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Long-term effect of fertilizer application on rice yield, potassium uptake in plants, and potassium balance in double rice cropping system

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Abstract A 27 years field experiment was conducted on a Fe-Accumli Stagnic Anthrosol to evaluate the effects of long-term application of fertilizer, pig manure (PM), and rice straw (RS) on rice yield, uptake, and usage efficiency of potassium, soil K pools, and the nonexchangeable K release under the double rice cropping system in South Central China. Common cropping pattern in the study was early rice-late rice-fallow (winter). The field treatments included CK (no fertilizer applied), NP, NK, NPK, and NK + PM, NP + RS, NPK + RS. The pig manure and rice straw was applied in both the early rice and late rice cropping season. The ranking order of 27 years average annual grain yield were the CK < NK < NP < NK + PM < NP + RS < NPK < NPK + RS treatments. The negative yield change trends were observed in the CK and NP and NK treatments of unbalanced nutrient application in the case of omitted-K and P-omitted. The positive yield change trends were observed in balanced applications of NPK and combined application of fertilizer (NPK) with pig manure (NK + PM) or rice straw (NP + RS and NPK + RS). The application of K fertilizer (NPK) increased grain yield by $56.7 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ over that obtained with no K application (NP). The combined application of pig manure with fertilizer (NK + PM) increased by $82.2 \text{ kg} \cdot \text{hm}^{-2}$ per

year compared with fertilizer application alone (NK). The combined application of rice straw with fertilizer (NP + RS and NPK + RS) increased on the average of $34.4 \text{ kg} \cdot \text{hm}^{-2}$ per year compared with fertilizer application alone (NP and NPK). In all fertilizer, pig manure and rice straw combinations, K uptake change trends in rice plants of the early rice was positive except for CK and NP treatments. The results showed that the total removal of K by the rice plants exceeded the amounts of total K applied to the soil in all treatments, which showed a negative K balance. This ranged from $106.3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ in CK treatment to $289.6 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ in the NPK + RS treatment. Continuous annual application of $199.2 \text{ kg} \cdot \text{hm}^{-2}$ to rice resulted in an accumulation ($58 \text{ kg} \cdot \text{hm}^{-2}$) of exchangeable K (1 mol NH_4OAc extractable K) in 0–45 cm soil depth over the study period, despite the higher average annual uptake of K by the system ($225.7 \text{ kg} \cdot \text{hm}^{-2}$). However, nonexchangeable K increased substantially from $1090 \text{ kg} \cdot \text{hm}^{-2}$ to $1113 \text{ kg} \cdot \text{hm}^{-2}$ and $1140 \text{ kg} \cdot \text{hm}^{-2}$ in the 0–45 cm soil layer in NPK + RS and NPK treatments after 27 years of the continuous double rice cropping system, respectively. Thus, long-term rational application of K fertilizer may increase sustainable K fertility of the continuous double rice cropped system.

Keywords fertilizer, pig manure, rice straw, rice yield, potassium balance, double rice cropping system

Received April 26, 2010; accepted June 25, 2010

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1 Introduction

Southern China commonly refers to the vast region south of Qing Maintain and the Huai River in China and involves a total of 16 provinces, municipalities, and autonomous regions in the tropic and subtropical zones and accounts for about 32% of the total land area of China. The climate in southern China is monsoon type, with high temperatures and rainfall. There are distinct wet and dry seasons. The

annual precipitation is about equal to the annual evaporation. With suitable natural conditions for agricultural development, such as a long wet and rainy season, many regions in southern China are important bases of grain crop, particularly rice, production.

A large portion of soil K has been lost from soils in southern China due to severe weathering, high rainfall, and intensive cropping. After a long history of weathering and cultivation, the clay fraction in paddy soil in the region is dominated by kaolinite with low K content, low cation exchange capacity, and, therefore, low K holding capacity. The total K content of soils varied from 0.5% to 2.5% and commonly about 1%, much less than the average K content in earth crust, indicating that a significant fraction of K in the soils has been removed from the soil profile. The extent of soil K loss from the soil profile is related to the degree of weathering. In soils derived from granite, for example, highly weathered latosols and laterites, some have lost between 84.0% and 91.2% of the total K. Red earth and yellow-brown earth soils with relatively less degree of weathering have lost from 27.8% to 40.3% of the total K. Surface runoff and leaching due to high rainfall in the subtropics lead to a great loss of K from the soils. For example, in the middle reaches area of Yangtze River, in southern China, the annual precipitation is about 1400 mm with surface runoff accounting for about one-half of the rain water (Ji et al., 2008). In the region, the amount of K loss due to runoff at each runoff event during two cropping rice growth season per year is $29.4 \text{ kg} \cdot \text{hm}^{-2}$. In any intensive cropping system, burning or removal of crop residues or discarding of organic manure is another factor governing K loss from the soils, as all crop residue is a source of returning soil K. Under such situation, due to large amount of soil K loss, the input of K to soil as fertilizer and manure is usually much less than that of removal. At the same time, there has been no proportional increase in the use of potassium fertilizers, despite heavy K depletion. Rice production in southern China is running under negative K balance, due to the use of rice straw by farmers for fodder and fuel. Research has noted a marked negative K balance even in the plots supplied with the recommended doses of N (165 kg), P (32 kg), and K (120 kg) per hm^2 to early rice and N (180 kg), P (19.4 kg), and K (156 kg) to late rice (Liao et al., 2008a). Therefore, maintaining K balance in the soil under double rice cropping systems is extremely important for stable and high yield rice crops.

Among the possible double rice cropping sequences, early rice, followed by late rice, has been identified as one of the profitable cropping sequences of this region (Zhang et al., 2006). In double rice cropping systems, early rice depletes more soil K, whereas late rice depends more on artificially applied K (Liao et al., 2008b). Continuous cropping with early hybrid rice and late hybrid rice for 3 years at an application level of $233 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ of

fertilizer K led to a negative K balance, even in Endogleyic-Hapli-Stagnic Anthrosols, which are known to be high in native K status (Liao et al., 2007). Therefore, the impact of continuous practice of intensive cropping is a matter of concern, considering the K-supplying potential of the paddy soils and high K removed by double rice cropping pattern.

The ever increasing removal of native soil K and the decline in nonexchangeable K and exchangeable K highlight the need to re-examine the current fertilizer recommendation for double rice cropping system on paddy soils to arrest the decline in native K fertility. To understand the accumulation and depletion of K residues and reserves, it is necessary to use long-term experiments in which K application have been carefully controlled and K off-takes in crops and soil K content regularly monitored or samples collected regularly and archived for later analysis (Blake et al., 1999). There are few reports using the release rate of nonexchangeable K to evaluate the capacity of soil to supply K to rice plants under long-term fertilization experiments in southern China. Therefore, in this study, the results of a long-term field experiment in Hunan Province, China, were analyzed for calculating the accumulation and depletion of different K pools in the soil profile and the apparent K balance, the efficiency of K applied in fertilizers, pig manure, and rice straw over a period of 27 years between 1981 and 2007 on experimental plots that had received varied K inputs either as fertilizer or its combinations with pig manure or rice straw.

2 Materials and methods

2.1 Site descriptions and soil

The field experiments were initiated in 1981 at the Ministry of Agriculture Key Field Monitoring Experimental Station for Reddish Paddy Soil Eco-environment in Wangcheng County, Hunan Province. The station is located in Huangjin Village Town ($112^{\circ}80'E$, $28^{\circ}37'N$, 100 m altitude), in the central region of the Xiangjiang River (a branch of Dongting Lake), China. The climate of this area is subtropical monsoonal climate. Average annual precipitation is approximately 1370 mm, and annual mean temperature is 17°C , with the lowest monthly temperature of 4.4°C in January and the highest monthly temperature of 30°C in July. The annual frost-free period is approximately 300 d. The soil is a Fe-accumuli-Stagnic Anthrosols derived from Quaternary red clay (clay loam). On the basis of the analysis of soil samples taken from the experimental site on October 1981, the characteristics of the surface soil (15 cm depth) were pH 6.9; soil organic matter (SOM) $34.7 \text{ g} \cdot \text{kg}^{-1}$, total N $2.05 \text{ g} \cdot \text{kg}^{-1}$, hydrolysable N $151.0 \text{ mg} \cdot \text{kg}^{-1}$, available P $10.2 \text{ mg} \cdot \text{kg}^{-1}$, and exchangeable K $62.3 \text{ mg} \cdot \text{kg}^{-1}$.

2.2 Crop and cropping pattern, experimental design, and treatments

Two rice crops were grown in the experimental field under irrigated condition. The early rice was transplanted in the last week of April and was harvested in the third week of July; the late rice was transplanted in the fourth week of July and harvested in the second week of October. Four/ five seedlings were transplanted with 16 cm × 23 cm spacing at maturity, the rice was harvested manually at 10 cm above ground level; however, 10 hills from each plot were harvested at the ground level for total straw yield data. After harvest, the straw was removed from each plot. Natural weed was allowed to grow during winter fallow period, and the weed biomass was incorporated into the soil by digging during land preparations for the next year’s planting of early rice. Weed biomass was not recorded. The experiment was conducted in a randomized complete block design with three replications. Each experimental plot was 6.67 m wide by 10 m long.

Nitrogen was applied as urea in two splits: 50% of the total N amount was applied as basal dressing on the first day before transplanting rice seedling, and 50% was applied at active tillering stage. Phosphorus and K were applied as super phosphate and potassium chloride, respectively, during the final land preparation, prior to transplanting. Rice straw was collected from a nearby rice field and applied as straw bedding. Rice straw was applied on a dry basis and mixed well with the soil, by manual digging, about one week before transplanting of two season rice each year. Pig manure was approximately two-month-old stockpiled pig manure from that which had been collected and was mixed into the soil using a rototiller and applied during final land preparation. Nutrient concentrations in pig manure and rice straw were determined from 1981 to 2007.

2.3 Sampling and sample analysis

Following the late rice harvest each year, soil samples from 0 to 15 cm depths were collected. After harvesting late rice in 2007, soil samples from 0 to 15, 15–30, and 30–45 cm depths were collected. The samples were mixed thoroughly, air-dried, crushed to pass through a 2 mm sieve, and stored in sealed glass jars for subsequent analysis. The soil samples were analyzed for different fractions of K (NH₄OAc-K, nonexchangeable K, and total K). Upon maturing, grain and straw samples of both the early and late rice each year were collected from each plot, oven-dried at 65°C to a constant weight, and ground to pass a 0.5 mm sieve for chemical analysis. The samples were digested in a mixture of HNO₃ and HClO₃ (3:1). The concentration of K in the filtered extract was measured by a flame photometer (Lu, 2000), and the mean K content data were obtained. The average removal of K by the rice crops per season was calculated using the average yield and the average K content data.

For release kinetic studies of nonexchangeable potassium in the soil, 10 g of surface (0–15 cm) soil was milled to pass through a 2 mm sieve and then saturated with calcium by equilibrating with 0.25 mol·L⁻¹ CaCl₂ (soil: solution, 1:5) overnight. The soil was then washed with alcohol and deionized water to remove free Cl⁻ and the native exchangeable K (Martin and Sparks, 1983). The samples were then dried in an oven at 60±1°C for 10 h. Duplicate samples of 1 g of Ca-saturated soils were suspended in 20 mL of 0.01 mol·L⁻¹ CaCl₂ and then allowed to equilibrate at 25°C for 1, 7, 14, 24, 48, 72, 96, 192, 384, 576, 692, and 796 h. The suspension was shaken for 1 h before each equilibrium time, centrifuged 10 min at 10000 r·min⁻¹, and the K in the supernatant was measured using a flame photometer.

Table 1 Amount of N, P, and K added through fertilizer, pig manure, and rice straw each year

treatment	chemical	nutrient added/(kg·hm ⁻²)					
		early rice			late rice		
		N	P	K	N	P	K
CK	chemical	0	0	0	0	0	0
NP	chemical	150	38.7	0	180	38.7	0
NK	chemical	150	0	99.6	180	0	99.6
NPK	chemical	150	38.7	99.6	180	38.7	99.6
NK + PM	chemical	150	0	99.6	180	0	99.6
	pig manure	27	30.3	17.4	27	30.3	17.4
NP + RS	chemical	150	38.7	0	180	38.7	0
	rice straw	21.4	2.8	54.6	21.4	2.8	54.6
NPK + RS	chemical	150	38.7	99.6	180	38.7	99.6
	rice straw	21.4	2.8	54.6	21.4	2.8	54.6

Note: Pig manure contained a mean measure of 1.80 N g·kg⁻¹, 2.02 P g·kg⁻¹, and 1.16 K g·kg⁻¹. Pig manure was added at the rate of 15 t·hm⁻²·season⁻¹, respectively. Rice straw contained a mean measure of 10.19 N g·kg⁻¹, 1.33 P g·kg⁻¹, and 25.99 K g·kg⁻¹. Rice straw was added at the rate of 2.1 t·hm⁻², respectively, in an oven dry weight basis in the early rice cropping season and late rice cropping season per year.

2.4 Data analysis

Least-squares linear regression analysis was done to determine the yield and potassium uptake trends (slopes) over the years to test the hypothesis that yield and potassium uptake trends throughout the experimental period were not significantly different from zero. The *P*-values on the slopes indicate the level of significance of the observed yield changes. Analysis of variance (ANOVA) was performed to determine the effects of treatment. To test the hypothesis on yield and potassium uptake trends, a simple linear regression analysis of grain yield and potassium uptake over the years was done to determine a time trend variable.

$$y = a + bt \quad (1)$$

where *y* is the grain yield ($\text{t} \cdot \text{hm}^{-2}$), *a* the constant, *t* the year, and *b* the slope or magnitude of yield trend (yield changes per year). Similarly, K uptake trends were also obtained with similar equation for different treatments, where *y* is the K uptake ($\text{kg} \cdot \text{hm}^{-2}$), *a* the constant, *t* the year, and *b* the slope or magnitude of K uptake trend (K uptake changes per year).

Input-output data of K through fertilizers, swine manure, rice straw, irrigation water, and rainwater was used over the year for calculating apparent input-output balance of K following the equation used by Saleque et al. (2004).

$$K_{ab} = K_{inp} - (K_{up} - K_{rec}) \quad (2)$$

where K_{ab} is the apparent potassium balance, K_{inp} the potassium input through fertilizer, swine manure, straw, irrigation water, and rain water, K_{up} the potassium uptake

by straw and grain, and K_{rec} the potassium recycled through the residual rice stubble.

Potassium concentrations in rain and irrigation water were measured occasionally for 5 years, and the average value was used. The rainfall record was collected from the Wangcheng weather station. Total irrigation water was assessed as 580 m^3 for the early rice planting season (ES) and 970 m^3 for late rice planting season (LS). The mean K concentration in irrigation water and rain water is $7.87 \text{ mg} \cdot \text{L}^{-1}$ and $0.35 \text{ mg} \cdot \text{L}^{-1}$, respectively.

3 Results

3.1 Grain yield, rate of yield change, and sustainability

The analysis of variance across the 27 years study period showed significant year $\times$ treatment interaction on rice yield (Table 2). Rice yield response to K fertilizer was observed each year. Early rice yield was significantly lower in NK treatment than in NP treatment, but NK and NP treatments was equally efficient in increasing late rice yield. Balanced fertilization treatment of N, P, and K fertilizers in each of the 27 years study period increased significantly the grain yields of both early and late rice each year.

Combined application of pig manure with NK (NK + PM) and combined application of rice straw with NP (NP + RS) yielded all higher grain yield of both early and late rice in 27 years study period than the treatment where only N and K fertilizers was applied, but lower than when balanced fertilization of N, P, and K fertilizer was applied.

Table 2 Grain yield, yield change trends, *t*-statistic, significance of yield change (*P*) over year, and analysis of variation (ANOVA) in long-term fertilizer, pig manure, and rice straw application experiment in Wangcheng, Hunan Province, China

treatment*	early rice				late rice			
	average yield #	change trend, slope§	<i>t</i> -stat	<i>P</i> - value	average yield	change trend, slope	<i>t</i> -stat	<i>P</i> - value
	/(t·hm ⁻²)	/(kg·hm ⁻² ·a ⁻¹)			/(t·hm ⁻²)	/(kg·hm ⁻² ·a ⁻¹)		
CK	2.84g	−0.022	−1.311	0.201	3.37e	−0.014	−1.238	0.227
NP	4.74e	−0.009	−0.436	0.666	4.70d	−0.032	−2.441	0.022
NK	3.57f	−0.093	−2.919	0.007	4.69d	−0.016	−0.682	0.051
NPK	5.46b	0.001	0.036	0.972	5.51b	0.017	0.941	0.356
NK + PM	5.14d	0.003	0.118	0.906	5.34c	0.009	0.408	0.686
NP + RS	5.25c	0.006	0.311	0.758	5.36c	0.013	0.658	0.516
NPK + RS	5.82a	0.003	0.158	0.875	5.85a	0.009	0.471	0.641
grain yield					grain yield			
ANOVA +	<i>df</i>	<i>F</i>	<i>P</i>		ANOVA	<i>df</i>	<i>F</i>	<i>P</i>
year	26	28.89	0.000		year	26	24.85	0.000
<i>T</i>	7	106.33	0.000		<i>T</i>	7	115.98	0.000
<i>Y</i> × <i>T</i>	182	19.25	0.000		<i>Y</i> × <i>T</i>	182	8.41	0.000

Note: *: CK: No fertilizer was applied; NK: N plus K; NP: N plus P fertilizer; NPK: K fertilize plus N and P fertilizer; NK + PM: K fertilizer plus N fertilizer and pig manure; NP + RS: No K fertilizer plus N, P fertilizer and rice straw; NPK + RS: K fertilizer plus N, P fertilizer and rice straw. #: The value within each column followed by the different letter differ significantly ($P < 0.05$) by Duncan's multiple range test. §: Yield change trends fitted by linear regression are shown; +: Significant test of treatment $\times$ year interaction. The same as follows.

These data suggest that either the amount of K released from pig manure or the amount of K released from rice straw was inadequate. There was a lack of synchronization of P and K release and rice crop demand during rice growth. In NPK + RS-treated plots, the combined application of RS and NPK usually produced the highest numerical rice yields (average $5.82 \text{ t} \cdot \text{hm}^{-2}$ for early rice and $5.85 \text{ t} \cdot \text{hm}^{-2}$ for late rice, respectively) among all the treatments and significantly out yielded the NPK treatment in each of the 27 years. The combined application of RS and N, P, and K fertilizers could meet total K needs of high yielding rice cultivars, particularly in hybrid rice, and could show synergetic effects in increasing rice yield. In addition, RS supplied significant quantities of N and P to rice.

The 27 years yield trends of both the early and late rice were different under different treatments. In early rice cropping season, there were negative yield trends with time in the CK-, NK-, and NP-treated plots, but positive yield trends were observed through the NPK, NK + PM, NP + RS, and NPK + RS treatments. The negative slop of the CK treatment (-0.022 for early rice to $-0.014 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ for late rice), NK (-0.093 to $-0.016 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$), NP (-0.009 to $-0.032 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$), and yield showed positive trend in other treatments, but all maintained relatively lower positive values. The positive slope of grain yield of the early rice was in range of 0.001 and $0.006 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, respectively, and that of the late rice was in range of 0.009 and $0.017 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$.

3.2 Uptake of potassium by rice crop

For this experimental site, the uptake of potassium by both the early rice and late rice was calculated for each year from the yield of rice grain and rice straw per hectare, as

expressed by the dry weight of the harvested crops and the percentage of K in the dry materials. The average K uptake for both early and late rice in 27 years study period is shown in Table 3.

The analysis of variance across the 27 years study period showed significant year $\times$ treatment interaction on K uptake of both the early and late rice (Table 3). The uptake of K by both the early rice and late rice on soils receiving K fertilizer increased significantly in all years. The lowest K uptake occurred at the unfertilized CK treatments, followed by NP treatments with no K applied. Average K uptake was far greater in NPK treatments than that in NP treatments. Similarly, average K was higher in NPK treatments than in NK treatments because of the limitation of the effectiveness of K due to P deficiency with NK-treated plots. K uptake in NK + PM treatments was greater than NK treatment but lower than in NPK treatment. This was most likely due to decline in total P concentration in grain + straw and the limitation in the effectiveness of K due to P deficiency in soil. In NPK + RS treatment, K uptake was greater compared with NPK treatment. The combined application of rice straw with NPK fertilizer could meet total K needs of high-yielding rice cultivar and may show synergetic effects in increasing rice yield. In addition, rice straw supplied significant quantities of N and P to rice.

Potassium uptake of early rice in all treatments decreased with time during the study period except NPK + RS-treated plots (Table 3). The values of the slope were significantly ($P < 0.05$) different from zero in NP, NK, and NP + RS treatments but not significantly in the NPK and NK + PM treatments. Linear regression analysis of K uptake of the early rice from 1981 to 2007 showed downward trends, with the decline ranging from 0.262 to $3.247 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ (Table 3). The rate of decline in K uptake was the lowest in NK + PM-treated plots, and the

Table 3 Potassium uptake, change trends, *t*-statistic significance of K uptake change (*P*) over year, and analysis of variation (ANOVA) in long-term fertilizer and straw application experiment in Wangcheng, Hunan Province, China

treatment*	early rice				late rice			
	average K, uptake #	change trend, slope§	<i>t</i> -stat	<i>P</i> - value	average K, uptake	change trend, slope	<i>t</i> -sat	<i>P</i> - value
	/(kg·hm ⁻²)	/(kg·hm ⁻² ·a ⁻¹)			/(kg·hm ⁻²)	/(kg·hm ⁻² ·a ⁻¹)		
CK	54.52g	−0.889	−3.418	0.002	51.74g	0.354	1.369	0.182
NP	60.04f	−1.032	−2.206	0.036	61.38f	−0.158	−0.705	0.487
NK	89.09c	−3.247	−5.540	0.001	98.60d	0.207	0.444	0.661
NPK	136.06b	−0.434	−0.667	0.510	119.66b	0.761	1.361	0.185
NK + PM	130.39c	−0.262	−0.298	0.768	117.76c	1.185	2.163	0.399
NP + RS	92.19d	−1.765	−3.116	0.004	77.09e	−1.897	−3.956	0.001
NPK + RS	147.27a	0.330	0.574	0.571	142.28a	0.404	0.769	0.448
K uptake				K uptake				
ANOVA +	<i>d.f.</i>	<i>F</i>	<i>P</i>	ANOVA	<i>d.f.</i>	<i>F</i>	<i>P</i>	
year	26	8.97	0.000	year	26	5.33	0.000	
T	7	101.18	0.000	T	7	147.57	0.000	
Y × T	182	43.34	0.000	Y × T	182	39.67	0.000	

highest in NP treatment, significant at $P < 0.001$. The decline in K uptake across treatments was correlated with initial K uptake. These observed trends in the K uptake decline in the early rice planting season are similar to those reported by Saleque et al. (2004).

Potassium uptake of the late rice was stable as no declining trends were noted, except NP and NP + RS treatments without fertilizer K applied. The positive K uptake trends in the late rice may be due to the use of a high N rate ($180 \text{ N kg} \cdot \text{hm}^{-2}$). The recommended N rate for the late rice in this region is $120 \text{ kg} \cdot \text{hm}^{-2}$. The high N rate used in this study was to document the residual effects of fertilizer K and organic materials to late rice. A contrasting K uptake trend of the early rice and late rice could also be due to a few reasons. Evidence suggests that continuing efforts in selection and breeding have led to improvements in the genetic potential of new cultivars, particularly late hybrid rice cultivars. A genetic gain of above $12 \text{ t} \cdot \text{hm}^{-2} \cdot \text{season}^{-1}$ has been reported in late hybrid rice since the mid-1970s (Yuan and Virnani, 1988). We reported that the K absorption capacity of hybrid rice was greater, as compared to conventional rice (Zheng and Xiao, 1992). In addition, in the double rice cropping region of southern China, the pest and disease attacks were more severe late in the year, as compared to early (Luo and Zheng, 1988) and late rice with K application, which is possibly less prone to the incidence of pest and disease attack.

3.3 Potassium-use efficiency

Recovery efficiency (RE) was calculated by the difference method and varied by more than threefold over the year (Table 4). Average RE was the highest for the NPK treatments in both the early and late rice, followed by the NPK + RS treatments, the lowest in the NK treatments. The low availability of K from NK treatments, as that by Shen et al. (2004), resulted in low RE values. The lower RE in treatments in which K only combined with N was due to lower K uptake during most of the years. Potassium recovery in the NK + PM-treated plots was significantly increased compared with the NK treatment. A different argument applies for the NPK + RS treatment, in which, despite high K uptake (Table 3), RE of K applied from

fertilizer and rice straw was lower than in the NPK treatment. In general, K recovery efficiency was decreased with increasing of K rate (Liao et al., 2007, 2009a), suggesting that it was affected by the amount of K application. The average K recovery efficiency for rice under the long-term experiment were relatively high (48%–66%) and exceed in the upper range of 34.7%–56.9%, as reported by Zheng et al. (1989), for irrigated rice fields in southern China.

3.4 Apparent potassium balance

The analysis of results for 27 years showed that the apparent K balance of the double rice cropping system was negative in the CK and NP treatments, whereas other treatments showed a positive balance (Table 5). The application of NP to the soils results in a greater negative K balance than that from the unfertilized CK. This was due to higher K uptake ($121.4 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) in the NP-treated plots compared with the plots in the unfertilized CK ($106.3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$). The plots under both NK and NPK treatments received similar amount of fertilizer K, but the NPK-treated plots showed a lower balance, due to significant yield responses of rice to the P applied. In the NK + PM-treated plots, the K uptake, $248.2 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$, was more than that observed in the plots with NK. With NP + RS treatment, where $169.3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ was applied annually from addition of rice straw, the amount of K added could maintain basically the balance with the removal of the rice plants. In the NPK + RS treatment, the amount of K added from the fertilizer and rice straw exceeded K removal by rice plants, leaving the highest positive K balance of $\sim 42.2 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$. These results showed that the major fraction of the K uptake is found mainly from the addition of rice straw. Thus, recycling rice straw may dramatically change the K balance and may keep the balance within reasonable limits.

3.5 Soil potassium fertility

The exchangeable K content in fertilized (NPK) treatments were significantly higher than those the unfertilized K treatments in the three soil depths (Table 6). There was a further increase in the exchangeable K under the RS

Table 4 Potassium use (recovery and agronomic) efficiency of fertilizer K, PM-K, and RS-K applied in double rice cropping system (1981–2007)

treatment*	early rice				late rice			
	recovery efficiency (range mean)/%		agronomic efficiency (range mean) /(kg grain $\cdot$ kg ⁻¹ K)		recovery efficiency (range mean)/%		agronomic efficiency (range mean) /(kg grain $\cdot$ kg ⁻¹ K)	
NK	12–60	29.7d	4.7–27.7	1.1d	33–68	59.8c	–7.4–13.4	3.4d
NPK	23–92	74.0a	3.5–15.6	7.4b	23–92	75.8a	6.3–14.3	8.4b
NK + PM	15–84	56.2bc	3.0–14	45.7c	15–84	65.1b	2.7–13.3	6.2c
NP + RS	35–83	55.4c	3.8–15.2	11.1a	35–83	54.7d	5.3–21.8	13.3a
NPK + RS	42–67	58.2b	2.8–11.4	7.6b	42–67	67.6 b	2.8–13.8	7.5b

Note: Values within each column followed the same letter do not differ significantly ($P > 0.05$) by Duncan's multiple range test.

Table 5 Apparent balance of K in double rice cropping system with different nutrient management over the period of 1981–2007 in Wangcheng, Hunan Province, China

treatment*	potassium added/(kg·hm ⁻² ·a ⁻¹)					potassium/(kg·hm ⁻² ·a ⁻¹)			
	fertilizer	pig manure	straw	irrigation	rain	total	uptake	recycled ^a	apparent balance
CK	0	0	0	12.2	4.8	17.0	106.3	2.2	–87.1
NP	0	0	0	12.2	4.8	17.0	121.4	1.9	–102.5
NK	199.2	0	0	12.2	4.8	216.2	187.7	4.8	33.3
NPK	199.2	0	0	12.2	4.8	216.2	255.7	5.5	–34.0
NK + PM	199.2	34.8	0	12.2	4.8	251.0	248.2	5.4	8.2
NP + RS	0	0	109.2	12.2	4.8	126.2	169.3	4.5	–38.6
NPK + RS	199.2	0	109.2	12.2	4.8	325.4	289.6	6.4	42.2

Note: a: K nutrient recycled through rice stubble residues.

Table 6 Distribution of different forms of K (kg·hm⁻² soil) in the three soil depths as influenced by the use of fertilizer, pig manure, and straw in different combinations after 27 years (1981–2007) of double rice cropping system

form of K	treatment*							
	initial soil	CK	NP	NK	NPK	NK + PM	NP + RS	NPK + RS
soil depth, 0–15 cm								
NH ₄ OAc-K	105	94	95	270	159	154	77	210
depletion/build up of NH ₄ OAc-K	–	–11	–10	165	54	50	–28	105
nonexchangeable K	292	272	282	319	311	282	267	281
depletion/build up of non exchangeable K	–	–20	–10	27	19	–10	–25	–11
total K	23688	22600	23136	22796	22641	22847	21541	22315
depletion/build up of total K	–	–1089	–552	–892	–1047	–841	–2147	–1373
soil depth, 15–30 cm								
NH ₄ OAc-K	114	89	86	207	116	129	88	170
depletion/build up of NH ₄ OAc-K	–	–25	–28	93	2	15	–27	56
nonexchangeable K	365	352	342	365	364	375	340	371
depletion/build up of non exchangeable K	–	–13	–23	0	–1	10	–26	6
total K	28296	28122	27478	28297	28311	28508	27478	28297
depletion/build up of total K	–	–174	–818	1	15	212	–818	1
soil depth, 30–45 cm								
NH ₄ OAc-K	142	138	106	163	122	128	116	163
depletion/build up of NH ₄ OAc-K	–	–4	–36	21	2	8	–26	21
non-exchangeable K	433	408	392	440	465	442	420	461
depletion/build up of nonexchangeable K	–	–25	–41	7	32	9	–13	28
total K	32376	31929	31462	32396	32446	32531	31470	32396
depletion/build up of total K	–	–447	–914	20	70	155	–906	20

amended treatments over NPK-treated plots in all the studied layers. In the surface layer (0–45 cm), the exchangeable K declined in the treatments under the unfertilized CK, NP, and NP + RS treatments, whereas a small accumulation of exchangeable K content was determined under the NK-, NPK-, NK + PM-, and NPK + RS-treated plots, and a significant accumulation of exchangeable K content under the NK- and NPK + RS-treated plots (Table 6). The depletion of exchangeable K content in the surface layer in the NP-treated plots (74 kg·hm⁻²) was higher than that observed in the

unfertilized plots (40 kg·hm⁻²). In the soil layer (0–45 cm depth), the highest depletion of exchangeable K was found in the NP + RS-treated plots (81 kg·hm⁻²).

Considerable depletion of nonexchangeable K content was observed throughout the soil profiles after 27 rice crop cycles for all the treatments. The results show that the soil profiles (0–45 cm depth) under the CK, NP, and NP + RS treatments underwent net loss of nonexchangeable K, ranging from 58 K kg·hm⁻² for the plots under CK treatment to a maximum of 74 K kg·hm⁻² for the NP-treated plots, whereas the other NK, NPK, NK + PM, and

NPK + RS treatments have a degree of increase in nonexchangeable K content, ranging from $9 \text{ kg} \cdot \text{hm}^{-2}$ for the plots under NK + PM treatment to a maximum of $50 \text{ kg} \cdot \text{hm}^{-2}$ for the NPK-treated plots (Table 6). For the NPK + RS plots, the rate of surplus of nonexchangeable K was $23 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ in soil depths (0–45 cm). Considerable mining of nonexchangeable K by the crops from deeper soil depths (30–45 cm) was also observed in all the treatments, ranging from the depletion rate $41 \text{ kg} \cdot \text{hm}^{-2}$ in the plots under NP treatment to the surplus rate $32 \text{ kg} \cdot \text{hm}^{-2}$ in the NPK-treated plots. Furthermore, there was an accumulation of exchangeable K content in the surface layer after 27 rice crop cycles in the plots under NK + PM and NPK + RS treatments, but the content of nonexchangeable K was depletion. The decrease in nonexchangeable K in the plots under NP + RS treatment over 27 years was $64 \text{ kg} \cdot \text{hm}^{-2}$, and negative K balance for 27 years was $\sim -38.6 \text{ kg} \cdot \text{hm}^{-2}$. Therefore, the weathering of soil K-bearing minerals must replace the loss of $53.9 \text{ kg} \cdot \text{hm}^{-2}$ plus the leaching losses of soil K (if any) over the 27 years period.

Unlike the exchangeable K and nonexchangeable K, the total soil K contents decreased after 27 years of cropping in the topsoil layer of all the plots. The highest depletion of total K in 0–15 cm soil layer was under the NP + RS-treated plots ($2147 \text{ kg} \cdot \text{hm}^{-2}$) (Table 6). The rate of depletion of total K was generally less in the subsoil (15–30 cm and 30–45 cm depths) than that in the topsoil (0–15 cm). Considerable mining of total K by the rice crops from deeper soil depths (30–45 cm) was also observed in all the treatment, ranging from $914 \text{ kg} \cdot \text{hm}^{-2}$ depletion in the plots under NP treatment to $155 \text{ kg} \cdot \text{hm}^{-2}$ surplus in the NK + PM treatment. The depletion of total K was not truly reflected by the soil test values of nonexchangeable K. For example, in the surface soil layer of NPK and NPK + RS treatment plots, there was an accumulation of nonexchangeable K, despite the net depletion of total K. Furthermore, there was an accumulation of exchangeable K content in the surface layer after 27 rice crop cycles in the plots under NK, NK + PM, NPK, and NPK + RS treatments, despite the depletion of total K, and the rate of depletion of total K in surface soil layer (0–45 cm) was $871 \text{ kg} \cdot \text{hm}^{-2}$, $962 \text{ kg} \cdot \text{hm}^{-2}$, $474 \text{ kg} \cdot \text{hm}^{-2}$, and $1352 \text{ kg} \cdot \text{hm}^{-2}$, respectively.

3.6 Nonexchangeable K release

The cumulative K release in $0.01 \text{ mol} \cdot \text{L}^{-1} \text{ CaCl}_2$ after 796 h varied from $390.56 \text{ kg} \cdot \text{hm}^{-2}$ in the plots under NP treatment to $483.59 \text{ kg} \cdot \text{hm}^{-2}$ in the plots under NPK + RS treatment, and the cumulative K release in over treatments was lower than that the initial soil (Fig. 1). The cumulative K release in the NPK-treated plots was 11.0% and 5.6% higher than those that under the NP and unfertilized plots. However, the application of rice straw along with NPK and pig manure along with NK treatments resulted in much

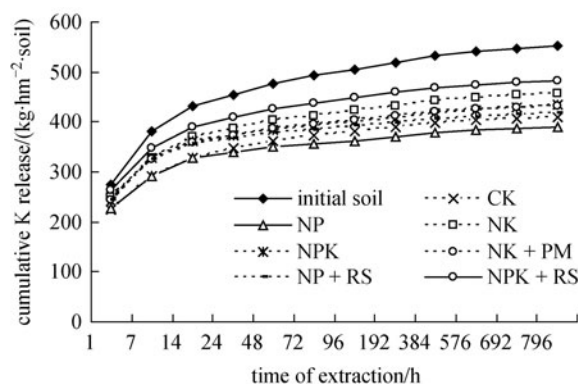


Fig. 1 Cumulative K release from non-exchangeable K as influenced by different nutrient management and cropping in the 0–15 cm soil layer after 27 years (1981–2007) of double rice cropping system.

higher cumulative nonexchangeable K release after 739 h. The plots under NPK + RS treatment increased in the cumulative nonexchangeable K release by $72.92 \text{ kg} \cdot \text{hm}^{-2}$ and $50.13 \text{ kg} \cdot \text{hm}^{-2}$ soil over those observed in the plots under unfertilized CK ($410.67 \text{ kg} \cdot \text{hm}^{-2}$) and NPK ($433.46 \text{ kg} \cdot \text{hm}^{-2}$) treatments.

4 Discussions

Yield decline in the NP plots was observed in early rice and late rice suggesting that the native soil K supply, K mineralized from subsoil and rice stubble residues, and K in irrigated water and rain was insufficient to sustain an average rice yield of approximately $10\text{--}11 \text{ t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$ in double rice cropping system. Similar rice yields were obtained in NP plots in other experiments at this experimental site (Liao et al., 2008a, 2009b). In northern China in a long-term experiment, the yield decline in the NP plots was sharp in the initial years, but the yield remained stable after a few years (Shen et al., 2004).

In contrast to the results of Flinn and Dedatta (1984) and Yadav et al. (1998), the rice yields of both the early rice and late rice in the study tended to increase over time in any treatment that received fertilizer K or from a combined application of fertilizer with pig manure and rice straw. In the early rice and late rice cropping season, an increasing trend in the rice yield was observed with NPK-, NK + PM-, NP + RS-, and NPK + RS-treated plots, while the yield trend with NK + PM was stagnant. These differing trends indicate that fertilizer management is a key factor determining rice yield trend in the double rice cropping system in southern China. At the experimental site, the causes of increasing yield trends may be due to the build-up of K content in the soil. The soil of the experimental field was deficient in K ($62 \text{ mg} \cdot \text{kg}^{-1}$). The continuous application of K as KCl, pig manure, and rice straw probably alleviated hidden K deficiency in the soil, which

resulted in a significant increase of rice yield with the NPK, NK + PM, NP + RS, and NPK + RS treatments.

The higher removal of K in the NK + PM-, NP + RS-, and NPK + RS-treated plots over those corresponding to NK, NP, and NPK treatments could be associated with other benefits of pig manure and rice straw (which may have supplied N, P, K, micronutrients, and improved physical properties). The negative apparent K balances under different inorganic and organic fertilizer sources treatments in the long-term experiments are attributed to higher crop uptake compared to the addition of K and labile K that either leached from the plough layer or fixed in the mineral lattice/ interlayer (Chen et al., 2000; Fan and Xie, 2005). In southern China, the results of several long-term experiments showed that considerable amounts of K have either leached from, and have been fixed, the soil (Shi et al., 1994; Ji et al., 2008). The greater uptake of K ($100.3 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) by rice plants from the NP plots over that of the unfertilized CK plots suggests that K was being released from the soil K reserves in the plots under NP treatment in greater quantities than that released from the unfertilized soils. As the changes in nonexchangeable K after 27 years in the soil profile (0–45 cm) were very small ($-74 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) compared to uptake of K ($121.4 \text{ kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) in the NP-treated plots, it must be assumed that either K was released from the reserves held in the clay interlayer, or some other form of K (presumably the nonexchangeable K) has been taken up. K might have been taken from below the studied soil layer (0–45 cm), most probably by the rice (Shi et al., 1994).

Significant accumulation of exchangeable K in the subsoil in the plots under NK treatment showed a downward movement of applied K in the soil profile, indicating its susceptibility to leaching (Ji et al., 2008). In contrast, the plots under NK + PM and NPK + RS treatments showed the great accumulation of exchangeable K in surface layers, possibly because of the increase in the sorption of K following continuous addition pig manure and rice straw, increase in the proportion of K specific internal exchange sites to K nonspecific external exchange sites, and increase in soil surface charge density (Poonia et al., 1986; Subba et al., 1993; Shi et al., 1994). The application of pig manure and rice straw increased the cation exchange capacity (CEC) of the soil (Liao et al., 2009b), which might have resulted in increased exchangeable K utilization by rice crops (Zheng et al., 1989). As the exchangeable K is removed by plant uptake, more K is released from nonexchangeable to exchangeable pools.

The decrease in nonexchangeable K and total K content in the plots with NP compared to that from the unfertilized plots was attributed to the residual acidity developed through urea-N application. The result of this was a greater release of nonexchangeable K into the soil solution, apart from the greater K uptake in the NP-treated plots than that in the unfertilized plots (Zheng and Luo, 1989; Chen et al.,

2000; Fan and Xie, 2005). Where fertilizer K was not applied, K was probably more effectively utilized from the soil layer, resulting in depletion of the soil K reserves. The observed results show the importance of the nonexchangeable K fraction in releasing K for rice uptake.

Two soil parameters affect the K supply to roots and have been successfully used for predicting K uptake by crops: (1) the exchangeable K in the soil and (2) the nonexchangeable K in the soil (Xie and Du, 1988). However, there is not always a clear relationship between the K balance and the K inputs. The K balance is controlled by the physico-chemical factors that determine the equilibrium among soil solution K, exchangeable K, nonexchangeable K, interlayer K, and mineral K in soil (Shi et al., 1994) and is associated with ion exchange and interlayer surfaces. This was the case for both the K-depleted and the K-fertilized soils and was also inferred by Blake et al. (1999) for the temperate European soils. Ranjan et al. (2006) showed that greater cumulative depletion of nonexchangeable K in the presence of organic matter indicates that organic matter plays an important role in redistribution of K among its various fractions. In this study, decline in nonexchangeable K in 0–45 cm soil depth and a simultaneous increase in exchangeable K contents clearly indicated that most K taken up by the rice crops had come from the nonexchangeable forms and exchangeable phase with the equilibrium among the K forms being reestablished (Singh et al., 2002; Ranjan et al., 2006). Greater K release in NK + PM-, NP + RS-, NPK + RS-treated plots over that in the NK-, NP-, and NPK-treated plots may also explain the organic matter and rice straw accelerating the process of structural K release (by increasing the exchangeable surfaces and by increasing the weathering of interlayer K). In general, the interlayer K is tightly held by electrostatic forces. This ‘fixed’ K can be replaced under appropriate conditions, either by ion exchangeable and transformation of micas into expansible 2:1 layer silicates, or by dissolution, particularly through the acidification of the rhizosphere by the excretion H^+ ions from plant roots. H^+ ions dissociated from organic acid might be responsible for the release of structural K (Singh and Goulding, 1997; Cui et al., 2002). That released available soil K (the exchangeable K) pool along with the annually added K probably maintained higher K uptake in the plots under pig manure and rice straw treatments as compared to those without manure and straw.

5 Conclusions

The soils in this experimental site are deficit in K and cannot sustain their current yields since current agricultural practices encourage the release of K from nonexchangeable sources. The practice of applying organic matter either through organic manure or rice straw is important in maintaining the supply of K as it mobilizes K from

nonexchangeable K into solution besides being an additional supply of available K.

Acknowledgements This research was funded by the International Plant Nutrition Institute (IPNI China Program: Hunan-14). The work was also supported in partial by the National Eleventh Five-year-plan Project, Key Technologies R&D Program of China (No. 2008BADA4B08) and Scientific and Technological Innovations Programs of Hunan Academy of Agricultural Sciences, China (No. 2009hnnkycx23). We thank our colleagues for providing basic soil data. We are also grateful to the hard work of all the technicians who assisted us in the field.

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