



Potassium assessment of grain producing soils in North China

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ARTICLE INFO

Article history:

Received 21 April 2011

Received in revised form

18 November 2011

Accepted 23 November 2011

Available online 17 December 2011

Keywords:

Potassium budgets

Soil potassium

Utilization efficiency of K fertilizer

Yield effect of K fertilizer application

ABSTRACT

Agricultural land around the world is often potassium (K) deficient, and decreasing soil K availability is a global challenge for grain producers. In China, negative K budgets are ubiquitous and K depletion is accelerating. Previous studies have mainly focused on the effect of insufficient K fertilizer on single soil types and cropping systems but have not evaluated the effects of balanced fertilizer application on K budgets. In this study, soil K budgets of grain producing soils and the effects of K fertilizer application on crops under different cropping systems and soil types were evaluated from 1992 to 2006. Two treatments each at nine locations in North China were replicated four times, four plots received nitrogen (N) and phosphorus (P) fertilizer application exclusively, and the other four plots received N, P, and K fertilizer application. Basic soil properties, available K, slowly available K, crop rotations, crop K absorption, and yield were monitored and evaluated and K budgets and K use efficiencies were calculated. Average annual K absorption by crops with K fertilizer application was $230.2 \text{ kg ha}^{-1} \text{ K}_2\text{O}$, and the average annual deficit was $46.8 \text{ kg ha}^{-1} \text{ K}_2\text{O}$. Long-term application of K fertilizer increased available soil K on all nine sites by an average of 35.7 mg kg^{-1} . Annual K absorption by crops averaged 99.0 kg ha^{-1} in the northeast region, 181.2 kg ha^{-1} in the north-central region, and 220.9 kg ha^{-1} in the northwest region. Annual K fertilizer use efficiency in the northeast (39.9%) and north-central (38.8%) regions were higher than in the northwest (17.8%). Correlations between annual K budgets and K use efficiency with fertilizer application, crop rotation, and soil type were weak. High spatial variability and low correlation between variables is a result of the complex mechanisms of K cycling. Research directions are proposed which would contribute to a better understanding of these mechanisms and processes and how they affect agronomic and economic objectives.

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1. Introduction

Potassium (K) deficiency is a world-wide problem (Dobermann et al., 1998). In Europe, 25% of soils routinely test low in available K (Johnston, 2003) and the majority of soils in sub-Saharan Africa test low in available K (Smaling, 1998). At the same time, the K status of agricultural soils is also decreasing across the globe, from Europe (Fagerberg et al., 1996; Bengtsson et al., 2003), to Africa (Harris, 1998; Wortmann and Kaizzi, 1998), to Asia (Hedlund et al., 2003; Wijnhoud et al., 2003), and North America (Malo et al., 2005).

In China, due to limited arable land and the necessity to increase production to ensure national food security, nitrogen (N) and phosphorus (P) fertilizer recommendations and subsequent application have increased annually (Gao et al., 2006). At the same time, K fertilizer application is increasingly inadequate. Zhao et al. (2008) found that in a county-wide survey in the Yangtze Delta Region,

38% of samples had K values below recommended levels according to Chinese testing standards. A study by the National Soil Survey Office (1998) found that 40% of agricultural land in South China was deficient in K.

Potassium deficiency in China has been well correlated with excess N and P application (Wang et al., 2008; Liu et al., 2009). This is partially because the majority of K fertilizer in China is imported and therefore cost prohibitive (Wang, 1996; Sheldrick et al., 2003) and because farmers are not aware of the economic benefit of K fertilizer application. Some farmers suppose that N and P application increases yield infinitely (Hu et al., 2007); and application of K fertilizer does not produce results as quickly as N and P fertilizer application, causing farmers to question the value of K fertilizer application (Jin, 1997).

Soil K is not only low in China, it is also decreasing (Li et al., 2002; Suo et al., 2002; Zhang et al., 2010). Soil fertility tests have shown that available soil K is declining, nation-wide, especially in already infertile soils (Xie and Zhou, 1999). Wang et al. (2008) found that on intensively cultivated vegetable plots in the Yangtze Delta Region, K balances in some areas were as low as -500 kg ha^{-1} . Available K decreased by 21% on a rice–wheat cropping system in Zhangjiagang

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Fig. 1. Location of the nine study sites in North China.

County (Darilek et al., 2009), where decreasing soil K is, reportedly, one of the top fertility concerns (Sheldrick et al., 2003; Gao et al., 2006) and TK decreased by 9% on agricultural land in Suzhou over an 18 year period (Li et al., 2007). Zhang et al. (2010) reported negative annual K balances on rice/wheat systems, even when K fertilizer application was applied at rates which resulted in a 20% increase of yield.

Recent studies have also shown that K fertilizer application is greatly improving production in China (Jiang et al., 2006), and particularly in the major grain producing areas of North China (Liu et al., 2000; Lin et al., 2006). Other studies have highlighted the importance of balanced K application for sustainable agricultural development (Singh et al., 2002; Liu et al., 2009). In Northern Shandong Province, K balance in one wheat–maize rotation study was $-163 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Ju et al., 2007) and in Heilongjiang, K balance was $-20.1 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Zhou et al., 2000). Another county-wide study in Hebei found that available K decreased by 64.9 mg kg^{-1} from 1980 to 1999 (Kong et al., 2006). However, these studies have mainly focused on single soil types and cropping systems. There is still a lack of understanding of K balance in grain producing soils of different soil types and under various popular fertilizer and crop rotation programs in North China. Additionally, although these studies called for balanced fertilizer application ratios and have evaluated the results of improper nutrient input, few of these studies have evaluated the results of fertilizer application which follows these recommendations. Without this knowledge, the economic and agronomic benefits of K fertilizer application for different regions and under different management strategies cannot be fully evaluated.

In this study, soil K budgets of grain producing soils and the effects of K fertilizer application on crop yield and soil K availability under different cropping systems and soil types were evaluated from 1992 to 2006. This investigation contributes to a more comprehensive understanding of the soil K status under current and recommended agricultural production practices, and provides a new, robust foundation for further research to answer critical soil K issues in North China and similar intensive grain producing regions around the world.

2. Materials and methods

2.1. Experimental sites

Nine sites, representative of different areas of North China, were selected for research (Fig. 1). Shuangcheng, Gongzhuling, and Shenyang represented the northeastern provinces of Heilongjiang, Jilin, and Liaoning, respectively; Xinji, Luoyang, and Linfen

represented the north-central provinces of Hebei, Henan, and Shanxi, respectively; and Yinchuan, Xining, and Changji represented the northwestern provinces of Ningxia, Qinghai, and Xinjiang, respectively (Table 1). Each crop was sampled annually at each site from 1992 to 2006 and soil was sampled in 1992 and 2006. Crops were local high-yield varieties, and management followed local best management practices. Xinji, Luoyang, and Yinchuan each had crop rotations and the other six sites were monoculture.

2.2. Experimental design

Each site had eight plots. Four plots at each site received only N and P fertilizer application according to the rates in Table 2, and four plots received N, P, and K fertilizer application according to the rates in Table 2. Application rates of N and P fertilizers were determined in 1992 at each site according to popular local practices and remained constant through 2006. Application of K fertilizer was determined based on crop yield, crop rotation, and K nutrient status of the soils in 1992 at each site according to prudent recommendations and remained constant through 2006. Fertilizer types were $\text{CO}(\text{NH}_2)_2$, $\text{Ca}(\text{H}_2\text{PO}_4)_2$, and KCl for N, P, and K, respectively.

2.3. Chemical analysis

Each plot was divided into four sections and the entire crop in each section was harvested and measured annually. Seed and straw subsamples were dried, ground, sieved, and digested in concentrated sulfuric acid and hydrogen peroxide (Lindner and Harley, 1942). Potassium concentrations were then determined using atomic absorption spectrometry (Wright and Stuczynski, 1996).

Topsoil samples (0–20 cm) ($n=12$) were collected after harvests in 1992 and 2006. Subsamples were mixed, dried, and sieved through a 1 mm sieve. Soil mineralogy was determined using X-ray diffraction (Whittig and Allardice, 1986); soil pH was determined in a water:soil ratio of 2.5:1 with a pH electrode; CEC was determined using the ammonium acetate method (Sumner and Miller, 1996); soil inorganic N was determined by steam-distillation reduction to nitrate and then determined by titration with standard acid (Mulvaney, 1996). Soil P was determined using the Olsen method (Olsen and Sommers, 1982). Organic matter was determined using the wet combustion method (Nelson and Sommers, 1996). Soil texture was determined using the hydrometer method (Gee and Bauder, 1986).

Total K was digested in a nickel crucible with sodium hydroxide at 750°C (Lu, 1999). Available K (also known as exchangeable K) was determined using the ammonium acetate method (Helmke and Sparks, 1996). Non-exchangeable K was determined using the nitric acid extraction method (Helmke and Sparks, 1996). All K determinations were conducted using atomic absorption spectrometry (Wright and Stuczynski, 1996). Slowly available K was calculated by subtracting available K from non-exchangeable K.

2.4. Statistical analysis

All data was subjected to analysis of variance appropriate to the experimental design. T-tests were conducted to test the significance of the treatment differences. Microsoft Excel and DPS7.05 were used for all statistical analysis. Annual K budgets were calculated by subtracting K crop removal (kg ha^{-1}) from total K fertilizer application ($\text{kg ha}^{-1} \text{ K}_2\text{O}$) and annual K efficiency indexes were calculated by dividing annual K fertilizer application by annual K crop removal. Annual K budgets and use efficiency indexes were reported as $\text{kg ha}^{-1} \text{ K}_2\text{O}$. Average annual K crop removal ($\text{kg ha}^{-1} \text{ K}_2\text{O}$) was calculated by multiplying the above ground plant biomass (kg ha^{-1}) by crop K concentrations. Potassium fertilizer effect on

Table 1
Soil and climate of soil at nine sites in North China.

Site location	Soil order ^a	Soil texture	Mineralogy hierarchy	Altitude (m)	Avg. annual rainfall (mm)	Avg. annual temp. (°C)
Shuangcheng	Isohumosol	Sandy loam	Montmorillonite > mica > chlorite > quartz	175	480	3.5
Gongzhuling	Isohumosol	Clay loam	Vermiculite > mica kaolinite > quartz	225	572	5.6
Shenyang	Cambosol	Sandy clay loam	Mica > quartz > kaolinite > vermiculite	51	722	8.1
Xinji	Cambosol	Loam	Vermiculite > mica > chlorite > quartz > kaolinite	35	488	12.5
Luoyang	Luvisol	Clay loam	Mica > montmorillonite > chlorite > quartz	353	546	14.2
Linfen	Luvisol	Loam	Mica > montmorillonite > chlorite > quartz	1035	498	12.6
Yinchuan	Anthrosol	Clay loam	Mica > kaolinite > quartz > chlorite > vermiculite	1111	152	8.5
Xining	Luvisol	Loam	Mica > chlorite > quartz > vermiculite	2295	368	5.9
Changji	Aridosol	Sandy loam	Mica > kaolinite > vermiculite > quartz	1748	215	8.5

^a According to Chinese Soil Taxonomy (2001) (CST).**Table 2**
Fertilizer application and crop rotations at nine sites in North China from 1992 to 2006.

Site location	Fertilizer application (kg ha ⁻¹)			Number of applications	Crop rotation	Plot size (m ²)
	N	P ₂ O ₅	K ₂ O			
Shuangcheng	172	110	112.5	1	Spring maize	30
Gongzhuling	225	113	112.5	1	Spring maize	40
Shenyang	300	150	112.5	1	Spring maize	43
Xinji	225	90	150	2	Wheat/maize	50
Luoyang	225	180	150	2	Wheat/maize	30
Linfen	195	105	150	1	Winter wheat	33
Yinchuan	110	103.5	150	2	Wheat/maize	34
Xining	110	55.2	150	1	Winter wheat	25
Changji	144	103.5	112.5	1	Wheat/maize	40

use efficiency was calculated by subtracting K uptake for treatments without K fertilizer from K uptake for treatments with K fertilizer divided by K fertilizer application. To compensate for variation among years, available and slowly available K differences between the beginning and end of the study period were calculated by subtracting the average of the last three years by the average of the first three years.

3. Results

3.1. Potassium absorption by crops

Regardless of fertilizer application, crop rotation, and soil type, K balances on all sites were negative. Average annual K absorption by crops was 230.2 kg ha⁻¹ K₂O and the average annual deficit was 46.8 kg ha⁻¹ K₂O. There was no discernable trend to explain annual K budgets and K use efficiency on the nine sites. The K deficit was higher in the north-central region than the northeast region. Annual K absorption by crops was higher in treatments with K fertilizer application than those without K fertilizer application (Fig. 2 and Table 5). Within treatment, annual K absorption

was significantly higher in locations where annual K application was 300 kg ha⁻¹ K₂O, which were also the areas that had a wheat/maize rotation; however, the annual K budgets and balance indexes of K were not well correlated with annual K application (Table 5). Annual K absorption by crops averaged 99.0 kg ha⁻¹ in the northeast region, 181.2 kg ha⁻¹ in the north-central region, and 220.9 kg ha⁻¹ in the northwest region. The northwest region had the highest regional annual K deficit (−67.7 kg ha⁻¹ K₂O), followed by the north-central region (−41.4 kg ha⁻¹ K₂O), followed by the northeast region (−31.4 kg ha⁻¹ K₂O). Potassium balance index ranged from 0.59 in Changji to 1.00 in Linfen.

3.2. Temporal variation of topsoil K

Basic soil properties were analyzed in 1992 (Table 6). Long-term application of K fertilizer increased available soil K on all nine sites by an average of 33.8 mg kg⁻¹ (Table 3). Except for Gongzhuling, available K plus slowly available K were higher at every site with application of K fertilizer. Available K decreased on six of the nine sites which did not receive K fertilizer application and available soil K during the study period on sites which did not receive K fertilizer application was −3.6 mg kg⁻¹. Slowly available soil K increased on five of the nine sites which received long-term application of K fertilizer and the overall difference was 21.0 mg kg⁻¹ (Table 4). Slowly available soil K increased on four of the nine sites which received no K fertilizer and the overall difference was −41.2 mg kg⁻¹. Comparing the difference between NP and NPK treatment effects on available soil K by region, K fertilization increased available soil K by 23.4 mg kg⁻¹, 53.0 mg kg⁻¹, and 30.8 mg kg⁻¹, and increased slowly available soil K by 30.2 mg kg⁻¹, 93.1 mg kg⁻¹, and 72.8 mg kg⁻¹, for the northeast, north-central, and northwest regions, respectively.

The capacity of the soil to release K increased along a gradient from the northeast to the northwest, and K fertilizer use efficiency variation is inversely correlated (Fig. 3). Annual K fertilizer use efficiency in the northeast (39.9%) and north-central (38.8%) regions were higher than in the northwest (17.8%), utilization efficiencies among the three sites of the northeast were not significantly different. In north-central China, K fertilizer use efficiency was relatively

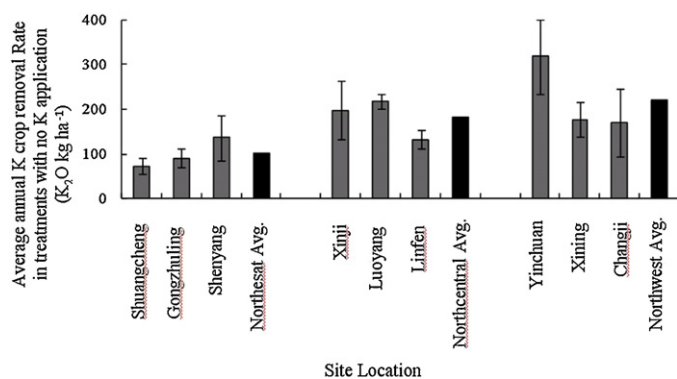
**Fig. 2.** Average annual K crop removal in treatments with no K application of nine sites in North China from 1992 to 2006.

Table 3
Temporal variation of soil available potassium at nine sites in North China.

Site location	Treatment	Available K (mg kg ⁻¹)						Difference ^a
		1992	1993	1994	2004	2005	2006	
Shuangcheng	NP	164.2	163.9	163.5	159.8	159.5	159.4	-4.3
	NPK	164.2	166.3	167.1	177.4	176.9	178.4	11.7
Gongzhuling	NP	158.6	158.3	157.7	152.3	151.8	151.4	-6.4
	NPK	158.6	158.8	159.2	162.6	163.5	161.7	3.7
Shenyang	NP	85.3	84.8	84.4	78.1	77.7	77.1	-7.2
	NPK	85.3	87.6	89.4	117.5	118.9	120.6	31.6
Xinji	NP	99.1	98.6	97.9	91.8	91.2	90.6	-7.3
	NPK	99.1	101.3	104.1	131.8	133.2	134.8	31.8
Luoyang	NP	128.8	128.4	128	123.7	123.3	122.5	-5.2
	NPK	128.8	130.5	133.8	159.7	161.5	163.8	30.6
Linfen	NP	137.9	140.1	141.9	162.5	164.2	165.7	24.2
	NPK	137.9	150.2	162.1	233.8	242.9	250.7	92.4
Yinchuan	NP	129.4	129.9	131.2	146.6	147.3	148	17.1
	NPK	129.4	132.5	135.6	173.8	176.9	178.1	43.8
Xining	NP	177.3	174.8	170.6	130.5	127.7	125.4	-46.4
	NPK	177.3	178.1	178.9	185.4	186.6	188.7	8.8
Changji	NP	198.8	199.3	199.6	201.5	200.7	203.8	2.8
	NPK	198.8	199.7	201.4	205.9	206.3	207.1	6.5

^a Difference is the average of years 1992–1994 subtracted from the average of years 2004–2006.**Table 4**
Temporal variation of soil slowly available potassium at nine sites in North China.

Site location	Treatment	Slowly available K (mg kg ⁻¹)						Difference ^a
		1992	1993	1994	2004	2005	2006	
Shuangcheng	NP	937.2	937.8	941.2	951.8	953.2	954.5	14.4
	NPK	937.2	941.5	943.8	984.6	986.4	989.7	46.1
Gongzhuling	NP	1065.4	1054.9	1045.7	1060.1	1055.8	1065.6	5.2
	NPK	1065.4	1048.7	1053.8	1057.5	1068.7	1032.3	-3.1
Shenyang	NP	890.4	891.2	891.8	901.9	902.9	903.3	11.6
	NPK	890.4	897.8	903.4	962.8	967.1	971.8	70.0
Xinji	NP	1070.7	1061.9	1053.6	933.2	920.8	911.9	-140.1
	NPK	1070.7	1067.7	1068.2	1043.6	1040.2	1038.6	-28.1
Luoyang	NP	1104.5	1098.1	1093.5	1021.3	1014.6	1008.2	-84.0
	NPK	1104.5	1104.2	1103.8	1090.7	1090.5	1089.8	-13.8
Linfen	NP	1149.3	1146.5	1143.7	1096.4	1093.1	1089.1	-53.6
	NPK	1149.3	1151.2	1153.4	1174.6	1178	1180	26.2
Yinchuan	NP	1087.3	1083.4	1078.9	1015.2	1013.9	1009.3	-70.4
	NPK	1087.3	1090.5	1093.7	1120.5	1122.7	1125.2	32.3
Xining	NP	1429.8	1421	1414.3	1334.2	1321.8	1310.2	-99.6
	NPK	1429.8	1427.5	1428.6	1420.3	1420.2	1419.5	-8.6
Changji	NP	881.8	896.2	899.3	944.8	931.4	952.8	50.6
	NPK	881.8	885.9	890.3	953.7	957.9	949.2	67.6

^a Difference is the average of years 1992–1994 subtracted from the average of years 2004–2006.**Table 5**
Effect of long-term application of potassium fertilizer on potassium balances of nine sites in North China from 1992 to 2006 (kg ha⁻¹ K₂O).

Region	Site location	Annual crop absorption	Annual soil budget	K balance index	Regional annual soil budget
Northeast	Shuangcheng	117.2 ± 16.3	-4.7	0.96 ± 0.13	-31.4
	Gongzhuling	141.1 ± 38.3	-28.6	0.80 ± 0.34	
	Shenyang	173.3 ± 58.6	-60.8	0.65 ± 0.24	
North-central	Xinji	379.5 ± 110.8	-79.5	0.79 ± 0.17	-41.4
	Luoyang	344.6 ± 22.8	-44.6	0.87 ± 0.06	
	Linfen	150.1 ± 28.8	-0.1	1.00 ± 0.17	
Northwest	Yinchuan	376.8 ± 114.8	-76.8	0.80 ± 0.18	-67.7
	Xining	197.8 ± 28.5	-47.8	0.76 ± 0.12	
	Changji	191.0 ± 79.6	-78.5	0.59 ± 0.31	

Table 6
Basic topsoil (0–20 cm) properties of North China in 1992.

Site location	pH	CEC (cmol kg ⁻¹)	Total N (g kg ⁻¹)	OM (g kg ⁻¹)	Alkaline hydrolysis N (mg kg ⁻¹)	Available P (mg kg ⁻¹)	Total K (g kg ⁻¹)
Shuangcheng	7.7	26.4	1.78	29.8	38	37	19
Gongzhuling	6.4	21.6	1.24	21.2	46.4	101.2	20
Shenyang	6.3	14.6	0.99	17.3	27.5	56.4	20.5
Xinji	7.7	15.2	1.05	14	37.6	19.1	18
Luoyang	7.6	15.1	0.97	13.1	32.9	18.6	19.5
Linfen	7.8	14.8	0.86	12.6	35	24.8	18
Yinchuan	7.8	10.8	0.97	11.5	28.6	31.8	20
Xining	7.6	13.8	1.27	18.3	33.8	90.4	20
Changji	7.5	15.5	1.01	16.8	36.8	23.4	21.5

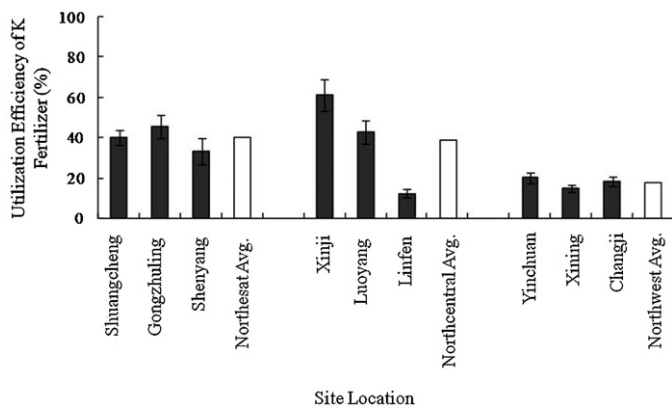


Fig. 3. Average annual K fertilizer use efficiency of nine sites in North China from 1992 to 2006.

higher in the crop rotation systems of Xinji (61.2%) and Luoyang (42.8%), and lower in Linfen (12.3%). Potassium fertilizer use efficiency was lowest in the northwest, and there was no significant difference among the sites in this region.

3.3. Potassium fertilizer effect on crop yield

The effect of K fertilizer application on maize yield was significant among the three regions (Table 7). In Shuangcheng, significant maize yield response to K application was found starting in the first year, in Gongzhuling significant yield response to K was found starting in the third year, and in Shenyang maize yield response to K application was unstable from 1993 to 2006. Yield effect of K application was similar in Xinji and Luoyang, which showed significant difference between the two fertilizer treatments in the seventh year of the study. It appeared that maize was more sensitive to K application than wheat, and significant yield increase occurred one year earlier for maize than wheat. In Linfen, yield effect of K application was not significantly different among years except 2000, 2001, and 2005. Effect of K fertilizer application on yield varied widely in the northwest. In Yinchuan, yield effect of K fertilizer was significant in maize starting in 2000 and in wheat starting in 2002. No significant yield increase from K application was found in Xining. In Changji, K fertilizer had a significant yield effect on maize starting in 1995 and had no effect on wheat during the study period.

Application of K fertilizer significantly increased yield of wheat and maize to varying degrees, except wheat in Xining. Among these sites, there was significant yield increase on maize in the three sites of the northeast, in Xinji of the north-central China, and in Changji of the northwest; and significant yield increase to a lesser degree on crops in Luoyang and Linfen of north-central China and in Yinchuan and Xining of the northwest. Comparing the three regions, K fertilizer application effect on yield was higher in the northeast than in the north-central and northwest regions (Fig. 4).

4. Discussion

4.1. Soil K balances

Negative K budgets on every site in the study, regardless of K fertilizer application, underscores the necessity of adequate and appropriate K supply to the soil. Lin et al. (2006) also found negative K balances for wheat and maize on the North China Plain despite K fertilizer application, however, application rates in that study were 105 kg ha⁻¹ and 45 kg ha⁻¹ for wheat and maize, respectively. Similarly, Ju et al. (2007) found a negative K balance of 163 kg ha⁻¹ year⁻¹ on a wheat/maize rotation system receiving

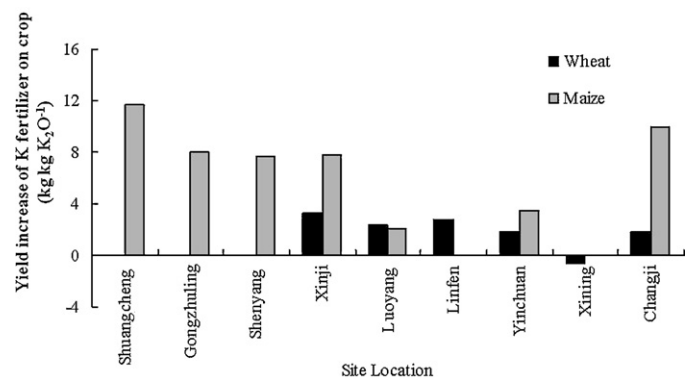


Fig. 4. Effect of K fertilizer on average yield from 1992 to 2006 at nine sites in North China.

38 kg ha⁻¹ year⁻¹ K fertilizer application on the North China Plain. Zhang et al. (2010) applied inorganic and organic K on a rice/wheat system at rates of 90–180 kg ha⁻¹ year⁻¹ and had average annual negative K balances of –27 to –86 kg ha⁻¹. Our study shows that negative K balances persist on wheat/maize rotation systems, even when K application rates are as high as 300 kg ha⁻¹; with wheat cultivation, when K application rates are 150 kg ha⁻¹; and with maize cultivation, when K application rates are 112.5 kg ha⁻¹.

Many studies have suggested balanced N:P:K application ratios (Sheldrick et al., 2003; Gao et al., 2006; Lin et al., 2006; Darilek et al., 2009), however soil K was still unbalanced in the treatments receiving K fertilizer application after 14 years of what many of those studies consider balanced N:P:K application ratios. Vitosh et al. (1989) suggested a 3:1:3 ratio for wheat, yet plots in this study which received K fertilizer had K application ratios similar to or higher than this recommendation.

One possibility is that K on these sites is being lost to luxury consumption (Goulding, 1983; Nishanth and Biswas, 2008). Generally, the capacity of the soil to release K increased along a gradient from the northeast to the northwest. Therefore, the use efficiency of K fertilizer varied by location of the cropping systems, perhaps largely as a result of mineralogy and climatic differences. From northeast to northwest, total K absorption by crops increased and the capacity of the soil to supply K increased during the study period. The differences in this study between annual K budgets and crop types directly relate to the results of Dong et al. (2005) which found high K absorption rates in wheat straw. On the other hand, K absorption rates in this study are within what is considered normal for maize, wheat, and maize/wheat rotation (Goulding, 1983; Haby et al., 1990). Luxury uptake in this study is also ambiguous because K fertilizer application improved yield to some degree on every site except, arguably, Shenyang and Xining.

4.2. Available soil K

At the same time, available soil K and slowly available soil K increased or only slightly decreased on many of the plots in this study. This is an abnormal trend compared to other similar studies in China (Xie and Zhou, 1999; Darilek et al., 2009). Also, available soil K in this study is within what many studies consider adequate and even optimal for maize and wheat production (Rehm et al., 1985; Haby et al., 1990) and on some plots available K increased even when soil K balance was negative.

This implies that K fertilizer application is not the only source of K for crop absorption. The primary source of K for crops on fields which do not receive fertilizer application is weathering of parent material. Sheldrick et al. (2003) estimated that 41% of K crop absorption comes from soil K reserves. Wheat absorbs more

Table 7
Effect of K fertilizer application on crop yield at nine sites in North China (T-test).

Site location	Crop	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Shuangcheng	Maize	**	**	**	**	**	**	**	**	**	**	**	**	**	**
Gongzhuling	Maize			**	**	*	**	*		*		*	**	*	*
Shenyang	Maize		**												
Xinji	Wheat														
	Maize							*	**	**	**	**	**	**	**
Luoyang	Wheat						*		*	*	**	**	**	**	**
	Maize								**	*	**	**	**	**	**
Linfen	Wheat								**	*				*	
Yinchuan	Wheat										*	*	*	*	*
	Maize								**	*	*	**	**	**	**
Xining	Wheat													*	
Changji	Wheat	–		–		–		–		–		–		–	
	Maize		–	*	–	*	–	**	–	**	–	**	–	*	–

Blank denotes no significant difference. –: no data.
* Significant difference at $p < 0.05$.
** Significant difference at $p < 0.01$.

nonexchangeable K in the rhizosphere than soil solution K further from the roots (Miller, 1988). Feldspars and micas contain 70–150 g kg^{−1} K (Malavolta, 1985) and weathering of these minerals contributes considerable amounts of K to soil solution (Haby et al., 1990). On all nine sites in our study, micas were either the primary or secondary mineral. Research has also shown that silt (Mengel and Kirkby, 2001) and subsoil K (Woodruff and Parks, 1980) may also be significant sources of K uptake for crops.

To a large extent, soil mineralogy also greatly affects soil K equilibrium and fixation. Soil mineralogy significantly influences cation exchange capacity and K saturation of the exchange complex (Goulding, 1983). This means that soils of differing mineralogy have starkly different K buffering capacities. Also, K in solution tends to be in equilibrium with available K, which tends to be in equilibrium with nonexchangeable K (Beckett, 1964). Therefore, K fixation, or conversion from available K to nonexchangeable K, maintains the K status of soils by reducing leaching and luxury consumption, but also reduces the short-term effectiveness of K fertilizer application because as available K increases, equilibrium moves toward nonexchangeable pools.

All of this suggests that it may not be agronomically or economically advantageous to apply K fertilizer based on K budgets alone, as these can be misleading about the actual K status of the soil. If nonexchangeable K and K buffering capacity are high, nonexchangeable K may be able to supply some K to crops over an extended period of time. Additionally, if high K application rates are causing increased fixation and yields are not limited by K, it may not be economically feasible to apply K fertilizer to balance K budgets, particularly because K resources are limited and K fertilizer costs continue to rise.

4.3. Spatial variation of K

Large spatial variation in this study highlights that fertilizer application and management practices must be site specific. Comparing the three regions, it is evident that soil K absorption by crops was highest in the northwest region, followed by the north-central region, and then the northeast region, which research has shown to be closely associated with crop yield levels and capacity of soils to supply K in North China (Huang et al., 1998).

It is well known from a theoretical and practical standpoint that external factors such as climate, mineralogy, pH, and texture all play an important role in soil K concentrations and transport (Malavolta, 1985) and that these factors must be considered before any management decisions can be made. In this regard, the specific mechanisms of soil K balances and use efficiency in North China are still vague. Additionally, management factors such as

fertilization rate and timing, fertilizer type, and crop rotation also play an important role in soil K availability and transport (Zhu et al., 2007; Tan et al., 2009). Though researchers argue that proper fertilizer application can increase use efficiency and minimize nutrient movement into nontarget areas, external and management factors taken together comprises a system which makes understanding K budgets in North China ambiguous and management decisions difficult.

5. Conclusions

This research confirms that soil K budgets continue to decrease, that soil K availability and K use efficiency are highly variable, and that the mechanisms of K cycling are highly complex. Soil K in North China becomes seriously depleted without application of K fertilizer and soil K balance continues to decrease with conventional NPK fertilizer application. The highest removal of soil K was found in the field trial of winter wheat–summer maize double cropping system. Maize yield was more sensitive to K application than wheat, and the effectiveness of K application on maize was more rapid than wheat. Use efficiency of K fertilizer in the northeast and north-central regions were higher than in the northwest, and also higher in double cropping systems. There was significant spatial variation of available soil K and slowly available soil K within fertilizer treatments, which highlights the role of external and management factors in the mechanisms of K transfer in agricultural systems of North China. In order to better understand these mechanisms and processes and how they affect agronomic and economic objectives, further research is needed on three fronts. A higher density study of soil properties and K pools in North China may reveal significant correlations among these variables. Regional studies using various K fertilizer rates while tracking K budgets would help to evaluate appropriate and sustainable K fertilizer rates for each region. And farm-level cost/benefit analysis of K fertilizer rates and yield would assist farmers in making well-informed management decisions.

Acknowledgments

We thank the National Natural Science Foundation of China (31101601), the National Basic Research Program of China (973 Program: 2007CB109306), the China Agriculture Research System (CARS-03), and the IPNI-Shandong Project for their financial support.

References

- Beckett, P.H., 1964. Studies on soil potassium. II. The ‘immediate’ Q/I relations of labile potassium in the soil. *J. Soil Sci.* 15, 9–23.

- Bengtsson, H., Öborn, I., Jönsson, S., Nilsson, I., Andersson, A., 2003. Field balances of some mineral nutrients and trace elements in organic and conventional dairy farming: a case study at Öjebyn, Sweden. *Eur. J. Agron.* 20, 101–116.
- Chinese Soil Taxonomy (CST), 2001. In: Li, F. (Ed.), *Chinese Soil Taxonomy*. Science Press, Beijing.
- Darilek, J.L., Huang, B., Wang, Z.G., Qi, Y.B., Zhao, Y.C., Sun, W.X., Gu, Z.Q., Shi, X.Z., 2009. Changes in soil fertility parameters and the environmental effects in a rapidly developing region of China. *Agric. Ecosyst. Environ.* 129, 286–292.
- Dobermann, A., Cassman, K.G., Mamaril, C.P., Sheehy, J.E., 1998. Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. *Field Crop Res.* 56, 113–138.
- Dong, Y.L., Lao, X.R., Bi, J.J., Sun, W.H., 2005. Effect of straw potassium on balance of soil K in wheat/maize rotation system. *Acta Agric. Boreali-occidentalis Sinica* 14, 178–181.
- Fagerberg, B., Salomon, E., Jönsson, S., 1996. Comparisons between conventional and ecological farming systems at Öjebyn. *Swed. J. Agric. Res.* 26, 169–180.
- Gao, C., Sun, B., Zhang, T.L., 2006. Sustainable nutrient management in Chinese agriculture: challenges and perspective. *Pedosphere* 16, 253–263.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods – SSSA, Book Series No. 5*. SSSA, Madison, WI, pp. 383–412.
- Goulding, K.W., 1983. Thermodynamics and potassium exchange in soils and clay minerals. *Adv. Agron.* 36, 215–264.
- Haby, V.A., Russelle, M.P., Skogley, E.O., 1990. Testing soils for potassium, calcium, and magnesium. In: Westerman, R.L., et al. (Eds.), *Soil Testing and Plant Analysis, Book Series, No. 3*. SSSA, Madison, WI, p. 784.
- Harris, F.M.A., 1998. Farm-level assessment of nutrient balance in northern Nigeria. *Agric. Ecosyst. Environ.* 71, 201–214.
- Hedlund, A., Witter, E., An, B.X., 2003. Assessment of N, P and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam. *Eur. J. Agron.* 20, 71–87.
- Helmke, P.A., Sparks, D.L., 1996. Lithium, sodium, potassium, rubidium, and cesium. In: Sparks, D.L., et al. (Eds.), *Methods of Soil Analysis, Part 3. ASA and SSSA, Madison, WI*, pp. 551–574.
- Hu, R.F., Cao, J.M., Huang, J.K., Peng, S.B., Huang, J.L., Zhong, X.H., Zou, Y.B., Yang, J.C., Buresh, R.J., 2007. Farmer participatory testing of standard and modified site-specific nitrogen management for irrigated rice in China. *Agric. Syst.* 94, 331–340.
- Huang, S.W., Jin, J.Y., Wang, Z.L., Cheng, M.F., 1998. Native potassium forms and plant availability in selected soils from northern China. *Plant Nutr. Fert. Sci.* 4, 156–164 (in Chinese).
- Jiang, D., Hengsdijk, H., Dai, T.B., Boer, D.W., Jing, Q., Cao, W.X., 2006. Long-term effects of manure and inorganic fertilizers on yield and soil fertility for a winter wheat-maize system in Jiangsu, China. *Pedosphere* 16, 25–32.
- Jin, J., 1997. Soil potassium and potassium fertilizer use in northern China. *Better Crop Int.* 11, 16–17.
- Johnston, A.E., 2003. Understanding Potassium and Its Use in Agriculture. European Fertilizer Manufacturers Association, Brussels, Belgium, <http://www.efma.org/>.
- Ju, X.T., Kou, C.L., Christie, P., Dou, Z.X., Zhang, F.S., 2007. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environ. Pollut.* 145, 497–506.
- Kong, X.B., Zhang, F.R., Wei, Q., Xu, Y., Hui, J.G., 2006. Influence of land use change on soil nutrients in an intensive agricultural region of North China. *Soil Till. Res.* 88, 85–94.
- Li, G.L., Chen, J., Sun, Z.Y., Tan, M.Z., 2007. Establishing a minimum dataset for soil quality assessment based on soil properties and land-use changes. *Acta Ecol. Sinica* 27, 2715–2724.
- Li, Q.M., Chen, X.P., Zhang, F.S., Römhild, V., 2002. Study on balance of phosphorus and potassium in winter wheat and summer maize rotation system. *Plant Nutr. Fert. Sci.* 8, 152–156 (in Chinese).
- Lin, Z., Zebisch, M.A., Chen, G.B., Feng, Z.M., 2006. Sustainability of farmers' soil fertility management practices: a case study in the North China Plain. *J. Environ. Manage.* 79, 409–419.
- Lindner, R.C., Harley, C.P., 1942. A rapid method for the determination of nitrogen in plant tissue. *Science* 41, 1–10.
- Liu, R.L., Jin, J.Y., Wu, R.G., Liang, M.Z., 2000. Study on the characteristics of potassium cycling in different soil-crop systems in Northern China. *Plant Nutr. Fert. Sci.* 6, 123–132 (in Chinese).
- Liu, X.M., Zhang, W.W., Zhang, M.H., Ficklin, D.L., Wang, F., 2009. Spatio-temporal variations of soil nutrients by an altered land tenure system in China. *Geoderma* 152, 23–34.
- Lu, R.K. (Ed.), 1999. *Chemical Analysis of Agricultural Soil*. China Agricultural Science and Technology Press, Beijing (in Chinese).
- Malavolta, E., 1985. Potassium status of tropical and subtropical region soils. In: Munson, R.D. (Ed.), *Potassium in Agriculture*. ASA, CSSA, and SSSA, Madison, WI, pp. 163–200.
- Malo, D.D., Schumacher, T.E., Doolittle, J.J., 2005. Long-term cultivation impacts on selected soil properties in the northern Great Plains. *Soil Till. Res.* 81, 277–291.
- Mengel, K., Kirkby, E.A., 2001. *Principles of Plant Nutrition*, 5th ed. Kluwer Academic Publishers, Dordrecht, Netherlands, p. 849.
- Miller, R.O., 1988. The bioavailability of potassium on Montana soils as influenced by edaphic and environmental factors. Ph.D. Dissertation. Montana State Univ., Bozeman (Diss. Abstr. 89-25777).
- Mulvaney, R.L., 1996. Nitrogen-inorganic forms. In: Sparks, D.L., et al. (Eds.), *Methods of Soil Analysis, Part 3. SSSA and ASA, Madison, WI*, pp. 1123–1184.
- National Soil Survey Office, 1998. *Soils of China*. China Agricultural Press, Beijing, p. 1016 (in Chinese).
- Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis. Part 3: Chemical Methods – Book Series No. 5*. SSSA, Madison, WI, pp. 961–1010.
- Nishanth, D., Biswas, D.R., 2008. Kinetics of phosphorus and potassium release from rock phosphate and waste mica enriched compost and their effect on yield and nutrient uptake by wheat (*Triticum aestivum*). *Biores. Technol.* 99, 3342–3353.
- Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page (Ed.), *Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties – Agron. Monogr. No. 9*, 2nd ed. ASA, SSSA, and CSSA, Madison, WI.
- Rehm, G.W., Rosen, C.J., Moncrief, J.F., Fenster, W.E., Grava, J., 1985. Guide to computer programmed soil test recommendations for field crops in Minnesota. Univ. Minnesota Agric. Ext. Serv. AG-BU-0519.
- Sheldrick, W.F., Syers, J.K., Lingard, J., 2003. Soil nutrient audits for China to estimate nutrient balances and output/input relationships. *Agric. Ecosyst. Environ.* 94, 341–345.
- Singh, M., Singh, V.P., Reddy, D.D., 2002. Potassium balance and release kinetics under continuous rice-wheat cropping system in Vertisol. *Field Crop Res.* 77, 81–91.
- Smaling, E.M.A. (Ed.), 1998. Nutrient balances as indicators of productivity and sustainability in sub-Saharan African agriculture. *Agric. Ecosyst. Environ.* 71 (1–3), 283 (special issue).
- Sumner, M.E., Miller, W.P., 1996. Cation exchange capacity and exchange coefficients. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis. Part 3: Chemical Methods – SSSA Book Series No. 5*. SSSA, Madison, WI, pp. 1085–1121.
- Suo, D.R., Wang, T.H., Li, D.Z., 2002. A long-time study on the effect and balance of potassium. *Chinese J. Eco-Agric.* 10, 90–92 (in Chinese).
- Tan, D.S., Jin, J.Y., Huang, S.W., Liu, Z.H., Jiang, L.H., 2009. Effect of long-term application of K fertilizer on potassium character of soil-crop system under continuous maize cultivation. *Chinese J. Soil Sci.* 40, 1376–1380.
- Vitosh, M.L., Johnson, J.W., Mengel, D.B., 1989. Tri-state Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa, Bulletin E-2567. Ohio State University, <http://ohioline.osu.edu/lines/bulls.html> (verified 31.01.11).
- Wang, H.J., Huang, B., Shi, X.Z., Darilek, J.L., Yu, D.S., Sun, W.X., Zhao, Y.C., Chang, Q., Öborn, I., 2008. Major nutrient balances in small-scale vegetable farming systems in peri-urban areas in China. *Nutr. Cycl. Agroecosyst.* 81, 203–218.
- Wang, S.J., 1996. Reflections on expansion of potassium fertilizer industry in China. *J. Chem. Fert. Ind.* 26, 12–14.
- Wijnhoud, J.D., Konboon, Y., Lefroy, R.D.B., 2003. Nutrient budgets: sustainability assessment of rainfed lowland rice-based systems in northeast Thailand. *Agric. Ecosyst. Environ.* 100, 119–127.
- Whittig, L.D., Allardice, W.R., 1986. X-ray diffraction techniques. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods – SSSA Book Series No. 5*. SSSA, Madison, WI, pp. 331–362.
- Woodruff, J.R., Parks, C.L., 1980. Topsoil and subsoil potassium calibration with leaf potassium for fertility rating. *Agron. J.* 72, 392–396.
- Wortmann, C.S., Kaizzi, C.K., 1998. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agric. Ecosyst. Environ.* 71, 115–129.
- Wright, R.J., Stuczynski, T.L., 1996. Atomic absorption and flame emission spectrometry. In: Sparks, D.L., et al. (Eds.), *Methods of Soil Analysis, Part 3. ASA and SSSA, Madison, WI*, pp. 65–90.
- Xie, J.C., Zhou, J.M., 1999. Progress in study on soil potassium and application of potassium fertilizers in China. *Soils* 31, 244–254.
- Zhang, H.M., Xu, M.G., Shi, X.J., Li, Z.Z., Huang, Q.H., Wang, X.J., 2010. Rice yield, potassium uptake and apparent balance under long-term fertilization in rice-based cropping systems in southern China. *Nutr. Cycl. Agroecosyst.* 88, 341–349.
- Zhao, Y.C., Xu, X.H., Darilek, J.L., Huang, B., Sun, W.X., Shi, X.Z., 2008. Spatial variability assessment of soil nutrients in an intense agricultural area, a case study of Rugao County in Yangtze River Delta Region, China. *Environ. Geol.* doi:10.1007/s00254-008-1399-5.
- Zhou, J.M., Chen, X.Q., Xie, J.C., Härdter, R., 2000. In: Zhou, J.M., et al. (Eds.), *Nutrient Cycling and Management in Agro-Ecosystems*. Hohai University Press, Nanjing, pp. 42–52 (in Chinese).
- Zhu, Q., Tu, S.H., Chen, Z.G., Wang, Z.Q., 2007. Potassium balance on sloping lands as affected by farming systems. *Better Crop Plant Food* 91, 6–9.