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

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ABSTRACT

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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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:

$$\text{Soil K budget}\,(\text{kg K}_2\text{O ha}^{-1}) = \text{K input}\,(\text{fertilizer K} + \text{straw K}) - \text{K removal by crops}$$