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Crop yield and soil available potassium changes as affected by potassium rate in rice–wheat systems

Dianjun Lu[a], Changzhou Li[a], Eldad Sokolwski[b], Hillel Magen[b], Xiaoqin Chen[a], Huoyan Wang[a,*], Jianmin Zhou[a]

[a] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 21008, China
[b] International Potash Institute, CH-6300, Zug, Switzerland

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ABSTRACT

Large areas of the arable soils of the world are deficient in potassium (K) due to the low application rate of K fertilizer. However, current soil test methods cannot precisely determine soil available K changes. From 2009 to 2014, a field experiment was conducted in a rice–wheat cropping system in the Yangtze Plains using five K rates. The objectives were to determine the responses of wheat and rice yield to different K rates and to compare the soil available K changes extracted by three methods (ammonium acetate (NH_4OAc), boiling nitric acid (HNO_3), and sodium tetraphenylboron (NaTPB)). Long periods without application of K fertilizer markedly decreased wheat yield by 47% and rice yield by 15% compared with local farmers' K practices (FKP, 90 and 120 kg K_2O ha^{-1} for wheat and rice, respectively). The FKP achieved optimal yields for wheat and rice; however, only 160% of FKP achieved a positive K balance for the cropping system. Soil-extractable K consistently decreased with increasing cropping rotations where the K rate was below 160% FKP for the three extraction methods. The extractable and changed amounts for the NH_4OAC and HNO_3 methods were significantly lower than that for the NaTPB method. The soil K changes for NaTPB were closer to the theoretical soil available K changes (TAKC) derived from an apparent K balance. The NaTPB method could be useful for accurately determining changes in soil available K in cropping systems.

1. Introduction

In the past few decades, potassium (K) has become the "forgotten" nutrient with regard to environmental quality, drawing less research attention than nitrogen and phosphorus (Öborn et al., 2005; Römheld and Kirkby, 2010). A negative K balance is extremely challenging for food security at regional and even global scales (Lal, 2009; Cakmak, 2010), and presents a challenge in most developing and many developed countries. Recently, a study found that 75% of rice fields in south China and 66% of the soil in the Australian wheat belt suffered from K deficits (Römheld and Kirkby, 2010; Zhang et al., 2010; Wu et al., 2013). One of the biggest causes of crop yield stagnation and low nutrient efficiency in modern intensive agriculture can be attributed to K depletion in the soil (Regmi et al., 2002; Ladha et al., 2003).

In soil-crop systems, the magnitude of a crop's growth response to the application of K fertilizer varies with soil available K levels, the K input rate (Wu et al., 2013), the soil K-supplying capacity (Dobermann et al., 1996b; Ladha et al., 2003), the status of straw recycle use (Zhao et al., 2014), and the crop species (Cassman et al., 1989). Bijay-Singh et al. (2004) reported the yield of rice and wheat increased due to application of fertilizer potassium in soils testing less than 100 mg K kg^{-1} of NH_4OAc extractable K. Potassium input rates are generally much lower than K uptake rates for cereal crops (Regmi et al., 2002). According to a recent study on the Yangtze Plain by Wu et al. (2013), the typical farmers' K rate of 90–120 kg ha^{-1} is applied in the rice-wheat system. Importantly, the amount of K accumulated in straw can account for nearly 80% of total K uptake (Panaullah et al., 2006), and the quantity and quality of straw returned to the fields also significantly affects K balance for many cropping systems. Unfortunately, in developing countries, straw is typically removed from the field, as it is used for other purposes such as household cooking or animal feed (Regmi et al., 2002; Miao et al., 2010). Even in the North China Plain, where there is a higher degree of mechanization, the percentage of returned field straw only accounts for 50–60% of crop systems due to the incurred additional cost (Gao et al., 2009). Recently, the emergence of biofuels has made this situation much worse (Propheter and

Abbreviations: K, potassium; FKP, farmers' K practices; NH_4OAc, ammonium acetate; HNO_3, nitric acid; NaTPB, sodium tetraphenylboron; TAKC, theoretical soil available K changes

* Corresponding author.
E-mail address: hywang@issas.ac.cn (H. Wang).

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Staggenborg, 2010). These integrated suboptimal behaviors will progressively deplete soil K fertility and cause significant soil available K changes.

Potassium application rate and crop K uptake immediately influence the soil available K content (Regmi et al., 2002; Römheld and Kirkby, 2010). Hence, soil available K change is a closely related parameter that directly reflect K budget in soil-crop system. Long term negative soil K changes are non-sustainable for agricultural system (Wang et al., 2007). Accurately determining changes in soil available K is important when developing optimal K management strategies. In terms of methodology, soil tests for fertilization recommendations typically extract exchangeable K with ammonium acetate (NH_4OAc). Exchangeable K often exhibits a close correlation with crop K uptake, as Johnston and Krauss (1998) showed for winter wheat and field beans in a silty, clay loam soil in the United Kingdom. However, Römheld and Kirkby (2010) reported that the K-NH_4OAc method can often, but not always, offer a precise indicator of the available K status of the soil because certain rates of interlays of labile K are available for crop uptake. Dobermann et al. (1996a) reported that current recommendations for K addition using NH_4OAc method in most intensive irrigated rice domains are insufficient to replace K removal. The most common method for determining nonexchangeable K is based on hot nitric acid (HNO_3) extraction via the replacement of K^+ by H^+ (Øgaard and Krogstad, 2005; Li et al., 2015). Additionally, Wang et al. (2007) recently found an improved method for simulating the process of available K depletion in crop roots using sodium tetraphenylboron (NaTPB). This method accurately evaluates available K released in the soil from non-exchangeable K via the formation of K precipitation in a soil solution. However, few studies have been conducted to compare the three extraction methods in terms of a precise prediction of available K changes in rice–wheat cropping systems. Field K depletion experiments can help achieve this goal.

In this study, we used a field experiment with varying levels of K to study the K-deficient status of a wheat–rice cropping system in China. The experiment covered five complete wheat–rice cropping rotations, from the 2009 rice season to the 2014 wheat season. The specific objectives were: (1) to determine the wheat and rice yield and apparent K balance in relation to different K levels; (2) to monitor the dynamics of soil extractable-K content under the three methods; and (3) to determine the relationship between theoretical soil available K changes based on K fertilizer input and K uptake and actual soil extractable-K changes for the three methods.

2. Materials and methods

A field experiment was conducted from 2009 to 2015 with five complete rice–wheat cropping rotations in Wuhu, Anhui Province, China. The area has a subtropical humid monsoon climate. Average annual temperature and rainfall are 15.5 °C and 1000 mm, respectively; two-thirds of the rainfall occurs between June and September. Winter wheat and summer rice make up the primary cropping system in this region, with wheat season lasting from November to June, and summer rice lasting from June to October. The soil is loamy soil with organic matter content of 21 g kg^{-1}, total N of 0.9 g kg^{-1}, Olsen-P of 12 mg kg^{-1}, NH_4OAc-K of 83 mg kg^{-1}, pH of 5, bulk density of 1.2 g cm^{-3}, CEC of 10.8 cmol kg^{-1}, feldspars content of 175 g kg^{-1}, 2:1 K-bearing minerals of 225 g kg^{-1} (Dong et al., 2014), and quartz of 600 g kg^{-1}. Table 1 summarizes the monthly mean temperature and rainfall data from 2009 to 2014.

2.1. Experimental design

A field experiment was laid out in a randomized block design with four replications. There were five K-rate treatments: 0 K control, 70% FKP (farmer K practice), FKP, 130% FKP, and 160% FKP. FKP was 90 and 120 kg K_2O ha^{-1} for wheat and rice, respectively. Source of K fertilizer was potassium chloride. N (as urea) and P fertilizer rates (triple superphosphate) in each plot were 180 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} for wheat, respectively, and 200 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} for rice. Urea-N fertilizer was applied in three splits for winter wheat, before sowing, tillering (30 days after sowing), and stem elongation stages (120 days after sowing), and also three splits for summer rice, before transplanting, tillering (30 days after transplanting), and anthesis stages (50 days after transplanting). All of the P and K fertilizer was basal fertilizer that was broadcast and incorporated into the surface soil by rotary tillage prior to sowing. Wheat and rice cultivars were Yangmai 15 and Liangyou 5867, respectively, with seeding densities of 375 and 68 seeds m^{-2}, respectively. The sowing date of wheat for each of the 5 years was November 2, 4, 1, 3, 2, and harvest date was May 20, 18, 19, 22, and 21, respectively. The transplanting date of rice for each of the 5 years was June 16, 18, 15, 17, 18, and harvest date was October 5, 8, 6, 7, and 10, respectively. Prior to transplanting, rice seedlings need to be raised in a nursery for 30 days. Plot area was 20 m^2 (4 × 5 m^2). Row spacing for wheat and rice was 25 cm, and the plant spacing was 13 cm for rice. Irrigation and pest and weed control were based on locally recommended practices. At crop maturity, all of the aboveground portions of the plants in each plot were harvested manually and removed from the plot.

2.2. Sampling and laboratory procedures

For each season, mature wheat and rice plants from a 6-m^2 area were harvested and thrashed in each plot, and grains were dried to determine grain yield. Subsamples of grain and straw for wheat and rice were collected and analyzed for K concentration using flame photometer. Potassium uptake by rice and wheat was estimated from grain and straw yields and K concentration.

During each seasonal harvest, soil samples were collected as five cores of 20 cm depth per plot randomly taken from each plot using an auger (5 cm i.d.) and mixed. The fresh soil was air-dried for 7 days and passed through a 1-mm sieve. All of the soil samples from each harvest were collected and assessed for NH_4OAc-K, HNO_3-K, and NaTPB-K.

For NH_4OAc-K, 2.5-g soil samples were extracted with 1 mol L^{-1} NH_4OAc (soil: solution 1:10), shaken for 0.5 h, and filtered to determine K using a flame photometer. For hot HNO_3-K, 1-g soil samples were placed in 50-cm digestion tubes, and 10 mL of 1 mol L^{-1} HNO_3 was added. The samples were heated to boiling for 10 min then cooled, and the diluted water was then added to a constant volume of 50 mL to determine the K concentration by flame photometer. For the NaTPB-K procedure, 1-g soil samples were added to 6 mL of 0.2 mol L^{-1} NaTBP in 50-mL centrifuge tubes and shaken for 1 h at 200 rpm. After shaking, 25 mL of quenching solution (0.5 mol L^{-1} NH_4Cl, 0.14 mol L^{-1} $CuCl_2$) was added to each sample to stop the extraction of soil K. The tubes were heated in boiling water for 1 h to dissolve the KTPB precipitate then cooled, and 1 mL of 6 mol L^{-1} HCl was added to prevent the formation of a film of Cu at the surface of the solution. Finally, the soil solution was filtered to determine K concentration by flame photometer.

2.3. Data analysis

Apparent K balance was computed based on the difference between inputs of K fertilizer and K uptake (Zhang et al., 2010).

$$\text{Apparent K } balance = K_{fer} - crop\ K\ uptake \quad (1)$$

Where K_{fer} was K application rate. Arable soil available K changes were mainly due to the application rate of K fertilizer and K uptake by crops in this region (Zhang et al., 2010).

$$TAKC = \frac{(1)}{W_S} \quad (2)$$

Where TAKC was theoretical soil available K changes; W_s was the arable