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Long-term effects of potassium fertilization on yield, efficiency, and soil fertility status in a rain-fed maize system in northeast China

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ABSTRACT

The effects of 20 years of potassium (K) fertilization (in two treatments: 113 and 225 kg K_2O ha^{-1}) on grain and stover yields, plant K concentrations, aboveground K uptake, K use efficiencies, soil K pools, and the K balance were examined in a Haplic Phaeozem soil under a rain-fed mono-cropped spring maize (*Zea mays* L.) system in the province of Jilin, northeast China. The indigenous K supply (zero K application) maintained an average grain yield of 7.0 t ha^{-1} per year, but the year-to-year variation was large. Application of K significantly ($P < 0.05$) increased the average grain yields by 15.1 and 13.8% in the 113 and 225 kg K_2O ha^{-1} treatments, respectively, over the experimental period. The mean K recovery efficiency, K agronomic efficiency, and K partial factor productivity decreased from 37.3 to 28.5%, 10.8 to 4.9 kg kg^{-1}, and 86.8 to 43.1 kg kg^{-1} when the K application rate increased from 113 to 225 kg K_2O ha^{-1}. The effect of K application was larger on stover K concentrations than grain K concentrations. In the top 100 cm of the soil profile, excessive or non-synchronized K application significantly ($P < 0.05$) increased the leaching of exchangeable K in comparison with the control, but K application had little effect on soil non-exchangeable K and total K. K fertilizer, therefore, plays an important role in increasing grain yields in China, but the K application rate can be reduced if farmers return stover to the soil and make full use of K below the soil surface.

1. Introduction

Potassium (K) is an essential plant macronutrient and plays a key role in the synthesis of cells, enzymes, protein, starch, cellulose, and vitamins, in nutrient transport and uptake, in conferring resistance to abiotic and biotic stresses, and in enhancing crop quality (Epstein and Bloom, 2005; Pettigrew, 2008). However, K has been given less attention than nitrogen (N) and phosphorus (P) with respect to increasing cereal production because the effect of K on increasing cereal production is more gradual compared with N and P, especially in K-enriched soils (Tan et al., 2012 Niu et al., 2011). In China, the current priority for agricultural policy is high crop yields to meet the food demands of a large and growing population. Long-term sustainable high crop yields require integrated management practices including the application of K fertilizers.

Aboveground K uptake in cereals is divided mainly into straw K and grain K, and the concentrations of K in straw and grain can indicate whether the K status is deficient or sufficient (Mallarino and Higashi, 2009). Optimum K application may contribute to a sustainable high yield and high nutrient efficiency. However, K taken up by aboveground parts of plants is assimilated mainly into the straw and not into the grain (Jouany et al., 1996). Continual removal of straw from agricultural fields will, therefore, hasten the depletion soil K (Dierolf and Yost, 2000). Considerable amounts of straw are burned in field or used as fuel or fodder in Chinese intensive agricultural systems to avoid the negative effects of straw return to the soil on the shoot growth of subsequent crops (Xu et al., 2010; Qiu

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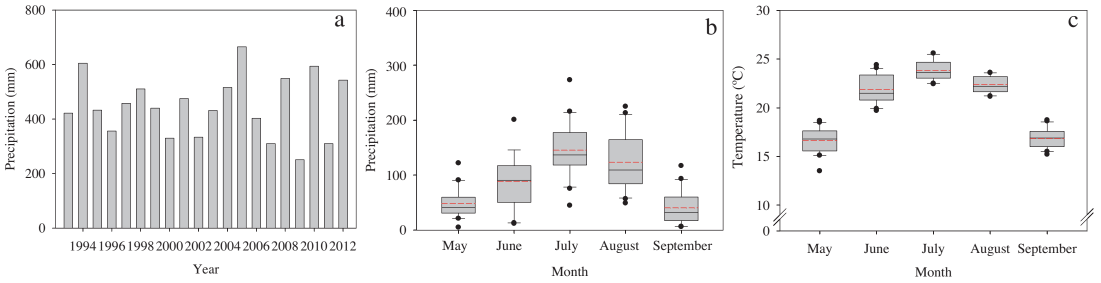

Fig. 1. Total precipitation from May to September in each year (a), monthly precipitation (b), and monthly mean temperature from May to September in the years from 1993 to 2012. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Black solid line and red break line, lower edge and upper edge, bars and dots in or outside the boxes (b, c) represent median and mean values, 25th and 75th, 5th and 95th, and 0.5th and 0.95th percentiles of all data, respectively.

et al., 2012). Potassium deficiency has appeared in 40% of the agricultural land in south China according to the National Soil Survey Office (1998), and the application of fertilizer K has markedly increased grain yields in North China (Niu et al., 2011; He et al., 2012; Tan et al., 2012). An understanding of K use and efficiency in the soil–crop system is, therefore, essential for the development of more sustainable K fertilization, especially as many Chinese soils are deficient in K.

Soil testing effectively estimates soil nutrient availability and determines the fertilization rate required to produce near-maximum yields while maintaining soil productivity (Slaton et al., 2009). Currently, an improved soil nitrate–nitrogen test for determining chemical fertilizer N rate is used successfully on the North China Plain by Chen et al. (2006, 2011). This is based on the difference between the "N demand of crop target yields" and "soil nitrate-nitrogen storage in the 0–90 cm depth root zone" and synchronized crop N demand and N supply from soil and fertilizer. The question arises whether soil K pools also effectively indicate or calibrate the appropriate fertilizer K rate with the method mentioned above. Exchangeable K and non-exchangeable K are the two important pools available to crops (Garcia et al., 2008), both of which can be regulated and replenished after the application of fertilizer K. Potassium may be retained in soil for several years following fertilizer application, therefore, long-term K fertilization experiments can monitor the effects of K fertilization on cereal production, K use efficiency, and soil K status at different soil depths.

The mono-cropped spring maize region in Jilin province, northeast China comprises the "golden maize belt" and accounts for 12.6% of total maize production nationally (Wang and Liu, 2009). The region is predominantly under rain-fed agriculture and contains highly fertile Haplic Phaeozem soils (Food and Agriculture Organization, 2002). Since the 1980s there has been a decline in the soil organic carbon content in northeast China (Huang and Sun, 2006) and an increase in soil acidification (Guo et al., 2010). These factors along with a history of high maize production with little K application have likely impacted soil K storage and buffering capacity. To develop recommendations for K fertilization and maintain soil fertility, the objectives of the present study were to elucidate the effects of chemical K fertilization on yields and fertilizer K efficiency as indicated by the results of a long-term field experiment and to examine the changes in soil K content from 0 to 100 cm depth and examine the input–output balance of K after long-term chemical fertilizer K application.

2. Materials and methods

2.1. Site

The experiment started in 1993 at Liufangzi village (43°34′ N, 124°53′ E, 200 m above sea level), Gongzhuling county, Jilin province, northeast China. This region has a typical continental monsoon climate, is predominantly under rain-fed agriculture and belongs to the "golden maize belt". The annual mean temperature is 4–5 °C, and the annual cumulative mean temperature for days with mean temperatures above 10 °C is 2000–3600 °C. The annual frost-free period is 125–150 days. The annual precipitation in the maize production area is 500–900 mm, with 60% of rainfall occurring during the summer (July–September). Information on precipitation and monthly mean temperatures from May to September from 1993 to 2012 is shown in Fig. 1 (weather data were accessed from the China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn/home.do). In the two decades of the experiment, more than 500 mm of precipitation occurred in seven years, less than 400 mm occurred in 6 years, and 400–500 mm occurred in the remaining seven years. The monthly mean temperature during the spring maize growing season from 1993 to 2012 was 20.3 °C ranging from 13.5 °C in May 1995 to 25.6 °C in July 1997.

The soil is a thin Haplic Phaeozem (Food and Agriculture Organization, 2002). The properties of the sampled surface soil (0–20 cm) at the start of the field experiment in 1993 are shown in Table 1.

Table 1
Soil basal properties and K-bearing minerals in the surface soil (0–20 cm depth) after the spring maize harvest at the end of September 1992.

Property	Value
pH	6.4
Soil organic matter (g kg^{-1})	22.4
Total N (g kg^{-1})	1.23
Total P (g kg^{-1})	1.14
Total K (g kg^{-1})	20.0
Alkaline hydrolyzable N (mg kg^{-1})	97.2
Olsen-P (mg kg^{-1})	32.4
Exchangeable K (mg kg^{-1})	156.5
Non-exchangeable K (mg kg^{-1})	1065.4
Coarse particle (>2 μm)	
Hydromica (H) (%)	7.3
Amphibole (%)	8.0
Chlorite (%)	2.9
Quartzite (%)	28.5
Feldspar (%)	26.3
Clay particle (<2 μm)	
Smectite (%)	2.4
Vermiculite (V) (%)	5.1
Mixed layer of V & H (%)	0
Hydromica (%)	6.5
Kaolinite (%)	6.5
Chlorite (%)	5.7
Quartzite (%)	0.8

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2.2. Experimental design

The field experiment was a randomized complete block with three replicates and comprised three treatments: (1) control (K_0), zero K application; (2) optimum K rate, application of 113 kg K_2O ha^{-1} (K_{113}); and (3) excessive K rate, application of 225 kg K_2O ha^{-1} (K_{225}). The optimum K rate was calculated by the K balance (Jin, 1994). In each treatment, fertilizer K was broadcast as a basal application in the form of KCl before the soil was ploughed. A total of 225 kg N ha^{-1} was applied in the form of urea, one quarter of the N was broadcast as a basal application, the remaining three quarters were top-dressed at the 8–9 leaf stage and 113 kg P_2O_5 ha^{-1} was basal broadcast as triple superphosphate. The spring maize was ridge-tilled, sown at the end of April or the beginning of May and harvested at the end of September or the beginning of October. The plot size was 10 m in length by 6 maize rows with 65-cm row spacing. The maize was over-seeded and thinned to a stand of 45,000–65,000 plants per hectare by hand-planter at the seedling stage. The details of plant number per hectare, plant spacing, cultivar, and date of maize sown and harvested are shown in Table 2. Conventional farming practices were followed in all other respects.

2.3. Sampling and analysis

At harvest, the plants were counted in three rows in each plot. The three rows were sampled to determine fresh ear and stalk yields together with ear number. Five plants were randomly selected from the harvested spring maize, separated into cobs, stalks, and grain, and the weight of each component was measured before and after oven-drying at 60 °C. Grain yield was calculated based on the fresh ear weight in the three sampled rows with cob yield deducted and was adjusted using the proportional oven-dried grain yield and cob yield in the 5-plant subsample. Stover yield was the sum of cob, husk, and stalk yields. Stalk yield was calculated based on the fresh stalk yield in the three sampled rows and the proportional oven-dried stalk yield in the 5-plant subsample, while cob and husk yields were calculated based on ear number in the three sampled rows and the average weight of oven-dried cob and husk in the 5-plant subsample. Grain and stover samples were ground and digested with H_2SO_4–H_2O_2 (Jones and Case, 1990), and the K concentration was determined using atomic absorption spectrophotometry (Helmke and Sparks, 1996). Grain yield, stover yield, plant N concentration, and plant N uptake are reported on an oven-dried basis.

After the maize was harvested in 2012, soil samples were taken from the top 100 cm of the soil profile in each plot using a tube sampler 3 cm in diameter and 100 cm in length. Soil cores were collected from seven points in each plot, separated into 0–10, 11–20, 21–30, 31–40, 41–60, 61–80, and 81–100 cm depth categories, and mixed thoroughly to obtain composite samples from each depth category. Soil bulk densities of the above depths were 1.39, 1.48, 1.39, 1.39, 1.39, 1.33 and 1.39 g cm^{-3}, respectively, in an adjacent field area. Each soil depth sample was air-dried and passed through a 2 mm sieve for determination of alkali-hydrolyzable N, Olsen-P, NH_4Ac extractable K, non-exchangeable K, and pH, and passed through a 0.15 mm sieve for the determination of soil organic carbon, total N, total P, and total K and the composition of soil K-bearing minerals.

Soil organic carbon was determined using the H_2SO_4–$K_2Cr_2O_4$ wet combustion method, with organic matter concentration calculated by multiplying the soil organic carbon concentration by 1.724 (Nelson and Sommers, 1996). Soil total N was determined by the Kjedahl method (Bremner, 1996). Soil alkali-hydrolyzable N was determined using the Mason jar diffusion method (Bremner, 1996). Soil total P and soil total K were digested in a nickel crucible with sodium hydroxide at 750 °C. Soil Olsen-P was extracted with 0.5 M $NaHCO_3$. Soil total P and Olsen-P were determined using the molybdenum colorimetric method at a wavelength of 880 nm (Kuo, 1996). Soil exchangeable K was extracted with 1 M NH_4OAc; non-exchangeable K was calculated as the difference between 1 M boiled HNO_3-extractable K and exchangeable K (Helmke and Sparks, 1996). Soil total K, NH_4OAc-extractable K, and boiled HNO_3-extractable K were determined using atomic absorption spectrophotometry (Helmke and Sparks, 1996). The soil composition of K-bearing minerals was determined using an X'Pert-Pro X-ray diffractometer with Cu Kα radiation (40 kV, 40 mA) and a graphite filter, from 3.0° to 60.0° with a scan speed of 2.0° min^{-1}. Soil pH was measured in a 1:2.5 soil: water suspension (Thomas, 1996).

Aboveground K uptake, K recovery efficiency (RE_K), K agronomic efficiency (AE_K), and K partial factor productivity (PFP_K) were calculated for each plot using the following equations:

Table 2
Plant number per hectare, plant spacing, maize cultivar, and date of maize sown and harvested in the K field experiment conducted from 1993–2012 at Jilin, northeast China.

Year	Plants (ha^{-1})	Plant spacing (cm)	Cultivar	Sowing date	Harvest date
1993	50,000	30	Danzao	April 28	September 29
1994	50,000	30	Danzao	April 28	September 30
1995	45,000	34	Sidan	April 26	September 27
1996	45,000	34	Sidan	May 3	September 28
1997	50,000	30	Haisi	April 30	October 4
1998	60,000	25	Simi	April 29	September 30
1999	50,000	30	Simi	May 1	October 1
2000	55,000	27	Simi	May 3	September 28
2001	55,000	27	Simi	May 3	September 28
2002	50,000	30	Jidan	May 2	September 26
2003	45,000	34	Tongyou	May 6	September 28
2004	50,000	30	Ping'an	April 29	September 30
2005	50,000	30	Ping'an	May 1	September 30
2006	60,000	25	Zhangyu	May 3	September 28
2007	65,000	23	Zhengdan958	May 2	September 26
2008	60,000	25	Xianyu335	May 3	September 28
2009	60,000	25	Xianyu335	May 4	September 28
2010	50,000	30	Lvyu	May 1	September 30
2011	50,000	30	Lvyu	April 29	September 29
2012	50,000	30	Lvyu	April 30	September 28

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$$\text{Aboveground K uptake} = \text{Grain K concentration} \times \text{Grain yield} + \text{Stover K concentration} \times \text{Stover boimass}$$

$$\mathrm{RE_K} = \frac{U - U_0}{\text{Krate}} \times 100\%$$

$$\mathrm{AE_K} = \frac{Y - Y_0}{\text{Krate}}$$

$$\mathrm{PFP_K} = \frac{Y}{\text{Krate}}$$

where U and Y represent aboveground K uptake and grain yield in the K application treatments, and U_0 and Y_0 represent aboveground K uptake and grain yield in the control plots. The K rate is the total amount of K applied during maize growth.

2.4. Statistical analysis

Analysis of variance was conducted using K rate, cultivar, density, and precipitation as fixed variables, using the GLM procedure (SAS 9.0). Density is arbitrarily divided into four levels of 45,000–49,999, 50,000–54,999, 55,000–59,999 and ≥60,000 plants per hectare. Precipitation is arbitrarily divided into three levels of <400, 400–499 and ≥500 mm. Correlation between total precipitation in each month during maize growing season and grain or stover yield was calculated by linear regression (PROC CORR). Mean values of the variables in each treatment were compared using least significant difference at the 5% level.

2.5. Results

In only three years, from 1993 to 2012, the grain yield did not increase significantly ($P > 0.05$) above the control value following both application rates of fertilizer K (Table 3). Correspondingly, the average grain yield increased to approximately 1.0 t ha^{-1} with average increases of 15.1 and 13.8% in K_{113} and K_{225} treatments, respectively, during the experimental period. Soil indigenous K (control) maintained an average grain yield 7.0 t ha^{-1} per year during the two decades of the experiment.

Compared with the control treatment, the application of both rates of K significantly ($P < 0.05$) increased stover yield in sixteen of twenty years and the average stover yield increased by 13.9–16.8% (Table 3). In contrast with grain yield, stover yield of the K_{225} treatment usually appeared to be higher than that of the K_{113} treatment, but the difference was not significant ($P > 0.05$).

Except for 4 of 15 years, the application of K did not significantly ($P > 0.05$) affect grain K concentrations in comparison with the control and the average grain K concentration remained stable (Table 4). Conversely, application of K significantly ($P < 0.05$) increased stover K concentrations. Prior to 2000, the maximum stover K concentrations occurred in the K_{225} treatment but in 2001 and from 2006 to 2012 the stover K concentrations in the K_{113} treatment were slightly higher than or equivalent to those of the K_{225} treatment. The stover K concentration in the control also increased after 2006. Application of K led to a significant ($P < 0.05$) increase in aboveground K uptake in comparison with the control and in both the K_0 and K_{113} treatments the aboveground K uptake after 2006 was higher than before 2006. Before 2006, the aboveground K uptake in the K_{225} treatment was significantly higher ($P < 0.05$) than in the K_{113} treatment although the aboveground K uptake in the K_{113} treatment usually appeared to be slightly higher than in the K_{225} treatment after 2006 there was no significant difference ($P > 0.05$). Averaged over all years the KHI significantly decreased with increasing K rate ($P < 0.05$). However, the significant difference in KHI occurred mainly before 2001 ($P < 0.05$) and there was no significant difference after 2006 between the different K treatments ($P > 0.05$).

Analysis of variance further suggests that K rate, cultivar, and precipitation significantly ($P < 0.01$) affected grain yield, stover yield, grain K concentration, stover K concentration, and aboveground K uptake (Table 5). The interaction between K rate and the other factors significantly ($P < 0.01$) affected stover yield and stover K concentration, but their interaction did not significantly

Table 3
Grain yield, stover yield, and their rate of increase in the K_0, K_{113}, and K_{225} treatments.

Year	Grain yield (t ha^{-1})			Stover yield (t ha^{-1})			Grain increase rate (%)		Stover increase rate (%)	
	K_0	K_{113}	K_{225}	K_0	K_{113}	K_{225}	K_{113}	K_{225}	K_{113}	K_{225}
1993	8.1^{a}a^{c}	8.3a	8.4a	7.7b	8.5b	11.0a	2.9a	3.7a	11.7b	44.0a
1994	7.1a	7.5a	7.6a	7.8a	7.9a	10.1a	5.3a	7.5a	0.8a	29.2a
1995	8.0b	8.8a	8.8a	9.8b	12.5a	11.6a	9.1a	10.0a	27.1a	18.9a
1996	5.9b	7.2a	6.8a	8.3a	8.4a	8.5a	21.4a	14.9a	0.6a	2.7a
1997	6.1b	7.5a	6.9a	6.1b	7.4a	8.3a	23.6a	14.7a	20.9a	35.8a
1998	7.4b	8.8a	8.8a	7.1b	8.7a	8.2a	19.8a	20.0a	22.6a	15.4a
1999	7.3c	8.5b	9.0a	6.8c	8.1b	8.5a	16.0a	22.9a	20.2a	25.4a
2000	3.7b	4.2ab	4.6a	4.3a	4.5a	4.8a	14.3a	26.5a	6.0a	12.2a
2001	7.4b	8.2a	8.1a	7.5ab	7.3b	7.8a	11.4a	9.6a	-3.2b	3.7a
2002	6.2b	7.6a	7.4a	5.5b	6.8a	6.1ab	22.1a	20.2a	22.3	11.7
2003	5.2a	5.9a	5.9a	4.3b	4.9a	5.0a	13.0a	14.3a	12.3a	15.1a
2004	7.9b	8.9a	8.8a	6.6b	7.5a	7.6a	13.8a	12.7a	13.2a	15.3a
2005	6.5c	7.6a	7.2b	5.6b	6.5a	6.0ab	16.6a	9.8a	16.1a	7.2a
2006	8.6b	9.6a	9.4a	7.6b	8.4a	8.3a	11.3a	9.3a	10.9a	9.6a
2007	6.2b	7.1a	7.0a	5.1b	5.6ab	6.0a	15.5a	13.0a	9.8a	17.9a
2008	7.7b	8.8a	8.9a	7.0b	7.8ab	7.9a	14.7a	15.5a	10.4a	11.6a
2009	5.7b	6.9a	6.6a	5.7b	7.0a	6.6a	21.1a	16.3a	22.7a	15.3a
2010	8.3b	9.8a	9.4a	7.2b	9.2a	8.8a	18.8a	13.7a	27.7a	21.9a
2011	8.4b	9.4a	9.3a	7.4b	8.3a	8.4a	13.0a	11.5a	12.7a	13.8a
2012	8.2c	9.6a	9.0b	7.5b	8.5a	8.3a	17.9a	10.6a	13.5a	10.7a
Mean^{b}	7.0b	8.0a	7.9a	6.8b	7.7a	7.9a	15.1a	13.8a	13.9a	16.8a

K subscript represents amount of K_2O in the different treatments.

[a] Mean of three replicates.

[b] Mean of all individual plots in the same treatment from 1993 to 2012.

[c] Lower case letter denotes difference at $P < LSD_{0.05}$ in different treatments.

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Table 4
Grain K concentration, stover K concentration, aboveground K uptake, and K harvest index (KHI) in the K_0, K_{113}, and K_{225} treatments. Data are from 1993 to 2001 and 2006 to 2012.

Year	Grain K concentration (g kg^{-1})			Stover K concentration (g kg^{-1})			Aboveground K uptake (kg ha^{-1})			KHI		
	K_0	K_{113}	K_{225}	K_0	K_{113}	K_{225}	K_0	K_{113}	K_{225}	K_0	K_{113}	K_{225}
1993	3.2[a]b[c]	3.5a	3.5a	8.1b	12.0a	14.1a	88.4c	130.8b	184.8a	0.30a	0.22b	0.16c
1994	–	–	–	7.5c	11.6b	17.2a	–	–	–	–	–	–
1995	3.1a	3.2a	3.2a	7.1c	11.3b	15.8a	94.3c	168.6b	211.6a	0.27a	0.17b	0.13c
1996	3.1b	3.2b	3.5a	5.9c	9.6b	17.9a	67.7c	103.4b	176.9a	0.27a	0.22b	0.14c
1997	3.6a	3.6a	3.6a	8.5c	11.1b	15.1a	74.5c	109.1b	149.8a	0.30a	0.25b	0.17c
1998	2.6a	2.7a	2.7a	5.4c	10.6b	16.0a	57.9c	116.4b	155.5a	0.33a	0.20b	0.15c
1999	3.1a	2.9a	3.0a	7.1c	9.9b	12.6a	71.0c	104.7b	133.5a	0.32a	0.23b	0.20c
2000	3.8b	4.0a	4.0a	7.0c	8.2b	11.6a	44.3c	54.1b	74.4a	0.32a	0.31a	0.25b
2001	3.1a	3.0a	3.1a	8.3b	14.4a	14.2a	85.6c	129.5b	136.2a	0.27a	0.19b	0.18b
2006	3.7a	4.2a	4.3a	14.1b	14.5a	14.4ab	138.5b	161.7a	160.1a	0.23a	0.25a	0.26a
2007	3.6b	4.1ab	4.6a	13.8c	14.4a	14.1ab	92.3b	109.2a	116.3a	0.24a	0.27a	0.27a
2008	3.9a	4.3a	4.1a	13.4b	14.3a	14.1ab	124.1b	148.6a	147.2a	0.24a	0.25a	0.25a
2009	4.6a	4.7a	4.6a	14.0b	14.7a	14.4ab	106.2b	135.2a	125.6a	0.24a	0.24a	0.24a
2010	3.9a	4.1a	3.9a	13.6b	14.4a	14.3a	130.9c	173.2a	163.5b	0.25a	0.23a	0.23a
2011	4.0a	4.1a	4.0a	13.5b	14.4a	14.1a	133.1b	158.3a	155.6a	0.25a	0.25a	0.24a
2012	3.8a	3.8a	3.7a	9.2b	11.1a	10.1a	100.3b	130.8a	117.2a	0.31a	0.28b	0.29b
Mean[b]	3.6a	3.7a	3.7a	9.8c	12.3b	14.4a	93.3c	128.1b	150.6a	0.28a	0.24b	0.21c

Subscript of K represents K_2O amount in different treatments.
– No data available.
[a] Mean of three replicates.
[b] Mean of all individual plots in the same treatment from 1993 to 2001 and 2006 to 2012 data accidentally from 2002 to 2005.
[c] Lower case letter denotes difference at $P < LSD_{0.05}$ in different treatments.

affect grain yield or grain K concentration ($P > 0.05$) (Table 5). Plant density significantly ($P < 0.05$ or $P < 0.01$) affected grain yield, grain K concentration, and stover K concentration (Table 5). In addition, a significant positive correlation existed between precipitation in July and grain or stover yield ($P < 0.05$ or $P < 0.01$) (Table 6).

In eleven of the fifteen years, from 1993 to 2001 (except for 1994 because of lack of grain K concentration data) and 2006 to 2012, K recovery efficiency, K agronomy efficiency, and K partial factor productivity were higher in the K_{113} treatment than in the K_{225} treatment. Between the two K treatments, there were significant differences ($P < 0.05$) in K recovery efficiency in nine of fifteen years, in K agronomy efficiency in seven of fifteen years, and in K partial factor productivity in all years. Over the experimental period, average K recovery efficiencies were 37.3 and 28.5%, average K agronomy efficiencies were 10.8 and 4.9 kg kg^{-1}, and average K partial factor productivity was 86.8 and 43.1 kg kg^{-1} in the K_{113} and K_{225} treatments, respectively.

Soil exchangeable K (Fig. 2a) increased with soil depth, especially in the K_0 and K_{113} treatments. At each soil layer above 60 cm, soil exchangeable K in the K_{225} treatment significantly larger ($P < 0.05$) than in K_0 and K_{113} treatments with the exception of the 30–40 cm soil layer. In all treatments, soil non-exchangeable K (Fig. 2b) remained stable above 40 cm and declined below 40 cm. Generally, total K (Fig. 2c) in 0–100 cm soil depth remained stable at approximately 20 g kg^{-1} in the three treatments, though the surface soil (0–10 cm) in the K_{225} treatment had a slightly higher total K concentration than the other two treatments ($P > 0.05$).

Throughout the top 100 cm of the soil profile after two decades of K application (Table 8), the K_{225} treatment significantly ($P < 0.05$) increased soil exchangeable K in comparison with the other treatments, while soil exchangeable K in the K_{113} treatment was similar to that in the control. Potassium application did not significantly ($P > 0.05$) increase soil non-exchangeable K or total K.

It was only determined K-bearing minerals at depths 0–10, 30–40 and 80–100 cm (Table 9), because the concentrations of non-exchangeable K and total K in the top 100 cm changed little after two decades of K application (Fig. 2b and c) and a clear inflexion of non-exchangeable K (Fig. 2b) was found at 30–40 cm soil depth. Quartzite and feldspar were the dominant minerals. Chlorite in coarse particles, vermiculite and mixed layers of vermiculite and hydromica in clay particles in the K_{113} treatment were predominant among the three treatments. In each treatment smectite,

Table 5
Analysis of variance for the effects of the K_2O application rate, cultivar, density, precipitation, and the interactions between K_2O rate and the other variables on grain yield, stover yield, aboveground K uptake, grain K concentration, and stover K concentration.

	Grain yield	Stover yield	Grain K concentration	Stover K concentration	Aboveground K uptake
Rate (*R*)	**	**	**	**	**
Cultivar (*C*)	**	**	**	**	**
Density (*D*)	*	ns	**	**	ns
Precipitation (*P*)	**	**	**	**	**
$C \times R$	ns	**	ns	**	**
$D \times R$	ns	**	ns	**	ns
$P \times R$	ns	*	ns	**	**

ANOVA data of aboveground K uptake, grain K concentration, and stover K concentration uses all individual plots from 1993 to 2001 and 2006 to 2012, data of grain or stover K concentration from 2002 to 2005 accidentally lost.
Density is arbitrarily divided into four levels of 45,000–49,999, 50,000–54,999, 55,000–59,999 and ≥60,000 plants per hectare.
Precipitation is arbitrarily divided into three levels of <400, 400–499 and ≥500 mm.
ns Not significant at $P > 0.05$.
[*] Denote significant difference in ANOVA at $P < 0.05$.
[**] Denote significant difference in ANOVA at $P < 0.01$.

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Table 6
Correction between monthly precipitation from May to September and grain or stover yield.

	May	June	July	August	September
Grain yield	0.1163	0.1603	0.5073^{**}	0.0542	−0.0156
Stover yield	0.254	0.0789	0.2865^{*}	−0.0057	−0.013

vermiculite and kaolinite in clay particles increased with increasing soil depth.

After two decades of K application, the annual aboveground K uptake values (output) were 90.1, 123.8, and 144 kg K ha^{-1} per year in the K_0, K_{113}, and K_{225} treatments, respectively (Fig. 3). The K_0 and K_{113} treatments experienced K losses of 90.1 and 30.3 kg ha^{-1} per year, respectively, and the K_{225} treatment exhibited a K surplus of 42.7 kg K ha^{-1} per year. According to the differences in the exchangeable K content in the top 20 cm of the soil profile between 1992 and 2012, the control experienced some loss in soil exchangeable K, the K_{225} treatment experienced a surplus, and soil exchangeable K in the K_{113} treatment remained stable (Table 10). Similarly, the order of K loss in non-exchangeable K was control $>K_{133} > K_{225}$.

3. Discussion

Maize is relatively sensitive to K deficiency (Sharma et al., 2010; Niu et al., 2011; He et al., 2012). Niu et al. (2011) reported that K application under farming management practices increased summer maize grain yields by 9.9–14.9% compared with crops to which no K was applied on the North China Plain. He et al. (2012) found that K application increased summer maize grain yields by an average of 46% in a 19-year field experiment on the North China Plain. Vyn et al. (2002) also reported that K application significantly ($P < 0.05$) increased maize grain yields (by 11.5% in a zero tillage system and by 8.6% in a mulch tillage system) in Canada. The average rate of increase in maize grain yield in our studies (Table 3) is similar to that found by Niu et al. (2011) and Vyn et al. (2002), but the variation in the rate of maize grain increase from 1992 to 2012 was large because of differences in precipitation, cultivar, and plant density (Table 5).

Sufficient precipitation can promote root growth, increase soil available K concentration, and increase K assimilation by roots. In July, in northeast China, maize develops from the elongation stage to the tasseling stage (V8-VT) (Li et al., 2012). This phase is important for aboveground biomass production and nutrient assimilation (Ciampitti and Vyn, 2011; Ciampitti et al., 2013) and further significantly affects grain yield and stover yield ($P < 0.05$ or $P < 0.01$) (Table 6). The cultivar response to K nutrition depends mainly on genotypic variation (Georage et al., 2002). Woodend et al. (1987) found genotypic variation in the efficiency of K uptake and use in wheat under K stress. The present study indicates that the indigenous K supply (K uptake in the zero K control) increased from 1993 to 2012 (Table 4). This further indicates that modern maize breeders have been paying more attention to K nutrition and its importance in increasing grain yield. Generally, the newer maize hybrid cultivars have higher potential yield than older cultivars (Wang et al., 2011), but maize yields in northeast China have not further increased because of the tradeoff of adverse climate change since the mid-1990s (Chen et al., 2013). Differences in the per-plant and per-area maize yield of the crops are partially a function of plant density. In general, the per-area yield increases, and the per-plant yield decreases when plant density increases from low to an optimum density or to an extremely high density of tolerant plants (Antonietta et al., 2014). In addition, the N/K ratio can affect grain yield, with optimum N/K ratio promoting healthy plant growth and imbalanced N/K ratios leading to maladjusted plant growth (Niu et al., 2011; Zhang et al., 2011). For example, in our study, the average grain yield in the two decades of the experiment decreased by only 0.1 t ha^{-1} when the K rate increased from 113 to 225 kg K_2O ha^{-1} (Table 3), but the N/K ratio decreased from 2.4 to 1.2. Heckman and Kamprath (1992) reported that yield increased linearly with K application rate below 135 kg K_2O ha^{-1}. Our results show that soil can maintain a K balance at an approximate rate of 150 kg K_2O ha^{-1} per year according to our K balance calculation (Fig.3).

Nutrients in different tissues can reflect the availability of the nutrients to plants and the three phases of plant nutrient uptake are designated minimum, poverty adjustment, and luxury consumption (Mallarino and Higashi, 2008; Chen et al., 2010). Grain K concentrations are well buffered against the deficiency or sufficiency of N or K supply (Zhang et al., 2010). For example, the average grain K concentration remained at 3.7 g kg^{-1} over the experimental period regardless of K application in the present study. Other studies have reported similar grain K concentrations following K application (Setiyono et al., 2010; Mallarino and Higashi, 2008; Niu et al., 2011). High variation in grain K concentrations was found at different experimental sites by Niu et al. (2011) and in different years in this study (Table 4). This was mainly because of the complex effect of climate, soil available K supply, cultivar, cultivation methods, and their interactions on stover and grain K concentration, as shown in Table 5. These factors can also explain the lower stover K concentration observed in our study (Table 4) than the mean value reported in Nebraska and southeast Asia (21.8 g kg^{-1}) (Setiyono et al., 2010). The majority of K is taken up in stover biomass (Mallarino and Higashi, 2008) and further results in differences in aboveground K uptake. The average percentage of stover K uptake to aboveground K uptake was 72.3, 76.4 and 79.4% in the control and K_{113} and K_{225} treatments, respectively. The difference in aboveground K uptake between before 2001 and after 2006

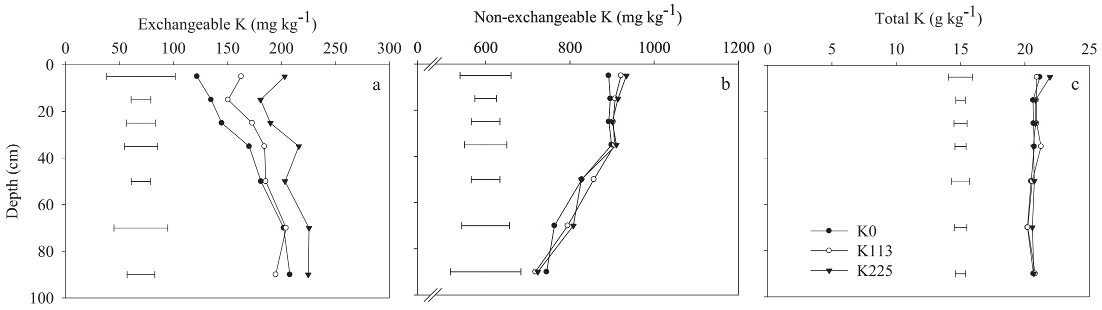

Fig. 2. Concentrations of exchangeable K, non-exchangeable K, and total K at different soil depths (in 10-cm increments from 0 to 40 cm and in 20-cm increments from 40 to 100 cm) in the control, K_{113}, and K_{225} treatments in 2012 (two decades following planting).
Legend represents the amount of K_2O applied in the different treatments. The horizontal line denotes the $LSD_{0.05}$ value.

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Table 7
Potassium recovery efficiency, K agronomic efficiency, and K partial factor productivity in the K_0, K_{113}, and K_{225} treatments. Data are from 1993 to 2001 and 2006 to 2012.

Year	K recovery efficiency (%)		K agronomic efficiency ($kg\,kg^{-1}$)		K partial factor productivity ($kg\,kg^{-1}$)	
	K_{113}	K_{225}	K_{113}	K_{225}	K_{113}	K_{225}
1993	45.2[a]a[c]	51.6a	2.4a	1.6a	88.6a	44.9b
1994	–	–	4.1a	2.8a	79.6a	40.8b
1995	79.3a	62.8a	7.8a	4.3a	93.5a	47.4b
1996	38.1b	58.5a	13.4a	4.6b	76.3a	36.2b
1997	36.9a	40.3a	14.7a	4.6b	79.6a	37.2b
1998	62.4a	52.3b	15.4a	7.7b	94.0a	47.2b
1999	36.0a	33.5a	12.5a	9.0a	90.8a	48.3b
2000	10.4a	16.1a	5.4a	5.0a	45.0a	24.9b
2001	46.8a	27.1b	8.8a	3.7a	87.4a	43.2b
2006	24.8a	11.6b	10.3a	4.3a	102.4a	50.6b
2007	18.0a	12.9a	10.1a	4.2a	76.2a	37.4b
2008	26.1a	12.3b	12.0a	6.3a	94.0a	47.5b
2009	30.9a	10.4b	12.8a	5.0b	73.2a	35.3b
2010	45.1a	17.5b	16.6a	6.0b	105.0a	50.4b
2011	26.8a	12.0b	11.6a	5.1b	100.8a	49.9b
2012	32.5a	9.0b	15.6a	4.6b	102.9a	48.5b
Mean[b]	37.3a	28.5a	10.8a	4.9b	86.8a	43.1b

K subscript represents amount of K_2O in different treatments.
– No data available.
[a] Mean of three replicates.
[b] Mean of all individual plots in the same treatment from 1993 to 2001 and 2006 to 2011, data of grain or stover K concentration from 2002 to 2005 accidentally lost.
[c] Lower case letter denotes difference at $P < LSD_{0.05}$ in different treatments.

was because of the stable KHI after 2006 (Table 4). Aboveground K transformation from source to sink might reach a ceiling in newer maize hybrid cultivars under current farming management practices when the K rate has increased from 113 to 225 kg $K_2O\ ha^{-1}$. In addition, the stable KHI in different treatments after 2006 indicates that the newer maize cultivar is more tolerant of nutrient deficit or surplus than before (Duvick, 2005).

Improvement in K use efficiency can effectively alleviate K deficit status and decrease the potential negative impacts of fertilizer N in China (Ardjasa et al., 2002; Zhang et al., 2010). At the same K application rate, maize K recovery efficiency in northeast China (39.9%) was similar to that in north central China (38.8%) (Tan et al., 2012), and the K use efficiencies in our study (Table 7) were higher than those observed by Niu et al. (2011) under a similar K application rate. This can be attributed largely to the stover and grain production of spring maize being higher than summer maize in China. Potassium use efficiencies decreased once the K application rate exceeded crop demand (Table 7) (Niu et al., 2011). The environment, cultivar, methods, soil indigenous K supply, and their interactions can affect K use efficiencies (Zhang et al., 2011; He et al., 2012) as shown by the variation in K use efficiencies in different years (Table 7). Therefore, integrated management practices adopted to improve K use efficiencies should be designed to incorporate the above factors.

Aboveground K uptake from the soil solution is regulated or replenished by soil exchangeable K and non-exchangeable K reserves (Sharma et al., 2010). Exchangeable K leaching in the K_{225} treatment (Fig. 2a) at 0–100 cm soil depth was the result of excessive K application or non-synchrony between K application and crop K demand because K fertilizer in the present study was applied as a basal dressing. Potassium leaching was also reported by Kolahchi and Jalali (2007). At 0–40 cm soil depth, the difference in exchangeable K in the different K treatments (Fig. 2a) may be attributed to root K uptake, the fixation of applied fertilizer K in the soil, and soil weathering (e.g. soil acidification as shown in Table S1). The stability of non-exchangeable K (Fig. 2b) indicates that maize K uptake or K fertilizer application did not substantially affect the release and supply capacity of K-bearing minerals in the two decades of the experiment because most of the roots were concentrated above 30–40 cm soil depth (Peng et al., 2010), and the fertilizer K was surface applied. At 40–100 cm soil depth, the increase in exchangeable K (Fig. 2a) and the decrease in non-exchangeable K (Fig. 2b) may have been due to differences in the K-bearing minerals (Table 9) as well as reduction in the high exchangeable K (Fig. 2a) by non-exchangeable K uptake and the decrease in soil weathering induced by roots or microorganisms at that depth. However, exchangeable K and non-exchangeable K at different soil depths are controlled by different physical, chemical and biological factors. The total amount of exchangeable K and non-exchangeable K above 100 cm soil depth was stable ($P > 0.05$) among the three treatments (data not shown).

Both chemical composition and particle size affect the release and fixation of non-exchangeable K and exchangeable K (Simonsson et al., 2009). For example, hydromica, vermiculite, smectite, and chlorite are the major K-bearing minerals. Andrist-Rangel et al. (2006) reported that vermiculite dominating in coarse particles tended to fix K and smectite or mica dominating in clay particles resulted in a lower fixation capacity of K. In our study, the large variation in K-bearing minerals in replicate plots of each treatment (Tables 1 and 9) covered the effect of two decades of K application on non-exchangeable K. Even so, vermiculite and hydromica might be responsible for maize K uptake and the trend of exchangeable K at 0–100 cm soil depth because the percentage of vermiculite in the top 10 cm of the soil was lower than in the other two depths (Table 9). A mixed layer of vermiculite and hydromica appeared in 2012 (Tables 1 and 9), and the K release rate in vermiculite was larger than the other K-bearing minerals (Xie et al., 2000). In

Table 8
Contents of exchangeable K, non-exchangeable K, and total K at 0–100 cm soil depth in the K_0, K_{113}, and K_{225} treatments in 2012 (two decades after the start of the experiment). Unit: $t\ K\ ha^{-1}$.

Treatment	Exchangeable K	Non-exchangeable K	Total K
K_0	2.4[a] b[b]	11.5 a	285.6 a
K_{113}	2.5 b	11.6 a	287.4 a
K_{225}	2.9 a	11.6 a	288.8 a

K subscript represents amount of K_2O in different treatments.
[a] Mean of three replicates.
[b] Lower case letter in each column denotes difference at $P < LSD_{0.05}$ in different treatments.

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Table 9
Potassium-bearing mineral composition of coarse particles (>2 μm) and clay particles (<2 μm) at 0–10, 30–40 and 80–100 cm soil depths in the K_0, K_{113}, and K_{225} treatments in 2012 (two decades after the start of the experiment). Unit: %.

K-bearing minerals	0–10 cm			30–40 cm			80–100 cm		
	K_0	K_{113}	K_{225}	K_0	K_{113}	K_{225}	K_0	K_{113}	K_{225}
Coarse particles (>2 μm)									
Hydromica (H)	7.0[a]a[b]	4.5a	3.0a	7.7a	8.1a	3.9b	4.0a	8.4a	4.5a
Amphibole	6.9b	5.9b	14.3a	4.5a	2.0a	3.9a	8.0a	1.2b	2.1b
Chlorite	3.8a	4.1a	1.9a	3.2b	6.1a	3.5b	2.5a	4.7a	2.4a
Quartzite	28.1b	31.7a	31.5a	28.1a	28.7a	32.1a	26.9a	30.1a	26.3a
Feldspar	23.6a	22.8a	22.8a	21.0b	19.7b	25.7a	20.6a	17.7a	20.7a
Clay particle (<2 μm)									
Smectite	1.4a	1.9a	1.8a	3.9a	2.3a	1.9a	4.3a	3.0a	4.1a
Vermiculite (V)	3.4b	4.3a	2.1c	4.4a	5.1a	4.0a	6.1a	6.5a	6.4a
Mixed layer of V and H	0.5a	0.8a	0.2a	0.4a	0.7a	0.4a	0.6a	1.0a	0.5a
Hydromica	8.7	9.0	8.6	8.3a	7.6a	7.6a	7.6b	8.2b	9.4a
Kaolinite	8.1a	7.4a	7.2a	8.7a	8.7a	8.4a	9.3ab	8.9b	10.8a
Chlorite	7.2a	6.2b	5.6c	8.2ab	9.2a	7.4b	8.9b	8.9b	10.8a
Quartzite	1.4a	1.4a	1.0b	1.6a	1.8a	1.2b	1.1b	1.5ab	2.0a

K subscript represents amount of K_2O in different treatments.
[a] Mean of three replicates.
[b] Lower case letter in each column denotes difference at $P < LSD_{0.05}$ in different treatments.

addition, soil acidification (Table S1) speeds up the weathering of soil minerals and K release (Bhattacharyya et al., 2006). For example, dissolved Ca^{2+} can increase K release from vermiculite because of soil acidification (Shen et al., 2009).

According to the K balance calculation K_0, K_{113}, and K_{225} treatments had K deficit, deficit, and surplus, respectively (Fig. 3). K_0 (control) showed that the total loss of exchangeable K plus non-exchangeable K in the top 20 cm of the soil (Table 10) was less than the aboveground K uptake (Table 4) because roots can assimilate soil exchangeable and non-exchangeable K below 20 cm soil depth and release available K from soil total K. The K_{225} treatment had an exchangeable K surplus and an non-exchangeable K loss in the top 20 cm of the soil (Table 10). The main explanation is that H^+ loss from the root zone, H_2CO_3 formation during root and microbial respiration, hydrolysis of urea and acidified fertilizer application (KCl) can promote soil Ca^{2+} release, further promoting the conversion of non-exchangeable K to exchangeable K and increasing K^+ leaching (Bhattacharyya et al., 2006; Kolahchi and Jalali, 2007). Similar results were reported by Bhattacharyya et al. (2006). In the K_{225} treatment, in our study, the pH value in the top 20 cm of the soil decreased from 6.4 in 1992 (Table 2) to 4.8–5.3 in 2012 (Table S1), and at 0–10 cm soil depth was lower than in the K_{113} treatment as exchangeable K in the surface soil was prone to leaching deeper into the soil (Fig. 2a). The K_{113} treatment showed K balance on the whole because the sum of the K rate and non-exchangeable K loss in the top 20 cm soil (116.0 kg K ha^{-1}), and the aboveground K uptake (128.1 kg K ha^{-1}) was similar (Tables 4 and 7).

Table 10
Estimation of K losses at 0–20 cm soil depth in the K_0, K_{113}, and K_{225} treatments in 2012 (two decades after the start of the experiment).

Treatment	Exchangeable K		Non-exchangeable K	
	Total (kg ha^{-1})	Δ (kg ha^{-1} per year)	Total (kg ha^{-1})	Δ (kg ha^{-1} per year)
K_0	81.4	4.1	502.6	25.1
K_{113}	1.3	0.1	444.8	22.2
K_{225}	−99.1	−5.0	417.1	20.9

After maize was harvested in 1992 the concentration of NH_4Ac-extractable K, slowly available K, and total K at 0–20 cm depth were 156.5 mg kg^{-1}, 1065.4 mg kg^{-1} and 20.0 g kg^{-1}, respectively. Soil bulk density at 0–20 cm depth was 1.44 g cm^{-3}, which was the mean of the 0–10 and 10–20 cm soil depths in 2012.
Negative value denotes K surplus.

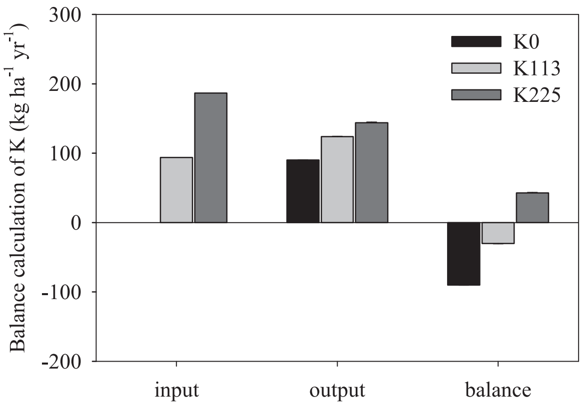

Fig. 3. Average K input and output in the K_0, K_{113}, and K_{225} treatments over the 20-year experimental period.
Legend represents amount of K_2O in different treatments.
Input is application rate of fertilizer K; output is aboveground K uptake; balance is the difference between output and input. During the calculation of aboveground K uptake, the omitted data for grain or stover K concentrations from 2002 to 2005 (accidentally lost) were replaced with the mean grain or stover K concentrations from 1993 to 2001 and 2006 to 2012.

In summary, the K deficit in some Chinese soils can be effectively alleviated if stover is returned to the soil (Tables 3 and 4), soil exchangeable and non-exchangeable K below 40 cm are fully utilized by deep rooting crops, and soil total K is further dissolved through a combination of physical, chemical and biological processes (Fig. 2).

4. Conclusions

Compared with the control plots, application of fertilizer K significantly ($P < 0.05$) increased maize grain yields, and treatments with K application rates of 113 and 225 kg K_2O ha^{-1} increased the average yields by 15.1 and 13.8% over the course of the twenty years of the field experiment, but the variation from year to year was large (Table 3). The optimum K rate was approximately 150 kg K_2O ha^{-1} according to the K balance calculation (Fig. 3). If the K application rate was exceeded or not synchronized to crop K demand, not only did grain yield cease to increase, but the K use efficiency also decreased and leaching of exchangeable K occurred (Fig. 2a). The K application rate can be

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reduced if stover is returned to soil, a highly K-efficient cultivar is selected, and deeper soil K is used by deep-rooting crops (Tables 4 and 5; Fig. 2). For example, soil indigenous K supply (control plots) did not decrease during the two decades of the field experiment (Table 4), and the weathering of soil below 40 cm decreased as shown by the non-exchangeable K results (Fig. 2b).

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2014.04.016.

References

Andrist-Rangel, Y., Simonsson, M., Andersson, S., Öborn, I., Hillier, S., 2006. Mineralogical budgeting of potassium in soil: a basis for understanding standard measures of reserve potassium. J. Plant Nutr. Soil Sci. 169, 605–615.

Antonietta, M., Fanello, D.D., Acciaresi, H.A., Guiamet, J.J., 2014. Senescence and yield responses to plant density in stay green andearlier-senescing maize hybrids from Argentina. Field Crops Res. 155, 111–119.

Ardjasa, W.S., Tomonori, A., Ho, A., K, Ken-Ichi, Makoto, K., 2002. Fate of basal N and growth of crops cultivated under cassava-based intercropping system with reference to K application rate. Soil Sci. Plant Nutr. 48, 365–370.

Bhattacharyya, R., Prakash, V., Kundu, S., Ghosh, B.N., Srivastva, A.K., Gupta, H.S., 2006. Potassium balance as influenced by farmyard manure application under continuous soybean–wheat cropping system in a Typic Haplaquept. Geoderma 137, 155–160.

Bremner, J.M., 1996. Nitrogen-total. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, American Society of Agronomy, Madison, WI, pp. 1085–1121.

Chen, X., Chen, F., Chen, Y., Gao, Q., Yang, X., Yuan, L., Zhang, F., Mi, G., 2013. Modern maize hybrids in northeast China exhibit increased yield potential and resource use efficiency despite adverse climate change. Global Change Biol. 19, 923.

Chen, X., Zhang, F., Römheld, V., Horlacher, D., Schulz, R., Böning-Zilkens, M., Wang, P., Claupein, W., 2006. Synchronizing N supply from soil and fertilizer and N demand of winter wheat by an improved N_{min} method. Nutr. Cycl. Agroecosyst. 74, 91–98.

Chen, X., Zhang, F., Cui, Z., Li, J., Ye, Y., Yang, Z., 2010. Critical grain and stover nitrogen concentrations at harvest for summer maize production in China. Agron. J. 102, 289–295.

Chen, X.P., Cui, Z.L., Vitousek, P.M., Cassman, K.G., Matson, P.A., Bai, J.S., Meng, Q.F., Hou, P., Yue, S.C., Römheld, V., Zhang, F.S., 2011. Integrated soil-crop system management for food security. PNAS 108, 6399–6404.

Ciampitti, I.A., Vyn, T.J., 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Res. 121, 2–18.

Ciampitti, I.A., Camberato, J.J., Murrell, S.T., Vyn, T.J., 2013. Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: I. Macronutrients. Agron. J. 105, 783–795.

Dierolf, T.S., Yost, R.S., 2000. Stover and potassium management in an upland rice–soybean rotation on an Indonesian ultisol. Agron. J. 92, 106–114.

Duvick, D.N., 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Adv. Agron. 86, 83–145.

Epstein, E., Bloom, A.J., 2005. Mineral Nutrition of Plants: Principles and Perspectives, second ed. Sinauer Association, Sunderland, MA.

Food and Agriculture Organization, 2002. Key to the FAO Soil Units in the FAO/Unesco Soil Map of the World. FAO, Rome Available: www.fao.org/ag/agl/agll/key2soil.stm (accessed 17.11.11).

Garcia, R.A., Crusciol, C.A.C., Calonego, J.C., Rosolem, C.A., 2008. Potassium cycling in a corn-brachiaria cropping system. Euro. J. Agron. 28, 579–585.

Georage, M.S., Lu, G., Zhou, W., 2002. Genotypic variation from potassium uptake and utilization efficiency in sweet potato (*Ipomoea batatas* L.). Field Crop Res. 77, 7–15.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K. W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010.

Heckman, J.R., Kamprath, E.J., 1992. Potassium accumulation and corn yield related to potassium fertilizer rate and placement. Soil Sci. Soc. Am. J. 56, 141–148.

He, C., Ouyang, Z., Tian, Z., Schaffer, H.D., 2012. Yield and potassium balance in a wheat–maize cropping system of the North China Plain. Agron. J. 104, 1016–1022.

Huang, Y., Sun, W.J., 2006. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. Chinese Sci. Bull. 51, 1785–1803.

Helmke, P.A., Sparks, D.L., 1996. Lithium, sodium, potassium, rubidium, and cesium. In: Sparks, D.L. (Ed.), Methods of Soil Analysis, Part 3. ASA and SSSA, Madison, WI, pp. 551–574.

Jin, J.Y., 1994. Development of K fertilizer application and status of soil K deficient in northern China. In: Institute of soil and fertility, Chinese Academy of Agricultural Science and Canadian Phosphate and Potassium Institute Beijing office (Ed.), Soil K Status and K Fertilization use in Northern China. China Agricultural Science and Technology Press, Beijing, pp. 1–6 (In Chinese).

Jones Jr, J.B., Case, V.W., 1990. Sampling, handling, and analyzing plant tissue samples, In: Westerman, R.L. (Ed.), Soil Testing and Plant Analysis. third ed. Soil Science Society of America, Madison, Wisconsin, USA, pp. 389–427.

Jouany, C., Colomb, B., Bosc, M., 1996. Long-term effects of potassium fertilization on yields and fertility status of calcareous soils of south–west France. Euro. J. Agron. 5, 287–294.

Kolahchi, Z., Jalali, M., 2007. Effect of water quality on the leaching of potassium from sandy soil. J. Arid Environ. 68, 624–639.

Kuo, S., 1996. Phosphorus. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, American Society of Agronomy, Madison, WI, pp. 869–919.

Li, W., He, P., Jin, J., 2012. Critical nitrogen curve and nitrogen nutrition index for spring maize in northeast China. J. Plant Nutr. 35, 1747–1761.

Mallarino, A.P., Higashi, S.L., 2008. Assessment of potassium supply for corn by analysis of plant parts. Soil Sci. Soc. Am. J. 73, 2177–2183.

Mallarino, A.P., Higashi, S.L., 2009. Assessment of potassium supply for corn by analysis of plant parts. Soil Sci. Soc. Am. J. 73, 2177–2183.

National Soil Survey Office, 1998. Soils of China. China Agricultural Press, Beijing (in Chinese), p. 1016.

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. Soil Science Society of America, American Society of Agronomy, Madison, WI, pp. 961–1010.

Niu, J., Zhang, W., Chen, X., Li, C., Zhang, F., Jiang, L., Liu, Z., Xiao, K., Assaraf, M., Imas, P., 2011. Potassium fertilization on maize under different production practices in the North China Plain. Agron. J. 103, 822–829.

Peng, Y., Niu, J., Peng, Z., Zhang, F., Li, C., 2010. Shoot growth potential drives N uptake in maize plants and correlates with root growth in the soil. Field Crops Res. 115, 85–93.

Pettigrew, W.T., 2008. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiol. Plant. 133, 670–681.

Qiu, S.J., Ju, X.T., Lu, X., Li, L., Ingwersen, J., Streck, T., Christie, P., Zhang, F.S., 2012. Improved nitrogen management for an intensive winter wheat/summer maize double-cropping system. Soil Sci. Soc. Am. J. 76, 286–297.

Setiyono, T.D., Walters, D.T., Cassman, K.G., Witt, C., Dobermann, A., 2010. Estimating maize nutrient uptake requirements. Field Crops Res. 118, 158–168.

Sharma, A., Jalali, V.K., Arora, S., 2010. Non-exchangeable potassium release and its removal in foot-hill soils of north–west Himalayas. Catena 82, 112–117.

Shen, Q.H., Wang, H.Y., Zhou, J.M., Du, C.W., Chen, X.Q., 2009. Dynamic release of potassium from potassium bearing minerals as affected by ion species in solution. Soils Chin 41, 862–868.

Simonsson, M., Hillier, S., Öborn, I., 2009. Changes in clay minerals and potassium fixation capacity as a result of release and fixation of potassium in long-term field experiments. Geoderma 151, 109–120.

Slaton, N.A., Golden, B.R., Norman, R.J., Wilson Jr, C.E., Delong, R.E., 2009. Correlation and calibration of soil potassium availability with rice yield and nutritional status. Soil Sci. Soc. Am. J. 73, 1192–1201.

Tan, D., Jin, J., Jiang, L., Huang, S., Liu, Z., 2012. Potassium assessment of grain producing soils in north China. Agri. Ecosys. Environ. 148, 65–71.

Thomas, G.W., 1996. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, American Society of Agronomy, Madison, WI, pp. 961–1010.

Xie, J.C., Zhou, J.M., Härdter, R. (Eds.), 2000. Potassium in Chinese Agriculture. Hehai University Press (In Chinese).

Vyn, T.J., Galic, D.M., Janovicek, K.J., 2002. Corn response to potassium placement in conservation tillage. Soil Till. Res. 67, 159–169.

Wang, T., Ma, X., Li, Y., Bai, D., Liu, C., Liu, Z., Tan, X., Shi, Y., Song, Y., Carlone, M., Bubeck, D., Bhardwaj, H., Jones, E., Wright, K., Smith, S., 2011. Changes in yield and yield components of single-cross maize hybrids released in China between 1964 and 2001. Crop Sci. 51, 512–525.

Wang, Y., Liu, Z., 2009. China Agriculture Year Book. China Agriculture Press, Beijing p.104, (In Chinese)..

Woodend, J.J., Glass, A.D.M., Person, C.O., 1987. Genetic variation in the uptake and utilization of potassium in wheat (*T. aestivum* L.) varieties grown under potassium stress. In: Gabelman, W.H., Loughman, B.C. (Eds.), Genetic Aspects of Plant Mineral Nutrition. Martinus Nihoff, Dordrecht, pp. 381–391.

Xu, Y., Nie, L., Buresh, R.J., Huang, J., Cui, K., Xu, B., Gong, W., Peng, S., 2010. Agronomic performance of late-season rice under different tillage, straw, and nitrogen management. Field Crops Res. 115, 79–84.

Zhang, F., Niu, J., Zhang, W., Chen, X., Li, C., Yuan, L., Xie, J., 2010. Potassium nutrition of crops under varied regimes of nitrogen supply. Plant Soil 335, 21–34.

Zhang, H.-M., Yang, X.-Y., He, X.-H., Xu, M.-G., Huang, S.-M., Liu, H., Wang, B.-R., 2011. Effect of long-term potassium fertilization on crop yield and potassium efficiency and balance under wheat-maize rotation in China. Pedosphere 21, 154–163.

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