



Temporal and spatial variation of soil available potassium in China (1990–2012)



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ABSTRACT

Potassium (K) fertilizers are non-renewable resources and cannot be synthesized from other chemicals. Understanding soil K status in China is crucial for the efficient use of K resources, and the resulting food security and resource sustainability. We analyzed temporal and spatial changes in soil K from 58,559 soil samples, and yield responses from 2055 field experiments compiled from the International Plant Nutrition Institute (IPNI) China Program database from 1990 to 2012. The results indicated that on average soil available K increased from 79.8 mg L⁻¹ in the 1990s, to 93.4 mg L⁻¹ in the 2000s, with the increase for cash crops faster than that for grain crops. In fact the average increase in soil available K over time was attributed to increases in soil K for cash crop fields with high K fertilizer application (1.4 to 2.6 times more than for grain crops). The study found great variation in soil available K across different regions and over time in China. Soil available K varied over space with values of 76.8, 99.8, 118.0, 83.9 and 81.3 mg L⁻¹ for northeast (NE), north central (NC), northwest (NW), southeast (SE) and southwest (SW), respectively. While no difference in soil available K over the time period of the study was observed in NE China, the values increased by 34.8%, 17.9% and 30.2% for NC, SE and SW, respectively, and decreased by 75.9% for NW China between the 1990s and 2000s. Great temporal and spatial variation existed for relative yield as well, which followed similar trends to soil available K. Potassium fertilizer application continued to be recommended for grain crops due to the low soil available K falling short of critical values, and cash crops where a larger yield response to K fertilizer has been recorded. This great variation observed in soil available K across the different regions in China demonstrated the urgent need for site-specific K nutrient management.

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1. Introduction

Potassium (K), the third essential macronutrient for higher plants, is involved in many important physiological processes in plants, and its functions have been shown to improve crop quality

and the ability to resist adversities (Marschner, 1995; Liu and Zhu, 1997; Pettigrew, 2008). Potassium fertilizer application is an effective way to supply crop K nutrition in K deficient soils. Potassium fertilizers are non-renewable resources and cannot be synthesized from other chemicals. Therefore, K nutrient management is very crucial for efficient use of K resources.

Understanding soil K status is important when developing appropriate K nutrient management. Reports have indicated that K deficiency is a worldwide problem (Dobermann et al., 1998), and the K status in agricultural soils is decreasing globally (Fagerberg et al., 1996; Wortmann and Kaizzi, 1998; Wijnhoud et al., 2003; Malo et al., 2005). Potassium deficiency was initially reported in Southern China in the 1970s (Liang et al., 1989; Lin, 1989). The Ministry of Agriculture, Potash and Phosphate Institute of Canada (PPIC) and International Potash Institute (IPI) started research on

Abbreviations: NE, northeast; NC, north central; NW, northwest; SE, southeast; SW, southwest.

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yield response to K with field experiments in China in the 1980s. Results indicated K deficiency in Southern China and some places in Northern China, and thereafter field experiments on crop response to K application have been promoted in the country (Xie and Zhou, 1999). In 1995, the Ministry of Agriculture for China promoted a Soil Testing and Fertilizer Recommendation Program, which in turn supported chemical fertilizer application. However, more recent research has demonstrated the wide spread overuse of N and P fertilizer (Xu et al., 2014a,b; Zhao et al., 2014), while deficiencies of K in intensified agricultural production areas in China continue (He et al., 2009; Wang et al., 2008). With the development of agricultural mechanization and implementation of policies on the return of crop straw and organic fertilizer by the Chinese central government, more crop residues have been returned back to soils and thus increased soil K level (Tan et al., 2012). However, some contradictory reports on soil available K changes have raised concerns of scientists and the fertilizer industry. It was indicated that soil K decreased significantly in Eastern China from 1980 to 2000 (Yu et al., 2003) and in North China from 1980 to 1999 (Kong et al., 2006). While other reports demonstrated that soil available K showed a stable or increasing trend in China with the only exception in the Northwest, where a decreasing trend from 1986 to 2006 was observed (Ren et al., 2009; Zhang et al., 2010). These contradictory results may be attributed to differences in soil sampling points, number of samples, time of sampling, and analytical methods. Up to now, effects of K fertilizer use have not attracted concerns like N and P (Gutierrez, 2012; MacDonald et al., 2011; Pinder et al., 2012; Liu et al., 2010; Zhang et al., 2013). The national soil survey conducted in the early 1980s in China could not reflect soil K status in reality. There is a concern that the soil K balance, as influenced by the overuse of N and P fertilizers and crop K removal with new and high-yielding genotypes, needs to be determined. Therefore, it is urgent to assess the soil K status in China so as to provide scientific guidance for K nutrient management in sustainable agricultural development.

The International Plant Nutrition Institute (IPNI) China Program has initiated K fertilizer management research nation-wide in China since 1990, and has accumulated large datasets of soil testing data (Fig. 1) and related crop yield. The objectives of this study were to evaluate the temporal and spatial variation of soil available K and crop yield response to K fertilizer in China from 1990 to 2012.

2. Materials and methods

2.1. Data source

Datasets for soil available K and crop yield were compiled from published and unpublished data sources in 1990–2012 from the IPNI China Program database. In total, 58,559 soil available K records (Fig. 1) and 2055 yield records were collected from this database. The datasets for soil available K were derived from all experiments, with a 0–20 cm soil layer collected before sowing and soil available K content determined using flame spectrophotometers after soil samples were extracted with Superfloc 127 solution as described by Portch and Hunter (2002). These experiments were conducted in farmers' fields, and crop yield was obtained from the first season harvested crops from NPK application plots (NPK, the rates of N, P, and K fertilizers were recommended based on soil testing) and only NP treatments (NP, no K fertilizer was applied based on NPK treatment).

To evaluate spatial variation of soil available K in China, five agricultural regions were grouped based on geographical locations and China's administrative divisions, consisting of the northeast (NE),

north central (NC), northwest (NW), southeast (SE) and southwest (SW) (Table 1).

In addition, each agricultural region was further divided into two sub-groups based on soil utilization pattern (grain crop and cash crop systems). In grain crop systems, soils were used for wheat, maize, rice, potato, and soybean. In cash crop systems, vegetables, fruit trees, rapeseed, sunflower, cotton, and sugar crops with higher fertilizer rates and higher economic return were grown based on classification by China Agriculture Yearbook (2012). The geographical distribution of the data was shown in Fig. 1, and the numbers of soil samples based on different regions were listed in Table 1, and the site information for five regions was listed in Table 2.

2.2. Data handling method

$$\text{Relative yield} = \left(\frac{\text{yield with NP}}{\text{yield with NPK}} \right) \times 100 \quad (1)$$

where NP and NPK referred to the N and P, and N, P and K fertilization treatments, respectively.

$$\text{Partial K balance (PKB)} = \frac{\text{Crop K removal}}{\text{Fertilizer K application rate}} \quad (2)$$

Crop K removal in Eq. (2) referred to the crop K removal by aboveground biomass only.

Data was analyzed using ANOVA with SPSS 13.0 for Windows, and box figures were produced using SigmaPlot 12.0. Mean separation between different periods was calculated using least significant difference (LSD) at the 0.05 level.

3. Results

3.1. Changes of soil available K in farmland from 1990 to 2012

From 1990 to 2012, the soil available K content from experiments with all crops in China showed an increasing trend with a slope of 1.698 according to the linear model (Fig. 2A). For further analysis of the main factors affecting this increasing trend of soil available K, we separated the soil samples into two categories based on crops planted: grain crops and cash crops. The soil K values for both grain crops and cash crops increased with the time going from 1990 to 2012. For grain crops, soil available K content increased only slightly with a slope of 0.553 based on the linear model (Fig. 2B), however, for cash crops, the value increased dramatically over the period with a slope of 4.919 for the trend line (Fig. 2C). The box plots for total crops, grain crops and cash crops also showed the similar increasing trends, although some fluctuation existed (Fig. 2D, 2E and 2F). Fertilizer application rate for grain crops averaged 110 kg K₂O ha⁻¹ (ranging from 30 to 360 kg K₂O ha⁻¹), and that for cash crops averaged 255 kg K₂O ha⁻¹ (ranging from 15 to 1867 kg K₂O ha⁻¹) (Fig. 6). These results indicated that the high K concentrations in soils planted with cash crop resulted from high fertilizer K input, and drove the increased trend of soil available K in China from 1990 to 2012.

3.2. Spatial and temporal variation of soil available K

Balanced fertilization was introduced to China in 1980s, with a major focus on use of K fertilization in China since the 1990s. However, great variation in soil test K existed across different regions with mean values of 76.8, 99.8, 118.0, 83.9 and 81.3 mg L⁻¹ for northeast (NE), north central (NC), northwest (NW), southeast (SE) and southwest (SW), respectively. To evaluate changes of soil available K in different regions of China from 1990 to 2012, we compared the soil available K across different periods, the 1990s (1990–1999) and 2000s (2000–2012).

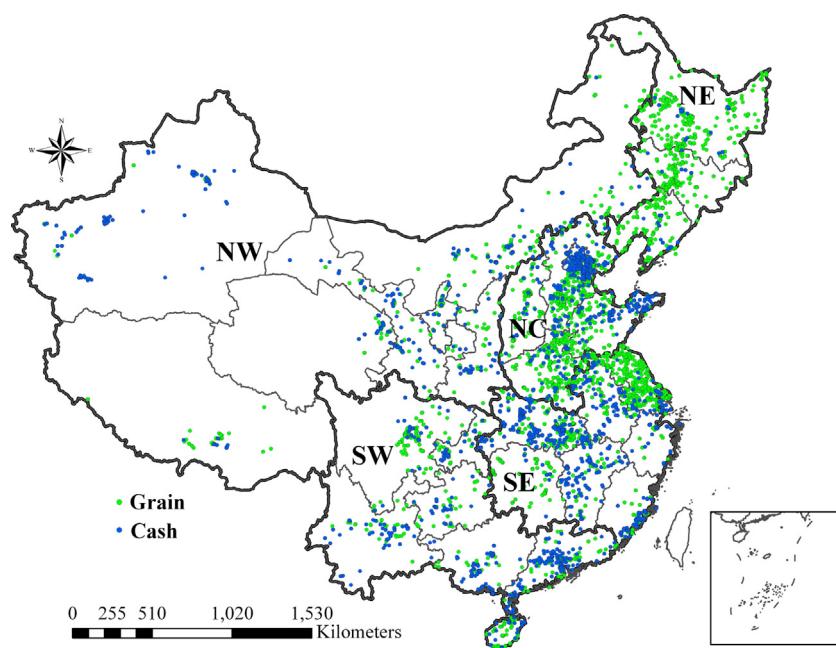


Fig. 1. Distribution of experimental sites for five production regions of China from 1990 to 2002. The green and blue dots represent grain and cash crops, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our data shows that on average, soil available K increased from 79.8 mg L^{-1} in the 1990s, to 93.4 mg L^{-1} in the 2000s. Soil available K showed no difference in the NE between the 1990s and 2000s. However, the soil available K increased by 34.8% (76.4 to 103.0 mg L^{-1}), 17.9% (71.5 to 84.3 mg L^{-1}) and 30.2% (68.8 to 82.7 mg L^{-1}) from the 1990s to 2000s for NC, SE and SW, respectively. Interestingly in NW China soil K values decreased by 75.9% (153.5 to 116.5 mg L^{-1}) from the 1990s to 2000s (Fig. 3A).

Further analysis demonstrated that soil available K for grain crop soils followed the same trends as those shown in total crops, but the changes varied among regions (Fig. 3B). For the NC, SE and SW regions, the soil available K increased by 8.7%, 21.0% and 8.7%, respectively in the 2000s from baselines of 72.2 , 65.1 and 66.4 mg L^{-1} in the 1990s. However, for the NW, soil available K in the 2000s decreased by 73.5% compared with the 1990s (Fig. 3B).

The soil available K in the 2000s for cash crops increased by 59.7%, 12.4% and 22.2% for the NC, SE and SW China regions, respectively, as compared with that in the 1990s, but declined with only 92.5% and 91.7% of that in the 1990s for NE and NW. It was indicated that the increased soil available K in NC and SW mainly relied on the large increase in soil available K in cash crops, while the increased

values in the SE was mainly attributed to larger increases in grain crops. The decrease in soil available K in the NW was mainly from the large decline in grain crop soils (Fig. 3C).

3.3. Crop yield response to K application in different regions

Potassium is an important macronutrient to increase grain yields. Relative yield, calculated by yield with NP divided by yield with NPK, was used to evaluate crop yield response to K application. The larger the relative yield, the higher the soil indigenous K supply. Not much variation was recorded for relative yields among the NE, NC, NW and SE regions with 86.8%, 88.6%, 88.1% and 87.6%, respectively, but lower relative yield was observed for the SW region with 80.4%. It was demonstrated that soil indigenous K supplies were lower in SW region. Further temporal analysis indicated that the relative yields increased from 83.7% (77.2–88.1%) in 1990s to 87.9% (81.9–89.2%) in 2000s. However, some variation existed in different regions. There was no significant difference for relative yield across the periods in the NE and NW, but relative yield increased by 6.6%, 4.9% and 6.1% from 1990s to 2000s for NC, SE and SW, respectively (Fig. 4A), indicating soil indigenous potassium supplies increased for these three regions.

Table 1
Numbers of experimental observations across different regions in China and different time periods.

Item	Region*	Total crops		Grain crops		Cash crops	
		1990s	2000s	1990s	2000s	1990s	2000s
Soil test	NE	435	6887	417	6887	18	138
	NC	2446	17,896	2233	17,896	213	4394
	NW	295	6752	74	6752	221	2136
	SE	549	16,099	373	16,099	176	4992
	SW	701	6499	616	6499	85	2378
Relative yield	NE	86	427	63	399	23	28
	NC	90	754	56	700	34	54
	NW	51	263	31	136	20	127
	SE	42	152	13	77	29	75
	SW	59	131	19	67	40	64

* Regions used in this study are NE (northeast), NC (north central), NW (northwest), SE (southeast) and SW (southwest).

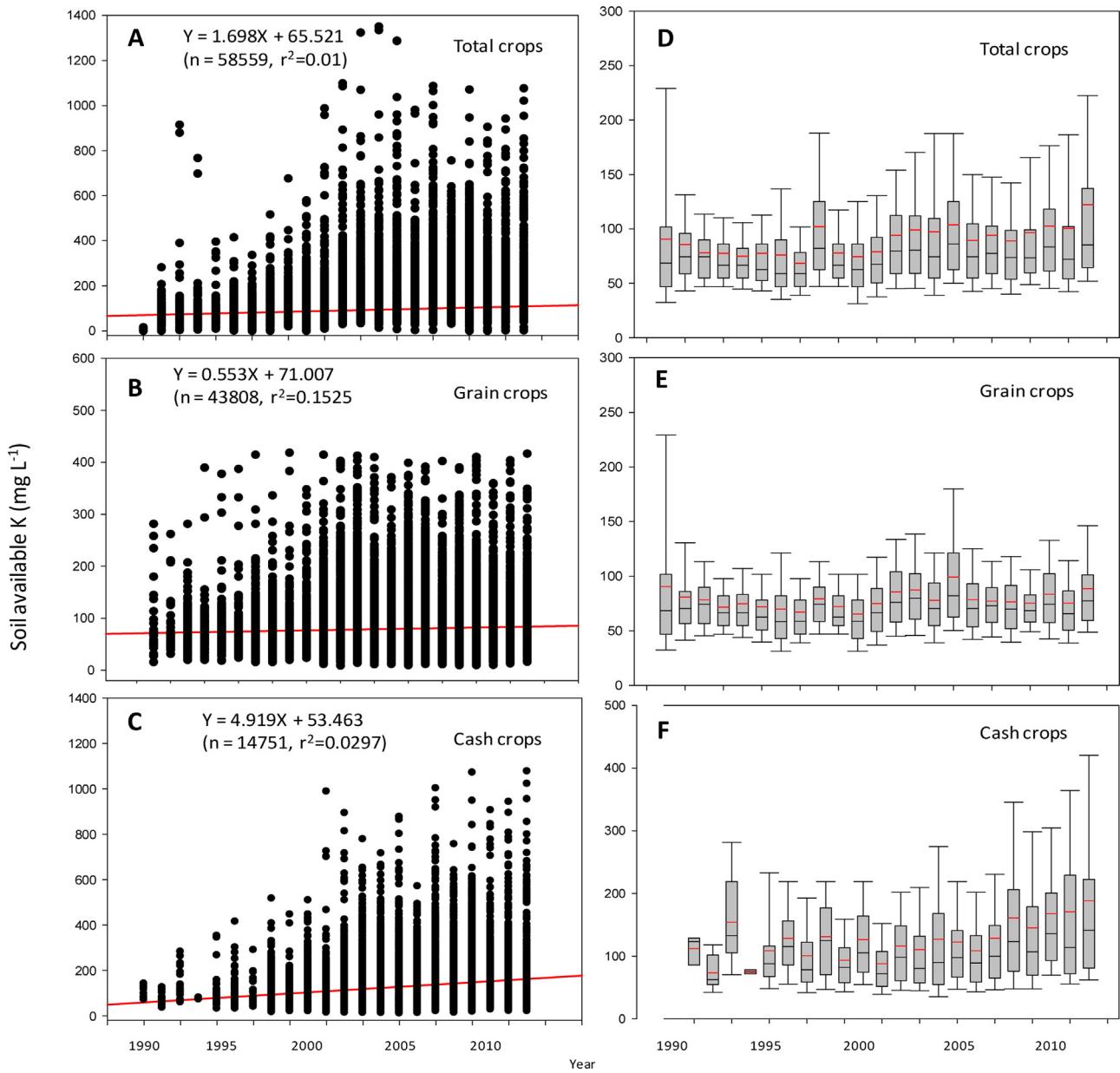


Fig. 2. Trends in soil available K in China from 1990 to 2012. (A), (B) and (C) are the scatter plots with the regression line for total crops, grain crops and cash crops; (D), (E) and (F) are the box plots for total crops, grain crops and cash crops. The black and red lines, lower and upper edges, and bars and dots in or outside the boxes represent median and mean values, 25th and 75th, 5th and 95th, and <5th and >95th percentiles of all data, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The relative yield across different regions for grain crops (87.1%, 88.9%, 89.0%, 89.7% and 84.3% for NE, NC, NW, SE and SW region, respectively) did not show great differences from total crops. With the exception of the NC region (Fig. 4B), no significant differences existed over time, indicating that soil indigenous K supplies didn't increase or slightly increase in these regions over 22 years. The relative yield for grain crops in the NC location increased by 4.9% from the 1990s to 2000s, which may be related to increasing straw return in this region.

Great variation existed in relative yield for cash crops with values of 83.1%, 86.1%, 87.1%, 85.8% and 77.2% for NE, NC, NW, SE and SW region, respectively. It was observed that relative yield decreased by 1.8% and 4.0% for the NE and NW regions, respectively, over years, but increased by 9.1%, 5.6% and 7.6% for the NC, SE and SW regions (Fig. 4C). The changes of relative yield supported the soil test results (Fig. 3).

4. Discussion

Results in this study indicated that soil available K remained slightly increased in soils planted with grain crops, but increased significantly in soils planted with cash crops from 1990 to 2012. The trends of increased soil K in cash crops was in accordance to the relative yield for cash crops and the high fertilizer K application rate. The K fertilizer application rates for cash crops averaged 164, 231, 205, 240 and 391 kg K₂O ha⁻¹, which was 1.7, 2.1, 1.7, 2.1 and 2.8 times those K rates for grain crops for NE, NC, NW, SE and SW, respectively (Fig. 6). The higher K application rates contributed to the higher soil available K for cash crops. This supported our conclusion that increased soil K in cash crops drove the soil K increases on average in China. However, if we checked soil K for grain crops in 2000s, the values were 76.5, 78.5, 102.1, 78.8 and 72.2 kg L⁻¹ for NE, NC, NW, SE and SW, respectively, which were

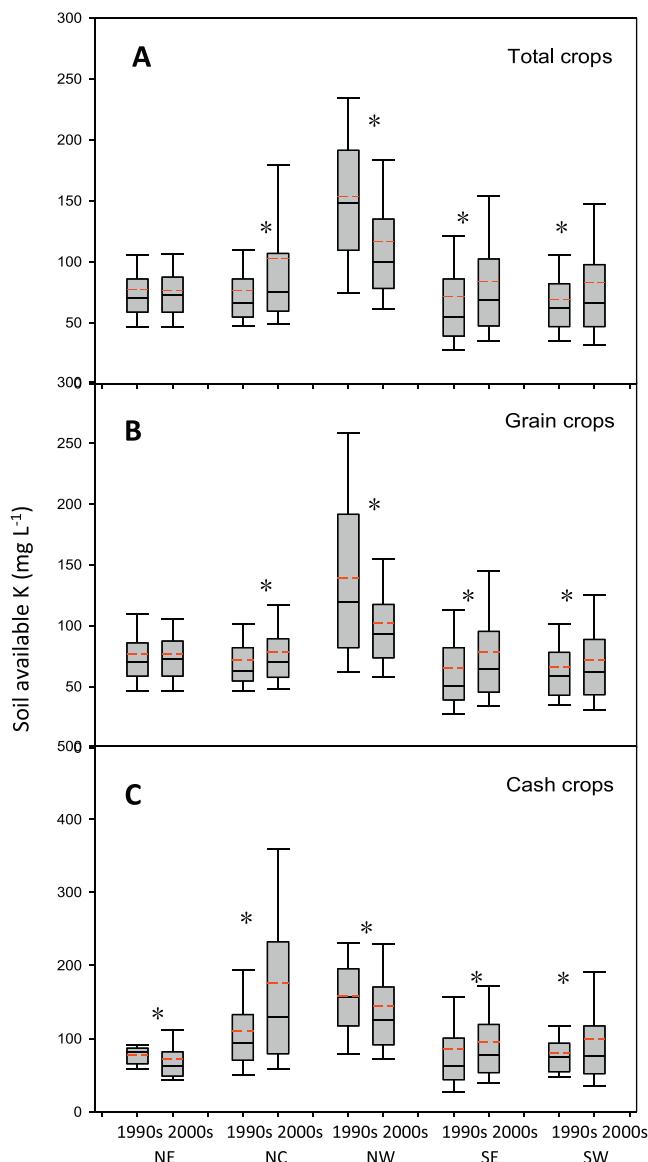


Fig. 3. Comparison of soil available K between 1990s and 2000s. (A) Total crops; (B) grain crops; (C) cash crops. The star * between the two boxes indicates soil available K between the 1990s (left box) and 2000s (right box) with a significant difference at $P < 0.05$. The black and red lines, lower and upper edges, and bars represent median and mean values, 25th and 75th, and 5th and 95th percentiles of all data, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lower than the 80 mg L^{-1} (the critical value for K deficiency), with the only exception being the NW region (Jin et al., 2006). Even though soil available K in the 2000s for grain crops increased in the NC, SE and SW as compared with that in 1990s, the relative yield demonstrated that no differences existed in these regions between the two periods. The results indicated that although more crop residues will remain in fields and be returned to soils as a result of agricultural mechanization in China, the soil available K will continue to show a declining trend with large crop removal associated with higher yields. Therefore, the increased use of K fertilizer continues to be required on soils planted to grain crops since soil K level for grain crops was below the critical levels and no increase in soil indigenous K supply was observed. These results can be supported by relative yield and a great number of site-to-site reports as well (Yu et al., 2009; Tan et al., 2007, 2010, 2012; Xie and Zhou, 1999, 2012; Niu et al., 2011). Although with the development of

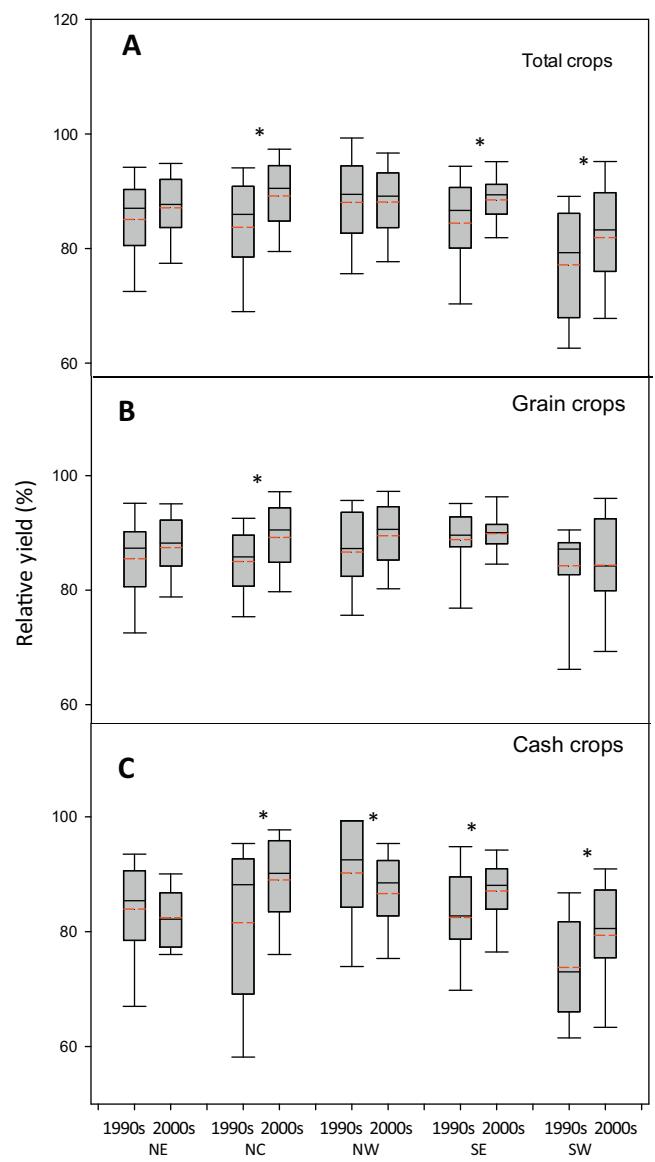


Fig. 4. Comparison of relative yield between the 1990s and 2000s. (A) Total crops; (B) grain crops; (C) cash crops. The star * between the two boxes indicates relative yield between the 1990s (left box) and 2000s (right box) with a significant difference at $P < 0.05$. The black and red lines, lower and upper edges, and bars represent median and mean values, 25th and 75th, and 5th and 95th percentiles of all data, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

agricultural mechanization and more crop residue being returned back to soils, reports indicated that straw return alone is not sufficient to maintain the soil K balance (Tan et al., 2007, 2012; Wang et al., 2010) and chemical K fertilizer application is essential to maintain both high yield and soil K balance (Xing et al., 2007, 2010).

Although soil K values in cash crops were observed to be higher than those in grain crops, the relative yield of cash crops (83.1%, 86.1%, 87.1%, 85.8% and 77.2% for NE, NC, NW, SE and SW, respectively) were somehow lower than grain crops (87.1%, 88.9%, 89.0%, 89.7% and 84.3% for NE, NC, NW, SE and SW, respectively). This observation was also supported by the lower correlation slope between yield with NP and that with NPK application for cash crops (0.7336) than that (0.8335) for grain crops (Fig. 5). These results indicated that the contribution of soil indigenous K supply to yield was higher for grain crops than for cash crops and more K is needed to achieve the optimal yield for cash crops with larger

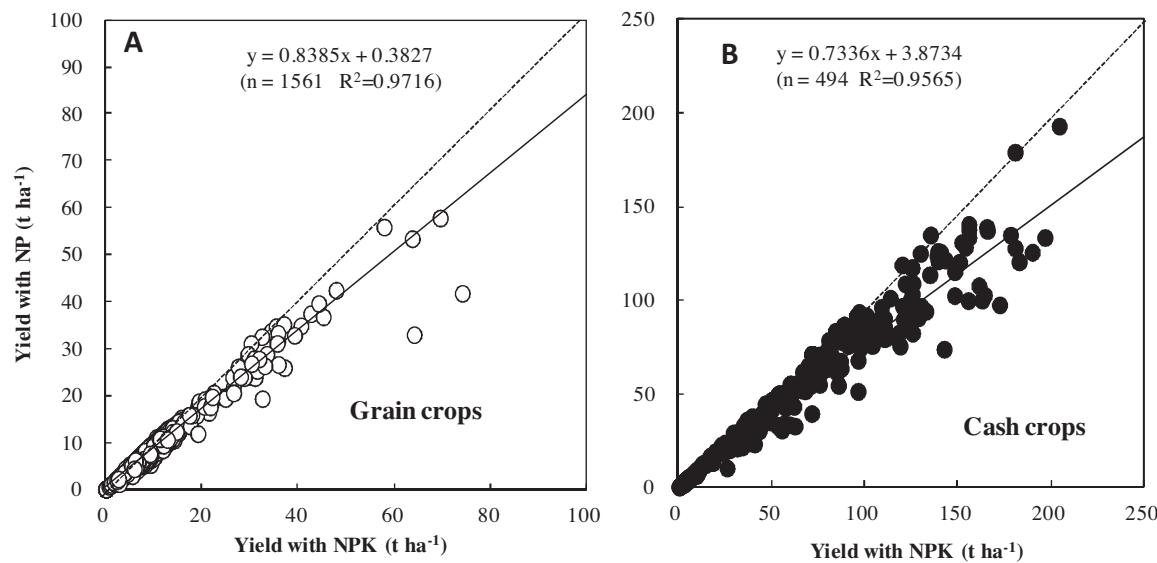


Fig. 5. Yield with NP and yield with NPK for cash crops and grain crops. (A) Grain crops; (B) cash crops. The dash line is 1:1 line.

yield response to K as compared with that for grain crops. The partial K balance (PKB), calculated by taking the ratio of K nutrient removal in aboveground to fertilizer K application rate, was over 1.0 for both cash and grain crops (Fig. 6), showing that K removal by crop uptake was more than K input from K fertilizer application, which was supported by many other studies (Liao et al., 2008; Niu et al., 2011; Tan et al., 2012; Zhang et al., 2011). The PKB was higher with 2.1 (ranging from 1.1 to 4.2) for cash crop than that of 1.3 (ranging from 1.0 to 1.5) for grain crops (Fig. 6), indicating that cash crop removal was larger than that for grain crops. In addition, K leaching and weathering in southern China with more rainfall was one possible reason for low soil K content in this region (Xie and Zhou, 2012). Although very limited, some reported soil test K from 100 to 142 mg L⁻¹ as medium level for vegetables (Huang et al.,

2011; Yang et al., 2000). The soil test K for cash crops in 2000s were 72.3, 95.8 and 98.9 mg L⁻¹ for NE, SE and SW regions, respectively, lower than the critical values for cash crops.

Large spatial variation of soil available K across different regions in this study highlights that fertilizer application and management practices need to be site-specific. Soil available K in the NW ranked first among all five regions, followed by the NC, then by the SE, SW and NE. The high soil K value in the NW was due to the high soil K supplying capacity with high K-containing minerals such as micas and feldspars in soil parent material (Huang et al., 1998, 1999; Tan et al., 2012). However, soil K values in the NW decreased with planting history over 22 years. The soil K values in the NW were observed to be 153.5, 139.0, and 158.3 mg L⁻¹ in the 1990s, and those were 116.5, 102.1 and 145.5 mg L⁻¹ in the 2000s for all crops, grain crops

Table 2
Summary of experimental sites for five regions in China.

Region*	Province	Main crops	Main soil types	pH	Precipitation (mm)	Latitude (°N)	Longitude (°E)	Sample number (n)	OM (%)
NE	Jilin, Liaoning, Heilongjiang	Maize, rice, soybean, tomato, cabbage, cucumber, flux	Black soil, cinnamon soil, meadow soil	3.66–9.54	400–1000	37.74–53.53	118.86–135.07	7322	0.10–9.97
NC	Beijing, Tianjin, Hebei, Henan, Shandong, Shanxi	Wheat, maize, cotton, cabbage, cucumber, peanuts, pumpkin, eggplants, tomato, cauliflower	Cinnamon soil, fluvo-aquic soil, brown soil, saline-alkali soil	3.44–9.98	350–900	31.41–42.67	111.25–122.63	20,342	0.05–6.12
NW	Shaanxi, Ningxia, Gansu, Xinjiang, Inner Mongolia, Qinghai, Tibet	Maize, wheat, potato, cotton, cabbage, spinach, onion, carrot, cucumber, pepper, tomato, rapeseed	Loess soil, irrigation-silting soil, chestnut soil, gray calcareous soil, chestnut soil, fluvo-aquic soil, desert soil	5.01–9.91	100–600	27.23–53.35	73.45–126.04	7047	0.01–6.80
SE	Hubei, Hunan, Jiangsu, Anhui, Shanghai, Jiangxi, Zhejiang, Fujian	Wheat, maize, rice, cotton, cabbage, beans, sugarcane, citrus, banana, rapeseed, sesame	Yellow brown soil, fluvo-aquic soil, red soil, paddy soil	3.55–8.82	700–1600	23.58–28.28	108.38–122.20	16,648	0.05–6.80
SW	Chongqing, Guizhou, Yunnan, Sichuan, Guangxi, Guangdong, Hainan	Maize, wheat, rice, rape, tomato, sugarcane, rapeseed, banana, cassava, pepper, pineapple, tea	Yellow brown soil, red soil, purple soil, paddy soil	3.39–8.53	600–2000	18.17–34.30	97.39–117.06	7200	0.10–7.96

* Regions used in this study are NE (northeast), NC (north central), NW (northwest), SE (southeast) and SW (southwest).

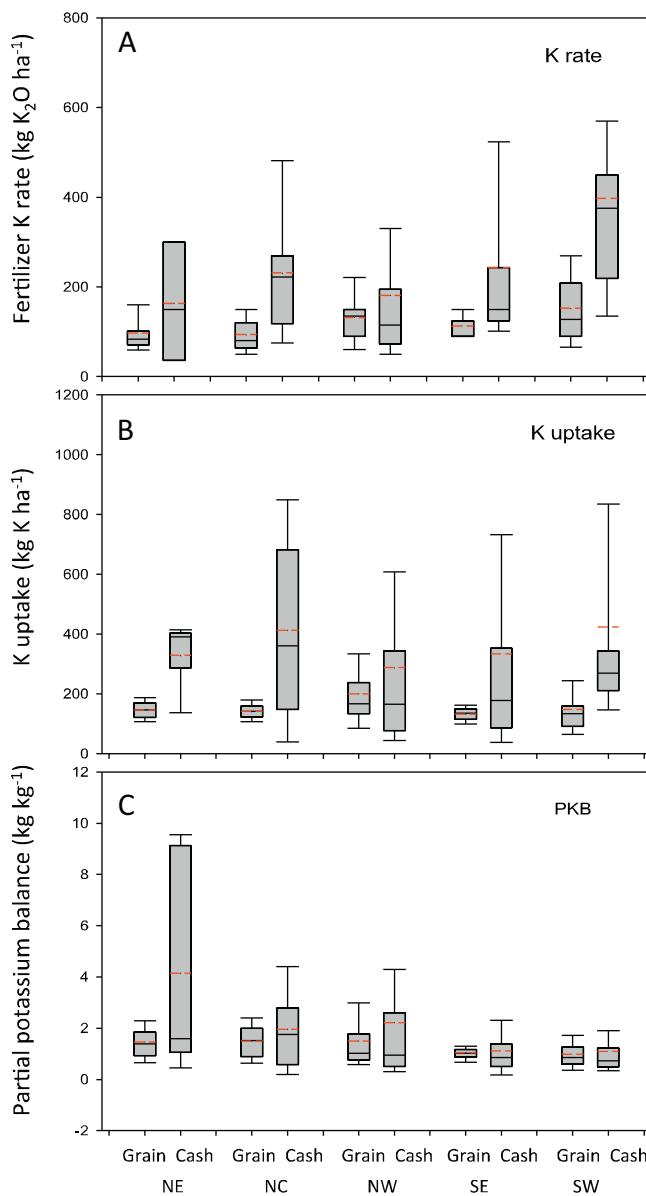


Fig. 6. Potassium application rate (A), K uptake (B) and partial K balance (C) across different regions for grain (left box) and cash crops (right box). The black and red lines, lower and upper edges, and bars represent median and mean values, 25th and 75th, and 5th and 95th percentiles of all data, respectively. The numbers of experimental observations were 242, 394, 95, 68 and 64 for grain crops, and 42, 76, 168, 64 and 86 for cash crops for northeast (NE), north central (NC), northwest (NW), southeast (SE) and southwest (SW) of China, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and cash crops, respectively. The decreasing pattern of relative yield for cash crops in the NW also supported the decline of soil K supplying capacity in the NW (Fig. 3C). Timely and efficient K fertilizer application in the NW was very essential to maintain soil K balance for the long-term. In addition, more K was recommended for Northern China, especially the NE and NW since crop removal in these regions was much larger due to a lower ratio of returning crop residues (Li and Jin, 2011). For Southern China, although more crop residues can be returned back to soils with the development of agriculture mechanization, K leaching and weathering caused by rainfall influences K balance in soils. Therefore, K fertilizer management needs to consider soil K nutrient balance to build up a soil K pool to guarantee both high yield and high efficiency of K fertilizer.

5. Conclusion

On average, soil available K in China kept increasing from 1990 to 2012 and these increases came from the increased soil K in cash crop fields due to higher K fertilizer application. Relative yield results supported soil test data, and yield response to K application for cash crop was larger than that for grain crops. Therefore, K fertilizer application is required not only for grain crops with lower soil K levels, but also for cash crops with large yield response to K application as well. The strategies used to address this challenge need to be regional, and site-specific. The information from the current study also guides the future research orientation, such as research on soil K critical values for cash crops, K nutrient cycling and 4R nutrient management strategies under agricultural mechanization.

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