Field Crops Research 169 (2014) 116–122

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China

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A R T I C L E I N F O

Article history:
Received 10 August 2014
Received in revised form
22 September 2014
Accepted 23 September 2014

Keywords:
Long-term experiment
K fertilizer
Straw return
Soil K levels
Crop yield

A B S T R A C T

Understanding the changes in soil potassium (K) and crop yield under K fertilization and straw return is important for proper K fertilizer management. A field experiment involving a wheat (*Triticum aestivum* L.)–maize (*Zea mays* L.) rotation was conducted to study the effects of long-term (20-year) K fertilization and straw return on soil K and crop yield in north-central China. Fertilization treatments included: nitrogen and phosphorus fertilizers (NP), NP plus wheat straw (NPS), NP and K fertilizers (NPK), and NPK plus wheat straw (NPKS). Annual soil K budget increased with increasing K inputs (including fertilizer K and straw K) in the order of NP < NPS < NPK < NPKS, and further increased after maize straw returned since 2008. The NP and NPS treatments decreased soil available K and slowly available K below the initial levels, K fertilization and/or straw return increased available K and slowly available K in the top 30 cm soil over the NP treatment. Fertilization did not significantly alter total K in the 0–100 cm depths, but in the 0–10 cm soil layer, the NP, NPS, and NPK treatments decreased total K by 4.3%, 3.4%, and 0.4% than the initial concentration, respectively. Compared with the NP treatment, K fertilization and/or straw return increased crop yields in most cases, and the effect of K inputs on yield increase was greater for maize than wheat. Additionally, increased straw return enhanced soil organic carbon (SOC) beyond the NP treatment, and SOC decreased with depths between 0 and 40 cm soil; however, fertilization did not change SOC below 40 cm. In conclusion, K fertilization and/or straw return alleviated soil K depletion and increased soil K fertility; crop yields increased with increasing K inputs, and yield response of maize to K fertilization was greater than wheat.

1. Introduction

Potassium (K) is an essential nutrient and is involved in many important physiological processes in plants; it can improve crop quality and the ability of plants to survive adverse conditions (Marschner, 1995; Pettigrew, 2008). Sufficient K supply in soil helps to ensure high crop yield (Dong et al., 2010; Zhang et al., 2011). K deficiency is a world-wide problem, and the K levels in agricultural soils is decreasing across the globe (Fagerberg et al., 1996; Dobermann et al., 1998; Wijnhoud et al., 2003; Malo et al., 2005). In China, the majority of K fertilizer applied is imported, and soil K deficiency is recognized as one of the limiting factors for crop production (Zhang et al., 2008). The imbalanced fertilizer use in China led to a surplus or balanced situation for soil nitrogen (N) and phosphorus (P) but a serious depletion of K (Lin et al., 2006; Wang et al., 2008). Extending balance fertilization technology has enhanced K fertilizer input in crop production, but the increasing price of K fertilizer has increased agricultural production costs (Wang, 2012). Therefore, efficient use of K fertilizer is crucial for this resource limited nutrient.

Crop straw is an important organic fertilizer resource, especially for Li and Jin (2011) reported that China produced 8.1×10^8 t of crop straw in 2008, and this supplied 1.2×10^7 t of K_2O. Therefore, straw

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http://dx.doi.org/10.1016/j.fcr.2014.09.017
0378-4290/

retention in fields can return a considerable amount of plant K to the soil. In addition, straw retention could also decrease mineral N fertilizer losses by causing N immobilization in the short term, and increase carbon (C) sequestration in soil and enhance soil quality (Yadvinder-Singh et al., 2004; Plante et al., 2006; Liu et al., 2011). Recently, both wheat and maize straws return was widespread in winter wheat–summer maize rotation system in north-central China because the use of straw returning machine was increased in response to a ban by the Chinese government on field burning of crop straws. However, straw decomposition and nutrient release from straw were slow in the field, and the effects of straw return on crop yield, soil fertility and quality were not obviously shown in short term (Brunetto et al., 2011; Partey et al., 2011; Wang et al., 2010). Long-term field experiment could demonstrate the effects of different nutrient management strategies on crop yield, soil nutrient dynamics, and soil quality (Gong et al., 2009; Malhi et al., 2011; Liang et al., 2012). Several long-term experiments on fertilization and straw return treatments have been established in northern China, but these studies on changes in soil quality and nutrients mainly focused on topsoil, while few have focused on the deeper layers (Cao et al., 2008; Liu et al., 2010; Zhang et al., 2010, 2011). Breulmann et al. (2012) indicated that research on the deeper soil layers could provide more information about soil nutrient properties. The objective of this study was to investigate the changes in soil K levels and crop yields under long-term K fertilization and straw return in north-central China.

2. Materials and methods

2.1. Experimental site

Field experiment was conducted in October 1992 in fluvo-aquic soil (Calcaric Cambisols, FAO) at Malan farm (37°55′ N, 115°13′ E), Hebei province, north-central China. This region has a warm temperate, sub-humid continental monsoon climate. The annual mean temperature and precipitation are 12.5°C and 490 mm, respectively, and 70–80% of the annual precipitation occurs during the summer maize-growing season. The soil tested has a light loam texture with following properties in top 20 cm soils at the beginning of the experiment in 1992: pH, 8.6 (soil:water = 1:2.5); organic matter, 14.1 g kg^{-1}; alkali-hydrolyzable N, 69.7 mg kg^{-1}; Olsen-P, 19.1 mg kg^{-1}; exchangeable K, 99.6 mg kg^{-1}; slowly available K, 1072 mg kg^{-1}; and total K, 23.4 g kg^{-1}.

2.2. Experimental design

The experiment was conducted on a typical winter wheat–summer maize rotation system. Winter wheat was generally planted in early or mid-October after a rotary tillage, and was harvested in early June of the following year. Summer maize was planted immediately after wheat harvest without any tillage and harvested in late September or early October. The experiment included four treatments: NP (fertilizer N and P), NPS (fertilizer NP plus wheat straw), NPK (fertilizer NP and K), and NPKS (fertilizer NPK plus wheat straw). All treatments were arranged in a randomized block design with four replicates, and the plot size was 50 m^2 (5 m × 10 m).

During the entire experiment period, the N fertilizer was applied at 225 kg N ha^{-1} for all treatments during each crop season. One third of total N was surface broadcast-applied by hand before sowing as basal and incorporated into the 0–15 cm soil by rotary tillage, and two thirds of total N was broadcast-applied as topdressing at shooting stage followed by an irrigation of 60 mm water in wheat season. In maize season, onethird of total N was band-applied as basal at three-leaf stage, and two thirds of total N was broadcast-applied at ten-leaf stage followed by an irrigation of 60 mm water. P fertilizer was basal applied at 90 kg P_2O_5 ha^{-1} in all plots and K fertilizer was basal applied at 150 kg K_2O ha^{-1} only in the NPK and NPKS treatments plots together with N in each crop season. Fertilizers applied were urea (46% N), calcium superphosphate (12% P_2O_5), and potassium chloride (60% K_2O). All wheat straw were crushed and returned in the NPS and NPKS treatment plots with exception for the NP and NPK treatments before maize planting. All maize straw were removed from all plots before wheat planting from 1993 to 2006, but were crushed into 3–6 cm pieces and incorporated into the 0–15 cm soil by rotary tillage in all plots since the maize harvest in 2007. Local high yielding varieties of wheat and maize were used for this experiment. Other field management practices including pest control followed farmer practices.

2.3. Crop harvest, plant and soil sampling

At annual wheat maturity, three separate areas (each 2 m^2) in the middle of each plot were harvested manually, dry weights of grain and straw were determined after separation. Maize ears were hand harvested from an area of 15 m^2 (three rows, 10-m length) in the middle of each plot and shelled, air-dried grains were weighed. Six maize plants were randomly selected from each plot for a separate harvest that was used for biomass determination; dry weights of grain and straw were determined after separation and oven-drying at 60 °C. For both crops, subsamples of grain and straw were ground and passed through a 0.5-mm sieve for K content determined.

After wheat harvest in 2012, five soil cores (2 cm in diameter) were collected in each plot in the 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm soil layers, respectively. Fresh soil samples of the same soil depth per plot were mixed as a composite sample. An aliquot of air-dried soil samples were passed through a 2-mm sieve for soil available K analysis, and the remaining soil samples were passed through a 0.15-mm sieve for analysis of slowly available K, total K, and soil organic carbon (SOC).

2.4. Plant and soil chemical analysis

Plant K in grain and straw was digested using the H_2SO_4–H_2O_2 method, soil total K was digested in a nickel crucible with sodium hydroxide at 750 °C (Lu, 1999). Soil available K (also known as exchangeable K) was extracted using 1 mol l^{-1} ammonium acetate, nonexchangeable K was extracted using the hot nitric acid extraction method (Helmke and Sparks, 1996), slowly available K was calculated by subtracting available K from nonexchangeable K. All K concentrations were determined with an atomic absorption spectrophotometer (AAnalyst 400, PerkinElmer, US). SOC was determined by potassium dichromate oxidation at 170–180 °C followed by titration with 0.1 mol l^{-1} ferrous sulfate (Walkley and Black, 1934).

2.5. Calculation

Plant K uptake was calculated based on plant K concentration and the weights of grain and straw. The annual soil K budget was calculated using the following equation:

$$\text{Soil K budget}\,(\text{kg } K_2O \text{ ha}^{-1}) = \text{K input}\,(\text{fertilizer K} + \text{straw K}) - \text{K removal by crops}$$

Table 1
Annual wheat and maize aboveground K uptakes (kg K_2O ha^{-1}) under different fertilization treatments in different experimental stages from 1993 to 2012.

Stage	NP	NPS	NPK	NPKS
Wheat				
1993–1997	164.2 ± 13.2a C	210.5 ± 13.8a B	238.4 ± 16.1a AB	250.2 ± 11.3a A
1998–2002	173.4 ± 6.3a C	229.5 ± 4.3a B	242.2 ± 4.6a AB	251.2 ± 4.7a A
2003–2007	165.3 ± 9.6a C	226.9 ± 4.3a B	247.0 ± 9.5a A	259.1 ± 9.2a A
2008–2012	174.8 ± 5.9a C	221.6 ± 4.4a B	243.3 ± 12.1a A	261.4 ± 10.1a A
Maize				
1993–1997	97.6 ± 4.2b C	140.5 ± 5.2c B	167.6 ± 10.6b A	179.6 ± 8.0b A
1998–2002	109.4 ± 3.5ab C	161.9 ± 9.7b B	181.8 ± 10.4b A	195.2 ± 11.3b A
2003–2007	108.3 ± 9.6ab C	184.2 ± 10.4a B	230.1 ± 13.9a A	246.1 ± 12.3a A
2008–2011	120.0 ± 4.9a C	204.3 ± 3.8a B	245.6 ± 4.8a A	264.8 ± 7.5a A

The values are mean ± standard error (n = 20). Different lowercase letters indicate significant differences among experimental stages for each crop, and different uppercase letters indicate significant differences among fertilization treatments (p < 0.05).

2.6. Statistical analysis

Data were analyzed by analysis of variance using SPSS 13.0 (SPSS, Inc., Chicago, IL, USA), and mean values of crop K uptake, grain yield for different treatments and stages, soil K levels and SOC for different treatments and soil layers were compared using least significant difference (LSD) at the 0.05 level of probability.

3. Results

3.1. Crop K uptake and soil K balance

Fertilization significantly affected wheat and maize K uptakes; however, experimental stage (five years as an experimental stage) only influenced maize K uptake (Table 1). Among the four treatments, annual wheat K uptake showed significant differences as: NP < NPS ≤ NPK ≤ NPKS in 1993–1997 and 1998–2002, NP < NPS < NPK = NPKS in 2003–2007 and 2008–2012. Annual maize K uptake in the same treatment increased with experimental time. The K uptake by maize in four treatments showed consistent trends as: NP < NPS < NPK = NPKS across different experimental stages. For the same treatment, annual wheat K uptake was higher than maize K uptake in most cases except in 2008–2012.

For the NPS and NPKS treatments, annual straw K inputs were similar among different experimental stages from 1993 to 2007; however, annual straw K inputs significantly increased in 2008–2012 compared with that in 1993–1997, 1998–2002, and 2003–2007 (Table 2). The changes in annual total K removal by crops (both wheat and maize) among fertilizer treatments and experimental stages were similar to that in maize K uptake in Table 1. Annual soil K budget was similar between 1993–1997 and 1998–2002 for each treatment, but the value was lower for the NPK and NPKS in 2003–2007 than 1993–1997 and 1998–2002, and annual soil K budget further decreased in 2008–2012 compared with that in different experimental stages from 1993 to 2007 for each treatment. Among all treatments across different experimental stages, soil K budget differed significantly as: NP < NPS < NPK < NPKS. Annual soil K budget was negative for the NP, NPS, and NPK treatments, but the value was 78.5, 62.9, and 19.6 kg K_2O ha^{-1} for the NPKS treatment in 1993–1997, 1998–2002, and 2003–2007, respectively. However, in 2008–2012, the value in the NPK and NPKS treatments were 8.5 and 183.6 kg K_2O ha^{-1}, respectively, and annual soil K budget increased by 60.0–83.0, 90.2–138.9, 114.5–186.1, and 103.0–163.0 kg K_2O ha^{-1} than that from 1993 to 2007 for the NP, NPS, NPK and NPKS treatments, respectively.

Table 2
Annual soil K balance (kg K_2O ha^{-1}) under different fertilization treatments in different experimental stages from 1993 to 2012.

Stage/treatment	Annual total K input		Annual total K removal by crops	Annual soil K budget
	Fertilizer K	Straw K[a]		
1993–1997				
NP	–	–	261.8 ± 13.9c	−261.8 ± 13.9d
NPS	–	175.4 ± 11.0b	350.9 ± 15.5b	−175.5 ± 17.2c
NPK	300	–	406.0 ± 11.6a	−106.0 ± 11.8b
NPKS	300	208.7 ± 14.6a	430.2 ± 16.6a	78.5 ± 16.9a
1998–2002				
NP	–	–	282.8 ± 6.8c	−282.8 ± 6.8d
NPS	–	190.8 ± 3.6b	391.4 ± 11.1b	−200.5 ± 14.6c
NPK	300	–	424.3 ± 11.0a	−124.3 ± 12.6b
NPKS	300	209.4 ± 6.7a	446.5 ± 11.7a	62.9 ± 8.9a
2003–2007				
NP	–	–	273.6 ± 13.3c	−273.6 ± 13.3d
NPS	–	187.2 ± 4.2b	411.4 ± 20.7b	−224.2 ± 20.1c
NPK	300	–	477.6 ± 7.5a	−177.6 ± 7.8b
NPKS	300	224.7 ± 9.3a	505.1 ± 9.6a	19.6 ± 4.5a
2008–2012				
NP	–	92.9 ± 4.7 d	294.7 ± 6.7c	−201.8 ± 9.9d
NPS	–	340.6 ± 22.1b	426.0 ± 12.6b	−85.4 ± 14.4c
NPK	300	197.3 ± 14.7c	488.8 ± 6.8a	8.5 ± 1.6b
NPKS	300	409.7 ± 21.2a	526.1 ± 17.6a	183.6 ± 11.8a

The values are mean ± standard error (n = 20). Different letters indicate significant differences among fertilization treatments in the same experimental stage (p < 0.05).
[a] Annual straw K input came from wheat straw in 1993–2007 and from both wheat and maize straws in 2008–2012.

Table 3
Soil available K (mg K kg^{-1}) in different soil layers (cm) under different fertilization treatments.

Soil layer	NP	NPS	NPK	NPKS
0–10	83.8 ± 5.9c D	96.1 ± 3.7b C	138.7 ± 2.1a B	194.7 ± 4.1a A
10–20	84.5 ± 6.4c D	98.2 ± 4.5b C	119.2 ± 7.7b B	150.7 ± 8.7b A
20–30	92.4 ± 2.8bc B	99.8 ± 6.6ab AB	113.4 ± 6.4b A	118.5 ± 6.6c A
30–40	102.3 ± 4.8ab A	110.6 ± 6.5ab A	115.8 ± 5.2b A	114.9 ± 3.0c A
40–60	114.0 ± 1.9a A	114.2 ± 5.2a A	114.0 ± 7.7b A	109.8 ± 3.1cd A
60–80	111.1 ± 2.7a A	112.4 ± 7.2a A	116.2 ± 5.1b A	105.3 ± 3.8d A
80–100	106.6 ± 4.5a A	111.4 ± 5.5ab A	117.2 ± 4.5b A	104.2 ± 2.9d A

The values are mean ± standard error ($n = 4$). Different lowercase letters indicate significant differences among soil layers, and different uppercase letters indicate significant differences among fertilization treatments ($p < 0.05$).

Table 4
Soil slowly available K (mg K kg^{-1}) in different soil layers (cm) under different fertilization treatments.

Soil layer	NP	NPS	NPK	NPKS
0–10	657.9 ± 10.0b D	756.2 ± 65.1ab C	1234.2 ± 48.7a B	1516.7 ± 46.1a A
10–20	663.1 ± 47.9b C	672.1 ± 38.4b C	867.5 ± 27.6b B	1099.9 ± 11.3b A
20–30	624.9 ± 49.0b C	667.9 ± 46.0b C	768.0 ± 24.5b B	881.8 ± 50.3c A
30–40	823.0 ± 47.2a A	790.1 ± 45.8a A	835.6 ± 21.9b A	876.2 ± 25.4cd A
40–60	778.6 ± 22.4a A	768.1 ± 20.7ab A	831.3 ± 46.0b A	838.9 ± 25.9cd A
60–80	768.9 ± 50.1a A	784.6 ± 37.4a A	790.0 ± 11.9b A	788.7 ± 30.1d A
80–100	782.3 ± 7.4a A	795.0 ± 55.0a A	823.5 ± 10.8b A	809.7 ± 37.5cd A

The values are mean ± standard error ($n = 4$). Different lowercase letters indicate significant differences among soil layers, and different uppercase letters indicate significant differences among fertilization treatments ($p < 0.05$).

3.2. Soil K level

Soil available K showed a decreasing trend from 30–40 to 0–10 cm soil layer in the NP treatment, but the opposite trend was observed in the NPK and NPKS treatments (Table 3). There were no differences in soil available K below 20 cm soil for the NPS treatment, but soil available K was higher in the 40–60 and 60–80 cm than in the 0–10 and 10–20 cm soil layers. Soil depth did not alter available K below 30 cm in all treatments except that available K was higher in the 30–40 cm compared with that in the 60–80 and 80–100 cm soil layers in the NPKS treatment. Among the four treatments, soil available K differed significantly in the following pattern: NP < NPS < NPK < NPKS in the 0–10 and 10–20 cm soil layers, and NP ≤ NPS ≤ NPK = NPKS > NPS in the 20–30 cm depth; however, soil available K was not significantly different in the same soil layer below 30 cm.

There were no significant differences in slowly available K among soil layers below 30 cm for the same treatment (Table 4). Soil slowly available K was similar among the 0–10, 10–20, and 20–30 cm soil layers, and they were lower than that below 30 cm in the NP treatment. For the NPS and NPK treatment, all soil layers had similar slowly available K except for lower concentration observed in the 10–20 and 20–30 cm soil layers in the NPS treatment and higher concentration in the 0–10 cm soil layer in the NPK treatment. For the NPKS treatment, slowly available K significantly increased from 30–40 cm to 0–10 cm soil layer. Among fertilization treatments, significant slowly available K differences as: NP < NPS < NPK < NPKS in the 0–10 cm, NP = NPS < NPK < NPKS in the 10–20 and 20–30 cm soil layers; however, slowly available K was similar in the same soil layer below 30 cm.

Fertilization treatment and soil layer did not significantly alter soil total K (Table 5). However, compared with the initial content before the experiment starting, the NP, NPS, and NPK treatments decreased total K by 4.3%, 3.4%, and 0.4% in the 0–10 cm depth, respectively, but the NPKS treatment increased total K by 2.6%.

3.3. Soil organic carbon

Fertilization treatment and soil layer significantly affected SOC (Table 6). SOC decreased with depths in the 0–40 cm soil in each treatment. There were no differences in SOC among soil layers below 30 cm for the NP and NPK treatments; however, for the NPS and NPKS treatments, SOC was higher in the 30–40 cm than in the 60–80 and 80–100 cm soil layers. Among treatments, SOC differed significantly as: NPS > NP ≤ NPK ≤ NPS ≤ NPKS > NPK in the 0–10 cm, NP ≤ NPK = NPS ≤ NPKS > NP in the 10–20 cm, NPK = NP < NPS = NPKS in the 20–30 cm, and NPS > NP ≤ NPK ≤ NPS = NPKS in the 30–40 cm soil layer. However, SOC was not significantly different among treatments below 40 cm.

3.4. Crop yield

Fertilization treatment and experimental stage significantly influenced annual wheat and maize yields (Table 7). Annual wheat yield was not significantly different from 1993 to 2012

Table 5
Soil total K (g K kg^{-1}) in different soil layers (cm) under different fertilization treatments.

Soil layer	NP	NPS	NPK	NPKS
0–10	22.4 ± 0.6a A	22.6 ± 1.1a A	23.3 ± 0.7a A	24.0 ± 1.0a A
10–20	23.1 ± 0.3a A	23.4 ± 1.2a A	23.3 ± 0.9a A	23.9 ± 0.2a A
20–30	24.0 ± 0.5a A	23.4 ± 0.9a A	23.4 ± 1.1a A	24.0 ± 0.5a A
30–40	24.1 ± 0.8a A	22.5 ± 1.0a A	23.3 ± 0.5a A	23.4 ± 0.2a A
40–60	24.0 ± 0.7a A	22.8 ± 0.9a A	23.8 ± 1.2a A	23.9 ± 0.4a A
60–80	24.2 ± 0.4a A	24.0 ± 1.7a A	23.7 ± 0.8a A	23.5 ± 0.7a A
80–100	24.3 ± 0.4a A	23.4 ± 1.7a A	24.0 ± 1.2a A	23.8 ± 0.2a A

The values are mean ± standard error ($n = 4$). Different lowercase letters indicate significant differences among soil layers, and different uppercase letters indicate significant differences among fertilization treatments ($p < 0.05$).

Table 6
Soil organic carbon ($g\,kg^{-1}$) in different soil layers (cm) under different fertilization treatments.

Soil layer	NP	NPS	NPK	NPKS
0–10	8.6 ± 0.8a C	10.1 ± 0.2a AB	9.3 ± 0.1a BC	10.8 ± 0.4a A
10–20	7.8 ± 0.4a B	8.7 ± 0.4b AB	8.5 ± 0.2a AB	9.2 ± 0.2b A
20–30	5.2 ± 0.1b B	7.1 ± 0.2c A	5.5 ± 0.1b B	7.7 ± 0.4b A
30–40	4.7 ± 0.6bc B	5.5 ± 0.2d A	4.9 ± 0.4bc AB	5.6 ± 0.6c A
40–60	4.5 ± 0.7bc A	5.0 ± 0.4de A	4.8 ± 0.2bc A	5.0 ± 0.1cd A
60–80	4.5 ± 0.3bc A	4.5 ± 0.4e A	4.0 ± 0.4c A	4.3 ± 0.3d A
80–100	4.0 ± 0.4c A	5.1 ± 0.3e A	3.9 ± 0.2c A	3.9 ± 0.6d A

The values are mean ± standard error ($n = 4$). Different lowercase letters indicate significant differences among soil layers, and different uppercase letters indicate significant differences among fertilization treatments ($p < 0.05$).

Table 7
Annual wheat and maize grain yields ($kg\,ha^{-1}$) under different fertilization treatments in different experimental stages from 1993 to 2012.

Stage	NP	NPS	NPK	NPKS
Wheat				
1993–1997	5783 ± 247a A	6035 ± 312ab A	6352 ± 274ab A	6381 ± 264b A
1998–2002	6173 ± 89a B	6475 ± 119ab A	6605 ± 148ab A	6829 ± 147ab A
2003–2007	5716 ± 126a B	5945 ± 165b AB	6280 ± 147b AB	6390 ± 117b A
2008–2012	6252 ± 264a B	6672 ± 251a AB	6883 ± 302a A	7081 ± 346a A
Maize				
1993–1997	5583 ± 90c B	5790 ± 184c B	6310 ± 148d A	6363 ± 93d A
1998–2002	5851 ± 223c B	6237 ± 206c B	6982 ± 154c A	7060 ± 176c A
2003–2007	6890 ± 189b C	7689 ± 148b B	8525 ± 118b A	8675 ± 121b A
2008–2011	7390 ± 94a C	8435 ± 136a B	9348 ± 117a A	9512 ± 125a A

The values are mean ± standard error ($n = 20$). Different lowercase letters indicate significant differences among experimental stages for each crop, and different uppercase letters indicate significant differences among fertilization treatments ($p < 0.05$).

for the NP treatment; however, annual wheat yield was higher in 2008–2012 than in 2003–2007 for the NPS and NPK treatments, and the value was higher in 2008–2012 than in 1993–1997 and 2003–2007 for the NPKS treatment. Among all treatments, annual wheat yield was similar in 1993–1997, but wheat yield was significantly decreased in the NP treatment compared with other three treatments in 1998–2002, and wheat yield differed significantly as: NP ≤ NPS = NPK ≤ NPKS in 2003–2007, and NP ≤ NPS = NPK = NPKS and NP < NPK in 2008–2012. Annual maize yield increased with experimental time in all treatments. Among fertilization treatments, annual maize yield differed significantly as: NP = NPS < NPK = NPKS in 1993–1997 and 1998–2002, and NP < NPS < NPK = NPKS in 2003–2007 and 2008–2012.

4. Discussion

4.1. Crop K uptake and soil K balance

The level of soil K supply significantly affected crop K uptake (Dobermann et al., 1998; Mallarino et al., 2012). In this study, annual wheat and maize K uptakes all increased with increasing K inputs (including fertilizer K and straw K) in the sequence of NP < NPS </≤ NPK ≤ NPKS. The NP, NPS, and NPK treatments resulted in negative annual soil K budgets due to total K inputs were lower than total K removal by crops from 1993 to 2007. Niu et al. (2011, 2013) also reported that the inorganic K application at 150 kg K_2O ha^{-1} resulted in negative soil K balance of −29 to −118 and −6 to −54 kg K_2O ha^{-1} in wheat and maize seasons, respectively, in north-central China. Annual soil K budget also increased in the order of NP < NPS < NPK < NPKS because the rate of the increase in total K inputs was significant higher than that in crop K removals from 1993 to 2007, maize straw K return further increased annual soil K budgets since 2008. Compared with the NP and NPK treatments without straw return in 1993–1997, 1998–2002, and 2003–2007, the NPS and NPKS treatments with double crop straws return increased annual soil K budgets by 176.4–197.4 and 289.6–361.2 kg K_2O ha^{-1} in 2008–2012, respectively. These data indicated that straw return played an important role in soil K fertility maintenance, K fertilization and straw return both alleviated soil K depletion, and higher rate of K inputs enhanced their effects.

4.2. Soil K nutrient variation

Because of negative soil K balance in the NP and NPS treatments, soil available K was gradually depleted in the 0–10 and 10–20 cm soil layers, and thus the values decreased than the initial concentration. Jin et al. (1994, 1999) and Yang et al. (2004) reported that the continuous unbalanced fertilization had led to serious depletion of soil K across large areas of China. A dynamic balance exists between soil exchangeable K and nonexchangeable K, and a portion of nonexchangeable K can be transformed into exchangeable K when exchangeable K is lower than a threshold concentration (Martin and Sparks, 1985; Wang et al., 2010). The significant decrease in slowly available K in the 0–20 cm depth for the NP and NPS treatments relative to the initial concentration likely because a lot of slowly available K was transformed into available K, which had been absorbed and removed by crops. In addition, the fluvo-aquic soil has high vermiculite and mica contents (Tan et al., 2012), the soil weathering induced by crop roots or microorganisms also could contribute considerable amounts of K to soil solution, and soil acidification resulted from long-term fertilization promoted the weathering (Haby et al., 1990; Sheldrick et al., 2003; Qiu et al., 2014). Sheldrick et al. (2003) indicated that most of the K used by crops came from soil K reserves under low fertilizer K inputs. Therefore, soil total K in the 0–10 cm soil also decreased than the initial level for the NP and NPS treatments under long-term K depletion by crops. Soil available K and slowly available K were greater in the NPS than the NP treatment, which was consistent with the higher soil K budget in the NPS treatment relative to the NP treatment, indicating that wheat straw return enhanced soil K levels. Although annual negative K balance from 1993 to 2007, the NPK treatment enhanced soil available K in 0–10 and 10–20 cm soil layers in 2012 compared with the initial level, the increase in soil available K mainly derived from maize straw return since 2007 and the release of soil K reserves. The decrease in soil slowly available K in the 10–20 cm soil and in total K in the 0–10 cm soil compared with the initial levels all could explain these changes.

For the NPKS treatment, annual positive soil K balance led to soil available K in the top 20 cm soil significantly increased compared with the initial level. Excessive soil available K could also be fixed into nonexchangeable K when the input of K fertilizer exceeds crop K demand (Yu et al., 2007). Therefore, a portion of fertilizer K applied was fixed into nonexchangeable K and then enhanced the soil slowly available K and total K.

Different fertilization treatments did not significantly alter soil total K in the 0–100 cm depth, but total K in the 0–10 cm soil layer in the NP, NPS, and NPK treatments decreased by 4.3%, 3.4%, and 0.4% than the initial concentration across this 20-year experiment, respectively. This fluvo-aquic soil is a highly weathered soil with high total K (Tan et al., 2012). A slight decrease in total K was associated with a large depletion of available K, therefore, soil total K would gradually decrease with experimental time under continuous unbalanced fertilization or neglect of K fertilization.

Fertilization treatment influenced soil available K and slowly available K mainly in the 0–30 cm soil layer because K fertilization was surface applied, crop roots and tillage disturbance mainly occurred in the top 30 cm depth (Dwyer et al., 1996), and excessive soil available K was easily fixed and its movement into deeper soil was limited (Sheldrick et al., 2003; Najafi-Ghiri and Abtahi, 2013).

4.3. Soil organic carbon

Compared with the NP and NPK treatments, the NPS and NPKS treatments increased SOC in the 0–40 cm depth, respectively, because more straw C was incorporated into soil, which was consistent with previous studies that crop straw retention enhanced SOC and it increased with increasing straw inputs (Powlson et al., 2008; Lou et al., 2011). These results also indicated that straw return not only enhanced soil fertility and quality, but also increased soil C sequestration. Han et al. (2010) observed that maize straw return increased soil C sequestration at 1011 kg ha^{-1} $year^{-1}$ in the 0–30 cm soil layer in a wheat–maize cropping system in northern China. SOC showed an increasing trend in the top 30 cm soil in the NPK treatment relative to the NP treatment, which was likely attributed to increased maize straw biomass and crop root residues by K fertilization. SOC was similar among soil layers below 30 cm in the NP and NPK treatments. Similar results have shown that SOC decreased with soil depths and its variation mainly occurred in the 0–30 cm (Dinesh et al., 2009; Sun et al., 2011). However, in the NPS and NPKS treatments, SOC was higher in the 30–40 cm than the 60–80 and 80–100 cm soil layers, maybe because high rate of straw retention caused part of organic C leaching into deeper soil layers (Vinther et al., 2006; Walmsley et al., 2011).

4.4. Crop yield and K fertilization

Results of the present study showed that it was the total amount of K inputs (fertilizer K and straw K) that influenced soil K balance, K level, and crop yield. Compared with the NP treatment, the NPS and NPK treatments increased wheat yield by 4.0–6.7% and 7.0–10.2% during this long-term experiment, respectively. These results demonstrated that straw return and/or K application all enhanced wheat yield in spite of the yield increases were not significant among treatments in 1993–1997 and 2003–2007. For maize, the NPS and NPK treatments increased yield by 3.7–14.1% and 13.0–26.5% than the NP treatment, respectively. The rate of yield increase was higher for maize than wheat, one season was that only wheat straw was returned from 1993 to 2007, the other season was that maize yield was more sensitive to K fertilization than wheat (Sharma et al., 2010; Tan et al., 2012). He et al. (2012) reported that K application alone significantly improved maize yield by 46% but wheat showed no response in a 19-year field experiment. Therefore, K fertilizer should be prior applied on maize to enhance crop yield and K efficiency in the wheat–maize cropping system when K fertilizer source was limited (Sheldrick et al., 2003).

Maize yield was lower in the NPS treatment as compared with the NPK and NPKS treatments, and annual soil K budget was–85.4 kg K_2O ha^{-1} for the NPS treatment even under double crop straws return in 2008–2012, which indicated that only crop straw return could not meet the demand of K for high maize yield and sustain soil K balance, and the application of K fertilizer was necessary to ensure high maize yield and maintain soil K fertility. The NPKS treatment did not significantly enhance crop yields than the NPK treatment, despite the fact that the NPKS treatment resulted in positive soil K balance and significantly increased soil K levels compared with the NPK treatment. Therefore, this fertilization strategy was not economical under limited K resources, and K fertilization rate (300 kg K_2O ha^{-1} $year^{-1}$) should be reduced modestly. Double crop straws return was prevalent in this wheat–maize cropping system in recent decades, based on these results in this study, the application of fertilizer K at 120 K_2O ha^{-1} $year^{-1}$ would be feasible to maintain high grain yield and soil K balance under this double crop straws return in this region.

5. Conclusions

Our study confirmed that K fertilization and/or straw return alleviated soil K depletion and enhanced soil K fertility, and high rate of K inputs enhanced their effects. Different fertilization strategies influenced soil available K and slowly available K mainly in the top 30 cm soil, and total K changed only in the 0–10 cm soil compared with the initial level. Straw return enhanced SOC, however, fertilization affected SOC mainly in the top 40 cm. K fertilization and/or straw return increased crop yields, only crop straw return could not meet the demand of K for high maize yield and soil K balance, and K fertilizer should be prior applied on maize to enhance yield and K efficiency.

Acknowledgements

This project was supported by the National Basic Research Program of China (973 Program) (2013CB127404 and 2013CB127405), the National Natural Science Foundation of China (31272243 and 31272245) and the International Plant Nutrition Institute (IPNI).

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