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ORIGINAL ARTICLE

Estimating the potential to reduce potassium surplus in intensive vegetable fields of China

Shuo Chen · Zhengjuan Yan · Qing Chen

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Abstract Potassium (K) is important for crop quality, and this knowledge has stimulated substantial K fertilizer application in intensive cropping systems of China, resulting in an unbalanced nutrient supply and the squandering of K resources. In this study, we assessed the status of K in China's intensive vegetable planting systems using data from the literature and our recent results. Scenario analysis was designed to estimate the potential for reducing chemical K fertilizer based on the K recommended strategy and manure replacement strategies. The results showed that K surplus, and soil exchangeable K levels in vegetable fields increased during the period with a stable growing area (2003–) compared to the period with an expanding growing area (before 2003). Much higher K surplus and accumulation and more severe K leaching were observed in greenhouse. Excessive K application contributed to low K use efficiency and K resource waste. Based on the data analysis, the K consumption derived from chemical fertilizer and organic amendments was 8.2 million Mg K, though the theoretical demand for vegetable planting was only 6.0 million Mg K with the K recommendation strategy of "build-up and maintenance (B&M)". Scenario analysis suggested that chemical K fertilizer application could be reduced by 21.7, 69.6 and 54.3% by considering alternative K sources derived from manure and straw, as based on the conventional proportion, N-based strategy and P-based strategy, respectively. Maximizing the use of K from organic amendments requires limiting manure application by considering environmental deterioration and the top-dressing requirement with chemical K fertilizer.

Keywords Potassium surplus · Vegetable · Reducing potential · Organic amendment · Replacing · Chemical fertilizer

Introduction

As an essential plant macronutrient, potassium (K) plays a key role in enhancing crop growth and quality (Hu and Schmidhalter 2005; Pettigrew 2008) because K deficiency can disrupt photosynthesis, respiration, translocation and functions of enzyme systems and reduce resistance to environmental stress (Tsonev et al. 2011; Zörb et al. 2014). The inadequate K supply in southern China still relies on chemical K fertilizer application, especially in cereal fields, e.g., 3/4 of the paddy soils in China (Römheld and Kirkby 2010). However, due to the benefit on product quality

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S. Chen · Z. Yan · Q. Chen (✉)
College of Resources and Environmental Sciences, China Agricultural University, No. 2 Yuanmingyuan Xilu, Haidian, Beijing 100193, People's Republic of China
e-mail: qchen@cau.edu.cn

of a K supply, high-value cash crop planting tends to place great emphasis on K fertilization and high-K formula compound fertilizer (Wang and Ai 2004). With the rapid development of the compound fertilizer industry, particularly high-K formula compound fertilizer, the proportion of total fertilizer production in China has increased by 25–35% over the past 10 years (China Statistical Yearbook 2015). A trend toward K accumulation in vegetable fields and fruit orchards is increasingly being observed, especially in greenhouse, with soil exchangeable-K as high as 278–590 mg K kg^{-1} (Cao et al. 2012; Gao et al. 2013) or over 900 mg K kg^{-1}(Tang et al. 2006). The use of high-K compound fertilizer requires farmers to split NPK (nitrogen/phosphorus/potassium) compound fertilizer to meet crop demands. However, the strong loss of N in flood-irrigated vegetable production systems leads to excessive K surplus and accumulation in the surface soil layer due to the relatively low mobility of K^+ in comparison to NO_3^- in the soil profile (Bai et al. 2014; Ju et al. 2007; Yu et al. 2010). In addition, the common application of large quantities of animal manure contributes to additional K sources and heightened K accumulation in vegetable fields (Liu et al. 2009; Zhou et al. 1997), though this aspect is consistently ignored by farmers with regard to K recommendation.

Potassium fixation occurs in soil until the adsorption sites of soil clay minerals are saturated; this consequently decreases the K fixation capacity and increases the mobility of K ions in soil, leading to leaching loss and surface runoff via soil erosion (Zhang et al. 2007). Therefore, higher K accumulation increases K loss from soil. The deficiency in K resources is obvious among the NPK nutrient fertilizer supply in the Chinese fertilizer industry. An economic analysis of K resources showed that the import of potash fertilizers reached 5.03 million Mg K_2O, 58.1% of the potash fertilizer production quantity in China in 2014 (FAO 2015a). Concomitant with the excessive use of chemical K fertilizers is the rapid depletion of K resources, thereby exacerbating the shortage of K resources in China. Moreover, excess K accumulation in soil may cause a nutritional imbalance for crop growth. For example, the recent increase in magnesium deficiency symptoms in fruity vegetables in North China was closely related to the high level of soil K, which contributed to the deficiency due to ion antagonism (Meng 2011; Römheld and Kirkby 2007).

The proportion of K consumed for vegetable planting is very high, as China's total vegetable production reached 596.1 million Mg in 2014 (FAO 2015b), accounting for 51.0% of the world's production. Compared to that in 1978, the area of greenhouse increased by more than 1000 times in 2015 (Fig. 1), and most high-value vegetable crops, i.e., vegetables grown for their fruit (e.g., tomato, cucumber) are commonly rotated in greenhouse. Based on the large scale of vegetable production in China (22.6 million ha in 2015; China Statistical Yearbook 2015), the high consumption of potash fertilizer needs to meet the policy of the chemical fertilizer reduction program by the Chinese government since 2015. Sustainable vegetable planting will play a critical role in China's food security paradigm, requiring the appropriate use of K to ensure optimum yields and save resources. To understand the critical role of K resource management and potential K loss from soil, a comprehensive evaluation of the current K overfertilization and soil K enrichment and the potential to reduce K use in intensive vegetable production systems in China is urgently needed.

The objectives of this study were to examine the historic and current K inputs derived from organic amendments and chemical K fertilizers, K removal by different vegetable crops, and K surplus and accumulation in soils on the basis of literature published over the last 30 years and on our recent research results. Considering soil K fertility and following the "build-up and maintenance (B&M)" strategy, the potential reduction in chemical K fertilizer was estimated using scenario analysis after designing different methods (conventional practice, N-based manure management, and P-based manure management) for using organic amendments (e.g., animal manure and cereal straw) at different levels of soil K fertility in vegetable greenhouse and open fields.

Materials and methods

Potassium surplus estimation

Potassium surplus is defined as the difference between seasonal K input and K removal by plants due to highly complex crop rotation. To assess K surplus, it was necessary to understand the main K input through the seasonal fertilization rate (e.g., manure and

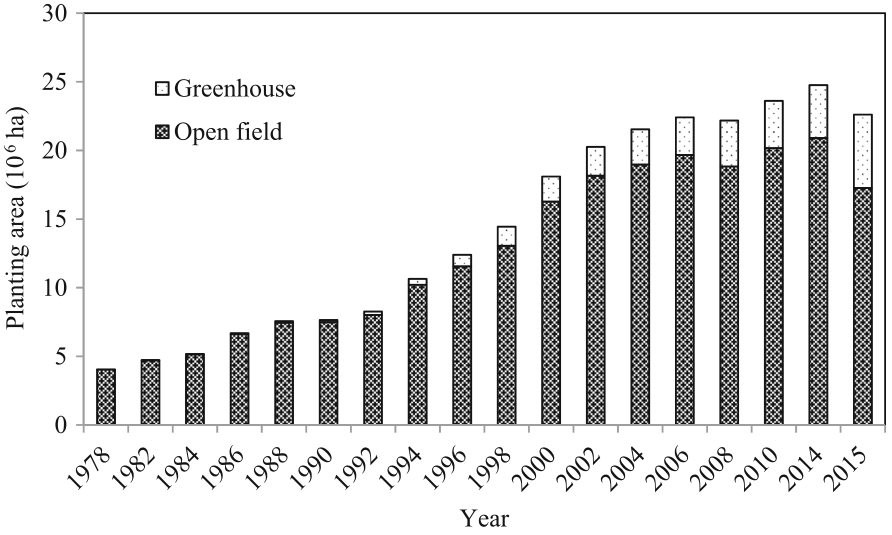

Fig. 1 Change of greenhouse and open field vegetable planting area from 1978 to 2015 in China

chemical fertilizer) and K removal ($K_{removal}$) by the above-ground parts of plants or the whole plants considering the differences in edible organs. In China vegetable crops have conventionally been classified as fruity vegetables (e.g., cucumber, tomato, eggplant, pepper), leafy vegetables (e.g., Chinese cabbage, broccoli, spinach), and tuberous root vegetables (e.g., radish, carrot, allium, garlic, ginger). Here crop K removal is defined as the above-ground parts of plants for non-tuberous root crops or the whole plants for tuberous root crops. Therefore, crop K removal ($K_{removal}$) by the vegetable crops per hectare involves K uptake by edible and nonedible organs per hectare, as follows:

$$K_{removal} = \text{Crop yield} \times \text{K uptake by per unit weight of edible organs and nonedible organs} \quad (1)$$

The K surplus per hectare was calculated as the difference between the seasonal K input per hectare and the seasonal K removal by plants per hectare as follows:

$$\text{K surplus} = K_{input} - K_{removal} \quad (2)$$

where K_{input} is the total K application derived from chemical fertilizers and organic amendments and $K_{removal}$ is crop K removal.

To assess K surplus, it was necessary to understand the main K input through the seasonal fertilization rate (e.g., manure and chemical fertilizer) and crop K removal ($K_{removal}$). The required data, including vegetable species, cultivation in greenhouse/open field, cultivation year, fertilizer type and applied rate, and manure type and applied rate, were collected from publications from 1996 to 2014, involving 52 events of field (greenhouse and open field) survey and covering 25 provinces (see Supplemental Table S1; Figure S1). Data on the national vegetable planting area were obtained from National Agro-Tech Extension and Service Center (NATESC), Ministry of Agriculture and Chinese Agricultural Statistical Book. The historic development of the Chinese vegetable planting industry revealed that the expanding stage of national vegetable planting ended in 2003 and that since 2003, the vegetable planting industry entered into the stabilized development stage, with a stable planting area and product supply (FAO 2015b). Considering specific stages, the literature data were classified into two groups of cultivation year before 2003 or since 2003. Additionally, the specific vegetable type (i.e., fruity vegetables) and related management practices in greenhouse has resulted in differences in K accumulation compared to open fields. In the data analysis for K surplus, K input and removal by crops were calculated for different types of vegetables (e.g., fruity, leafy) in greenhouse and open-field systems (Table 1).

Table 1 Potassium input, crop removal, and surplus before and since 2003 in different vegetable production systems in China

Year	System	Vegetable type[a]	K input(kg K ha^{-1})			Proportion of organic K fertilizers applied (%)	Crop removal (kg K ha^{-1})	K surplus (kg K ha^{-1})
			Organic fertilizer	Chemical fertilizer	Total			
Before 2003	Greenhouse	Fruity vegetables	354 (1–1406)[b]	266 (0–1709)	621	57.0	287	334
		Leafy vegetables	128 (0–528)	121 (0–1106)	249	51.4	254	−5
		Other	190 (51–323)	146 (0–645)	336	56.5	140	196
		Average	296 (0–1406)	233 (0–1709)	529	55.9	281	248
	Open field	Fruity vegetables	162 (41–243)	112 (4–346)	274	59.1	214	60
		Leafy vegetables	106 (0–720)	46 (0–102)	153	69.2	254	−101
		Other	80 (9–202)	90 (0–386)	170	47.0	206	−36
		Average	114 (0–720)	79 (0–386)	193	59.1	230	−37
Since 2003	Greenhouse	Fruity vegetables	862 (80–4350)	617 (30–2606)	1480	58.2	488	992
		Leafy vegetables	91 (58–114)	198 (53–435)	290	31.4	268	22
		Other	241 (85–361)	176 (129–237)	417	57.8	193	224
		Average	699 (58–4350)	524 (30–2606)	1223	57.1	445	778
	Open field	Fruity vegetables	139 (67–361)	179 (54–491)	319	43.6	302	17
		Leafy vegetables	79 (6–360)	83 (0–366)	162	48.8	178	−16
		Other	131 (0–385)	92 (0–357)	223	58.7	208	15
		Average	108 (0–385)	107 (0–491)	215	50.2	248	−33

Data summarized from 52 published works in 1996–2014 conducted in 25 provinces. See Supplemental Table S1 for details

[a] Fruity vegetables included tomato, cucumber, eggplant, and pepper. Leafy vegetables included lettuce, cabbage, spinach, celery, and leek. Other included radish, allium, garlic, and ginger

[b] Values in parentheses are reported ranges

Soil potassium accumulation

To evaluate the extent of soil K enrichment in China's intensive vegetable production systems, data on soil exchangeable-K levels in vegetable fields were collected from 35 publications covering 16 provinces (Supplemental Table S2; Figure S2) to compare differences in soil K accumulation among vegetable open field & greenhouse and cereal fields at similar locations. To estimate the extent of K downward movement in the soil profile, we pooled the exchangeable-K data of soil profiles from 20 published studies together with our own survey results in Shouguang, Shandong Province (Supplemental Table S3).

Datasets for increases in exchangeable-K levels and related K surplus were established using data from greenhouse trials distributed among five locations (Supplemental Table S4). Crop K removal was calculated using Eq. (1). Correlations were then determined between the annual K surplus Eq. (2) and the measured increase in soil exchangeable-K at different periods, as follows:

$$\begin{aligned}&\text{Increment in soil exchang.} - \text{K}\\&\quad = \text{Soil exchang.} - \text{K}_{\text{end}} - \text{Soil exchang.} - \text{K}_{\text{initial}}\end{aligned} \tag{3}$$

where soil exchang. $-$ K_{end} and soil exchang. $-$ $\text{K}_{\text{initial}}$ are the soil exchangeable-K levels at harvest and before planting the next crop, respectively.

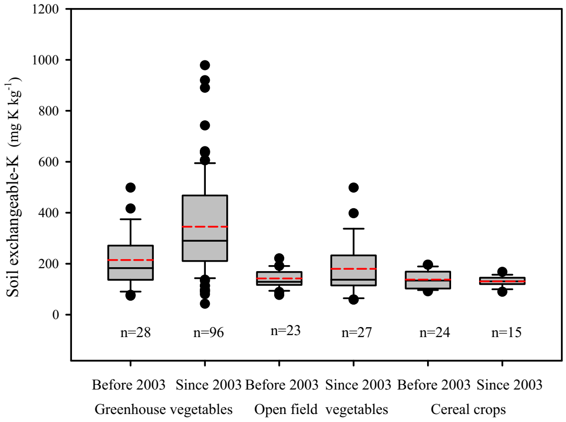

Fig. 2 Accumulation of potassium (K) in soils (0–20 cm) of different cropping systems before and since 2003 (Data summarized from 35 published works. See Supplemental Table S2 for details.)

Scenario analysis of the potential for reducing K input

Scenario analysis was used to understand the demand of chemical K fertilizer in vegetable production systems of China. The most efficient method for reducing K surplus is to control the K applied during crop cultivation. In China, the "B&M" strategy has been to farmers for over 10 years (Chen and Lu 2015). According to this strategy, soil K fertility is classified at three levels, "high", "moderate" and "low", based on the corresponding class ranges of soil exchangeable-K levels in greenhouse and open fields (Fig. 2). Based on the "B&M" approach, average K application rates from all possible sources are recommended as proportions of K uptake by crops (Table S5): for example, to deplete excessive K reserves, 0.8 and 0.7 times the crop K removal by fruity and leafy/other vegetables in a field with a "high" level of soil K fertility; to maintain soil K reserves, 1.2 and 1.1 times the crop K removal by fruity and leafy/other vegetables in a field with a "moderate" level of soil K fertility; and to increase soil K reserves, 2.0 and 1.5 times the crop K removal by fruity and leafy/other vegetables in a field with a "low" level of soil K fertility (Chen and Lu 2015). In light of the differences among various types of vegetables, K removal by crops was separated into greenhouse and open fields.

Assuming that the strategy is completely accepted and used in vegetable production, the second strategy for reducing chemical K fertilizer is to assess alternatives for replacing chemical K fertilizer. In practice, organic amendments (e.g., manure, straw) and mineral amendments (e.g., potash feldspar) are the main sources for replacing chemical K fertilizer. Manure is commonly used in vegetable fields, although farmers have been encouraged to return cereal straw to the field, especially greenhouse with commonly degraded soil and a low C/N ratio, in China only a very low proportion of cereal straw is directly incorporated. A low proportion of straw is used as an additive in manure composting and is indirectly applied to fields. Potash feldspar is seldom used in vegetable fields due to its characteristics of insolubility and slow release.

Scenario analysis was employed to estimate the potential for reducing chemical K fertilizer on the basis of the recommended K demand following the strategy for different soil fertility levels. Three scenarios describing the possibilities of organic amendment for replacing chemical K fertilizer were as follows.

Scenario 1 Follow the conventional manure application, whereby chicken manure and pig manure are the major sources used in vegetable fields (N:P:K ratio of 2.8:1:1.8, Jia 2014). If the K supply derived from manure is over the crop K demand, the recommendation is that 30% of the total K demand should be chemical K fertilizer as sidedressing at the late growth stage in greenhouse to maintain vegetable quality.

Scenario 2 In this scenario, manure application is controlled to reduce the environmental pollution due to excessive manure application under conventional management. Two additional scenarios were designed to regulate manure application: (1) N-based strategy: manure application following the regulation that 50% of the recommended crop N demand needs to be supplied by manure application (Scenario 2.1); (2) P-based strategy: manure application following the regulation that the P supply from manure should be the same as the P uptake by the crop (Scenario 2.2).

Scenario 3 In this scenario, manure application is the same with in the scenario 2 and cereal (e.g., rice, maize, wheat) straw incorporation into fields is considered. Two additional scenarios were: (1) N-based manure application + straw incorporation (Scenario 3.1); (2) P-based manure application + straw incorporation (Scenario 3.2). Due to mechanical considerations and the limitation of soil structure after straw incorporation, the incorporated rate of cereal straw maximized 8 t ha^{-1} (Fan 2014) with an average straw K concentration of 16.7 g kg^{-1} (Jia 2014).

Statistical analysis

The data analysis was conducted using regression analysis in Microsoft Excel 2010. The soil exchangeable-K content was analyzed using the box plot function of the SigmaPlot (Version 10.0) software package.

Results and analysis

Potassium input and surplus

Based on 52 published studies, the average seasonal K input was 529 and 1223 kg K ha^{-1} for greenhouse before and since 2003 and 193 and 215 kg K ha^{-1} for open fields before and since 2003, respectively (Table 1). The average K removal by harvested crops was 281 and 445 kg K ha^{-1} for greenhouse before and since 2003 and 230 and 248 kg K ha^{-1} for open fields before and since 2003, respectively. The amount of K input was much higher than crop removal in greenhouse, especially since 2003; i.e., K application exceeded K removal by 2.7-fold.

Potassium input from manure should not be ignored, and over 50% of the K input was derived from manure in most vegetable fields, especially in fruity vegetable fields (Table 1). The K input based on manure and chemical K fertilizers was 699 and 524 kg K ha^{-1} in greenhouse since 2003, respectively, and the input from manure exceeded the removal by crops (445 kg K ha^{-1}). This result indicates excessive rates of K application from chemical fertilizer and manure and general inattention regarding the nutrients contained in organic manures and in soils used for vegetable production.

Soil potassium accumulation and possible leaching

The summarized results from 35 published studies on major vegetable production regions in China showed that the average exchangeable-K levels in the soil layer (0–20 cm) were 215 (before 2003) and 345 (since 2003) mg K kg^{-1} in greenhouse and 142 (before 2003) and 180 (since 2003) mg K kg^{-1} in open fields (Fig. 2). These values were in contrast to the exchangeable-K values of 138 (before 2003) and 131 (since 2003) mg K kg^{-1} in soils used for cereal crop production. Additionally, 86.5% of the greenhouse sites and 40.0% of the open-field sites had soil exchangeable-K values >172 mg K kg^{-1} since 2003, which is the critical soil level of exchangeable-K for vegetable production (He et al. 2011; Chen and Zhang 2007). Thus, K enrichment in the soils of greenhouse vegetable production systems is clear and paramount.

A very high K surplus led to high K accumulation in the soil of vegetable fields, and there was a strong positive correlation between seasonal K surpluses (i.e., input—crop removal) and soil exchangeable-K enrichment at the end of the growing season in greenhouse soils (sandy loam soil: $r = 0.503$, $P = 0.04$; silt loam soil: $r = 0.811$, $P < 0.0001$; Fig. 3). The annual increases in soil exchangeable-K

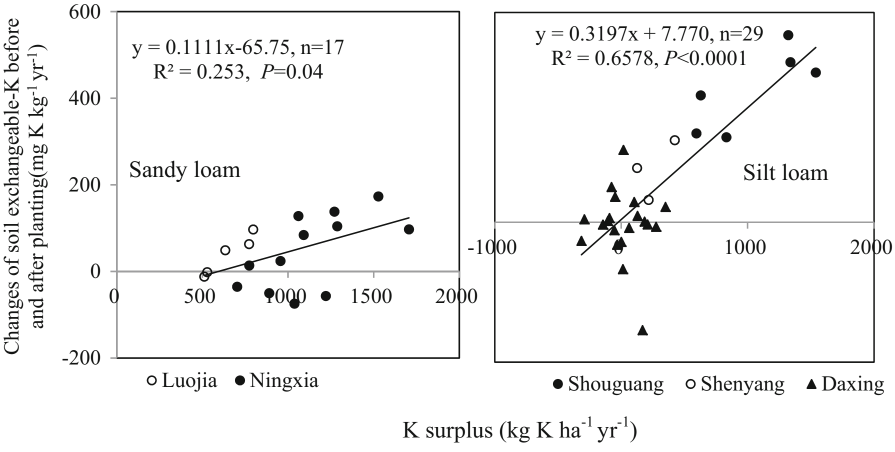

Fig. 3 Relationship between changes in soil exchangeable-K (mg K kg^{-1} yr^{-1}) before and after vegetable growing seasons and K surplus (kg K ha^{-1} yr^{-1}) in several greenhouse vegetable fields with different soil textures

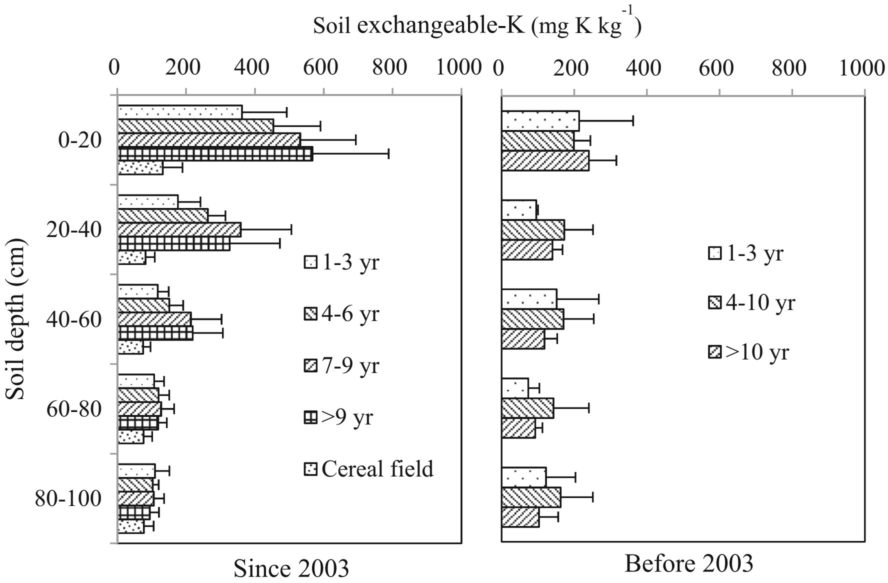

Fig. 4 Changes in exchangeable-K for 20-cm increments to a 100 cm soil depth with different years [since 2003, 1–3 years (n = 19), 4–6 years (n = 12), 7–9 years (n = 12), and >9 years (n = 13); before 2003, 1–3 years (n = 6), 4–10 years (n = 7), and >10 year (n = 10)] of vegetable production in greenhouses compared with those in wheat production fields [since 2003, (n = 3)]

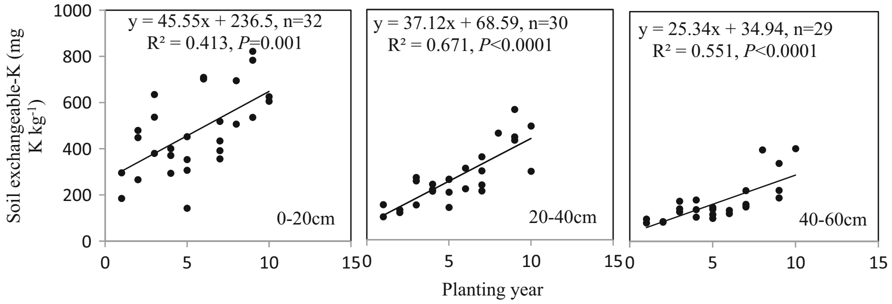

Fig. 5 Relationship between soil exchangeable-K and planting year for greenhouse vegetable fields

in the surface layer (0–30 cm) were 0.11 and 0.32 mg K kg^{-1}/1 kg ha^{-1} surplus K in sandy loam and silt loam soils, respectively.

The distribution of soil exchangeable-K in the soil profile during different planting years indicated the occurrence of downward K movement in soils used for

Table 2 Current amount of potassium fertilizers used for different vegetable cropping systems in China

System	Area (10^6 ha)[a]	K fertilizer application rates (kg K ha^{-1})[b]			Percent of planted area with K application (%)[c]		K fertilizer consumption (10^6 Mg K)		
		Organic manure	Chemical fertilizer	Total	Organic manure	Chemical fertilizer	Organic manure	Chemical fertilizer	Total
Greenhouse	5.3	699	524	1223	73.9	100	2.7	2.8	5.5
Open field	17.3	108	107	215	49.4	95.0	0.9	1.8	2.8
Total	22.6						3.6	4.6	8.2

K fertilizer consumption = Planting area × Percent of planted area with K application × Average K fertilizer application rate per unit area

[a] Total data and protected field data were from National Bureau of Statistics of China 2015; Open field data = Total − protected field

[b] From the several survey studies (Table S1)

[c] Pertentages of manure and chemical fertilizer were from the literatures investigation (Table S1)

Table 3 Scenarios analysis on amount of chemical K demand based on K recommended strategy and different manure replacement strategies

Systems	Total K demand (10^6 Mg)[a]	Different K resource demand in different scenarios[b]											
		Scenario 1[b]		Scenario 2				Scenario 3					
				Scenario 2.1		Scenario 2.2		Scenario 3.1			Scenario 3.2		
		M	C[c]	M	C	M	C	M	S[d]	C	M	S	C
Greenhouse	2.1	2.7	0.6	0.5	1.6	0.4	1.7	0.5	0.7	0.9	0.4	0.7	1.0
Open field	3.9	0.9	3.0	1.1	2.8	0.5	3.4	1.1	2.3	0.5	0.5	2.3	1.1
Total	6.0	3.6	3.6	1.6	4.4	0.9	5.1	1.6	3.0	1.4	0.9	3.0	2.1

[a] The total K demand is based on "B&M" approach and calculated in Table S5

[b] Scenario 1, follow the conventional manure application; Scenario 2, manure application is controlled: scenario 2.1 and scenario 2.2 are N-based and P-based strategy, respectively; Scenario 3, manure application is the same with in the scenario 2 and cereal (e.g., rice, maize, wheat) straw incorporation into fields is considered

[c] Chemical K in scenario 1 is 30% of the total K demand as the sidedressing to maintain vegetable quality in greenhouse, and the difference between manure K, straw K and total K demand in open field and in scenario 2 and scenario 3

[d] The incorporated rate of cereal straw is 8 t ha^{-1} (Fan 2014), with an average straw K concentration of 16.7 g kg^{-1} (Jia 2014)

vegetable production, especially since 2003 (Fig. 4). A large proportion of the K enrichment was within the plow layer before 2003 and within the top 60-cm soil layer since 2003. In addition, a positive correlation between the exchangeable-K concentration and the planting year was observed for the 0–60 cm soil layer in greenhouse (Fig. 5).

Potential for reducing K input

Chemical fertilizer K use was estimated at 2.8 and 1.8 million Mg and that for manure K use at 2.7 and 0.9 million Mg in China's greenhouse and open-field vegetable production systems in 2015, respectively (Table 2). The total K usage for vegetables in China was 8.2 million Mg (Table 2), and this could be significantly reduced to 6.0 million Mg if K application rates are based on the well-established, economically optimum "B&M" management principles (Table 3, Table S5). Total manure K consumption was 3.6 million Mg (Table 2), which could be satisfied with 60.0% of the total vegetable requirement of K (6.0 million Mg) in the vegetable production systems in China. Therefore, chemical K fertilizer use could be significantly reduced from 4.6 to 3.6 million Mg if manure K was not neglected and kept at the present application rate and chemical K fertilizer as side-dressing at the late growth stage in greenhouse (Table 3, scenario 1). However, considering the excessive N and P in manure, chemical K fertilizer application could be 4.4 million Mg and 5.1 million Mg based on N and P balance methods, respectively (Table 3, Scenario 2). When considering cereal straw incorporation, the supplemental chemical K fertilizer could be 1.4 million Mg and 2.1 million Mg (Table 3, Scenario 3).

Discussion

Excessive K application and K rock resource consumption

We found that overfertilization occurred in vegetable fields, especially in greenhouse. The seasonal average K input was 529 and 1223 kg K ha^{-1} before and since 2003, 1.9 and 2.7-fold greater than the amount of removed K by crops, respectively (Table 1), in greenhouse. Farmers are likely to apply a high K compound fertilizer to greenhouse because of the greater economic value compared to open or cereal crop systems. In addition, large amounts of manure are applied to vegetable fields to improve soil quality. However, the contribution of K in manure is always neglected, increasing the amount of K input to greenhouse. Furthermore, the higher cropping index of greenhouse contributes to the higher application and accumulation of K compared with other crop systems.

The excessive use of chemical K fertilizers raises the issue of the inefficient use of natural resources, thus exacerbating the shortage of K rock resources in China. We estimated that 33.6% of the total amount of chemical K fertilizer (4.6 million Mg, Table 2) was used for vegetable planting in China, even though this accounted for only 13.6% of the total arable land (China Statistical Yearbook 2015). In addition, we estimated that the K fertilizer utilized for vegetables in China could be reduced significantly if K application rates were based on the well-established, economically optimum “B&M” management principles used in many other countries (Hochmuth and Hanlon 2010; Leikham et al. 2003; Olson et al. 1987). China’s K rock reserve was estimated at 210 million Mg in 2014, which accounted for approximately 6% of the world’s reserve (USGS 2015). However, the total K demand for crop planting in China accounted for 19% of that worldwide (USGS 2015), and >60% of the K fertilizer depended on import (Yang and Cao 2015). As a medium-term projection, China’s K fertilizer consumption will continue to grow by an average annual growth rate of 10% (Yang and Cao 2015). However, due to the shortage of K resources, insufficient productivity and poor sustainable deliverability, potash minerals can only be exploited for 27 years under the current production levels. Furthermore, even if high-grade potash were restrictively protected, it could maintain a supply for no more than 50 years. As excessive K input contributes to the rapid depletion of K resources, it is important to reduce chemical K fertilizer application and increase the use efficiency of chemical K fertilizer in vegetable production systems.

Soil K accumulation and negative consequences

The present conceptual understanding of soil K availability is the existence of four distinct K pools (i.e., SK, soluble K; EK, exchangeable K; SEK, slowly or non-exchangeable K; MK, mineral K;) that differ in accessibility to plant roots with the reversible transfer of K between the pools (Syers 2003). EK, i.e., K held at negatively charged sites of clay minerals and soil organic matter, comprises approximately 1–2% of the total K. EK is in rapid equilibrium with K in the soil solution and is readily available to plants; it is commonly used as an indicator of soil K availability. There is a critical soil EK level, and the crop yield response to K application that would be small or not occur when EK is greater than the critical level. Rayment (2013) suggested the use of a critical level plus the total K/EK ratio as a guide for a sustainable soil K supply and noted that there is a need to seriously consider the addition of plant-available K when the levels of EK are at or below critical levels and the corresponding total K/EK ratio is approximately less than 2 to 3. In our study, approximately 86% of the greenhouse sites and 41% of the open-field sites covering all major vegetable production regions in China had soil exchangeable-K values greater than the critical level of 172 mg K kg^{-1} (He et al. 2011; Chen and Zhang 2007). The average exchangeable-K reached 345 mg K kg^{-1} (since 2003), and the total K/EK ratio was 56 in the topsoil of greenhouse, which indicates the severity of K accumulation in soil. This result is undoubtedly related to the excessive application of organic manure and chemical P fertilizers (Table 1), as illustrated by the strong positive correlation between the change in soil exchangeable-K and K surplus (Fig. 3). More seriously, K accumulation was observed in soil with an increasing number of cropping years (Figs. 4, 5).

Excess K accumulation in vegetable production soils can lead to an unbalanced nutrition status in the soil, which in turn may affect crop yield and quality due to ion antagonism, e.g., K and magnesium (Römheld and Kirkby 2007). The occurrence of magnesium deficiency symptoms in fruity vegetable species has increased in North China in recent years. Meng (2011) reported that the high accumulation of K in the soil contributed to magnesium deficiency in greenhouse tomatoes. Additionally, many researchers have reported that the antagonistic effect of K and Ca lead to decreased fruit quality (Adams and Ho 1995; Neilsent and Edwards 1982; Nzanza 2006). Furthermore excess K accumulation can result in increases in the degree of K saturation and risk of K loss due to leaching (Zhang et al. 2007). The increase in K in deep soil clearly indicated a high level of K leaching in China's intensive vegetable production (Fig. 4). Indeed, the results of our field experiments in Shouguang, Shandong, showed that seasonal K leaching at the 90-cm depth soil was 3–22 kg K ha^{-1} (Chen 2015). Soil K accumulation also contribute to soil salinization and microflora imbalance (Li et al. 2011). At the same time, a higher demand of chemical K fertilizer promotes industrial production, which accelerates K resource consumption and enhances field gas emissions.

The movement of K in soil is markedly affected by the soil texture (Zhang et al. 2014), and serious K leaching generally occurs in coarse soil due to a low K fixation capacity (Zhan et al. 2012). Simmelsgaard (1996) measured soil water-soluble K concentrations and reported 0.5–1.7 mg K L^{-1} in clay soils, 5–7 mg K L^{-1} in a loamy sand, and 10–15 mg K L^{-1} in a coarse sandy soil. The annual increases in exchangeable-K in the topsoil (0–30 cm) were 0.11 and 0.32 mg K kg^{-1}/1 kg ha^{-1} surplus K in sandy loam and silt loam soils, respectively (Fig. 3), which also indicated that K is likely to move or leach from coarse soil. In sandy soils and acid lateritic soils containing kaolinitic clay minerals with a low cation exchange capacity (CEC), the rates of K leaching can be very high (Goli-Kalanpa et al. 2008). K^+ transport also depends on the concentrations of cations and anions. For example, a high concentration of NH_4^+ can reduce the fixation of K^+ or favor the release of mineral K due to the same possibility of entering the crystal lattice of 2:1 clay minerals (Dhillon et al. 1989; Liang et al.2002). When NO_3^- and Cl^- are leached, equivalent cations will migrate (Öborn et al. 2005). In a vegetable greenhouse, strong urea or ammonium-N application and high NO_3^- leaching under intense irrigation also contribute to K leaching. In addition, large amounts of manure input can promote soil K leaching by increasing the water-soluble K and lowering K fixation onto minerals (Evangelou and Blevins 1988; Lu et al. 2013; Mortland et al. 1956; Zhang et al. 2009). This relationship could be attributed to the blocking effect of the complex compounds of organic matter with Ca^{2+} at the fixation sites of clay minerals and the diadochy between NH_4^+ and K^+ caused by manure application (Evangelou and Blevins 1988; Mortland et al. 1956; Zhang et al. 2009). Some of the K in manure may be associated with organic matter and would be available for leaching only after equilibrium is reached between the soil and fertilizer (Williams 1988). Therefore, manure application could increase soil K leaching at late stages of plant growth (Alfaro et al. 2004). In a vegetable production system, >50% of the total K input is sourced from manure (Table 1), and Chen (2015) reported that manure application significantly increases K leaching in vegetable fields.

K management in vegetable greenhouse

Rational K management is very important for the sustainable development of vegetable production systems. Given the shortage of K resources and the growing availability of organic sources, the key to sustainable K management is to manage total K input to meet crop needs while preserving natural resources by drastically reducing chemical K fertilizer application and reasonably using organic sources.

Compared with other cropping systems, vegetable production soils typically receive high rates of manure, and >50% of the total K input is from manure (Table 1). In general, manure is applied as a soil amendment without taking into account how manure is related to crop nutrient requirements based on yield goals and results of soil testing. The transformation rates of available K in manure in soil are approximately 50.7–63.7% (Zhou et al. 2003), and manure application can indirectly increase the soil EK level (Jalali and Ranjbar 2009; Lu et al. 2013) and favor the release of mineral K (Lu et al. 2013).

With the rapid development of animal husbandry, the total generation of manure (dry matter) reached 545 million Mg, containing 12.8 million Mg of K, in China in 2013 (Jia wei unpublished). Thus, the appropriate use of manure as a K source in vegetable fields is a sustainable, win–win strategy for conserving K rock resources while reducing environmental pollution from manure. However, long-term repeated applications of large amounts of manure lead to intense accumulation of K may favor K leaching from vegetable fields. Furthermore, the ratio of N:P:K (2.8:1:1.8; Jia 2014) in chicken manure and pig manure is inconsistent with the corresponding ratio of plant uptake (4.5–10.0:1:5.0–11.1; Tang 2010; Wang et al. 2013; Zhang et al. 2011). If manure application is based on the N or K demand by vegetable crops, then it will result in high P accumulation in the soil and accelerated P loss and water pollution. N-based would be a choice to recommend manure application rates in the low fertility soils for rapid increase soil fertility or some soils that soil P level are below environmental threshold. Therefore, organic K sources as a substitute for chemical fertilizer K should utilize manure plus organic materials with a low P content, e.g., cereal straw. It was estimated that the total generation of crop straw (dry matter) was 814 million Mg, containing 6.5 million Mg of K, in China in 2013 (Jia wei unpublished). Dai et al. (2010) reported that the cumulative K release rate of crop straw was 98% over 12 days under waterlogged conditions, which suggests the availability of K in crop straw for crop growth. Some studies have reported that the application of straw is beneficial for sustaining the soil K balance and alleviating the depletion of soil K, thereby maintaining a stable soil potassium supply (Xie et al. 2014, 2015). Cereal straw can be used as a good organic K source that can also reduce P accumulation in the soil. Based on our estimation, the total K demand for vegetables in China was 6.0 million Mg (Table S5). Considering the amounts of N and P accumulation due to high manure input, employing N-based (Velthof et al. 2009) and P-based (Sharpley et al. 2007) strategies to apply manure can supply 1.6 million Mg and 0.9 million Mg K, respectively (Table 3). Another 4.4 million Mg and 5.1 million Mg K to meet the demand for vegetable production can be satisfied with chemical fertilizer K and crop straw, respectively. In some typical greenhouse, cereal straw has been applied to improve soil quality, increase soil temperature, accelerate soil microorganism turnover and increase activities of certain enzymes (Zheng and Chi 2012). When considering incorporating straw K based on the amount of conventional practice in China, cereal straw can supplement 3.0 million Mg K to vegetable fields and utilize 46.2% of the straw K generated in the country (Table 3). Overall, using manure and crop straw as K sources for vegetable production can save K rock resources, utilize large amounts of organic waste products and protect the environment.

Conclusions

Our study assessed the K status of China’s intensive vegetable production systems and found that gross overfertilization is widespread, with seasonal K inputs typically exceeding crop K removal by 1.9- and 2.7-fold in greenhouse before and since 2003, respectively. Excessive K application in vegetable systems contributes to soil K accumulation and loss, accelerating the depletion of K rock resources. The annual total K usage for vegetables in China could be significantly reduced from 8.2 to 6.0 million Mg if the K application rates are based on “B&M” management principles. The key to sustainable K management is to manage the total K input to meet crop needs while preserving natural resources by drastically reducing chemical K fertilizer application and reasonably applying organic resources (i.e., manure and straw).

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