Phosphorus fractions and sorption characteristics in a subtropical paddy soil as influenced by fertilizer sources

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A B S T R A C T

Continuous excessive application of phosphorus (P) fertilizer and/or manure can lead to P accumulation in soils and progressive saturation of soil P sorption capacities, thus resulting in increased P loss from soil to aquatic ecosystems. Yet the responses of P fractions and sorption characteristics to P fertilization in paddy soil, a special type of arable soil with long periods of waterlogged conditions, are not fully understood. The aim of this study was to determine the P fractions and its sorption indices in the plow layer of a typical subtropical paddy soil under different fertilization regimes. We selected 15 sites that varied in three fertilization regimes (i.e., chemical fertilizer [CF, n = 6], rice straw [RS, n = 3], and swine manure [SM, n = 6]) with equivalent P input (59 kg P ha^{-1} yr^{-1}) from a long-term field experiment station (initiated in 1981). A sequential fractionation scheme identified that NaOH-extractable inorganic P (NaOH-Pi) was the primary P form in the paddy soil followed by residual P (P_{res}). The paddy soil that received long-term SM application presented significantly ($p < 0.05$) higher contents of KCl-extractable P (P_{KCl}), NaOH-Pi, and total P than the soil that received only CF. In addition, SM significantly increased the proportion of NaOH-Pi, but reduced that of P_{res} ($p < 0.05$). In contrast, paddy soil treated with RS incorporation showed a similar allocation of P fractions as in CF treatment. Compared with CF, SM and RS increased the Langmuir P sorption maximum (S_{max}) of the paddy soil by 30 and 10%, respectively ($p < 0.05$). Organic amendments (i.e., SM and RS) significantly increased the contents of amorphous Fe and Al (i.e., oxalate-extractable Fe and Al, $p < 0.05$), and this appeared to contribute mostly to the increased P sorption capacity and variations in P fractions in the paddy soils. Thus, soil P buildup and related environmental assessments need to consider the increment of amorphous Fe and Al in paddy soil due to organic amendments.

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1. Introduction

Phosphorus (P) is one of the essential nutrients required for the growth of plants; however, continued long-term application of P fertilizers and other P sources, such as manures, can lead to P accumulation in soil, which is becoming a concern in certain geographical regions (Daniel et al., 1998). Paddy soil is a special type of arable soil, which undergoes long periods of waterlogged conditions during the rice (*Oryza sativa*) growing period. The waterlogged conditions usually last for more than six months in the double-cropping rice system (e.g., in southern China), and result in a low soil redox potential, which can in turn affect P transformation and sorption (Kögel-Knabner et al., 2010). As major cultivated soils in China, the total area of paddy soils is 46 Mha, mostly in the southern part of China in the Yangtze and Huaihe River Valleys (or further south) where ample supplies of water are available (Liu et al., 2006). Long-term fertilizer and/or manure application that often exceeds seasonal plant nutrient uptake has resulted in significant

P accumulation and loss in many parts of the paddy fields, such as the Taihu Lake region (Zhang et al., 2003; Shan et al., 2005).

Knowledge of P fraction dynamics in paddy soils is important to assess P mobility in order to reduce the danger of P loss to nearby water sources. In soils, P is present in several forms or pools, and different forms are often designated as either inorganic or organic, and commonly further distinguished as P in soil solution, P sorbed to surfaces of clay or Fe and Al oxides, P in phosphate minerals, and P in organic substances and living organisms (Hedley et al., 1982; Reddy et al., 1998). These descriptions imply differences among P forms with respect to reactivity in the environment. Phosphorus fertilization can result in changes in soil P fractions and the rates of total P accumulation in surface paddy soils, which provide valuable information on the impacts of P additions on soil P transformations (Zhang et al., 2006; Lan et al., 2012). Therefore, it is critical to investigate the status of P fractions in paddy soils in response to long-term P fertilization to better understand P behavior in paddy soils.

In risk assessment systems for P losses, soil P sorption characteristics are important factors controlling P release from soil to water. Determination of soil P isotherms provides a useful means for studying soil P sorption dynamics (Nair et al., 1984). For example, soil P sorption

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capacity, a measure of the maximum amount of P that a soil can retain, is generally calculated using the Langmuir sorption maximum (S_{max}) derived from soil P sorption isotherms. Generally, amorphous Fe and Al minerals contribute to P sorption of the paddy soils in subtropical China (Yan et al., 2013; Yan et al., 2015). Moreover, P fertilizer sources can influence P sorption capacity of paddy soil via direct or indirect effects (Yan et al., 2013). This information highlights how knowledge on the P fraction and sorption characteristics of paddy soils is essential to advance our understanding of P transformation and transport in the agroecosystem.

Manure application based on crop nitrogen needs will cause significant P accumulation in soil (Daniel et al., 1998). Moreover, the accumulated P in soil due to manure application can be mobilized, thereby favoring P leaching and subsurface transport from soil, as organic anions released during the decomposition of organic residues can reduce the sorption of P by competing for binding sites on soil colloids (Jiao et al., 2007; Yan et al., 2013). In contrast, application of chemical fertilizer increases soil extractable P but has a smaller impact than manure on P sorption indices and leaching (Pizzeghello et al., 2016). Currently, the incorporation of organic amendments is highly advocated in China, as improper disposal of these materials is both a serious waste of nutrient resources and is contributing to environmental pollution. It is urgent to comprehensively evaluate the P accumulation forms and sorption characteristics in paddy soils in response to different fertilizer applications, as such information is not available yet. The aim of this study was to determine the P fractions and sorption indices in a typical subtropical paddy soil under different fertilization regimes.

2. Materials and methods

2.1. Study site and experimental design

The paddy soils (0–15 cm depth) with different fertilization regimes were collected from the Experiment Station (initiated in 1981) of Jiangxi Agricultural University (28°45′50″ N, 115°49′45″ E), Jiangxi, China. This station is located in the Poyang Lake region, the largest lake in middle reaches of the Yangtze River. In this station, an area of about 11 ha is implemented long-term field trial with annual rice-rice-winter fallow rotation under different fertilization regimes and management periods. The climate of the study area is humid subtropical. The average annual precipitation is 1624 mm and annual mean temperature is 17.0 °C with the lowest mean monthly temperature occurring in January (2.7 °C) and the highest in July (33.4 °C). The soil is classified as Hydragric Anthrosol (IUSS Working Group WRB, 2014) developed from the Quaternary red clay as a result of long-term rice cultivation and has a silt-loam texture.

We selected 15 study sites at the experimental station that have experienced rice cultivation with three fertilization regimes from 1981: (i) CF, chemical fertilizer; (ii) RS, rice straw; and (iii) SM, swine manure. On average, the SM (based on dry weight) contained 88 g C, 3.1 g N, 3.9 g P, and 1.1 g K kg^{-1}; the RS contained 342.1 g C, 5.7 g N, 0.56 g P,

and 1.8 g K kg^{-1}. The basal fertilizer applications for both early and late rice were made to supply 50, 100 and 100% of the total N, P and K, respectively. The remainder of the N was topdressed during the panicle forming stage. The SM and RS were only used as basal fertilizer. All sites were designed to receive equivalent P input at a rate of 29.5 kg P ha^{-1} for both early and late rice. Thus, for RS and SM treatments, the amounts of chemical P applied depended on the P input from the RS or SM. In some years, P input in SM treatment may be a little higher than the other two treatments (depending on P concentration of swine manure slurry) because the basal fertilization of SM at a rate based on N supply may provide a greater P input than proposed. Generally, additional chemical P was needed in RS treatment, as the P input via RS was not sufficient to obtain 29.5 kg P ha^{-1}. Chemical P applied for all the study sites was fused calcium-magnesium phosphate (FMP). Crop cultivation and field management were performed according to local farming practices. Generally, the early rice-growing season in the study area lasts from April to July, while the late rice-growing season lasts from the end of July to late October. Chinese milk vetch (A. sinicus L.), a green manure for paddy fields, grows in all the selected study sites during the winter fallow season, and is incorporated before early rice transplanting in the following year.

2.2. Soil sampling and analyses of basic soil properties

Soil samples that consisted of five separate cores (5-cm diameter) were collected from the plow layer (0–15 cm depth) from each site after the harvest of late rice in October 2014. The samples were air-dried and ground to pass a 2-mm sieve prior to analyses.

Soil pH was measured in a 1:2.5 (soil/water ratio, w/v) mixture using a glass electrode, and soil organic matter (SOM) was determined using the potassium dichromate sulfuric acid oxidation method (Nelson and Sommers, 1982) by a conversion factor of 1.724. Soil texture was determined using the pipette method (Kroetsch and Wang, 2006). Olsen-P was obtained by shaking 2.5 g of soil with 50 mL of 0.5 M NaHCO$_3$ (pH 8.5) for 30 min (Olsen and Sommers, 1982). Phosphorus collected with an anion-exchange resin (Resin-P) was also measured following the method of Sharpley (2000). After filtration, the P concentration in the extracts mentioned above was determined colorimetrically using the ascorbic acid-molybdenum blue method (Murphy and Riley, 1962). Ammonium oxalate-extractable P, Al, and Fe (P_{ox}, Al_{ox}, and Fe_{ox}, respectively) were determined by shaking 1:40 (w/v) soil/ammonium oxalate extracting solution (pH 3.0) for 2 h in the dark (Schoumans, 2000). Mehlich-3 (M3) extractable Ca (Ca_{M3}) was extracted by shaking 1:10 (w/v) soil/M3 extracting solution (containing 0.2 M CH$_3$COOH, 0.25 M NH$_4$NO$_3$, 0.015 M NH$_4$F, 0.013 M HNO$_3$, and 0.001 M EDTA) for 5 min (Mehlich, 1984). Then the sample solutions treated with ammonium oxalate and M3 extraction solutions were centrifuged at 5000 rpm for 15 min and the supernatant was analyzed for P, Al, Fe, and Ca using an Optima 8000 inductively coupled plasma optical emission spectrometer (PerkinElmer, USA).

Table 1
Soil characteristics for the paddy soil at 0–15 cm depth under different fertilization treatments.

Treatments	pH (H$_2$O)	Al_{ox}	Fe_{ox}	Ca_{M3}	SOM	Clay
		------------------mg kg^{-1}------------------			----------------g kg^{-1}----------------	
CF (n = 6)	5.19 (0.19)	1134 (98)b	4340 (251)b	641 (101)	33.35 (3.06)	133 (57.0)
RS (n = 3)	4.99 (0.05)	1348 (108)a	5093 (543)ab	560 (50)	37.02 (0.90)	153 (1.7)
SM (n = 6)	4.97 (0.10)	1365 (102)a	5853 (760)a	604 (73)	35.75 (3.11)	96 (49.4)
p value	NS	**	**	NS	NS	NS

CF, chemical fertilizer; RS, rice straw; SM, swine manure.
Al_{ox}, ammonium oxalate-extractable Al; Fe_{ox}, ammonium oxalate-extractable Fe; Ca_{M3}, Mehlich 3-extractable Ca; SOM, soil organic matter.
Means with different letters within a column are significantly different at $p < 0.05$, standard deviation is given in parentheses.
NS not significant.
 ** $p < 0.01$.