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Yield-increase effects via improving soil phosphorus availability by applying K_2SO_4 fertilizer in calcareous–alkaline soils in a semi-arid agroecosystem

Chang-An Liu[a], Feng-Rui Li[b], Chun-Chen Liu[c], Rong-He Zhang[a], Li-Min Zhou[a], Yu Jia[a,*], Wen-Juan Gao[a], Jun-Ting Li[a], Qi-fu Ma[d], Kadambot H.M. Siddique[e], Feng-Min Li[a,e,*]

[a] State Key Laboratory of Grassland Agro-Ecosystem, Institute of Arid Agroecology, School of Life Sciences, Lanzhou University, 730000, China
[b] Linze Inland River Basin Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, 730000, China
[c] School of Life Sciences, Qufu Normal University, 273100, China
[d] School of Environmental Science, Murdoch University, Murdoch WA 6150, Australia
[e] The UWA Institute of Agriculture, The University of Western Australia, Crawley WA 6009, Australia

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ABSTRACT

Many studies have reported evidence describing the effects of K_2SO_4 fertilizer on crop productivity, but there is scant information about the yield-increasing mechanisms when influencing soil properties by K_2SO_4 application in calcareous and alkaline soils. In this study, one field and incubation experiments were conducted to investigate the effects of K_2SO_4 fertilizer on crop yields and soil properties in calcareous and alkaline soils on the Loess Plateau of Northwestern China. In field experiments, four K_2SO_4 treatments were applied to potato (*Solanum tuberosum* L.) in 2007 and spring wheat (*Triticum aestivum* L.) in 2008: (1) CK: no K_2SO_4; (2) T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; (3) T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; and (4) T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008. In 2007, potato yield increased by 17.4% in T2 and 21.5% in T3 compared with CK, but did not significantly increase in T1. In 2008, spring wheat yields increased by 10.0%, 15.8% and 18.7% in T1, T2 and T3 treatments, respectively, compared with CK. Stepwise regression ($P \leq 0.05$) revealed that soil-available K at tuber formation and starch accumulation stage, and available P at starch accumulation stage correlated well with potato yield. Soil available P before sowing and at anthesis correlated well with spring wheat yield. Soil available P content was mostly higher in T1, T2 and T3 than in CK from June 2007 to August 2008 when the same dose P fertilizer was applied in all plots. Applying K_2SO_4 decreased soil pH. Soil available P was significantly negatively correlated with soil pH ($R = -0.5721$, $P = 0.0015$). In an incubation experiment, the four K_2SO_4 treatments were designed: (1) CK: no K_2SO_4; (2) S1: K_2SO_4 @ 0.44 g kg^{-1} dry soil; (3) S2: K_2SO_4 @ 0.88 g kg^{-1} dry soil; (4) S3: K_2SO_4 @ 1.32 g kg^{-1} dry soil. The results also showed that addition of K_2SO_4 significantly decreased soil pH and increased available P in calcareous and alkaline soils. Our study suggests that K_2SO_4 is desirable for improving crop productivity by increasing soil P availability via decreasing soil pH in calcareous and alkaline soils besides K effect in a low input dryland agroecosystem.

1. Introduction

Nitrogen, P and K are the most essential plant nutrients with respect to increasing yield. In recent years, much attention has been paid to the effects of N and P fertilizers on crop yields, soil quality and the environment, as high amounts of N and P fertilizers are applied all over the world (Halitligil et al., 2002; Malhi and Lemke, 2007; Halajnia et al., 2009; Ma et al., 2009; Valkama et al., 2009; Ferrise et al., 2010; Liang et al., 2011); less attention has been paid to changes in soil parameters and increased crop yields by K_2SO_4 fertilizer.

Compared to individual inorganic N and P fertilization, combined inorganic NPK fertilization significantly increased grain yields of wheat and maize in alkaline soils in four distinctive agroecological zones across China (Zhang et al., 2011). We found that that K_2SO_4 fertilizer may increase soil Ca_2-P and Ca_8-P in alkaline soils by analyzing the report of Zhou and Zhang (2005). Potato is a K-favoring crop, and many researchers have reported evidence describing the significant effect of K_2SO_4 fertilizer on increased yield in calcareous–alkaline soils (Li et al., 2002; Qin, 2003; Wang and Lu, 2005; Ierna et al., 2011). K_2SO_4 fertilizer has been recently introduced into rainfed farming systems on the Loess Plateau of

* Corresponding author at: State Key Laboratory of Grassland Agro-Ecosystem, Institute of Arid Agroecology, School of Life Sciences, Lanzhou University, 730000, China. Tel.: +86 931 8912848; fax: +86 931 8912848.
E-mail addresses: juyu@lzu.edu.cn (Y. Jia), fmli@lzu.edu.cn (F.-M. Li).

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China as the production of potato and spring wheat has increased. However, there is scant information about the effects of K_2SO_4 fertilizer on soil properties, and no information is available on the yield-increasing mechanism when influencing soil properties by K_2SO_4application in calcareous and alkaline soils.

Soil becomes more acidic after applying sulfur-containing fertilizers (Li and Wang, 2004; Zou et al., 2004). P fertilizer added to calcareous soils was mostly converted to relatively less soluble Ca_8-P within a very short time due to high soil Ca^{2+} content (Wang et al., 2005; Jalali and Ranjbar, 2010). Decreased soil pH favored increased available P content in calcareous–alkaline soils (Qin et al., 2006).

Potato and wheat are the two major crops grown in semi-arid regions of China (Xiao et al., 2007). From the above mentioned information, we have a hypothesis that $SO_4{}^{2-}$ of K_2SO_4 application would decline soil pH, which may improve soil phosphorus availability and then be favorable to crop yield improvement. Therefore, the primary objectives of this study were to investigate: (1) the effect of K_2SO_4 application on soil pH and P availability; (2) the relationship among crop yields, available K and available P; and (3) the principal mechanism of yield-increase of crops by K_2SO_4 application in calcareous–alkaline soils.

2. Materials and methods

2.1. Field experiment

2.1.1. Description of study site

The field experiment was conducted for two growing seasons in 2007 and 2008 at the Semiarid Ecosystem Research Station of Lanzhou University on the Loess Plateau (36°02′N, 104°25′E, 2400 m above sea level) in Zhongliangchuan of Yuzhong County, Gansu Province, China. The site has a medium-temperate semi-arid climate, with a mean annual air temperature of 6.5 °C and mean maximum and minimum temperatures of 19.0 °C (July) and −8.0 °C (January). Average annual open-pan evaporation is about 1300 mm. Average annual precipitation is 320 mm, of which approximately 56% is received from June to September. The water table lies about 60 m deep and is not available to plants. The soil has a mean soil bulk density of 1.15 g cm^{-3}, pH 7.8, 145.0 g kg^{-1} $CaCO_3$, 65.3 mg kg^{-1} mineral N (NO_3—N + NH_4—N), 7.7 mg kg^{-1} available P and 89.6 mg kg^{-1} available K. The soil is Heima (Calcic Kastanozems, according to the FAO taxonomy), with a field water holding capacity of 22.9% and a permanent wilting coefficient of 6.2% (Shi et al., 2003). In 2006, prior to the experiment, the site was planted with field pea followed by a fallow of 260 days before potato was sown in 2007.

2.1.2. Experimental design and field management

One crop was grown each year: potato (*S. tuberosum* L.) in 2007 and spring wheat (*T. aestivum* L.) in 2008. Considering that 100–300 kg K_2SO_4 ha^{-1} for potato and 50–150 kg K_2SO_4 ha^{-1} for spring wheat are generally applied by farmers in the region, the experiment had four K_2SO_4 treatments: (1) CK: no K_2SO_4; (2) T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; (3) T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; and (4) T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008. In addition, 70 kg N ha^{-1} as urea, 20 kg P ha^{-1} as single superphosphate and 1.5 t ha^{-1} sheep manure were applied to every plot each year. The composition of sheep manure varied from year to year, with average values (as g kg^{-1}) of 219 organic C, 10 total N, 0.85 total P, 21 total K, 0.09 N (NH_4—N + NO_3—N) and 0.16 available P. All K_2SO_4, N and P fertilizers were applied 20 cm deep by rotary tillage and harrowing at the time of sowing. Manure was applied using the same method at the time of sowing and after potato harvest in October 2007. The experiment had a randomized block design with three replications.

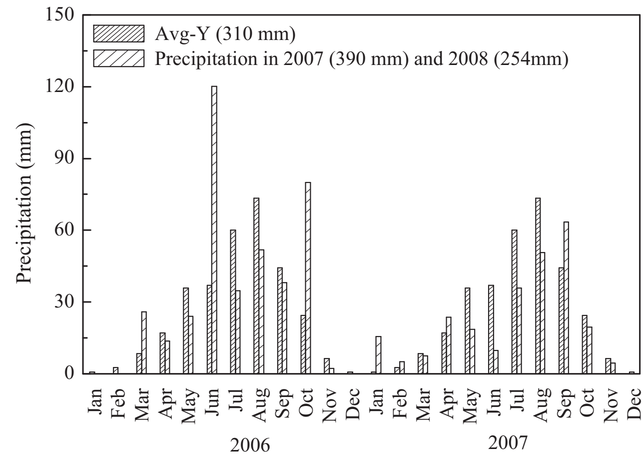

Fig. 1. Precipitation (mm) in 2007 and 2008, monthly average precipitation in past 30 years in Yuzhong (Avg-Y).

Each plot was 6 m × 6 m, separated by a ridge 0.4 m high and 1 m wide. These treatments were repeated in the same plots for 2 years.

The seeding rate was 180 kg ha^{-1} for spring wheat and 300 kg ha^{-1} for potato. Spring wheat was grown from early April to early August, and potato was grown from late April to late September. Precipitation at the site was measured using an automatic weather station (WS-STD1, England). Precipitation during the growing season was 293.3 mm in 2007 and 94.7 mm in 2008 (Fig. 1). Potato had the longer growing season of 155 days and spring wheat had 122 days. Precipitation in the potato growing period accounted for 75.2% total annual precipitation. The corresponding value for spring wheat was 37.3%.

2.2. Incubation experiment

An incubation experiment was undertaken to confirm whether addition of K_2SO_4 decreases soil pH and soluble Ca, and then increases available P. Soil from 0 to 20 cm depth was collected from the Semiarid Ecosystem Research Station of Lanzhou University on the Loess Plateau. The soil has a mean 7.8 g kg^{-1} organic C, 0.8 g kg^{-1} total N, 2.2 mg kg^{-1} available P, pH 8.2 and 148.0 g kg^{-1} $CaCO_3$. The samples were air-dried, ground and sieved (2 mm) before incubation. The laboratory incubations were performed in 250-mL glass jars using a completely randomized experimental design with four treatments. Three replicates from each treatment were assigned to each of 3 sampling dates for a total of 36 incubation jars. The four K_2SO_4 treatments: (1) CK: no K_2SO_4; (2) S1: K_2SO_4 @ 0.44 g kg^{-1} dry soil; (3) S2: K_2SO_4 @ 0.88 g kg^{-1} dry soil; (4) S3: K_2SO_4 @ 1.32 g kg^{-1} dry soil. Air dried soil (50 g) was weighed into each jar and adjusted to moisture content of 0.22 g H_2O g^{-1} soil [~80% water holding capacity (WHC)] with deionized water in dark at 28 ± 1 °C. Sampling dates were at day 0 prior to incubation and at 7, 14 and 42 d during the incubation period.

2.3. Soil pH buffer capacity

Soil samples (5 g, 2 mm) from 0 to 20 cm depth was collected in the same site for the incubation experiment were weighed into each of 18 plastic containers (100 mL), the 18 plastic containers were divided into 3 groups, and incremental amounts (0, 0.5, 1, 2, and 4 mL) of standardized hydrochloric acid (HCl) (0.1 mol L^{-1}) were added, the final volume of suspension after acid addition was equal to 25 mL, and then sealed the containers tightly and arranged randomly. The suspensions were equilibrated for 24 h on an isothermal shaker (30 r/min, 25 °C), and then removed from the shaker to equilibrate for 0.5 h, soil pH was measured by muti-electrode.

2.4. Sampling and measurements

Plants were harvested manually at maturity from an area of 16 m^2 in the center of each plot in each of three blocks. Spring wheat grains and straw and potato tubers and aboveground biomass were oven-dried at 105 °C for 1 h and then at 70 °C for 72 h, and the dry mass weighed as the measure of crop yield and total biomass. Plant tissue samples of potato tubers and aboveground biomass were collected at maturity. Plant tissue samples of wheat grain and straw were collected at maturity. The sample plants were oven-dried for dry matter content at 60 °C for 48 h and were ground and analyzed for total nutrient concentrations. In order to increase soil fertility, the aboveground biomass and roots of potato were left when potato tubers were harvested, and returned to the soil with manure in October 2007. In each plot, three soil cores (diameter 80 mm and depth 200 mm) were randomly taken at four growth stages of potato crop (before sowing, tuber formation, starch accumulation and maturity) in 2007, and three growth stages of spring wheat (before sowing, anthesis and maturity) in 2008. The samples were air-dried, ground and sieved (2, 1, 0.15 mm) before analyses. The samples collected for incubation were air-dried, ground and sieved (2 mm) before analyses.

SOC and total nitrogen (TN) were measured by the dry combustion method using a CHNS-analyzer (Elementar Vario El, Elementar Analysensysteme GmbH, Hanau, Germany), and total phosphorus (TP) was determined colorimetrically after digestion with perchloric acid. Available phosphorus (AP) was determined using the Olsen method (Olsen et al., 1954). The ratio of SOC to TN (C/N ratio) and SOC to available P (C/P ratio) were calculated for all samples. For soil NO_3—N and NH_4—N, 10 g dried sample was added to 50 mL of 2 M KCl, shaken for 1 h, and analyzed with a FIAstar 5000 Analyzer (FOSS Tecator, Sweden). Available K (AK) was extracted with an ammonium acetate solution (1 mol L^{-1}) and then determined with a flame photometer. Soil available sulfur (AS) was measured using the method developed by Nanjing Agricultural University (1996): Extracted by shaking a 10 g soil sample with 50 mL 0.01 mol L^{-1} $CaCl_2$ for 1 h, and then filtered through a slow filter paper. Sulfate in the solution was determined by turbidimetry. Soil pH was measured with a glass electrode at a soil: water ratio of 1:2.5 (w/v). Soil water soluble calcium (SWSC) was determined by titration (Rowell, 1994). P and K concentrations in the plant dry matter were determined after wet digestion with H_2SO_4 and H_2O_2, and P by the vanadomolybdate method and K by flame photometry.

The density fraction scheme for light fraction organic carbon (LFOC) used the methods of Gregorich and Ellert (1993). In the fraction, 25 g air-dried soil (2 mm) was shaken with 50 mL NaI solution (sp. gr = 1.70) for 1 h. After centrifugation, the supernatant was passed through a Millipore filter and the light fraction collected. The soil residue in the centrifuge was extracted again with NaI and additional light fraction collected. The two light fraction components were combined and the concentration of organic matter determined using the CHNS-analyzer.

2.5. Statistical methods

One-way analysis of variance was used to evaluate the effects of soil K_2SO_4 treatments on yields and total biomass of potato and wheat, and soil quality parameters. Comparisons between K_2SO_4treatments or changes in soil parameters over time were made by the method of least significant differences (LSD) at $P = 0.05$. Regression analysis was also conducted between crop yields and soil parameters. Correlation analysis was conducted for available P with soil pH. The analyses were conducted using the SAS package (SAS Institute, 1989).

Table 1
Crop yields and total biomass (t ha^{-1}) of potato and spring wheat in K_2SO_4 treatments in 2007 and 2008.

	Treatments	2007 Potato	2008 Spring wheat
Crop yields	CK	3.45c	1.65b
	T1	3.68bc	1.82a
	T2	4.05ab	1.91a
	T3	4.19a	1.96a
Total biomass	CK	4.12b	6.72b
	T1	4.41b	7.69a
	T2	4.85a	8.10a
	T3	5.02a	8.22a

CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.; Values within a column followed by the same letter do not differ significantly at $P \leq 0.05$.

3. Results

3.1. Field experiment

3.1.1. Crop yield, aboveground biomass and nutrient uptake

In 2007, the yields of potato in T2 and T3 treatments increased by 17.4% and 21.5% compared to CK, but there was no significant difference between T1 and CK yields. In 2008, yields of spring wheat were significantly higher in T1, T2 and T3 than in CK, but the three K_2SO_4treatments did not differ (Table 1). In 2007, the total biomass was significantly higher in T2 and T3 than in CK and T1 (Table 1). In 2008, the total biomass was significantly higher in T1, T2 and T3 than in CK.

In 2007, the P uptake of potato tissues were significantly in T2 and T3 higher than in CK, but there was no significant difference between T1 and CK. A similar changing pattern was also observed for K uptake between treatments. In 2008, the P uptake of wheat tissues was significantly higher in T1, T2 and T3 than in CK. The K uptake of wheat tissues was significantly higher in T2 and T3 than in CK, but there was no significant difference between T1 and CK (Table 2).

3.1.2. Relation between yield and soil parameters

The stepwise regressions for evaluating the relationship between soil nutrients at different growth stages and yields of potato and spring wheat, soil nutrients included soil total N (TN), mineral N (MN), total P (TP), available P (AP), available K (AK) and available S (AS). The relationship of potato yield to soil parameters was:

$Y_p = 0.985\text{AK}$ ($R^2 = 0.956$, $n = 4$, $P \leq 0.05$) (at tuber formation)
$Y_p = 0.608\text{AK} + 0.404\text{AP}$ ($R^2 = 0.999$, $n = 4$, $P \leq 0.05$) (at starch accumulation stage)

Table 2
P and K uptake (kg ha^{-1}) of plant tissues in K_2SO_4 treatments in 2007 and 2008.

Year	Treatments	P uptake	K uptake
2007	CK	7.6b	81.9b
	T1	8.7ab	97.0ab
	T2	9.8a	110.3a
	T3	10.1a	112.8a
2008	CK	5.0b	69.5b
	T1	5.9a	82.2ab
	T2	6.0a	90.3a
	T3	6.4a	92.2a

CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.; Values within a column followed by the same letter do not differ significantly at $P \leq 0.05$.

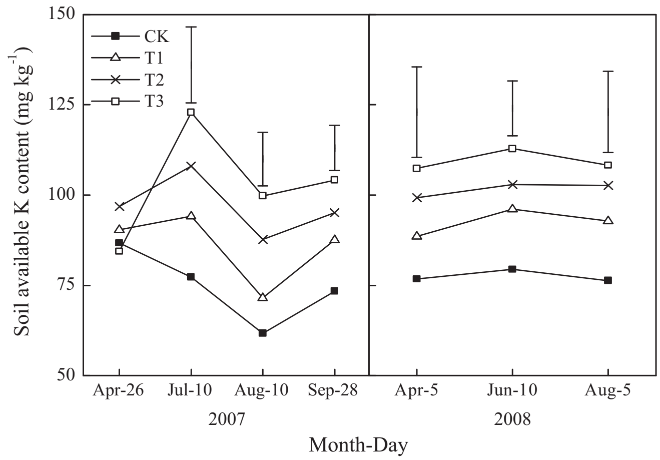

Fig. 2. Soil available K content in the 0–20 cm soil layer in the K_2SO_4 treatments in 2007 and 2008. Vertical bars are the LSD at $P \leq 0.05$. CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.

where Y_p is the yield of potato. Therefore, AK at tuber formation and starch accumulation stage, and AP at starch accumulation stage were closely correlated with the yield of potato.

The relationship of spring wheat yield to soil parameters was:

$Y_w = 0.998\text{AP}$ ($R^2 = 993$, $n = 4$, $P \leq 0.05$) (before sowing)
$Y_w = 0.998\text{AP}$ ($R^2 = 0.995$, $n = 4$, $P \leq 0.05$) (at anthesis)

where Y_w is the yield of spring wheat. Therefore, AP before sowing and at anthesis was closely correlated with the yield of spring wheat.

3.1.3. Soil nutrients and soil pH

Soil AK contents were significantly increased by K_2SO_4 fertilizer from June 2007 to August 2009 (Fig. 2). In the 2007 season, soil AK content was significantly higher in T2 and T3 than in CK from June to September. In the 2008 season, soil AK content in T3 was significantly higher than in CK in April, and it was significantly higher in T2 and T3 than in CK in June and August. Soil AS contents significantly increased with K_2SO_4 fertilizer from August 2007 to June 2008 (Fig. 3).

There were no significant differences in soil TP between treatments or sampling dates (Table 3), but soil AP content was mostly significantly higher in T1, T2 and T3 than in CK from June 2007 to August 2009 (Fig. 4). Soil TN did not differ among treatments for the duration of the experiment (Table 3). Soil MN content was also similar among treatments before August 2007. Even though soil MN was significantly higher in T2 and T3 than in CK in August 2007, no significant differences were observed among all treatments by the end of the growing season (Fig. 4). In 2008, soil MN content did not differ among treatments at the beginning of the season, but was mostly higher in CK than in other treatments in June and the end of the season.

Fig. 5 shows soil pH in the upper 20 cm layer with K_2SO_4 treatments over the two growing seasons. Soil pH was lower in T1, T2 and T3 than in CK late in the 2007 season, whereas only T2 and T3 lowered soil pH late in the 2008 season.

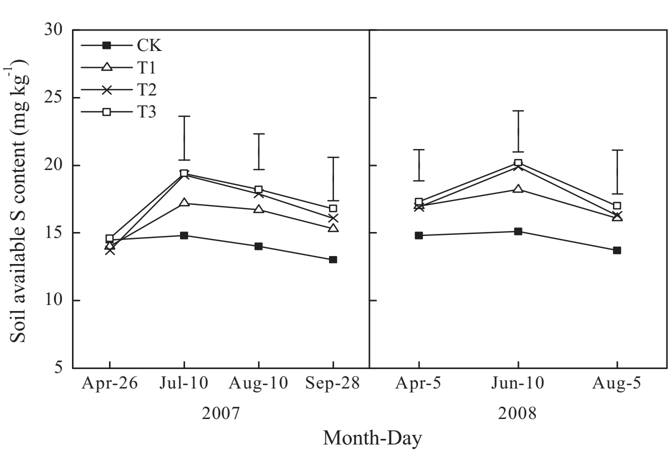

Fig. 3. Soil available S content in the 0–20 cm soil layer in the K_2SO_4 treatments in 2007 and 2008. Vertical bars are the LSD at $P \leq 0.05$. CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.

Table 3
Soil total P (TP, g kg^{-1}) and total N (TN, g kg^{-1}) in the 0–20 cm soil layer of the K_2SO_4 treatments in 2007 and 2008.

Treatments	Year/month						
	2007/4	2007/7	2007/8	2007/9	2008/4	2008/6	2008/8
TP CK	0.66aA	0.67aA	0.67aA	0.67aA	0.67aA	0.68aA	0.68aA
T1	0.66aA	0.67aA	0.67aA	0.67aA	0.67aA	0.68aA	0.68aA
T2	0.65aA	0.66aA	0.67aA	0.66aA	0.67aA	0.68aA	0.67aA
T3	0.66aA	0.67aA	0.67aA	0.67aA	0.67aA	0.68aA	0.67aA
TN CK	0.81aA	0.84aA	0.80aA	0.80aA	0.83aA	0.86aA	0.82aA
T1	0.79aA	0.81aA	0.79aA	0.78aA	0.83aA	0.85aA	0.83aA
T2	0.81aA	0.83aA	0.80A	0.81aA	0.84aA	0.85aA	0.83aA
T3	0.82aA	0.85aA	0.78aA	0.79Aa	0.84aA	0.87aA	0.84aA

CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.; Values within a column followed by the same letter (lowercase) or within the same row (uppercase) do not differ significantly at $P \leq 0.05$.

3.1.4. SOC, LFOC, C/N and C/P

SOC content of the CK, T1, T2 and T3 treatments ranged from 0.75, 0.75, 0.74 and 0.76% to 0.78, 0.80, 0.81 and 0.83%, respectively. SOC content did not significantly differ between treatments in 2007 or 2008. Soil LFOC content in the upper 20 cm layer was significantly higher in T1, T2 and T3 than in CK from September 2007 to August 2008 (Table 4). By the end of the 2008 season, LFOC content in T1, T2 and T3 increased by 9.2%, 14.8% and 15.5%, respectively, but did

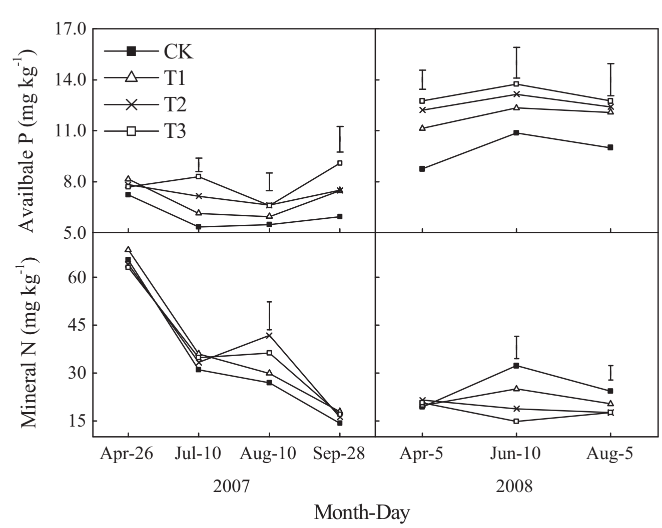

Fig. 4. Soil available P and mineral N in the 0–20 cm soil layer of the K_2SO_4 treatments in 2007 and 2008. Vertical bars are the LSD at $P \leq 0.05$. CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.

Table 4
Light fraction organic C (g kg^{-1}) in the 0–20 cm soil layer from the K_2SO_4 treatments over a two-year period.

Treatments	Year/month						
	2007/4	2007/7	2007/8	2007/9	2008/4	2008/6	2008/8
CK	1.06aA	0.96aA	0.95aA	0.98bA	1.05bA	0.99bA	1.02bA
T1	1.09aAB	0.93aC	1.03aBC	1.13aAB	1.19aA	1.08abAB	1.19aA
T2	1.08aBCD	0.98aD	1.05aCD	1.16aABC	1.29aA	1.20aAB	1.24aA
T3	1.10aC	0.92aD	1.05aCD	1.18aABC	1.30aA	1.21aAB	1.27aA

CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.; Values within a column followed by the same letter (lowercase) or within the same row (uppercase) do not differ significantly at $P \leq 0.05$.

Table 5
Ratio of organic C to total soil N (C/N) in the 0–20 cm soil layer of the K_2SO_4 treatments over a two-year period.

Treatments	Year/month						
	2007/4	2007/7	2007/8	2007/9	2008/4	2008/6	2008/8
CK	9.64aA	9.29aAB	9.38aAB	9.51aAB	9.37aAB	8.92aB	9.45aAB
T1	9.54aA	9.26aA	9.46aA	9.86aA	9.53aA	9.30aA	9.72aA
T2	9.46aA	9.19aA	9.25aA	9.28aA	9.55aA	9.35aA	9.84aA
T3	9.48aA	9.10aA	9.74aA	9.71aA	9.65aA	9.20aA	9.84aA

CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.; Values within a column followed by the same letter (lowercase) or within the same row (uppercase) do not differ significantly at $P \leq 0.05$.

not change in CK compared to the beginning of the experiment in 2007.

During the entire experiment, there was no significant difference in soil C/N ratio among all treatments (Table 5). By the end of the 2008 season, the C/N ratio increased by 1.85%, 4.02% and 3.80% in T1, T2 and T3, respectively, but decreased by 1.97% in CK compared to initial values in 2007.

Soil C/P ratio in the upper 20 cm layer changed with time (Table 6). The C/P ratio was significantly higher in CK than in T1, T2 and T3 in July and September in 2007, and at the beginning of the 2008 season. By the end of the 2008 season, there was no significant difference in C/P ratio among the treatments.

3.2. Incubation experiment

AP content was significantly higher in S1, S2 and S3 than in CK during the entire incubation period (Fig. 6). Soil water-soluble calcium content in S1, S2 and S3 was significantly higher than in CK as days 7 and 14, and it was significantly higher in S2 and S3 than in CK at day 42 (Fig. 7). Soil pH was significantly lower in S1, S2 and S3 than in CK during the entire incubation (Fig. 8).

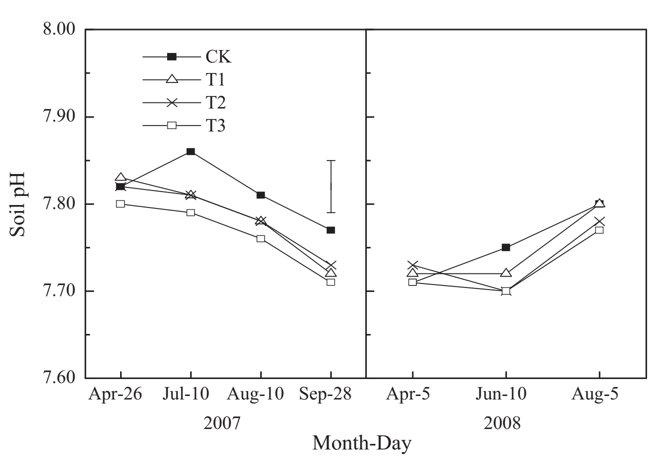

Fig. 5. Soil pH in the 0–20 cm soil layer in the K_2SO_4 treatments in 2007 and 2008. Vertical bars are the LSD at $P \leq 0.05$. CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008.

4. Discussion

This study showed that soil AK content at both tuber formation and starch accumulation stage was important for improving potato yield, as was soil AP content at starch accumulation stage. Soil AP content was crucial for improving spring wheat yield, and the increase in wheat yield was attributed to increased AP content by an indirect effect of SO_4^{2-}. In the semi-arid Loess Plateau of China, the problem is not always due to lack of P reserves in soil, but to P being unavailable to plants under high soil pH (Li et al., 2008). In many arid and semiarid areas, soil pH is often >7.0 because soil was in the oxidation environment. So, our results can be applied to crop production in the most arid and semiarid areas.

Chen (1990) and Huang (2000) reported that when C/P ratios were >300, MBC increased rapidly, leading to soil AP absorption in large quantities by microorganisms, thereby immobilizing organic P. In the present study, the C/P ratio was >300 in all treatments, i.e. soil AP was very low, suggesting that soil microorganisms were

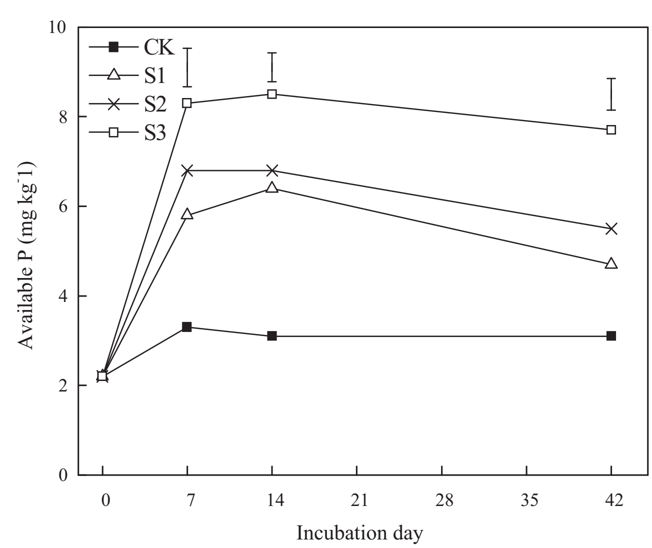

Fig. 6. Effect of additional K_2SO_4 on soil available P content in calcareous-alkaline soils during the incubation period at 28 °C. Vertical bars are the LSD at $P \leq 0.05$. CK: no K_2SO_4; S1: K_2SO_4 @ 0.44 g kg^{-1} dry soil; S2: K_2SO_4 @ 0.88 g kg^{-1} dry soil; S3: K_2SO_4 @ 1.32 g kg^{-1} dry soil.

Table 6
Ratio of organic C to available P (C/P) in the 0–20 cm soil layer of the K_2SO_4 treatments over a two-year period.

Treatments	Year/month						
	2007/4	2007/7	2007/8	2007/9	2008/4	2008/6	2008/8
CK	1088aB	1462aA	1368aA	1287aA	893aBC	713aD	785aCD
T1	932aB	1222bA	1257abA	1035bB	707bC	644abC	672aC
T2	987aB	1068bcAB	1121bA	1013bcAB	656bC	607abC	658aC
T3	1010aB	932cBC	1155bA	848cC	642bD	580bD	650aD

CK: no K_2SO_4; T1: K_2SO_4 @ 100 kg ha^{-1} in 2007 and 50 kg ha^{-1} in 2008; T2: K_2SO_4 @ 200 kg ha^{-1} in 2007 and 100 kg ha^{-1} in 2008; T3: K_2SO_4 @ 300 kg ha^{-1} in 2007 and 150 kg ha^{-1} in 2008. Values within a column followed by the same letter (lowercase) or within the same row (uppercase) do not differ significantly at $P \le 0.05$.

competing with crops for soil AP. We found that soil AP content significantly increased and C/P ratio decreased in K_2SO_4 fertilizer treatments compared to CK when the same dose P fertilizer was applied in all plots. It is not the shortage of P reserves in soil (Table 3) but the activation of P from residual P sources that is pivotal in Calcic Kastanozem soils (Wang et al., 2005). Phosphate anions are highly reactive and can be immobilized through sorption and/or precipitation with cations such as Ca^{2+}, and Mg^{2+} (Wang, 1992). In field experiment, soil $CaCO_3$ content is 145 g kg^{-1} in soils, and fertilizer P is mostly in the less available form of Ca_8-P (Wang et al., 2005). In the incubation experiment, we also found that addition of K_2SO_4 decreased soil pH and increased available P and soluble Ca content. So, the increase of available P in this study was not implemented by decreasing water soluble Ca^{2+} content. There are two possible reasons for increased AP in our study. Firstly, many researchers have reported that fertilizer with $SO_4{}^{2-}$ decreases soil pH values (Li and Wang, 2004; Zou et al., 2004), e.g. soil pH decreased significantly (by 2 units) after treatment with 0.670 g kg^{-1} sulfur compared to no sulfur treatment (Wang et al., 2011). In this study, we found that soil pH can decrease 0.25 units after treatment with 1.32 g kg^{-1} K_2SO_4 compared to no K_2SO_4 treatment even in the soil with high pH buffer capacity (Fig. 9). P had the highest release rate when soil pH was 6.0–7.0 (Wang, 1992). A reduction in soil pH favors an increase in available P content in calcareous soil (Qin et al., 2006). In the present study, soil pH decreased in K_2SO_4 treatments compared to CK. In alkaline soil, soil AP can increase 1.9–4.3 ppm when soil pH decreased 0.1 unite (Cai et al., 2008). A significant negative correlation was also observed between AP and soil pH in the 0–20 cm soil layer in field experiment, and AP and soil pH in incubation experiment (Fig. 10). Secondly, attributed to high absorbing capacities of the soils for $SO_4{}^{2-}$, soil can release $H_2PO_4{}^-$ by adsorbing $SO_4{}^{2-}$ when applied inorganic fertilizers containing $SO_4{}^{2-}$ (Zeng and Liu, 2000).

The light fraction of soil organic matter consists mainly of plant residues, small animals and microorganisms in various stages of decomposition. It serves as a readily decomposable substrate for soil microorganisms and as a short-term reservoir of plant nutrients. Hence, it can be a better indication of soil quality than total organic matter in soils (Gregorich et al., 1994; Jia et al., 2006;

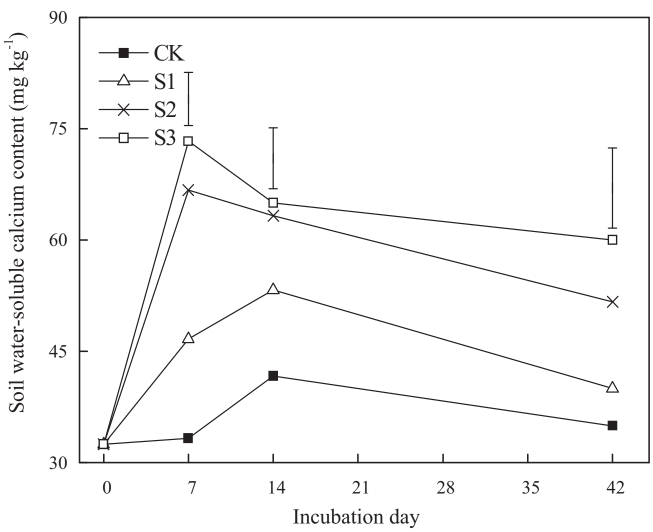

Fig. 7. Effect of additional K_2SO_4 on soil water-soluble calcium content in calcareous-alkaline soils during the incubation period at 28 °C. Vertical bars are the LSD at $P \le 0.05$. CK: no K_2SO_4; S1: K_2SO_4 @ 0.44 g kg^{-1} dry soil; S2: K_2SO_4 @ 0.88 g kg^{-1} dry soil; S3: K_2SO_4 @ 1.32 g kg^{-1} dry soil.

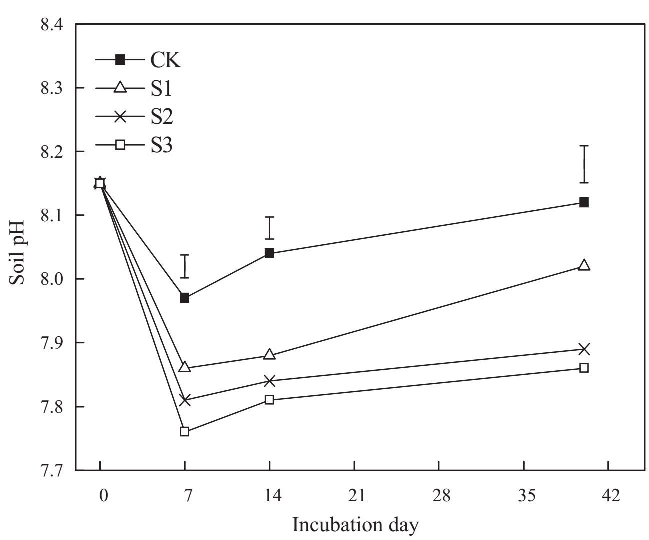

Fig. 8. Effect of additional K_2SO_4 on soil pH in calcareous-alkaline soils during the incubation period at 28 °C. Vertical bars are the LSD at $P \le 0.05$. CK: no K_2SO_4; S1: K_2SO_4 @ 0.44 g kg^{-1} dry soil; S2: K_2SO_4 @ 0.88 g kg^{-1} dry soil; S3: K_2SO_4 @ 1.32 g kg^{-1} dry soil.

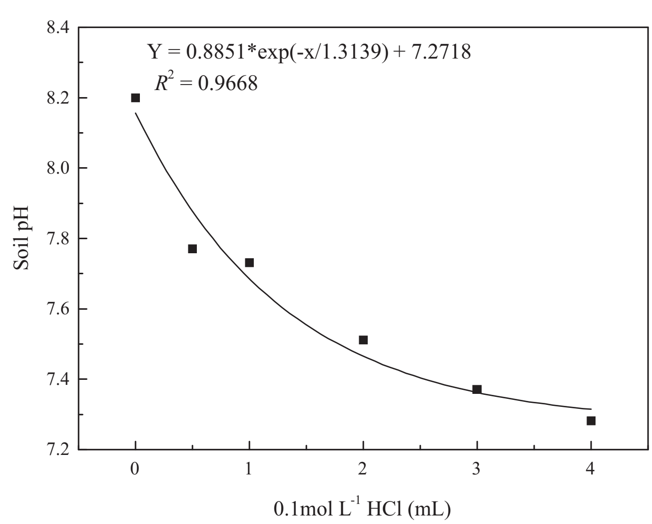

Fig. 9. Soil pH buffer capacity.

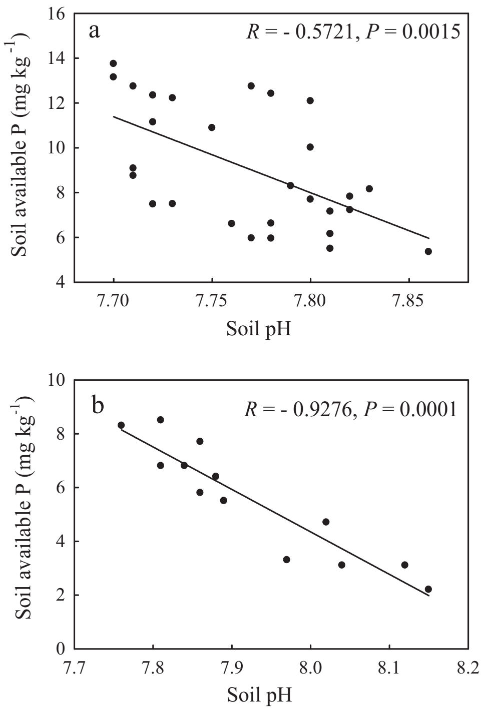

Fig. 10. Soil available P correlations with soil pH in the 0–20 cm soil layer in field experiment (a) and soil pH in the incubation experiment (b).

Gong et al., 2009). Soil LFOC content did not change in CK and T1 over two years, but significantly increased by 14.8% and 15.5% in T2 and T3, respectively. The increase in LFOC by K_2SO_4 fertilizers may be explained by increased productivity, which also returned more root residue and crop stubble to the soil (Ghosh et al., 2003; Fan et al., 2005).

The ratio of SOC and TN (C/N) is a reliable indicator of the ability of soil microorganisms to assimilate and mineralize N. Chen (1990) and Huang (2000) reported that a C/N ratio of 6–11 enhanced mineralization of soil organic N and significantly increased MBC, and soil organic matter also decomposed more quickly when the C/N ratio was <11. Therefore, increasing SOC and C/N ratio may be crucial for improving soil quality and reducing N loss. However, Wang et al. (2009) found that alfalfa grassland and alfalfa-crop rotation were all not sustainable because of decrease in soil total N in dry and fragile agro-ecosystem, even though a C/N ratio was over 11. In the present study, soil C/N ratio declined by 1.97% in CK in 2 years but increased in the K_2SO_4 treatments by 1.85–4.02%. In our study, in order to increase soil fertility, the aboveground biomass and roots of potato were left when potato tubers were harvested, and returned to the soil with manure in October 2007. So, the increase of C/N ratio in K_2SO_4 treatments probably is due to more crop straw in the soil than CK treatment. Our study suggests that application of K_2SO_4 fertilizer is important in improving the sustainability of cropping systems in dry agro-ecosystem.

5. Conclusions

Soil available K at tuber formation, and available K and available P at the starch accumulation stage correlated well with potato yield. Soil available P before sowing and at anthesis correlated well with spring wheat yield. The increase in soil AP by adding K_2SO_4 fertilizer was effective by decreasing soil pH. Applying K_2SO_4 fertilizer also increased LFOC and C/N ratio, which attributed to the improvement of P and K availability. The application of K_2SO_4 fertilizer not only increased soil AK content but also increased soil AP content, thereby significantly increasing yields of potato and spring wheat in calcareous and alkaline soils when the same dose of P fertilizer was applied.

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