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RESEARCH ARTICLE

Effects of nutrient cycling on grain yields and potassium balance

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Abstract Soybean-maize rotation is a profitable cropping system and is used under rain fed conditions in north China. Since crop yields have been reported to decrease when K fertilizers are not used, we analyzed the productivity trends, soil-exchangeable and non-exchangeable K contents, and K balance in a continuous cropping experiment conducted in an area with an alfisol soil in the Liaohe River plain, China. The trial, established in early 1990 and continued till 2007, included 8 combinations of recycled manure and N, P, and K fertilizers. In the unfertilized plot, the yields of soybean and maize were 1,486 and 4,124 kg ha^{-1} respectively (mean yield over 18 years). The yields of both soybean and maize increased to 2,195 and 7,476 kg ha^{-1}, respectively, in response to the application of inorganic N, P, and K fertilizers. The maximum yields of soybean (2,424 kg ha^{-1}) and maize (7,790 kg ha^{-1}) were obtained in the plots under treatment with N, P, and K fertilizers and recycled manure. K was one of the yield-limiting macronutrients: regular K application was required to make investments in the application of other mineral nutrients profitable. The decrease in the yields of soybean and maize owing to the absence of K application averaged 400 and 780 kg ha^{-1}, respectively. Soybean seed and maize grain yields significantly increased with the application of recycled manure. For both these crops, the variation coefficients of grain were lower with treatments that included recycled manure than without treatment. After 18 years, the soil-exchangeable and non-exchangeable K concentrations decreased; the concentrations in the case of treatments that did not include K fertilizers were not significantly different. Treatment with N, P, and K fertilizers appreciably improved the fertility level of the soil, increased the concentration of soil-exchangeable K, and decreased the non-exchangeable K concentration. In soils under treatment with N, P, and K fertilizers and recycled manure, the soil-exchangeable and non-exchangeable K levels in the 0–20 cm-deep soil layer increased by 34% and 2%, respectively, over the initial levels. Both soil-exchangeable and non-exchangeable K concentrations were the highest with on treatment with N, P, and K fertilizers and recycled manure, followed by treatment with N, P, and K fertilizers. These concentrations were lowest in unfertilized soils; the other treatments yielded intermediate results. The results showed a total removal of K by the crops, and the amount removed exceeded the amount of K added to the soil; in treatments that did not include K fertilizers, a net negative K balance was observed, from 184 to 575 kg ha^{-2}. The combined use of N, P, and K fertilizers and recycled manure increased the K content of the 0–20 cm-deep soil layer by 125%

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compared to the increase obtained with the application of N, P, and K fertilizers alone. The results clearly reveal that current mineral fertilizer applications are inadequate; instead, the annual application of recycled manure along with N, P, and K fertilizers could sustain future yields and soil productivity.

Keywords Different treatments · Grain yields · Potassium balance

Introduction

Increase in crop yield due to the use of modern crop varieties has enhanced nutrient-mining from the soil: in fact, nutrient removal exceeds annual replacement. Moreover, farmers in China have mainly focused on the application of N and P fertilizers, and not K fertilizers, for crop cultivation; this is primarily because K fertilizers are often not as effective as they were in the past. Such imbalanced nutrient-management practises may impair the productivity of soil in China, which contains low levels of organic matter.

Yield declines have been reported in long-term experiments (Wang et al. 2005; Ma et al. 2007). In spite of balanced inputs of N, P, and K fertilizers, Yu et al. (2007) observed yield declines in north China, particularly in fields that were not treated with P or K fertilizers rather than in fields that received balanced treatment with fertilizers. In a long-term experiment, Cai and Qin (2006) calculated that the mean annual yield of maize on treatment with N and P fertilizers (NP treatment) was 96% of that on treatment with N, P, and K fertilizers (NPK treatment) for the first several years. However, this figure declined to 86% in subsequent years. Zhang et al. (2006) also reported significant yield declines with unbalanced treatments.

Regmi et al. (2002) found that even with recommended NPK or farmyard manure treatments, the yields of wheat and the first rice crop declined in rice-wheat cropping systems (no yield decline was observed in the second rice crop). They speculated that the yield declines in the first rice and wheat crops were due to inadequate K input. The cultivation of modern rice varieties increases the removal of P, K, S, and other plant nutrients from the soil because of the greater biomass of these varieties (Dobermann et al. 1996); eventually, more rice soils will become increasingly N, P, and K deficient (Ali et al. 1997).

It is therefore important to understand crop-yield trends under different nutrient-management conditions, so that a strategy for maintaining crop production and growth can be planned. Integrated nutrient management—i.e., the combined use of chemical fertilizers and organic amendments—can be used to maintain sustainable soil productivity. It is well recognized that organic soil matter is an important fertility parameter and that it largely determines soil quality. The application of swine waste—one of the potential sources of organic manure in China—may reduce the need for chemical fertilizers in crop fields.

The management of straw is another issue critical to sustainable agriculture in China. The burning of maize straw is common, particularly in north China. This leads to not only the loss of most organic C and large losses of N, P, and K, but also significant air pollution and the death of beneficial soil fauna and microorganisms (Liu et al. 2003). The use of maize straw is therefore an important environmental issue in north China.

The application of straw has been shown to improve soil structure and increase soil nutrient content (Liu et al. 2006; Zhang et al. 2005; Zhuang et al. 2000), but to date, few attempts have been made to assess the sustainability of rain fed soybean-maize systems that involve the application of recycled manure. The objectives of the present experiment are to examine the impact of the continuous use of inorganic fertilizers with and without recycled manure on the trends of soybean and maize yields as well as their impact on soil properties and the long-term sustainability of soybean-maize rotation under rain fed conditions in the plain of the Liaohe River.

Materials and methods

Experimental site, design, and treatments

A long-term field experiment has been conducted since 1990 at the experimental station of the Institute of Applied Ecology, Chinese Academy of Sciences. The station is located in Shilihe village of Sujiatun District, 35 km from south Shenyang (latitude 41°32′N, longitude 123°23′E); it has an average elevation of 31 m and a mean annual temperature of 7.0–8.0 °C (maximum, 39.3 °C; minimum, −33.1 °C). Its annual precipitation is about 700 mm, and the frost-free period is 147–164 days. The soil of the experimental field is an alfisol soil, which is the main soil type used for agricultural production.

The initial properties of the surface soil (depth, 0–20 cm) were as follows: soil texture, clay loam; pH, 6.7; organic C content, 22.1 g kg^{-1}; total N, 0.8 g kg^{-1}; available P, 10.6 mg kg^{-1}; and soil-exchangeable K, 82.5 mg kg^{-1}.

The experiment had 8 treatments: no fertilizer (CK), recycled manure (M), N, NM, NP, NPM, NPK, and NPKM treatments. N, P, and K fertilizers were applied at the rates of 150, 25, and 60 kg ha^{-1} $year^{-1}$ in the form of urea, double superphosphate, and potassium chloride, respectively. All P and K fertilizers were basal-applied prior to sowing: 40 kg ha^{-1} N fertilizer was basal-applied prior to sowing, and 110 kg ha^{-1} N was top-dressed at the stem-elongation stage. Each plot area was 162 m^2, with a buffer zone of 1.0 m. Initially, in 1990, the experiment was started with a soybean–maize–maize 3 year rotation. Each treatment consisted of three replications.

Through feeding-composting cycles, 80% harvested seeds, 100% soybean straw, and 50% corn stalk were returned to the original treatment. This completed a nutrient-recycling process that consisted of "fertilization-crop yield-absorption-feeding-composting-return to fields."

Conventional tillage practises were used. Crops were manually harvested, and the above-ground crops were removed from the field. Soil was plowed approximately 20 cm deep, and stubble was incorporated into the field after harvesting.

Soil sampling and analysis

Every year since 1990, soil sampling has been conducted at depths of 0–20 cm in autumn. Five soil samples were collected from each plot and mixed to form a composite sample from that plot. The samples were air-dried, ground and passed through a 2 mm sieve, and stored for analysis.

Standard techniques were used to measure pH (1:2.5 soil-water suspension) (Anon 1986), extractable P (0.5 mol dm^{-3} $NaHCO_3$ at pH 8.5) (Olsen et al. 1954), soil-exchangeable K (1 mol dm^{-3} NH_4OAc at pH 7) (Jones 1973), non-exchangeable K (1 mol dm^{-3} HNO_3) (Wood and DeTurk 1940), and total N and C (Vario EL, III; Elementary Co. Ltd. Germany).

Apparent K balance was estimated in the maize-soybean cropping system for an 18 year period (1990–2007) and calculated using the following equation:

$$\text{K balance} = \sum(\text{fertilizer K; recycled manure K; rain K; seed K}) - \text{plant K}$$

The K content of the mineral fertilizer, recycled manure, rainwater, and seeds were determined. It was assumed that no K-leaching losses occurred in the soil system, when the cation-exchange capacity (CEC) exceeded 40 mmol kg^{-1} (Shen 1998).

Data analysis

Differences in each measurement were examined by ANOVA, and the mean values were separated by the least significant difference, which was set at $p = 0.05$.

Results

Effects of treatments on crop yields

The soybean yield varied with the different fertilizer treatments. The lowest grain yield of soybeans was obtained with the control treatment, and the highest yield was consistently obtained with the NPKM treatment. Although the grain yield of soybeans with the NP treatment was approximately 20.76% greater than that with the control treatment, the difference was not significant. NPK treatment increased soybean yield by about 22% over that obtained with the NP treatment, and the difference was significant. This indicates that K is one of the most yield-limiting macronutrients for soybeans.

Similar trends were observed in the case of maize yields: NPKM treatment resulted in the highest grain (7,790 kg ha^{-1}) and straw (6,939 kg ha^{-1}) yields, followed by the NPK treatment (7,476 and 6,789 kg ha^{-1}, respectively). Fertilizer application significantly increased the grain yield of maize throughout the 18 year cropping period. The maize yields clearly differed between the N and control treatments as well as

Table 1 Average yield of crop seeds in different treatments, from 1990 to 2007

Treatments	Seeds of soybean (kg ha^{-2})	Variation coefficient	Straw of soybean (kg ha^{-2})	Variation coefficient	Seeds of maize (kg ha^{-2})	Variation coefficient	Straw of maize (kg ha^{-2})	Variation coefficient
CK	1486d	0.4785	1372c	0.4164	4124d	0.3836	4545d	0.1998
M	1984bc	0.2841	1837b	0.2828	5502c	0.2558	5416bcd	0.1780
N	1503d	0.4286	1437c	0.4068	5935bc	0.3084	5023cd	0.2207
NM	2017abc	0.2528	1934b	0.2445	7133a	0.2374	5861bc	0.1997
NP	1795cd	0.3141	1961b	0.2513	6696ab	0.2213	5770bc	0.2515
NPM	2210ab	0.2080	2366a	0.1785	7409a	0.2046	6337ab	0.2484
NPK	2195ab	0.2554	2205ab	0.2497	7476a	0.2169	6189ab	0.2373
NPKM	2424a	0.2117	2469a	0.2057	7790a	0.1916	6939a	0.2281

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between the N and NPK treatments. However, no significant difference was detected in the maize yields between the N and NP treatments or between the NP and NPK treatments. The application of NPK fertilizer increased the maize yield by about 11.65% over that obtained with the NP treatment.

The N fertilizer had a significant yield-increasing effect on maize crops. However, the mean soybean yield was not affected by the N fertilizer (Jagadamma et al. 2008), most probably due to N fixation by soybeans.

In almost every year, soybean seeds and maize grain yields significantly increased with the application of recycled manure; this indicates that recycled manure is essential for yield increment. It was evident from the pooled data that with the M, NM, NPM, and NPKM treatments, the soybean yield increased by 33.51%, 34.13%, 23.13%, and 10.43%, respectively, and the maize yield, by 33.43%, 20.18%, 10.65%, and 4.20%, respectively. It is obvious that the yield-increasing effect would be minimized, and the fluctuation in yields, reduced with the development of fertilization strategies for both soybean and maize cultivation.

For both soybeans and maize grains, the variation coefficients were lower for the treatments that included recycled manure than for those that did not. The values of the variation coefficients were in the order of NPKM < NPM < NM < M, with a range of 0.21–0.28 for soybean yield. Thus, fluctuations in crop yield declined with the use of recycled manure. Similar trends were also seen for straw yields. In addition, the variation coefficient for maize was lower than that for soybeans (Table 1).

Soil-exchangeable K

Treatments that did not include manure or K fertilizers tended to significantly decrease the soil-exchangeable K content in the first few years, from an initial level of 80 mg kg^{-1} (Table 2). The soil-exchangeable K content reduced to minimum levels after 7 crop cultivations; however, the content did not continue to decrease because of homeostasis between soil-exchangeable K and non-exchangeable K. These results are in accordance with those of Yang et al. (1999) and Zhang et al. (1999).

The soil-exchangeable K content tended to significantly increase with the NPK and NPKM treatments, and it significantly decreased with all K-omitted treatments. The greatest value thereof was 17.3%, which was obtained with the NP treatment, followed by the values obtained with the N (12.5%) and M treatments(10.6%). These findings are contrary to the general belief that most soils in north China are rich in K, and that K is rarely a limiting factor (Su 2001). Further, Liu et al. (2000) also found similar declines in soils in northwest China. The decline in soil-exchangeable K was greater with the NP treatment than with the N treatment, suggesting that N and P both limit the uptake of K by crops at this location.

In contrast, soil-exchangeable K levels increased over time with treatments that included K fertilizers (i.e., NPK and NPKM). This shows that the addition of K to organic materials resulted in a large increase in the soil-exchangeable K because manure generally contains high amounts of K, as previously mentioned. This study clearly showed that high levels of crop production resulting from the use of inorganic N and

Table 2 Soil-exchangeable K content with different treatments, from 1990 to 2007

Years	CK (mg kg^{-1})	M (mg kg^{-1})	N (mg kg^{-1})	NM (mg kg^{-1})	NP (mg kg^{-1})	NPM (mg kg^{-1})	NPK (mg kg^{-1})	NPKM (mg kg^{-1})
Original value	78.37	83.47	82.37	81.64	88.87	80.55	84.3	80.55
1990	73.27	79.82	76.91	73.27	84.93	83.93	83.77	85.6
1991	71.45	76.91	75.09	69.63	80.55	73.27	99.4	100.73
1992	69.63	73.27	73.27	71.45	76.91	76.91	101.03	109.5
1993	65.98	71.45	62.34	73.27	73.27	76.91	90.87	101.37
1994	69.63	75.09	73.27	73.27	76.91	73.27	98.1	109.03
1995	73.27	69.63	67.81	73.27	69.63	73.27	94.67	95.5
1996	74.12	73.79	70.48	72.13	73.12	75.44	84.37	98.76
1997	73.71	78.67	73.38	72.71	67.09	73.71	83.63	103.47
1998	72.05	71.72	69.74	73.04	66.43	77.67	85.61	90.9
1999	76.02	81.97	79.33	81.31	73.71	78.67	101.82	106.78
2000	68.08	67.42	72.38	73.71	75.69	73.71	89	91.89
2001	74.41	77.68	79.91	83.27	77.8	89.7	100.22	108.98
2002	71.8	74.2	77.37	80.67	78.03	82.57	85.7	97.53
2003	70.85	73.35	67.52	71.68	68.35	73.35	75.02	87.52
2004	73.32	73.82	64.35	67.49	63.79	73.03	81.11	82.96
2005	63.64	63.64	67.14	74.14	70.64	77.64	88.14	116.14
2006	67.85	76.53	63.52	71.11	63.52	72.19	87.37	106.89
2007	68.79	75.07	72.98	77.16	67.16	76.34	89.7	108.51
Mean	71.38d	74.61cd	72.06d	74.43cd	73.49cd	76.95c	89.67b	99.08a
Amplitude reduction	8.92%	10.62%	12.52%	8.83%	17.30%	4.47%	−6.38%	−23.01%

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P fertilizers, as well as the removal of above-ground biomass, greatly reduce the levels of soil-exchangeable K.

K-omitted treatments, irrespective of whether they included recycled manure, resulted in a significant decline in the soil-exchangeable K content compared to the content at the beginning of the experiment. Greater reduction in soil-exchangeable K was observed with the treatments that did not include recycled manure than with those that did.

The aforementioned changes occurred over the entire experimentation period, though not continuously. Large discontinuities were observed between 2 successive sampling dates. There are 2 possible explanations for this behavior (Quemener 1986):

(1) The determination of soil-exchangeable K was influenced by the water content of the soil at the time of sampling; alternation of wetting and drying cycles favors fixation or release of soil-exchangeable K, depending on whether the soil was fertilized before sampling.

(2) The average amount of K returned to the field by residue at harvest was different for each year.

Non-exchangeable K content of soil

Changes in the non-exchangeable K content of soil between the beginning of the experiment and 2007 are shown in Table 3. During this period, K-omitted treatments significantly decreased the soil non-exchangeable K content (initial value, 543 mg kg^{-1}). The application of K fertilizers alone resulted in a slight decrease (5 mg kg^{-1}). In contrast, treatments that included K fertilizers and recycled manure led to a slight increase in the non-exchangeable K content (11 mg kg^{-1}). Throughout the 18 year study period, the non-exchangeable K content was greater in soils that were subjected to treatments that included K

Table 3 Non-exchangeable K content in different treatments, from 1990 to 2007

Years	CK (mg kg^{-1})	M (mg kg^{-1})	N (mg kg^{-1})	NM (mg kg^{-1})	NP (mg kg^{-1})	NPM (mg kg^{-1})	NPK (mg kg^{-1})	NPKM (mg kg^{-1})
Original value	543	553	562	558	564	559	555	554
1990	553	541	542	554	526	533	569	558
1991	518	534	515	539	471	500	506	550
1992	536	504	503	511	508	517	543	541
1993	516	538	498	506	522	555	541	581
1994	451	523	445	456	505	504	524	537
1995	495	544	421	424	488	507	550	566
1996	455	485	444	448	452	458	504	554
1997	436	544	440	441	443	468	541	568
1998	459	505	493	503	440	488	517	530
1999	475	531	458	456	441	509	531	572
2000	439	510	469	469	479	506	510	550
2001	483	513	463	506	468	496	514	543
2002	486	498	477	487	485	493	529	565
2003	480	503	488	462	452	501	568	604
2004	480	475	431	453	423	433	553	521
2005	479	511	467	500	464	497	518	591
2006	473	473	460	476	486	477	588	593
2007	479	514	475	498	462	488	550	565
Mean	486de	516c	476e	487de	478e	499cd	537b	560a
Amplitude reduction	11.82%	7.05%	15.57%	10.73%	18.04%	12.64%	0.85%	−1.94%

The same letter is not significantly different according to Fisher's Protected LSD test at the 5% level of probability

fertilizers than in soils that were not treated. Non-exchangeable K content was lower in the soils that were treated with N and P, but not K, than in unfertilized soils. The non-exchangeable K soil content decreased significantly to approximately 15.57% and 18.04% with N and NP treatments, respectively. It is clear that non-exchangeable K content decreased with time until 1999 and since then non-exchangeable K content tended to steady in all treatments without K fertilizers except M treatment. One possible explanation for this result is experimental error.

The mean values of non-exchangeable K content were much higher with treatments that included recycled manure than with treatments that did not. The decline in non-exchangeable K was several times greater than that in soil-exchangeable K; this suggests that K associated with the latter fraction could be utilized by plants, and it thus represents a viable K reserve in this soil.

The average non-exchangeable K content values showed marked yearly variations, regardless of the type of treatment. For a given treatment, the difference in this value between 2 successive sampling dates was larger than that in the values between treatments for a given date.

In the case of the NP treatment, plant K uptake resulted in a considerable decrease in the soil-exchangeable K with time; this might enhance K release from the non-exchangeable K forms, because the balance between soil-exchangeable K and non-exchangeable K had changed.

K balance

K concentration in grain and straw

In both soybean and maize straw, K concentrations were greater in treatments with K fertilizers or recycled manure. Further, the K concentration in straw (i.e., 5.57 g kg^{-1}) was highest after treatment with both K fertilizers and recycled manure, followed by that after NPK treatment. In the case of maize, while no remarkable differences were observed in the yields, the K concentrations clearly differed between the NPK and NPKM treatments. It has been suggested that the application of K fertilizers and recycled manure leads to the excessive absorption of K by maize straw and decreases the K-utilization efficiency. However, no significant difference was noted in the K concentrations of the grains, of either soybeans or maize, among the treatments. When the K supply is adequate, a relatively high proportion of K can be transferred from the roots to the stalk and grains (Guan et al. 1997); therefore, the mean K concentrations varied little: soybean grains, 10.96–11.91 g kg^{-1} and maize grains, 2.34–2.41 g kg^{-1}. It has been reported that K concentrations in the grains are similar across various treatments and seasons, but that concentrations in the straw vary more between treatments—in accordance with K additions—and between replicates within treatments (Wihardjaka et al. 1999), (Table 4).

K removal

The K contained in the straw and grain is removed from the field during harvest, and before harvest, this content will decrease. It was believed that the potassium was partly washed from the leaves and straws back into the soil or simply moved to back into the soil through the root system. (Sayre 1948). In view of this fact, the calculated results according to K concentration in crops must be lower at harvest. From an agronomic point of view, the K washed from crops and transferred to root eventually returns to the soil; therefore, it is appropriate to treat K removed from the field during harvest as K removed from the soil.

The uptake of K followed the same trend as that observed with grain yield. K uptake was the highest with the NPKM treatment followed by that with the NPK treatment, and it was considerably lower with the control treatment. A better physical environment, coupled with sufficiency of water and nutrients, facilitated the uptake of nutrients and hence crop yield. Yang et al. (2004) found that the incorporation of organic residues significantly increased K uptake by rice plants, and facilitated the allocation and transfer of nutrient elements to rice grains.

The results of several long-term experiments have shown that considerable amounts of K are either leached from or have been fixed in the soil (Srinivasa et al. 1999b; Singh et al. 2002a). The greater uptake of K by crops after NP treatment as compared to that after the control treatment suggests that K was released from the soil K reserves in the plots under NP treatment in greater quantities than that released in unfertilized soils (Table 5).

K budget

K fertilizers, manure, rainfall, and seeds are the sources of K, while K output occurs because of the removal of crop-based K and leaching losses. Stubble was incorporated into the soil using rotary tilling before sowing, and it was not removed from the field following harvest. The K balance, therefore, was independent of the presence of stubble.

Table 6 shows that over the 18 year study period, the total K input with the control treatment was 59 kg ha^{-2}, which was mainly attributable to rainfall. The total K uptake in the control treatment was

Table 4 Average concentration of K in grains and stalks of crops subjected to different treatments, from 1990 to 2007 (g kg^{-1})

Treatments	Soybean grain K (g kg^{-1})	Soybean straw K (g kg^{-1})	Maize grain K (g kg^{-1})	Maize straw K (g kg^{-1})
CK	10.59a	3.39d	2.30a	4.57bcd
M	11.15a	3.83cd	2.36a	4.63bcd
N	10.86a	3.62cd	2.32a	4.81bc
NM	11.24a	3.96bcd	2.34a	4.89bc
NP	10.74a	3.64cd	2.29a	4.21d
NPM	11.25a	4.18bc	2.34a	4.45cd
NPK	11.24a	4.56ab	2.34a	5.09b
NPKM	11.56a	4.88a	2.39a	5.57a

The same letter is not significantly different according to Fisher's Protected LSD test at the 5% level of probability

Table 5 Average K output with different fertilizer treatments, from 1990 to 2007

Treatments	Soybean grain (kg ha^{-2})	Soybean straw (kg ha^{-2})	Soybean grain (kg ha^{-2})	Soybean straw (kg ha^{-2})
CK	278d	87e	172d	376d
M	393bc	127cd	234c	451cd
N	293d	97de	250bc	434cd
NM	403bc	140c	302ab	509bc
NP	343cd	129cd	278abc	436cd
NPM	445ab	178b	311a	501bc
NPK	436ab	184ab	315a	564b
NPKM	501a	218a	338a	703a

The same letter is not significantly different according to Fisher's Protected LSD test at the 5% level of probability

Table 6 Budget of K with different fertilizer treatments, from 1990 to 2007

Treatments	Seeds (kg ha^{-2})	Rainfall (kg ha^{-2})	Fertilizer (kg ha^{-2})	Recycled manure (kg ha^{-2})	Output of K (kg ha^{-2})	Budget (kg ha^{-2})
CK	5	54	0	0	487	−428
M	5	54	0	387	630	−184
N	5	54	0	0	586	−527
NM	5	54	0	433	721	−229
NP	5	54	0	0	634	−575
NPM	5	54	0	496	750	−195
NPK	5	54	1,080	0	793	346
NPKM	5	54	1,080	574	933	780

487 kg ha^{-2}; however, only 59 kg ha^{-2} K was recycled to the soil through seeds and rainfall. Thus, the apparent negative balance of K with the control treatment was 428 kg ha^{-2}. NP or N treatment of the soils resulted in a greater negative K balance than that in the control treatment. This was because of higher K uptake in the NP and N treatments compared to that in the control treatment.

In both the N and NP treatments, the K input was similar, but a significant negative K balance was observed with the NP treatment because of the higher yield responses of the crops treated with P fertilizers. Analyzes of the results of the M, NM, and NPM treatments revealed that the total K removed by the crops surpassed the amount of K recycled to the soil over the 18 year period, which shows a net negative K balance ranging from 184 to 229 kg ha^{-2}.

Compared to treatments that involved the addition of recycled manure, those that did not resulted in greater K deficits; this indicates that the addition of recycled manure can correct the K deficit to a large extent. In the case of the NPK treatment, the K input from chemical fertilizers was 1,080 kg ha^{-2} over the 18 year study period, and the total K removal from the crops was 793 kg ha^{-2}. Compared to the control treatment, the NPK treatment resulted in an apparent K balance of 346 kg ha^{-2} because under this treatment, 60 kg $year^{-1}$ K was derived from chemical K fertilizers. This result demonstrates that under these experimental conditions, an annual application of 60 kg K is adequate for maintaining the soil K concentration at its initial value, apart from the annual fluctuations that were not fully explained. NPKM treatment consistently improved the apparent K balance by about 43 kg ha^{-2} $year^{-1}$. The positive K balance observed with NPKM treatment was greater than that with NPK treatment because the addition of recycled manure in the former resulted in greater K input.

Discussion

Nutrient limitations for crops and cropping systems

Increasing crop yields is a primary concern for farmers in the plain of the Liaohe River because land is scarce in this region. However, future increments in crop yields are likely to become smaller and will depend on changes in nutrient management (Dobermann et al. 2002). It has been shown that high crop yields can be attained through N and P management strategies that take into account plant requirements and better matching of K supply with plant demand (Mussgnug et al. 2006). However, K fertilizer application is much less common than N and P fertilizer application owing to the lack of awareness of the effects of K on crop growth. A 20 year field experiment in north China (Kong et al. 2006) showed that the content of soil-exchangeable K had decreased by 30%. K is the most yield-limiting macronutrient for soybeans in north China, and fortunately, K application has been studied in greater detail and considerable progress has recently been made in this area. Many reports are available regarding the yield-increasing effects of K fertilizers (Zhou et al. 2007; Tan et al. 2007a; Liu et al. 2007).

Exchangeable and non-exchangeable K

The results showed that imbalanced fertilization (i.e., N and NP treatments) significantly decreases the soil-exchangeable K content. This shows that nutrient depletion and deterioration of soil fertility are inevitable when only chemical fertilizers are used (Su et al. 2006). In contrast, the soil-exchangeable K content declined slightly over the experimental period in the case of the treatments that included recycled manure (M, NM, and NPM), but did not reach levels expected on the basis of nutrient-balance estimates. Even long-term application of K (60 kg ha^{-2}) without the addition of recycled manure did not significantly increase the soil-exchangeable K content. It was reported that the annual application of 33 kg ha^{-2} K was adequate to maintain the soil-exchangeable K content at its initial value (Jouany et al. 1996). These results were obtained for soils with high concentrations of K.

Among all the treatments, the NPKM treatment resulted in the highest soil-exchangeable K content. Soil-exchangeable K content is usually used a primary index for determining the availability of soil K for plants in a given season, while the content and release velocity of non-exchangeable K should be taken into account to determine the long-term availability of soil K (Xie and Zhou 1999). The soil-exchangeable K content in brown soil was low in the beginning of the experiment and approached the "lowest level." (The decomposability of K^+ in soil colloids is affected by the large amounts of Ca^{2+} in calcareous brown soil.) Therefore, the K absorbed by the crops chiefly consisted of mineral K and K released from non-exchangeable K; their content-and-release velocity was adequate to meet the demands of the crops because the release of soil K can be hastened by treatment with only N or P fertilizers for long periods (Jouany et al. 1996). The decline in non-exchangeable K and a simultaneous increase in soil-exchangeable K concentrations, as was clearly observed in the case of the NPK treatment, showed that most of the K taken up by the crops had originated from non-exchangeable forms—i.e., via the soil solution and soil-exchangeable phase—with the equilibrium among the K forms being reestablished (Mengel and Rahmatullah 1994; Singh et al. 2002b). Greater amounts of K were released when organic manure was applied together with NPK fertilizers, which is consistent with the findings of Srinivasa et al. (1999a).

K depletion and apparent K balance

The greater removal of K (i.e., 52 kg ha^{-1} $year^{-1}$) with the NPKM treatment than that with the NPK treatment could be associated with other benefits of the application of recycled manure (such as decreased loss of nutrients from the soil and improved soil physical properties), apart from additional nutrient supply (Bhattacharyya et al. 2006). The negative apparent K balance observed with different fertilizer and manure treatments in the long-term experiments was attributed to the uptake of larger quantities of K by crops than the amount of K added to the soil or the amount of labile K that had been either leached from the plow layer or fixed in the mineral interlayer (Swarup and Wanjari 2000). The intensification of crop production, in combination with unbalanced fertilization practises, has already resulted in a depletion of K in soils over large areas of China (Tan et al. 2007b). Our results show that recycled manure combined with K fertilizers can satisfactorily be used to attain positive K balance.

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References

Ali MM, Shaheed SM, Kubota D, Masunaga T, Wakatsuki T (1997) Soil degradation during the period 1961–1995 in Bangladesh .1. Carbon and nitrogen. Soil Sci Plant Nutr 43:863–878

Anon (1986) Analysis of agricultural materials, reference book 427, 3rd edn. HMSO, London

Bhattacharyya R, Prakash V, Kundu S, Ghosh BN, Srivastva AK, Gupta HS (2006) Potassium balance as influenced by farmyard manure application under continuous soybean–wheat cropping system in a Typic Haplaquept. Geoderma 137:155–160. doi:10.1016/j.geoderma.2006.08.006

Cai ZC, Qin SW (2006) Crop yield, N use efficiency and environmental impact of a long-term fertilization experiment in fluvor aquic soil in north China. Acta Pedol Sin 43:885–891

Dobermann A, Cassman KG, Sta Cruz PC, Adviento MAA, Pampolino MF (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. III. Phosphorus. Nutr Cycl Agroecosyst 46:111–125. doi:10.1007/BF00704311

Dobermann A, Witt C, Dawe D, Abdulrachman S, Gines HC, Nagarajan R, Satawathananont S, Son TT, Tan CS, Wang GH, Chien NV, Thoa VTK, Phung CV, Stalin P, Muthukrishnan P, Ravi V, Babu M, Chatuporn S, Sookthongsa J, Sun Q, Fu R, Simbahan GC, Adviento MAA (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res 74:37–66. doi:10.1016/S0378-4290(01)00197-6

Guan YX, Dai JY, Xu SC (1997) Effects of soil drought during flowering and rewatering on plant compensative growth and yield of maize. Acta Agron Sin 23(6):740–745

Jagadamma S, Lal R, Hoeft RG, Nafziger ED, Adee EA (2008) Nitrogen fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central Corn Belt, USA. Soil Tillage Res 98:120–129. doi:10.1016/j.still.2007.10.008

Jones JB (1973) Soil testing in the United States. Commun Soil Sci Plant Anal 4:307–322. doi:10.1080/00103627309366451

Jouany C, Colomb B, Bosc M (1996) Long-term effects of potassium fertilization on yields and fertility status of calcareous soils of Southwest France. Eur J Agron 5:287–294. doi:10.1016/S1161-0301(96)02042-4

Kong XB, Zhang FG, Wei Q, Xu Y, Hui JG (2006) Influence of land use change on soil nutrients in an intensive agricultural region of North China. Soil Tillage Res 88:85–94. doi:10.1016/j.still.2005.04.010

Liu EK, Zhao BQ, Hu CH, Li XY, Li YT (2007) Effects of long-term nitrogen, phosphorus and potassium fertilizer applications on maize yield and soil fertility. Plant Nutr Fertil Sci 13:789–794

Liu SP, Nie XT, Zhang HC, Dai QG, Huo ZY, Xu K (2006) Effects of tillage and straw returning on soil fertility and grain yield in a wheat-rice double cropping system. Trans Chin Soc Agric Eng 22:48–51

Liu XJ, Wang JC, Lu SH, Zhang FS, Zeng XZ, Ai YW, Peng SB, Christie P (2003) Effects of non-flooded mulching cultivation on crop yield, nutrient uptake and nutrient balance in rice–wheat cropping systems. Field Crops Res 83:297–311. doi:10.1016/S0378-4290(03)00079-0

Liu RL, Jin JY, Wu RG, Liang MZ (2000) Study on the characteristics of potassium cycling in different soil–crop systems in northern China. Plant Nutr Fertil Sci 2: 123–132

Ma JY, Li KJ, Cao CY, Zheng CL (2007) Effect of long-term located organic-inorganic fertilizer application on fluvo-aquic soil fertility and crop yield. Plant Nutr Fertil Sci 13(2):236–241

Mengel K, Rahmatullah K (1994) Exploitation of potassium by various crop species from primary minerals in soils rich in micas. Biol Fertil Soils 17:75–79. doi:10.1007/BF00418676

Mussgnug F, Becker M, Son TT, Buresh R, Vlek PLG (2006) Yield gaps and nutrient balances in intensive, rice-based cropping systems on degraded soils in the Red River Delta of Vietnam. Field Crops Res 98:127–140. doi:10.1016/j.fcr.2005.12.012

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium carbonate. US Department of Agriculture, Circular no. 939, p 19

Quemener J (1986) Important factors in potassium balance sheets. In: Laudelout H (ed) Nutrient balances and the need for potassium. I.·P. I, Bern, pp 41–72

Regmi AP, Ladha JK, Pathak H, Pasuquin E, Bueno C, Dawe D, Hobbs PR, Joshy D, Maskey SL, Pandey SP (2002) Yield and soil fertility trends in a 20-year rice–rice–wheat experiment in Nepal. Soil Sci Soc Am J 66:857–867

Sayre JD (1948) Mineral accumulation in corn. Plant Physiol 23:267–281

Shen SM (1998) Soil fertility in China. Chinese Agricultural Press, Beijing

Singh M, Singh VP, Reddy D (2002a) Potassium balance and release kinetics under continuous rice–wheat cropping system in Vertisol. Field Crops Res 77:81–91. doi:10.1016/S0378-4290(01)00206-4

Singh M, Tripathi AK, Reddy D (2002b) Potassium balance and release kinetics of non-exchangeable K in a Typic Haplustert as influenced by cattle manure application under a soybean–wheat system. Aust J Soil Res 40:533–541. doi:10.1071/SR00064

Srinivasa RC, Subba R, Srivastava S, Singh SP (1999a) Crop response, uptake and the efficiency of potassium in berseem and sudan grass on a Typic Haplustert. J Potassium Res 15:113–118

Srinivasa RC, Anand SM, Subba RA, Raja GV (1999b) Kinetics of non-exchangeable potassium release from a Tropaquept as influenced by long-term cropping, fertilization and manuring. Aust J Soil Res 37:317–328. doi:10.1071/S98049

Su YZ, Wang F, Suo DR, Zhang ZH, Du MW (2006) Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat–wheat–maize cropping system in northwest China. Nutr Cycl Agroecosyst 75:285–295. doi:10.1007/s10705-006-9034-x

Su YZ (2001) Potassium balance and potash application effect in cultivated lands of Gansu Province. Soils 2:73–76

Swarup A, Wanjari RH (2000) Three decades of all-Iindia co-ordinated research project on long-term fertilizer experiments to study changes in soil quality crop productivity and sustainability. Indian Institute of Soil Science, Bhopal, India

Tan DS, Jin JY, Huang SW (2007a) Effect of long-term application of K fertilizer on spring maize yield and soil K in northeast China. Sci Agric Sin 40:2234–2240

Tan DS, Jin JY, Huang SW, He P (2007b) Effect of long-term K application on corn yield and potassium forms in plough layer of black soil and meadow soil in northeast of China. Plant Nutr Fertil Sci 13:850–855

Wang BR, Xu MG, Wen SL (2005) Effect of long-term fertilizers application on soil characteristics and crop growth in red soil upland. J Soil Water Conserv 19(1):97–101

Wihardjaka A, Kirk GJD, Abdulrachman S, Mamaril CP (1999) Potassium balances in rain fed lowland rice on a light-textured soil. Field Crops Res 64:237–247. doi:10.1016/S0378-4290(99)00045-3

Wood LK, De Turk EE (1940) The adsorption of potassium in soil in non replaceable forms. Soil Sci Soc Am Proc 5:152–161

Xie JC, Zhou JM (1999) Progress in study on soil potassium and application of potassium fertilizers in China. Soils 31:244–254

Yang CM, Yang LZ, Yang YX, Ouyang Z (2004) Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. Agric Water Manage 70:67–81. doi:10.1016/j.agwat.2004.05.003

Yang ZM, Zhou WZ, Bao SD (1999) Comprehensive evaluation on potassium supplying potential of main soils in China. Acta Pedol Sin 36(3):377–385

Yu WT, Zhao X, Zhang L, Ma Q (2007) Contribution of long-term fertilization to crop yield. Chin J Ecol 26(12):2040–2044

Zhang DX, Han ZQ, Liu W, Gao SG, Hou DJ, Li GF, Chang LS (2005) Effect of different treatments on the space-time dynamic changes of soil nutrients by returning maize straw under different decay conditions. Chin J Soil Sci 36:360–364

Zhang SM, Hao MD, Chen L (2006) Effects of long-term fertilization on yield of wheat and soil fertility in dry 1and of Loess Plateau. Agr Res Arid Areas 24:85–89

Zhang SM, Yan H, Liu GD (1999) Soil K supplying capacity and release of non-exchangeable K in Shandong soils. Plant Nutr Fertil Sci 5(3):26–31

Zhou LY, Li XD, Tang X, Lin YJ, Li ZF (2007) Effects of different application amount of N, P, K fertilizers on physiological characteristics, yield and kernel quality of peanut. Chin J Appl Ecol 18:2468–2474

Zhuang HY, Cao WX, Shen XP, Lu JF (2000) Soil nutrient balance and adjustment under intensive wheat-rice double cropping. Acta Ecol Sin 20:765–770