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Yield, phosphorus use efficiency and balance response to substituting long-term chemical fertilizer use with organic manure in a wheat-maize system

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ABSTRACT

The over-application of mineral phosphorus (P) fertilizer has become common in the North China Plain, meanwhile, most of organic manure cannot be recycled into the soil. To make full use of organic manure and decrease the applied rate of mineral P fertilizer, a 20-year fertilization experiment in a continuous wheat-maize rotation was carried out to assess the long-term effects of substituting mineral fertilizer with organic manure on the yield, P use efficiency, and P balance. Treatments included organic compost (OM), half compost in combination with half mineral fertilizer NPK (1/2 OM), mineral fertilizer NPK (NPK), mineral fertilizer NK (NK), and an unfertilized control (CK). The results showed that the grain yield in the NK plots was less than 1.0 t ha-1 for both wheat and maize. The highest grain yield was obtained for the NPK treatment, which was slightly higher than the yields of the 1/2 OM treatment over all the years. The effects of the compost application were greater on the maize yield than on the wheat yield. Compost addition can significantly increase the P content and P uptake. The mean P fertilization use efficiencies were 53.7, 59.9 and 61.7% in the NPK, 1/2 OM and OM treatments for the wheat-maize system, respectively. In considering the P from the fertilizer, seed and irrigation as inputs and P uptake from crops and P storage in the 0–20 cm soil layer as outputs, no significant P loss was observed in all the treatments. The results indicated that an application of mineral fertilizer alone at a reasonable level could result in a high crop yield and a relatively high P use efficiency. Considering the improvements in the P use efficiency and the benefits of soil fertility, replacing less than half the chemical fertilizer with organic fertilizer might be a promising alternative in the North China Plain.

1. Introduction

Phosphorus (P) was a key limiting nutrient for crop production in the North China Plain where produces almost 60–80% of China's wheat and 35–40% of China's maize every year (Kong et al., 2014). The average available P in soil was below 10 mg kg^{-1} in most counties in the early 1980s (Cao and Zhou, 2008). To achieve higher crop yields and ensure food security, P fertilizer rates have been tripled over the past three decades (National Bureau of Statistics of China, 2010). The over-application of mineral P fertilizer has become common in the North China Plain (Miao et al., 2011), and less than 20% of fertilizer P can be recovered by crops during the growing season (Zhang et al., 2008; MacDonald et al., 2011). However, more than 50% of organic manure cannot be recycled into the soil in this region (Li and Jin, 2011), and the discarded portions can result in negative effects on the environment, such as water eutrophication (Li et al., 2015). Therefore, it is crucial to make full use of organic manure, decrease the applied rate of mineral P fertilizer and further optimize P fertilizer use efficiency in the North China Plain.

Organic manure such as compost has been considered an excellent soil amendment that can provide P and enhance P availability to improve crop yields (Smith and Siciliano, 2015; Xin et al., 2015). Manure applications led to high yields when manure was applied with mineral fertilizer for 15 years in China (Duan, 2011). Diacono and Montemurro (2010) also consistently found that organic amendments did not reduce crop yield, based on results from over twenty long-term experiments. However, in most cases, organic manure combined with mineral fertilizer gave significantly higher yields primarily because of the higher total nutrient input (Schröder, 2005; El Sheikha, 2016) Zhao et al. (2010) suggested that the contribution of manure should be estimated at the similar nutrient input. Blake et al. (2000) compared the P uptake and P balance in three long-term field experiments in Europe (UK, Germany and Poland), and they found that the most efficient use of P was in soils that were treated with organic manure at two sites and

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with mineral fertilizer at another site. They suggested that differences in the soil properties, climate, and applied P form influenced the effectiveness of P fertilization and P balance and that care is required when transferring conclusions from one type of environment to another (Blake et al., 2000). In the North China Plain, Tang et al. (2008) reported that the 15-year P recovery efficiency was approximately 43% when the soil was treated with NPK mineral fertilizers, but little information is available on the P use efficiency as affected by substituting long-term chemical fertilizer with organic manure in winter wheat and summer maize cropping systems.

Another concern regarding organic manure application is P leaching. Many studies have demonstrated that manure application can cause similar or even higher risks of P loss from soils compared to the use of mineral P fertilizers (Shepherd and Withers, 1999; Liu et al., 2012). Zhao et al. (2010) summarized the results of eight long-term experiments in China, and they showed that there was a risk of over-fertilization and water pollution with P if inorganic fertilizer applications were supplemented with manure. Therefore, we hypothesized that long-term chemical fertilizer application that was partially substituted with organic manure could enhance crop yield and improve P use efficiency.

On the basis of a 20-year fertilization experiment that included organic manure and mineral fertilizer treatments at the same nutrient input level in the North China Plain, the objectives of the present study were to assess the effects of different fertilization regimes on (i) grain yield trends, (ii) P use efficiency, (iii) P input-output balance and P loss.

2. Materials and methods

2.1. Site description and experimental design

This long-term experiment was established in 1989 at the Fengqiu State Key Agro-Ecological Experimental Station (35°00′N, 114°24′E), Fengqiu County, Henan Province, China. The climate type is a warm temperate continental monsoon-type. The 30-year mean annual temperature was 13.9 °C, with the lowest mean monthly value of −1.0 °C occurring in January, and the highest mean monthly value, 27.2 °C, was recorded in July. The mean precipitation was 596 mm. The soil (0–20 cm) is classified as an Aquic Inceptisol, and it contained 52% sand, 33% silt, and 15% clay. The field trial was set up in a well irrigation area with a winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) rotation system within 1 year, which is typical of the North China Plain. The experimental field was not fertilized in the 3 years before the start of the experiment to make the soil more homogeneous. The properties of the soil (0–60 cm) at the start of the field trial in September 1989 are shown in Table 1.

The experiment was performed in a randomized block design with four replicates. The treatments consisted of OM (compost), 1/2 OM (half compost in combination with half mineral fertilizer NPK), NPK (mineral fertilizer NPK), NK (mineral fertilizer NK), and CK (an unfertilized control). Each replicate plot area was 47.5 m^2, and the plots were separated by cement banks, which were 60 cm deep and extended 10 cm above the soil surface. The N, P, and K application rates for each treatment are described in Table 2. The compost was applied at an average of approximately 4500 kg ha^{-1} (oven dry weight) for the OM treatment and 2250 kg ha^{-1} for the 1/2 OM treatment each crop season. The compost was made up of a powdered mixture of wheat straw, oil rapeseed cake, and cottonseed cake at a ratio of 100:40:45, and it was composted for 2 months. The total N, total P, and total K contents of the compost were measured before fertilization, and the amount of organic manure applied during the OM and 1/2 OM treatments contained 150 kg N ha^{-1} and 75 kg N ha^{-1}, respectively. To match the same rate of NPK, chemical P and K fertilizers were supplied to the OM and 1/2 OM treatments. The P input from compost is relatively stable, and 30% and 70% of the annual P input comes from organic fertilizer for the 1/2 OM and OM treatments, respectively (Table 2). The mineral N, P, and K fertilizers used here were urea, calcium superphosphate, and potassium sulfate, respectively. All the organic compost and mineral P and K fertilizers were applied as a basal fertilizer for each crop. The N application ratio between the basal fertilizer and the supplemental fertilizer was 6:4 and 4:6 for maize and wheat, respectively. The amounts of seed and irrigation water were also recorded in this experiment.

Table 1
Soil basal characteristics in September 1989.

Characteristic		Soil depth 0–20 cm	20–40 cm	40–60 cm
pH		8.66	8.47	8.44
Soil organic matter	(g kg^{-1})	5.83	5.52	7.03
Total N	(g kg^{-1})	0.44	0.44	0.52
Total P	(g kg^{-1})	0.50	0.49	0.50
Total K	(g kg^{-1})	18.6	18.0	20.1
Inorganic N	(mg kg^{-1})	9.50	6.95	7.27
Olsen-P	(mg kg^{-1})	1.92	1.07	1.11
Exchangeable K	(mg kg^{-1})	78.7	82.4	116.5

Note: Each value was the mean of 28 samples.
CK: an unfertilized control; NK: mineral fertilizer NK; NPK: mineral fertilizer NPK; 1/2 OM: half compost in combination with half mineral fertilizer NPK; and OM: compost.

2.2. Sampling and analytical procedures

At maturity, all of the aboveground crop parts were harvested manually from each plot, and the grain yield was obtained. Approximately 10 point samples for wheat and 5 maize plants were collected from each plot. The straw and grain were separated manually and dried at 80 °C to a constant weight to obtain an oven-dry weight. Then, the ratio between the straw and grain was determined. The straw biomass produced in each plot was calculated by multiplying the oven-dried yield by the ratio between the straw and grain. For some plots that were treated with CK, NK and PK, the straw yield of summer maize was determined by weighing all the straw in a plot because the straw biomass cannot be calculated accurately by finding the ratio between straw and grain due to large variations. Oven-dried samples were finely ground to pass through a 0.25 mm sieve for total P content analysis. Crop grain and straw samples were digested with H_2SO_4-H_2O_2, and the P content in the digesting solution was determined using the molybdenum-blue colorimetric method. The total amounts of P uptake by grain and straw were calculated by multiplying the concentrations by the yields. Grain yield, straw yield, crop P content, and crop P uptake are reported on an oven-dried basis.

After maize harvest, mixed soil samples (0–20 cm, 20–40 cm, and 40–60 cm) from nine points in each plot were taken using a tube sampler that measured 3 cm in diameter and 100 cm in length. The soil samples were collected in 2009. The samples were digested with HF-$HClO_4$, and the total soil P was determined by molybdenum-blue colorimetry. Additionally, the available soil P was extracted with 0.5 mol L^{-1} $NaHCO_3$ and determined using the molybdenum blue method (Olsen et al., 1954). Four 100-cm^3 intact soil cores in soil top layer were collected from each treatment to measure the bulk density, and the bulk density at the 20–40 cm and 40–60 cm soil layers was measured by sampling intact soil cores from adjacent fields.

2.3. Calculation and statistical analysis

Based on the amount of P fertilizer applied and the crop P uptake over 20 years, the P fertilizer use efficiency (PUE) (Cassman et al., 1996; Tang et al., 2008) was calculated for each plot using the following equations:

$$PUE = (U_p - U_0) \times 100/F$$