although organic fertilizers sustained rice production for several thousand years before the introduction of inorganic fertilizers, farmers in China seek to apply inorganic fertilizers instead of organic fertilizers in the past decades due to increased labor cost (Zhu and Chen 2002). This change without inputs of organic fertilizers to the soil is assumed unsustainable due to the loss of soil organic matter (Lee et al. 2009, Nayak et al. 2012). As a main concern of soil fertility degradation by the replacement of organic fertilizers by inorganic fertilizer, a number of LTEs were set up in the 1980s in paddy rice systems to monitor yield trends and system sustainability in subtropical China, where rice is mainly grown as staple food. The objectives of this study were to (1) examine yield and yield trends of rice under long-term chemical fertilization; (2) monitor changes in soil nutrient contents; (3) estimate apparent balances of N, P and K nutrients under different fertilizer managements.

MATERIAL AND METHODS

Location and soil. The experimental site locates at the experimental farm of the Research Institute of Red Soil of Jiangxi province, Jinxian county, China (28°21'N, 116°10'E). The annual mean rainfall is 1723 mm, with about 38% and 15% of annual total distributing to the first rice and second rice growth period, respectively. The minimum mean temperature in January is around 5.5°C and the highest in July is around 29.5°C. The experimental fields are about 25 m a.s.l. and the soils are classified into Stagnic Anthrosol (IUSS Working Group WRB 2006). The topography is low hilly and then the experimental site is a terraced field with soil parent materials of Quaternary red clay.

Experimental design. The fertilization experiment was carried out with a complete randomized design with three replicates. The experiment includes six treatments: no fertilization (control); full doses of N, P and K were applied (NPK); full doses of N and P were applied without K (NP); full doses of N and K were applied without P (NK); double dose of N, P and K were applied (2NPK) (Table 1). Chemical fertilizers were urea, KCl and fused calcium magnesium phosphate (P 7.0%). The plot area was 46.7 m^2 and each plot was separated by cement plates to avoid interaction through irrigation water. The first rice crop was transplanted around 29th April and harvested around 20th July. The second rice was transplanted around 28th July and harvested around 1st November. Rice seedlings were grown for 30 days in separated seedbeds and then transplanted into the experimental plots. Hill spacing was 25 cm by 20 cm, with two or three seedlings per hill. Fertilization operation was similar with full dose of P and K fertilizers applied as basal fertilizers and two thirds of N fertilizer applied as basal fertilization and the rest as topdressing for the first and the second rice.

Data collection and analysis. Rice grain yield was weighed for the whole plot and expressed on drying base with a water content of 13% (w/w). Straw yield was also weighed for the whole plot and water content was measured using 1 kg straw samples. N, P and K concentration in rice seedling and in grain and straw was measured occasionally for 8 years and then mean values were used to calculate nutrient input and output. Means for selected soil properties were compared by using the Fisher's *LSD* method, and rice yields were compared by using Tukey's *HSD* method, respectively. The significance of time trend (slopes) of rice yield and agronomic efficiency (AE) was determined by

Table 1. The amount of mineral fertilizers annually applied for each rice season, and the mean rice grain yield during the period of 1981–2013 for the long-term chemical fertilization experiment in subtropical China

Treatment	Fertilizer			Yield			
	N	P	K	first rice (t/ha)	*CV* (%)	second rice (t/ha)	*CV* (%)
	(kg/ha)						
Control	0	0	0	2.81^f	22.7	3.16^e	22.6
N	90	0	0	3.09^e	27.2	3.64^d	21.1
NP	90	19.6	0	4.01^c	16.7	3.97^c	18.3
NK	90	0	62.2	3.34^d	28.8	3.94^c	20.7
NPK	90	19.6	62.2	4.32^b	17.3	4.41^b	18.2
2NPK	180	39.2	124.4	5.11^a	15.0	5.08^a	19.9

Means within each column followed by the same letter do not differ significantly at $P < 0.05$ level using Tukey's *HSD* test. *CV* – coefficient of variation testing the statistical significance of slopes at 5, 1 and 0.1% levels of probability.

Agronomic efficiency of N, P or K (AE_N, AE_P and AE_K, respectively) was calculated as:

$$AE = \Delta Y/F_n \quad (1)$$

Where: ΔY – incremental grain yield due to difference in fertilizer N or P or K; F_n – amount of N or P or K input with chemical fertilizers.

Apparent nutrient balances of applied N, P and K nutrients were calculated as:

$$N_{ab} = N_{inp} - N_{cr} \quad (2)$$

Where: N_{ab} – apparent nutrient balance; N_{inp} – nutrient input through fertilizer, rice seedlings, irrigation water and rain water; N_{cr} – crop removed nutrient. Nutrient concentrations in rain and irrigation water were based on the monitored data from 2001–2003 in a nearby study carried out in the Yujiang county, Jiangxi province of China (Tang 2005).

RESULTS AND DISCUSSION

Rice yields and yield trends. The mean rice yield and its coefficient variance (*CV*) for both first and second rice were influenced by fertilization (Table 1). The lowest grain yield was obtained in the treatment with no fertilizer (control) in most years of study and full doses of N, P and K (NPK) increased mean rice yield by about 53.7% and 39.6% for the first and second rice season, respectively. The highest grain yields were obtained in doubled dose of N, P and K treatment (2NPK) in all the years of study. Mean rice yield in NP treatment was significantly higher than that in NK treatment for the first rice ($P < 0.05$). However, the yield difference between NP and NK treatments was not significant ($P > 0.05$) in the second rice season. This discrepancy can be partly explained by the differences in indigenous nutrients supplies in different rice seasons. Further analysis showed that mean yield of first rice in NP treatment was nearly equal to that of the second rice, which suggested that the difference in indigenous supplies of K nutrient was not significant between two rice seasons. In contrast, the mean yield of first rice in NK treatment was significantly lower than that of the second rice, which suggested that the indigenous supplies of P nutrient in the second rice season was higher than that in the first rice season. The coefficient of variation was 16.7, 17.3 and 15.0% for the first rice and 18.3, 18.2 and 19.9% for the second rice in NP, NPK, and 2NPK (treatments with P fertilizer), respectively. In contrast, they were 22.7, 27.2 and 28.8% for the first rice and 22.6, 21.1 and 20.7% for the second rice in control, N, and NK (treatments without P fertilizer), respectively. The result suggested that the application P fertilizer not only increased the rice yield, but improved yield stability.

The yield trends of the first rice and the second rice crops are shown in Figure 1. The yield trends of control treatment were maintained for the first rice and increased for the second rice ($P < 0.05$). This result suggested that the indigenous soil fertility was high enough to sustain a mean rice yield about 3 t/ha for each rice season, which is consistent with the reports by Saleque et al. (2004) and Bi et al. (2009). Significant declining trends were observed in N, NK and NPK treatments for the first rice ($P < 0.05$) and the slopes of the trends suggested that the yields decreased by 59 kg/ha/year, 71 kg/ha/year and 27 kg/ha/year in N, NK and NPK treatment, respectively, for the first rice crop. Declines in N and NK treatment can be attributed to the depletion of soil P nutrient and few indigenous P supplies for the first rice season, which was consistent with former results of mean rice yield and *CV*. Although declining trend in recommended N, P and K treatment (NPK) was smoother than those in N and NK treatments, significant declining trend proved that the present equal distribution of fertilizers in two rice seasons should be optimized for the consideration of the difference in indigenous nutrient supplies in two rice seasons.

Soil properties. Selected soil properties changed over time in the present study (Table 2). Compared with the initial soil, the long-term fertilization treatments had lower soil pH and higher soil organic carbon (SOC) contents. Soil pH decreased by 0.2–0.3, which was conformed to the national mean level of pH decrease in cereal crop systems (Guo et al. 2010). SOC content increased also in no fertilization control treatment and this increase can be attributed to the increased underground biomass due to the introduction of modern rice cultivars as well as increased nutrient inputs through rainfall and irrigation water in recent years (Bi et al. 2009). Soil nutrients content in control treatment either maintained or increased when compared with those of initial soil (Table 2). This result explained why no fertilizer treatment (control) maintained a mean rice yield about 3 t/ha for each rice season in the past 33 years.

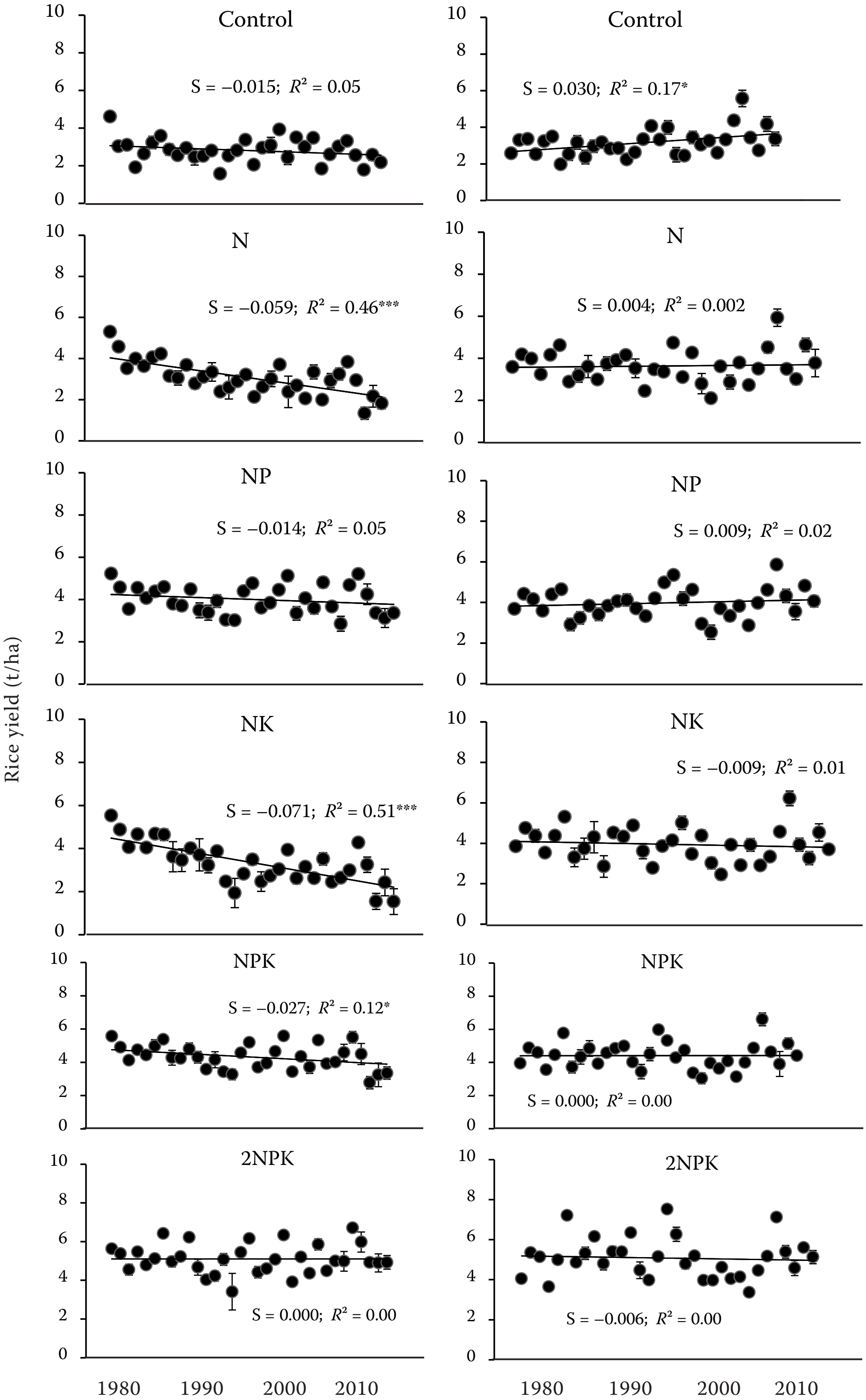

Figure 1. Trends of the rice yield for the first (left) and the second (right) rice in the long-term chemical fertilization experiment in subtropical China from 1981–2013. Bars followed with means represent standard deviation. $^{*}P \leq 0.5$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$; S – slope value of regression curve

Table 2. Selected soil properties of the Ap horizons in different fertilization treatments sampled before the start of the experiments (initial soil) and in 2013

Treatment	pH	SBD (g/cm^3)	SOC	TN	TP	AH-N	Olsen P	EK
			(g/kg)			(mg/kg)		
Initial soil*	5.4	1.06	16.3	1.49	0.49	144	9.5	41.2
Control	5.17^{a}	1.13^{a}	19.4^{a}	2.02^{d}	0.55^{d}	146^{d}	13.6^{c}	50.3^{b}
N	5.16^{a}	1.12^{a}	19.8^{a}	2.06^{cd}	0.48^{d}	165^{b}	9.9^{c}	49.9^{b}
NP	5.17^{a}	1.08^{ab}	20.1^{a}	2.12^{abc}	0.69^{c}	163^{b}	25.8^{b}	50.1^{b}
NK	5.15^{a}	1.08^{ab}	20.8^{a}	2.17^{a}	0.51^{d}	165^{b}	12.9^{c}	65.8^{a}
NPK	5.15^{a}	1.05^{b}	20.8^{a}	2.10^{bc}	0.82^{a}	165^{b}	32.3^{b}	65.0^{a}
2NPK	5.12^{a}	1.03^{b}	20.9^{a}	2.15^{ab}	1.09^{a}	177^{a}	73.7^{a}	67.7^{a}
$LSD_{0.05}$	0.11	0.05	1.9	0.06	0.10	3.5	9.3	5.1

Means within each column followed by the same letter do not differ significantly at 0.05 level of Fisher's *LSD*. SBD – soil bulk density; SOC – soil organic carbon; TN – total nitrogen; TP – total phosphorus; AH-N – alkali hydrolyzable nitrogen; Olsen P – Olsen phosphorus; EK – ammonia acetate extractable potassium. *Average values were available

Compared with the control, all fertilization treatments had no significant effects on soil pH and SOC contents ($P > 0.05$), but generally increased nutrients content when corresponding elements were applied (Table 2). These findings are in agreement with the results of Regmi et al. (2002) and Zhang et al. (2009), who reported that the contents of N, P and K were increased when compared with those of no fertilizer control. Furthermore, soil bulk densities (SBD) in NPK and 2NPK treatment were significantly lower than those in control and N ($P < 0.05$). As more fertilizers were applied in NPK and 2NPK than in control and N, it is inevitable that more underground biomass were returned to the soil, which contributed to the decrease in SBD (Sharma et al. 1995).

Nutrient balance. Apparent nutrient balance for average rice yield over 33-year period was calculated for N, P and K (Table 3). Total N, P and K inputs through rice seedlings, rainfall and irrigation water in the control treatment was estimated 35.1 kg/ha/year, 2.1 kg/ha/year and 54.5 kg/ha/year, while total removals through rice grain and straw were 72.7 kg/ha/year, 14.6 kg/ha/year and 64.7 kg/ha/year, respectively. Then, the apparent balance of N, P and K in the control treatment was negative, being –37.6 kg/ha/year, –12.5 kg/ha/year and –10.2 kg/ha/year. Similarly, the other treatments with nutrients application showed a positive balance when corresponding nutrient were applied (Table 3). Above estimates generally appear to be consistent with the soil N, P and K analyses described earlier. Although negative balances of N,

Table 3. Apparent annual balances of N, P and K element in different treatments during the observation period

Treatment	Input (kg/ha)		Output (kg/ha)		Balance (kg/ha)
	fertilizer	other^{a}	straw	grain	
Nitrogen					
Control	0	35.1	15.9	56.8	–37.6
N	180	35.1	31.2	73.2	110.7
NP	180	35.1	33.1	84.0	98.0
NK	180	35.1	29.8	75.3	110.0
NPK	180	35.1	32.3	95.9	86.9
2NPK	360	35.1	50.4	119.3	225.4
Phosphorus					
Control	0	2.1	2.4	12.2	–12.5
N	0	2.1	3.3	13.5	–14.7
NP	39.2	2.1	4.3	16.4	20.6
NK	0	2.1	2.3	13.9	–14.1
NPK	39.2	2.1	4.0	19.5	17.8
2NPK	78.4	2.1	6.6	24.7	49.2
Potassium					
Control	0	54.5	44.0	20.7	–10.2
N	0	54.5	50.7	21.5	–17.7
NP	0	54.5	49.4	26.7	–21.6
NK	124.4	54.5	65.5	25.3	88.1
NPK	124.4	54.5	74.3	31.7	72.9
2NPK	248.8	54.5	94.6	36.5	172.2

^{a}Other sources including irrigation water (17.0 kg N/ha, 1.2 kg P/ha and 47.7 kg K/ha), rain (15.3 kg N/ha, 0.4 kg P/ha and 4.0 kg K/ha), and rice seedlings (2.8 kg N/ha, 0.5 kg P/ha and 2.8 kg K/ha)

P and K were estimated, soil nutrients content in control treatment either maintained or increased when compared with those of initial soil (Table 2). This result suggested that potential of nutrient fixation was likely to be underestimated for the paddy soils derived from kaolinite dominated Quaternary clay (Li 1992).

Nutrient use effect and efficiency. Positive effects of N, P and K on rice yield were observed for both first and second rice in the present study. The effects of N (treatment N vs. control) and K (NPK vs. NP) fertilizers on rice yield were more profound for the second rice crop than for the first rice crop. Conversely, application of P fertilizer (NPK vs. NK) had higher yield for the first rice crop than for the second rice. The means of AE_P were 50.1 kg grain/kg P and 24.0 kg grain/kg P for the first and second rice crop, respectively. Time trends of AE_N, AE_P and AE_K are shown in Figure 2. As rice yield declined and maintained, in N and control treatment, respectively, significant negative trends of AE_N (N vs. control) were observed during the studied period. The slopes were –0.483 kg grain/kg N/year ($P < 0.001$) for the first rice and –0.290 kg grain/kg N/year ($P < 0.001$) for the second rice crop. The trend of AE_P was significantly positive ($P < 0.05$) only for the first rice crop, suggesting that P fertilizer played a less important role in the second rice season than in the first rice season. The trend of AE_K declined significantly only for the first rice crop ($P < 0.05$). Those results indicated that the current local fertilizer recommendations should be optimized for the consideration of potential supplies of nutrients from soil in different rice seasons.

In conclusion, the study revealed that application of N, P and K was crucial for maintaining long-term rice yield and yield trend. The application of P fertilizer was not only important in increasing rice yield, but in improving yield stability, which was proved to be more significant in the first rice season than in the second rice season. Although soil nutrients content were either maintained or increased, this long-term study indicated that the present equal distribution of fertilizers, particularly for P, in two rice seasons should be optimized for the double rice cropping systems.

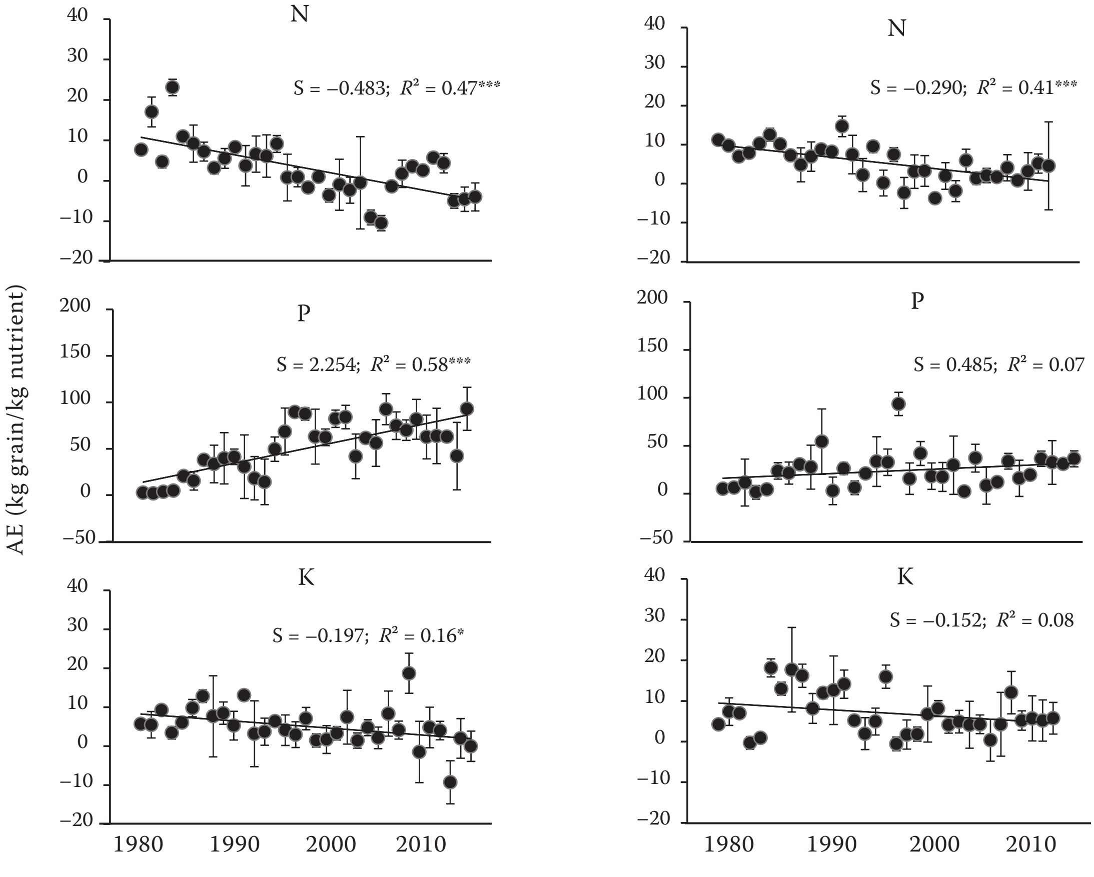

Figure 2. Trends of agronomic efficiency (AE) of applied N, P and K for the first rice (left) and the second rice (right) in the long-term chemical fertilization experiment in subtropical China from 1981–2013. Bars followed with means represent standard deviation. $^*P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$; S – slope (kg grain/kg nutrient/year)

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