Potassium Fertilization on Maize under Different Production Practices in the North China Plain

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ABSTRACT

Potassium fertilization is uncommon in the North China Plain (NCP), especially in maize (*Zea mays* L.) production. Our specific objectives in this study were to determine yield response to K fertilization as affected by conventional as well as high-yielding production practices. Seven field experiments were conducted in the NCP. The factorial study compared three levels of K fertilization (K0 = no K; K1 = medium K rate; K2 = high K rate) and two levels of production practices: conventional (CP) and high yielding (HP). At all sites, HP outperformed CP in terms of maize grain yield except at ZD in 2006. On average, maize grain yields were enhanced by 9.9 and 14.9% under CP and 15.7 and 21.0% under HP at the K1 and K2 levels, respectively. Maize yield response, as well as economic profit from applied K, were greater under HP than CP, on average, across seven site-years. Medium K inputs improved partial factor productivity (PFP) of applied N and P, while higher rates had inconsistent results. Overall, PFP and agronomic efficiency of applied K were improved under HP, as was the apparent recovery efficiency of applied K, which suggests positive interactions among K and other high-yielding production practices. Negative K balances were observed in all of the K0 and K1 treatments in both years and under both production practices, especially under HP. In intensive agricultural soils of the NCP with higher K content relative to South China, optimal K fertilization will improve soil fertility and support high grain yield.

Agricultural intensification through the use of high-yielding crop cultivars, chemical fertilizers and pesticides, irrigation, and mechanization has been responsible for dramatic increases in grain production in developing countries during the past three decades (Matson et al., 1998). There is, however, a growing global challenge of meeting increased food demand while protecting environmental quality, and this challenge must especially be met in cropping systems that produce maize, rice (*Oryza sativa* L.), and wheat (*Triticum aestivum* L.) (Cassman et al., 2002). The NCP is one of the most important areas in China for cereal production, accounting for about 48% of the wheat and 39% of the maize produced in the entire country. The intensive farming in this region features a continuous wheat–maize cropping system, which requires careful management of soil nutrients.

Intensive agriculture has dramatically increased grain production in developing countries, but yield records in the dominant food-producing regions indicate a large gap between the current and potential yields for maize (Neumann et al., 2010), which is an important crop because it contributes to food security in China. Obtaining an increased and sustainable maize yield will probably require integrated measures that could include K fertilization to maintain soil fertility.

Potassium is one of the essential nutrient elements for plants; it is involved in the processes of osmoregulation and cell extension, stomatal movement, activation of enzymes, protein synthesis, photosynthesis, phloem loading, and transport and uptake (Marschner, 1995; Pettigrew, 2008). Potassium fertilization is, however, uncommon in the NCP and especially in maize production, primarily due to the relatively high soil test K as surveyed in the 1980s (National Extension Center of Agricultural Technique in China, 2004). In reality, it has often been reported that continuous wheat–maize cropping with unbalanced fertilization has rapidly depleted the soil available K (Jin, 1994; Liu et al., 2000; Cao et al., 2007).

Many studies have focused on crop response to K fertilization as affected by soil properties, application methods, planting systems, etc. (Heckman and Kamprath, 1992; Rehm and Lamb, 2004; Mallarino et al., 1999; Borges and Mallarino, 2001; Vyn and Janovicek, 2001). It is the biological yield (the dry matter produced), however, that largely determines the amount of minerals absorbed by crops (Osaki et al., 1991). High-yielding crops with high biological yield absorb a large amount of nutrients to satisfy healthy plant growth (Osaki et al., 1991). The higher yields now commonly obtained must impose a greater drain on K reserves in the soil (Gething, 1993). Therefore, the yield level would be one reason for different responses to K fertilization. Nutrient management recommendations may change with yield levels and profit

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Abbreviations: AEK, agronomic efficiency of applied potassium; CP, conventional production practices; HI, harvest index; HP, high-yielding production practices; KUE, potassium use efficiency; NCP, North China Plain; PFP, partial factor productivity; PFPK, partial factor productivity of applied potassium; REK, recovery efficiency of applied potassium; VCR, value cost ratio.

Table 1. Locations and characteristics of seven experimental site-years in the North China Plain.

Year	Province	Site	Code	Soil type (FAO)	pH	Organic matter	Total N	Available N	Olsen P	Available K	Slowly available K	Precipitation
						g kg^{-1}		mg kg^{-1}		mg K_2O kg^{-1}		mm
2005	Shandong	Dajin	DJ	Haplic Cambisol	6.3	16.8	na†	35.1	10.2	144.9	842.6	na
		Shuitun	ST	Haplic Cambisol	6.2	13.5	na	45.4	41.5	140.6	765.2	na
	Hebei	Qingyuan1	QY1	Alfisol	8.2	16.3	0.9	60.2	13.6	104.8	na	367.9
		Qingyuan2	QY2	Alfisol	7.9	13.0	0.8	43.8	11.4	85.8	na	367.9
2006	Shandong	Laiyang	LY	Alfisol	6.8	19.2	1.4	na	16.5	72.3	348.2	318.7
	Hebei	Qingyuan	QY	Alfisol	8.1	14.3	0.8	58.6	11.8	99.5	na	353.6
		Zhengding	ZD	Alfisol	7.6	15.3	0.9	55.0	13.8	91.9	na	353.6

† na, not available.

maximization in crop production. In Nebraska, where maize yields often exceed 15 Mg ha^{-1} nowadays, K recommendations were based on research conducted when the mean maize grain yield was <5 Mg ha^{-1} (Wortmann et al., 2009). There are few reports about rational K recommendation in the North China Plain under a high-yielding maize production system.

The overall goal of this study was to develop a K fertilizer recommendation and evaluation system for high grain yield. High-yielding cropping practices were devised to increase yield, and these practices included increased rates of N and P application, split-applications of N fertilizer, adjustment of row spacing, and application of micronutrient fertilizer. Our specific objectives were: (i) to determine yield response to K fertilizer as affected by conventional as well as high-yielding production practices; (ii) to quantify the effects of K fertilization on N and P use efficiency; and (iii) to evaluate K fertilizer recommendations based on soil nutrient balances and economic profits from high-yielding production practices.

MATERIALS AND METHODS

Experimental Sites

The climate of the NCP is warm-temperate, subhumid, continental monsoon, with cold winters and hot summers. The annual cumulative mean temperature for days with mean temperatures >10°C is 4326.6°C averaged for 45 yr from 1961 to 2005 (Tan et al., 2010), and the annual frost-free period is 175 to 220 d. Summer maize is normally planted in the middle of June, after the harvest of winter wheat, and is harvested at the end of September. About 70 to 80% of the annual precipitation is concentrated during the summer maize-growing season from June to September. This would correspond, for example, to an average of about 482 mm yr^{-1} at the Luancheng Agro-Eco Experimental Station of the Chinese Academy of Sciences, located in the central part of the plain, for the years between 1982 and 2002 (Zhang et al., 2005). The amount and distribution pattern of rainfall vary widely from year to year, however, as affected by the continental monsoon climate. The maize crop receives no irrigation except in extreme drought years.

The field experiments were conducted in four farmer fields at Dajin (DJ), Shuitun (ST), and Qingyuan (QY1 and QY2) in 2005 and in three additional farmer fields at Laiyang (LY), Qingyuan (QY), and Zhengding (ZD) in 2006. The locations and characteristics of the seven experimental site-years are provided in Table 1.

Experimental Design

At each site, a factorial experiment was conducted in a split-plot randomized complete block design with three replications. Factors were production practice (two levels) and K application rate (three levels). Main plots were production practice, including CP and HP. For CP, farmers were interviewed and production practices typical for the local area were followed, including selection of the maize cultivar, plant density, plant spacing, and fertilizer rate. High-yielding practices included increased chemical N and P inputs at all sites other than LY; split application of N or K fertilizer at ST, DJ, and LY; and the use of planting of alternating wide and narrow rows and the application of microelements at LY. The differences in production practices are listed in detail in Table 2. The subplots (50 or 60 m^2) were K application rate: K0 (control, no K applied), K1 (medium rate), and K2 (high rate), with K1 and K2 being site specific (Table 2) depending on the crop yield history and experimental conditions. Table 2 provides treatment details for each site. Fertilizers applied were urea (46% N), diammonium phosphate (48% P_2O_5 and 16% N), and muriate of potash (60% K_2O). All sites had winter wheat as the preceding crop.

Sampling and Measurement

At maturity, 10 plants from each plot at all sites were randomly selected for a separate harvest that was used for the determination of biomass. The aboveground parts of the maize plants were divided into two parts: the grain and the rest of the aboveground plant (including stalk, leaves, husks, and cobs). Samples were first dried at 105°C for 30 min to stop biological enzyme activity and then at 70°C to constant weight. After grinding, the dried material was passed through a 0.5-mm sieve. The aboveground biomass per hectare was calculated based on the dried plant samples.

To determine the grain yield, all maize plants in a 6-m length of the three center rows in each subplot were hand harvested, and the yield was calculated from the air-dried grain of the sample ears. The harvest index (HI) was calculated as the fraction of grain dry matter divided by the total aboveground biomass on a hectare basis.

About 0.25 g of the ground plant samples was digested in 70% concentrated H_2SO_4 and 30% H_2O_2 following the procedure outlined by Bao (2000). The K concentrations were determined with a flame spectrophotometer (Cole-Parmer 2655-00, Vernon Hills, IL). Total K uptake per plant was calculated by multiplying the concentration and aboveground biomass for all plots.

Partial factor productivity was obtained to indicate the nutrient use efficiency of the applied N, P, and K, and was calculated as grain yield (kg) per unit (kg) of N, P_2O_5, and K_2O applied. In addition, the K use efficiency was also assessed by: (i) agronomic efficiency (AEK), calculated as the increase in grain yield from applied nutrients relative to the control

Table 2. Conventional production practices (CP) and high-yielding production practices (HP) at all experimental sites.

				Planting		Fertilization rate				Fertilizer distribution		
											Topdressing	
Site†	Cultivar	Production practice	Population	Form‡	Row × plant spacing	N	P_2O_5	K1 (K_2O)	K2 (K_2O)	Basal dressing	Six-leaf stage	Pretasseling§
			plants ha^{-1}		— cm —	—	—	kg ha^{-1}	—			
ST	Luyuandan22	CP	60,000	ERS	50 × 33	180	80	120	240	1/3 N, P, K	0	2/3 N
		HP	60,000	ERS	50 × 33	240	120	120	240	1/3 N, P, K	1/6 N	1/2 N
DJ	Zhengdan958	CP	68,000	ERS	50 × 29	180	80	120	240	1/3 N, P, K	0	2/3 N
		HP	68,000	ERS	50 × 29	240	120	120	240	1/3 N, P, K	1/6 N	1/2 N
QY1	Liyu16	CP	45,000	ERS	60 × 37	150	0	75	150	1/2 N, P, K	0	1/2 N
		HP	45,000	ERS	60 × 37	225	75	75	150	1/2 N, P, K	0	1/2 N
QY2	Liyu16	CP	49,500	ERS	60 × 34	150	0	75	150	1/2 N, P, K	0	1/2 N
		HP	49,500	ERS	60 × 34	225	75	75	150	1/2 N, P, K	0	1/2 N
LY	LN3	CP	75,000	ERS	60 × 22	300	100	90	180	1/3 N, P, K	2/3 N	0
		HP	75,000	WNRS	(80 + 40) × 22	240	100	90	180	1/3 N, P, 2/3 K, 15 kg ha^{-1} $ZnSO_4$	1/6 N	1/2 N, 1/3 K
QY	Zhengdan958	CP	67,500	ERS	60 × 25	150	0	75	150	1/2 N, P, K	0	1/2 N
		HP	67,500	ERS	60 × 25	225	75	75	150	1/2 N, P, K	0	1/2 N
ZD	Xundan20	CP	60,000	ERS	60 × 28	150	0	75	150	1/2 N, P, K	0	1/2 N
		HP	60,000	ERS	60 × 28	225	75	75	150	1/2 N, P, K	0	1/2 N

† ST, Shuitun; DJ, Dajin; QY, Qingyuan; LY, Laiyang; ZD, Zhengding.

‡ ERS, equal row spacing; WNRS, alternating wide–narrow row spacing, which was described in Li et al. (2010).

§ Pretasseling is the stage when the maize tassels have budded but are not yet open.

treatment in the same production practice (kg grain kg^{-1} K_2O applied via fertilizer); (ii) apparent recovery efficiency (REK), defined as the percentage of added K_2O that was recovered in the aboveground plant biomass at the end of the cropping season; and (iii) K use efficiency (KUE), which is the ratio of the amounts of absorbed K to the sum of K supplied from the soil and fertilizer, calculated as

$$\mathrm{PFPK}=\frac{\mathrm{GY}_i}{F_{\mathrm{K_2O}}} \qquad [1]$$

$$\mathrm{AEK}=\frac{\mathrm{GY}_i-\mathrm{GY}_{\mathrm{CK}}}{F_{\mathrm{K_2O}}} \qquad [2]$$

$$\mathrm{REK}=\frac{U_i-U_{\mathrm{CK}}}{F_{\mathrm{K_2O}}} \qquad [3]$$

$$\mathrm{KUE}=\frac{U_i}{K_{\mathrm{soil}}+F_{\mathrm{K_2O}}} \qquad [4]$$

where GY_i is the grain yield (kg ha^{-1}) of the *i*th treatment (i = 1–6), $\mathrm{GY}_{\mathrm{CK}}$ is grain yield of the control treatment subjected to the same production practice (kg ha^{-1}), U_i is K uptake in the *i*th treatment (kg K_2O ha^{-1}), U_{CK} is K uptake in the control treatment under the same production practice (kg K_2O ha^{-1}), F_{K2O} is the amount of K_2O applied in the *i*th treatment (kg K_2O ha^{-1}), and K_{soil} is the K supplied by the soil (kg K_2O ha^{-1}), i.e., the amount of K supplied to the crops by the soil when no K fertilizer was applied, which is equal to U_{CK} in the control treatments.

Soil samples were collected at all sites before the start of maize sowing. Composite soil samples (10 cores per site) were collected from the 0- to 30-cm depth for separate analyses. The samples were dried at 40°C and crushed to pass through a 2-mm sieve for chemical analyses. Organic matter, total N, available N, available P, exchangeable K, slowly available K, and pH were determined for each site following procedures recommended for the North China Plain by Bao (2000). Organic matter was analyzed by the chromic acid titration method, total N by the Kjeldahl method, available N by the alkali hydrolysis and diffusion method, available P by the $NaHCO_3$ method, exchangeable K by the HN_4OAC extraction and flame photometer method, and slowly available K by the hot HNO_3 extraction and flame photometer method. Soil pH was determined with a pH electrode at a soil/water ratio of 1:2.5. The partial K balance (kg K_2O ha^{-1}) in the soil was defined as the quantity of K fertilizer applied minus the quantity of K removed by the maize plants (grain and straw); no other inputs or outputs were considered.

The economic profit from applied K (EPK) was calculated as the difference between the income through maize yield increments relative to the control subjected to the same production practice and the cost of K fertilizer. The value cost ratio (VCR) of the applied K was defined as the ratio of the income through yield increments relative to the control subjected to the same production practice and the cost of additional K fertilizer, calculated as

$$\mathrm{EPK}=\left[\left(\mathrm{GY}_i-\mathrm{GY}_{\mathrm{CK}}\right)P_{\mathrm{g}}\right]-F_{\mathrm{K}}P_{\mathrm{F}} \qquad [5]$$

$$\mathrm{VCR}=\frac{\left(\mathrm{GY}_i-\mathrm{G}_{\mathrm{CK}}\right)P_{\mathrm{g}}}{F_{\mathrm{K}}P_{\mathrm{F}}} \qquad [6]$$

where P_{g} is the price of maize grain at a specific site (yuan kg^{-1}), F_{K} is the amount of K fertilizer applied (kg ha^{-1}), and P_{F} is the price of K fertilizer at a specific site (yuan kg^{-1}).

Statistical Methods

A two-way ANOVA was used to test for main effects and interactions between production practices and K application rates. A one-way ANOVA was used to test for the PFP of P fertilizer at four site-years (QY1, QY2, QY, and ZD). The SAS System for Windows, Release 8.2 (SAS Institute, Cary, NC) was used for all statistical analyses.

Table 3. Maize grain yield, biomass, and harvest index (HI) as affected by K fertilization under conventional (CP) and high-yielding (HP) production practices with no (K0), medium (K1), and high (K2) K fertilization rates.

	K	Grain yield				Biomass				HI	
Site†	treatment	CP	Increase	HP	Increase	CP	Increase	HP	Increase	CP	HP
		Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%		
ST	K0	7.57 a‡		7.85 b*		15.02 b		15.77 b*		0.50 a	0.50 a
	K1	8.11 a	7.2	8.64 a	10.1	17.60 a	17.2	18.83 a	19.4	0.46 ab	0.46 a
	K2	8.12 a	7.3	8.63 a	9.9	18.31 a	21.9	18.69 a	18.5	0.44 b	0.46 a
DJ	K0	6.44 c		6.55 c*		19.60 b		19.81 b*		0.33 b	0.33 c
	K1	7.59 a	18.0	8.20 a	25.2	20.46 a	4.4	20.82 a	5.1	0.37 a	0.39 a
	K2	7.28 b	13.1	7.39 b	12.8	20.28 a	3.5	20.97 a	5.9	0.36 a	0.35 b
QY1	K0	5.95 c		6.19 c*		16.99 b		16.92 c*		0.35 b	0.37 a
	K1	6.52 b	9.6	7.43 b	20.0	18.11 a	6.6	19.53 b	15.4	0.36 ab	0.38 a
	K2	7.14 a	20.0	8.03 a	29.7	18.80 a	10.6	21.14 a	24.9	0.38 a	0.38 a
QY2	K0	5.59 c		5.66 b*		14.72 c		15.30 c*		0.38 a	0.37 a
	K1	6.06 b	8.4	6.64 a	17.3	15.83 b	7.6	17.02 b	11.2	0.38 a	0.39 a
	K2	6.48 a	15.9	6.93 a	22.4	17.29 a	17.5	18.23 a	19.2	0.37 a	0.38 a
LY	K0	6.62 b		6.39 c*		15.13 a		15.10 b*		0.44 a	0.42 ab
	K1	7.04 a	6.4	7.17 b	12.2	15.55 a	2.8	17.31 a	14.6	0.45 a	0.41 b
	K2	6.97 a	5.4	7.93 a	24.0	15.53 a	2.6	18.16 a	20.3	0.45 a	0.44 a
QY	K0	7.45 b		7.86 b*		17.74 c		19.17 c*		0.42 a	0.41 a
	K1	8.02 b	7.6	8.87 a	12.4	19.10 b	7.7	21.11 b	10.1	0.42 a	0.42 a
	K2	8.92 a	19.7	9.67 a	22.6	20.74 a	16.9	23.03 a	20.1	0.43 a	0.42 a
ZD	K0	5.57 c		5.59 c		16.37 c		16.93 c*		0.34 a	0.33 a
	K1	6.33 b	13.7	6.36 b	13.8	17.59 b	7.4	18.16 b	7.3	0.36 a	0.35 a
	K2	7.06 a	26.8	7.17 a	28.4	19.61 a	19.8	20.49 a	21.0	0.36 a	0.35 a
Avg.	K0	6.46 c		6.58 c*		16.51 c		17.00 c*		0.39 a	0.39 a
	K1	7.10 b	9.9	7.62 b	15.7	17.75 b	7.5	18.97 b	11.6	0.40 a	0.40 a
	K2	7.42 a	14.9	7.96 a	21.0	18.65 a	13.0	20.10 a	6.7	0.40 a	0.40 a

* Significant difference at $P \leq 0.05$ between CP and HP from each site.

† ST, Shuitun; DJ, Dajin; QY, Qingyuan; LY, Laiyang; ZD, Zhengding.

‡ Means in a column from each site followed by different letters are significantly different at $P \leq 0.05$.

RESULTS

Yield Response and Potassium Uptake

For grain yield, a significant positive response to K fertilization was obtained under both CP and HP at all site-years except for ST in 2005 (Table 3). Overall, K fertilization increased grain yield and biomass by 7.2 to 26.8% and 2.6 to 21.9%, respectively, under CP and by 9.9 to 29.7% and 5.1 to 24.9%, respectively, under HP. The greatest grain yields were obtained at the higher K rate (K2) at all except two sites (DJ and LY); at those two site-years, grain yields were slightly less for the K2 than for the K1 treatment. The increases in grain yield and biomass yield relative to the corresponding control were higher under HP than CP (Table 3). On average, maize biomass and grain yield were enhanced significantly by the increase in applied K fertilizer, and HP surpassed CP during all seven site-years (Table 3). The HI was not significantly affected by production practice at any site or by any K fertilization level at four site-years under CP or at six site-years under HP (Table 3).

Potassium fertilization significantly increased the grain K concentration at four of the seven site-years under CP and at six of the seven site-years under HP; K concentrations in stalks were also enhanced by K application at four of the seven site-years under both CP and HP (Table 4). At two site-years (QY1 and QY), the grain K concentration under CP was significantly higher than under CP, and the same results were found at LY in terms of straw K concentration. The straw K concentration was higher under HP than CP at two of the seven site-years. At the medium K rate, the K uptake (kg ha^{-1}) into the aboveground biomass was higher than the control at four of the seven site-years under CP and six of the seven site-years under HP (Table 4). Potassium uptake was greater for K2 than K1 at four of the seven site-years under CP and five of the seven site-years under HP. Potassium uptake was greater under HP than CP at four of the seven site-years (Table 4).

Nutrient Use Efficiency

Potassium use efficiency decreased significantly with increasing K application whether under CP or HP at all site-years except for DJ and LY under CP (Table 4); HP outperformed CP at two site-years (QY2 and LY) (Table 4). At the medium K level, K fertilization apparently enhanced the PFP of N, compared with the control that received no K fertilizer, at five of the seven site-years under CP and all site-years under HP (Table 5). For the K2 treatments, the K supply increased the PFP of N significantly at all sites under CP and HP except at ST under CP (Table 5). Under HP, K fertilization also apparently enhanced the PFP of P, compared with the control, at five of the seven site-years for the K1 treatment and at all sites for the K2 treatment (Table 5). The PFP and agronomic efficiency of the applied K (PFPK and AEK, respectively) were increased at five of the seven site-years and four of the seven site-years, respectively, under HP compared with CP at the same K level (Table 5). Whether under CP or HP, the PFPK at all sites declined significantly with increased K levels but for the AEK there were no consistent results between K levels. On average, HP surpassed CP with regard to PFPK and AEK across the seven site-years (Table 5).

In this study, REK ranged from –11.9 to 37.9%. Under the K1 and K2 treatments, REK averaged 0.18 and 0.21, respectively,

Table 4. Potassium uptake by maize plants and K use efficiency (KUE) as affected by no (K0), medium (K1), or high (K2) K fertilization rates under conventional (CP) or high-yielding (HP) production practices.

Site†	K treatment	Grain K		Straw K		K uptake		KUE‡	
		CP	HP	CP	HP	CP	HP	CP	HP
		g K_2O kg^{-1}						kg kg^{-1}	
ST	K0	4.0 a§	4.1 a	12.8 b	12.8b	124.9 b	133.5 b	–	–
	K1	4.0 a	4.1 a	13.9 a	14.1a	163.3 a	179.0 a	0.67 a	0.71 a
	K2	4.2 a	3.7 a	13.9 a	13.5ab	175.4 a	167.4 a	0.48 b	0.45 b
DJ	K0	3.9 b	4.0 b	18.6 b	20.8b*	269.1 b	301.9 b*	–	–
	K1	4.0 b	4.3 a	20.1 b	22.9a	289.6 b	323.4 b	0.75 a	0.77 a
	K2	4.3 a	4.5 a	24.2 a	24.9a	345.7 a	371.0 a	0.68 a	0.68 b
QY1	K0	4.5 b*	4.1 b	12.3 a	12.9a	162.0 b	163.6 c*	–	–
	K1	5.3 a	4.9 a	12.6 a	13.1a	181.2 ab	195.6 b	0.77 a	0.82 a
	K2	5.7 a	5.1 a	12.9 a	13.1a	190.8 a	212.7 a	0.61 b	0.68 b
QY2	K0	4.2 a	4.2 b	11.8 b	12.3a*	131.3 c	142.3 c*	–	–
	K1	4.5 a	4.8 a	12.3 ab	13.0a	146.1 b	167.0 b	0.71 a	0.77 a*
	K2	4.5 a	4.8 a	12.6 a	13.0a	165.4 a	180.3 a	0.59 b	0.62 b
LY	K0	2.9 b	2.9 b	18.1 a*	15.2b	173.2 a	150.9 b	–	–
	K1	3.4 a	3.1 a	16.4 b	15.2b	162.5 a	175.4 a	0.62 a	0.73 a*
	K2	3.1 ab	3.0 ab	18.8 a	16.6a	181.9 a	193.6 a	0.51 a	0.59 b
QY	K0	4.3 b*	4.1 b	8.7 a	8.4b	121.7 c	127.6 c*	–	–
	K1	4.8 ab	4.6 a	9.0 a	8.9ab	138.8 b	149.7 b	0.71 a	0.74 a
	K2	5.1 a	4.6 a	9.3 a	9.2a	154.8 a	166.5 a	0.57 b	0.60 b
ZD	K0	4.6 a	4.2 b	9.2 a*	8.8a	124.6 c	123.2 c	–	–
	K1	4.9 a	4.8 a	9.6 a	9.0a	139.6 b	137.2 b	0.70 a	0.69 a
	K2	4.9 a	4.8 a	9.9 a	9.4a	158.6 a	159.7 a	0.58 b	0.58 b

* Significant difference at $P \leq 0.05$ between CP and HP from each site.

† ST, Shuitun; DJ, Dajin; QY, Qingyuan; LY, Laiyang; ZD, Zhengding.

‡ Ratio of the amount of absorbed K and the sum of K supplied from the soil and fertilizer.

§ Means in a column from each site followed by different letters are significantly different at $P \leq 0.05$.

under CP and 0.30 and 0.25, respectively, under HP (Table 5). There were no significant differences for REK between K levels and production practices but, on average, HP outperformed CP for the REK across the seven site-years (Table 5).

Economic Performance and Soil Potassium Balance

In general, the medium K rate (K1) led to economic profits at all sites in both years and under both production practices, ranging from 259 to 1913 yuan ha^{-1} (Table 6). Economic profits were significantly higher under HP than CP at five of the seven site-years. On average, HP outperformed CP in terms of economic profit across the seven site-years but there were no significant differences between the K1 and K2 treatments within the same production practice.

In all cases, the VCR under HP was equivalent to or greater than under CP. The VCR values were significantly higher under HP than CP at four of the seven site-years. On average, the VCR was significantly higher under HP than CP (Table 6).

Negative partial K balances were found for all K0 and K1 treatments in both years and production practices at all sites (Fig. 1). Positive partial K balances were obtained only under the high-K treatments (K2) at ST under both HP and CP in 2005 and at LY under CP in 2006.

DISCUSSION

In this study, at all site-years except for ZD in Hebei Province, HP significantly improved maize grain yield compared with CP (Table 3). At all sites and in both years and with both production practices, maize grain yield and biomass responded positively to K application; the positive responses ranged from 2.6 to 29.7% (Table 3). Maize grain yield increased significantly in response to K fertilization at six of seven site-years under CP and at all sites under HP (Table 3). On average, maize grain yield increased by 9.9 and 14.9% under CP and by 15.7 and 21.0% under HP at the K1 and K2 levels, respectively (Table 3). In general, HP surpassed CP in terms of maize yield increases in response to K application. Changes in the dry matter of stover as affected by K fertilization were not consistent with the grain yield at ZD in 2006 (Table 3). The same results were shown by Heckman and Kamprath (1992), whose trials were conducted on sandy Coastal Plain soils with lower K buffer capacity. Grain yields were not increased by K fertilization, although stover yields were increased in 2 yr due to the decrease in the HI for K application (Heckman and Kamprath, 1992). In our study, however, there were no consistent changes in the HI due to K application. At ST, in Shandong Province, application of K did not significantly increase maize grain yield relative to the control under CP (Table 3), indicating that the limiting factor was not K.

Recent research has shown that yield responses to K fertilization are related to the exchangeable K content of the soil and to the soil texture. In sandy Coastal Plain soils, yield increased linearly with K rates up to 135 kg K_2O ha^{-1} when the initial exchangeable-K level was 0.21 cmol L^{-1} (Heckman and Kamprath, 1992). Potassium did not improve maize yields if soil-test K measurements were greater than approximately 180.7 mg K_2O kg^{-1} (Rehm and Lamb, 2004). In the current study, available K in the soils at all sites was <150 mg kg^{-1} and

Table 5. Partial factor productivity of applied N, P, and K (PFPN, PFPP, and PFPK, respectively, expressed in terms of K_2O), K agronomic efficiency (AEK), and K apparent recovery efficiency (REK) as affected by no (K0), medium (K1), or high (K2) K fertilization rates under conventional (CP) or high-yielding (HP) production practices.

Site†	K treatment	PFPN		PFPP		PFPK		AEK		REK	
		CP	HP	CP	HP	CP	HP	CP	HP	CP	HP
		kg kg^{-1}									
ST	K0	42.0 a‡*	32.7 b	94.6 a*	65.4 b	–	–	–	–	–	–
	K1	45.1 a	36.0 a	101.4 a	72.0 a	67.6 a	72.0 a	4.5 a	6.6 a	0.32 a	0.38 a
	K2	45.1 a	35.9 a	101.5 a	71.9 a	33.8 b	35.9 b	4.6 a	3.2 b	0.21 a	0.14 a
DJ	K0	35.8 c*	27.3 c	80.5 c*	54.6 c	–	–	–	–	–	–
	K1	42.2 a	34.2 a	94.9 a	68.4 a	63.3 a	68.4 a*	9.7 a	13.8 a*	0.17 a	0.18 a
	K2	40.5 b	30.8 b	91.0 b	61.5 b	30.3 b	30.8 b	3.5 b	3.5 b	0.32 a	0.29 a
QY1	K0	39.6 c*	27.5 c	–	82.5 c	–	–	–	–	–	–
	K1	43.5 b	33.0 b	–	99.0 b	86.9 a	99.0 a*	7.7 a	16.5 a*	0.26 a	0.43 a
	K2	47.6 a	35.7 a	–	107.1 a	47.6 b	53.6 b	8.0 a	12.3 a	0.19 a	0.33 a
QY2	K0	37.3 c*	25.2 b	–	75.5 b	–	–	–	–	–	–
	K1	40.1 b	29.5 a	–	88.5 a	80.2 a	88.5 a*	5.6 a	13.0 a*	0.20 a	0.33 a
	K2	43.2 a	30.8 a	–	92.4 a	43.2 b	46.2 b	5.9 a	8.5 b	0.23 a	0.25 a
LY	K0	22.1 b	26.6 c*	66.2 b*	63.9 c	–	–	–	–	–	–
	K1	23.5 a	29.9 b	70.4 a	71.7 b	78.3 a	79.7 a*	4.7 a	8.7 a*	–0.12 a	0.27 a
	K2	23.2 a	33.0 a	69.7 a	79.3 a	38.7 b	44.0 b	1.9 b	8.5 a	0.048 a	0.24 a
QY	K0	49.7 b*	34.9 b	–	104.8 b	–	–	–	–	–	–
	K1	53.5 b	39.4 a	–	118.2 ab	106.9 a	118.2 a*	7.6 a	13.4 a	0.23 a	0.30 a
	K2	59.5 a	43.0 a	–	128.9 a	59.5 b	64.5 b	9.8 a	12.1 a	0.22 a	0.26 a
ZD	K0	37.1 c*	24.8 c	–	74.5 b	–	–	–	–	–	–
	K1	42.2 b	28.3 b	–	84.8 ab	84.4 a	84.8 a	10.2 a	10.3 a	0.20 a	0.19 a
	K2	47.1 a	31.9 a	–	95.6 a	47.1 b	47.8 b	9.9 a	10.6 a	0.23 a	0.24 a
Avg.	K0	37.7 c*	28.4 c	–	74.5 c	–	–	–	–	–	–
	K1	41.4 b	32.9 b	–	86.1 b	81.1 a	87.2 a*	7.1 a	11.8 a*	0.18 a	0.30 a*
	K2	43.7 a	34.4 a	–	91.0 a	42.9 b	46.1 b	6.2 a	8.4 b	0.21 a	0.25 a

* Significant difference at $P \le 0.05$ between CP and HP from each site.

† ST, Shuitun; DJ, Dajin; QY, Qingyuan; LY, Laiyang; ZD, Zhengding.

‡ Means in a column from each site followed by different letters are significantly different at $P \le 0.05$.

even <100 mg kg^{-1} at five of the seven site-years (Table 1). Brown soil is one of the soils with a low exchangeable-K concentration in the NCP (Xie, 2000), and significant yield increases resulting from K fertilization could be explained by the relatively low K concentrations in this soil. Some studies have reported, however, that K fertilization increased yields in several soils that tested optimum or higher in soil-test K (Mallarino et al., 1999; Borges and Mallarino, 2001). Similarly, in the present study, a significant and positive response to applied K occurred at DJ in 2005 (Table 3), where the available-K concentration in the soil was high (144.9 mg K_2O kg^{-1}, Table 1), under both CP and HP.

In addition to soil K content, the application method and other management practices (tillage) could influence the response of maize to applied K. In the present study at LY, Shandong Province, in 2006, the split application of K fertilizer as basal and topdressing increased maize yield under HP (Table 2). Vyn and Janovicek (2001) showed that maize yield response to starter K was greater under no-till than conventional tillage. In this study, HP exceeded CP at all sites in terms of response of maize grain yield to K fertilization (Table 3).

Many long-term experiments have shown that a balanced supply of N, P, and K can increase crop yield (Wang et al., 2007). The yield response to K uptake depends to a great extent on the level of N nutrition, and this interaction is normally positive (Bruns and Ebellhar 2006). Optimal N/K ratios favor healthy plant growth and development, whereas an imbalance of N and K supply results in maladjusted plant growth (Xie, 2000). At DJ, under both production practices, maize grain yield was the highest in the K1 treatment and then decreased in the K2 treatment (Table 3). At LY, however, although the N fertilization rate was lower under HP than CP (Table 2), yields were higher under HP than under CP. These results indicate that the quantity of N fertilizer applied by local farmers had exceeded the optimal amounts, as has been reported previously by Ju et al. (2009). This may have caused an imbalance in the N/K ratios. At all sites, except for LY in 2006, the N inputs were higher under HP than CP (Table 2). Maize plants whose yields had increased because of N application required more K under HP. According to Gething (1993), N × K interaction effects are greater as yield increases. This may be one of the primary reasons for the greater response to applied K under HP than CP. Interactions between P and K were clearly evident in the current study and in a previous study (Xie, 2000), as were interactions between K and microelements. At LY, Shandong Province, $ZnSO_4$ fertilizer application was included as part of the HP (Table 2), and the addition of $ZnSO_4$ may be one reason for the better yield responses under HP than under CP.

Balancing the N/P/K ratio by increasing the input of K fertilizers is a practical way to improve N agronomic efficiency and to minimize the environmental impacts of N fertilization (Zhu and Chen, 2002). It appears that K application alleviates the N

Table 6. Economic profits and value cost ratio (VCR) as affected by medium (K1), or high (K2) K fertilization rates under conventional (CP) or high-yielding (HP) production practices.

Site†	K treatment	Economic profit‡		VCR	
		CP	HP	CP	HP
		—— yuan ha^{-1} ——			
ST	K1	359 a§	714 a	1.9 a	2.8 a
	K2	–27 a	290 a	1.0 a	1.4 a
DJ	K1	1221 a	1913 a*	4.1 a	5.8 a*
	K2	383 b	370 b	1.5 b	1.5 b
QY1	K1	554 b	1479 a*	3.2 a	6.9 a*
	K2	1176 a	2083 a	3.4 a	5.2 a
QY2	K1	344 b	1119 a*	2.4 a	5.5 a*
	K2	738 a	1275 a	2.5 a	3.6 b
LY	K1	259 a	760 a*	1.8 a	3.3 a*
	K2	–169 a	1486 a	0.7 a	3.3 a
QY	K1	415 a	984 a*	2.3 a	4.0 a
	K2	1257 a	1704 a	2.9 a	3.6 a
ZD	K1	670 a	677 a	3.1 a	3.1 a
	K2	1288 a	1412 a	3.0 a	3.2 a
Avg.	K1	546 a	1087 a*	2.7 a	4.5 a*
	K2	664 a	1250 a	2.1 a	3.1 a

* Significant difference at $P \leq 0.05$ between CP and HP from each site.

† ST, Shuitun; DJ, Dajin; QY, Qingyuan; LY, Laiyang; ZD, Zhengding.

‡ Production price and fertilizer price were 1.4 and 2.0 yuan kg^{-1}, respectively, at ST, DJ, QY1, and QY2 in 2005. In 2006, production price and fertilizer price were 1.3 and 2.6 yuan kg^{-1}, respectively, at QY and ZD in Hebei Province and 1.4 and 2.2 yuan kg^{-1}, respectively, at LY in Shandong Province.

§ Means in a column from each site followed by different letters are significantly different at $P \leq 0.05$.

pollution problem by inducing a higher rate of N fertilizer uptake by crops (Ardjasa et al., 2002). In the present study, the average PFP of N increased 9.8 and 15.8% under CP and 15.9 and 21.1% under HP at the K1 and K2 levels, respectively (calculated from data in Table 5). In general, the PFP of N was improved with the increased K input under the same production practice, which indicates positive interactions between N and K (Table 5). Likewise, the PFP of P showed the same trend at most sites because of a positive interaction between P and K (Table 5). Under HP, the PFP of N and P were inferior to the values under CP as a result of increasing N and P inputs under HP (Table 5). Relative to CP, HP enhanced the KUE, including PFPK, AEK, and REK, on average, because of the better yield responses under HP (Table 5). Moreover, the KUE was also improved by HP compared with CP at six of the seven site-years at the K1 level (Table 4). The biological yield is the main factor that determines the amount of minerals absorbed by crops (Osaki et al., 1991). Increased yields, improved management of production factors other than fertilizer (planting system), and improved N and K management contributed to the improvement in nutrient use efficiency.

Intensive crop production in combination with unbalanced fertilization has already resulted in depletion of soil K across large areas of China (Jin et al., 1999; Yang et al., 2004). In the present study, at all sites and in both years and under both production practices, K deficits in the soil were serious (Fig. 1). Deficiency of K in crop production usually appears following increases in N and P fertilizer applications and neglect of K fertilization (Ju et al., 2005). Our results suggest that K fertilization at rates of 75 to 240 kg K_2O ha^{-1} would greatly mitigate the present depletion of soil K (Fig. 1). Moreover, economic profits under HP were higher than under CP, on average, across seven site-years (Table 6).

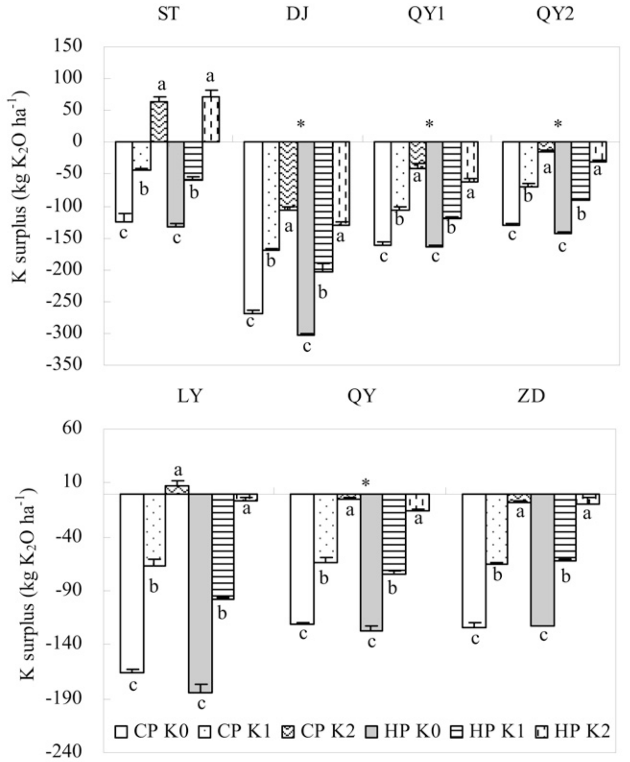

Fig. 1. Potassium balance in field experiments on maize in 2005 (upper) and 2006 (lower) in the North China Plain (ST, Shuitun; DJ, Dajin; QY, Qingyuan; LY, Laiyang; ZD, Zhengding) for conventional production practices (CP) and high-yielding production practices (HP) treatments receiving no K fertilizer (0K) or medium (K1) or high (K2) K fertilizer rates. The partial K balance in the soil was defined as the quantity of K fertilizer applied minus the quantity of K removed by the maize plants (grain and straw); no other inputs or outputs were considered. Bars denote standard errors of the mean from each site, *n* = 3. Means from each site with different letters are significantly different at $P \leq 0.05$ with the same production practices. *Significant difference at $P \leq 0.05$ between CP and HP from each site; otherwise no significant differences occurred.

Therefore, farmers who are using HP (including the application of high rates of N and P fertilizers) must pay attention to the K fertility of their soils for sustainable crop production. The K uptake by maize straw relative to the whole plant was about 80% (calculated from data in Tables 4 and 5) and was not influenced by K fertilization. Returning maize stalks to the land would be an effective way to improve the K fertility of soils.

CONCLUSIONS

In conclusion, maize yield response and economic profit from applied K were greater under HP than CP at most sites in this study. On average, maize grain yields were enhanced by 9.9 and 14.9% under CP and 15.7 and 21.0% under HP at the K1 and K2 levels, respectively. Yield response to K application under HP was an integrated effect that involved soil conditions, nutrient management, and planting systems.

Nutrient use efficiency of N and P were improved by K application, especially under HP. On average, the PFP of N increased by 9.8 and 15.8% under CP and 15.9 and 21.1% under HP for the medium- and high-K treatments, respectively. Overall, HP improved the PFPK, AEK, and REK. Our data suggest positive interactions among K fertilization and other high-yielding production practices.

Negative K balances were observed in all of the control and medium-K treatments in both years and under both production practices, especially under HP. In intensive agriculture in the NCP, which has soils with higher K content relative to South China, optimal K fertilization and other practices such as returning straw to the soil and applying manure to improve the K fertility of soils are essential for obtaining high and sustainable grain yields.

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