Agriculture, Ecosystems and Environment 175 (2013) 47–53

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Organic amendments affect phosphorus sorption characteristics in a paddy soil

Xiao Yan[a,b], Dejian Wang[a,*], Hailin Zhang[c], Gang Zhang[a], Zongqiang Wei[d]

[a] *Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, United States*
[d] *School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China*

ARTICLE INFO

Article history:
Received 8 November 2012
Received in revised form 9 May 2013
Accepted 13 May 2013

Keywords:
Phosphorus sorption capacity
Path analysis
Manure amendments
Straw incorporation
Paddy soil

ABSTRACT

Continuous excessive application of phosphorus (P) fertilizer and/or manure in areas with intensive agriculture can lead to an accumulation of P in soils and progressive saturation of soil sorption capacities, thus resulting in increased P loss from soil to aquatic ecosystem. An 8-year field experiment with four fertilization patterns (chemical fertilizer only, fertilizer plus straw, fertilizer plus 7.5 t ha^{-1} manure, and fertilizer plus 15 t ha^{-1} manure) was conducted in the Taihu Lake region of eastern China to investigate the effects of incorporation of straw and manure on P accumulation and the changes of P sorption capacity of a paddy soil. Degrees of P saturation, contents of Olsen-P and total P in manure treated soils were significantly higher than those treated with fertilizers alone or with straw retention ($P < 0.05$). Phosphorus accumulation in studied soil was less labile in straw treatment than in manure treatments, but it remained extractable by ammonium oxalate. The Langmuir P sorption maximum (S_{max}) ranged from 24.7 mmol kg^{-1} to 43.2 mmol kg^{-1}, and was highly correlated with oxalate extractable Al (Al_{ox}, $r = 0.85$) and Fe (Fe_{ox}, $r = 0.79$). Moreover, path analysis showed that the direct effect of Al_{ox} on S_{max} was significant ($P < 0.05$) while that of Fe_{ox} on S_{max} was insignificant; and that Al_{ox} could also exert influence on S_{max} via its indirect effect through Fe_{ox} and organic matter. Thus, Al was the most important soil property associated with S_{max} in the paddy soil based on path analysis results.

1. Introduction

Phosphorus (P) accumulation caused by the continual application of manure that often based on crop nitrogen needs has become a concern in certain geographical regions (Daniel et al., 1998; Gburek et al., 2000). The Taihu Lake region of the Yangtse River Delta is an area with intensive agricultural production in China, where animal manure application and rice & wheat straw incorporation are widely practiced as effective methods to improve soil fertility and productivity. Long-term fertilizer and/or manure application that often exceeds seasonal plant nutrient uptake has resulted in a significant P accumulation and loss in this area, becoming a potential source of eutrophication in the Taihu Lake (Zhang et al., 2003a,b).

Phosphorus sorption capacity, a measure of the maximum amount of P that a soil can retain, and the degree of P saturation (DPS) can provide valuable information for proper P management in order to minimize the transport of P from soil to water. Degree of P saturation, defined as the amount of P adsorbed divided by the P sorption capacity of the soil, is viewed as a good environmental indicator of soil P loss potential to runoff and leachate (Beauchemin and Simard, 1999; Kleinman and Sharpley, 2002). The P Langmuir adsorption maximum (S_{max}) is generally used to determine soil P sorption capacity (Kuo, 1988). As P sorption isotherms are labor intensive, Al and Fe extracted by acid ammonium oxalate (Al_{ox} and Fe_{ox}, respectively) have been widely used to estimate the S_{max} of acidic and neutral soils (Van der Zee and Van Riemsdijk, 1988; Maguire et al., 2001).

Phosphorus sorption varies among soil types and depends on one or more soil properties. Soil properties that have been correlated with S_{max} are extractable Al and Fe, soil pH, and organic matter (OM). These soil properties are often inter-related, which makes it difficult to determine how each component contributes to P adsorption in soils. Therefore, simple correlation analysis alone may not be sufficient for establishing a causal relationship between S_{max} and soil properties. As a means of partitioning correlations into direct and indirect effects and distinguishing between correlation and causation, path analysis has been recently used in P sorption studies (e.g., Zhang et al., 2005; Ige et al., 2007; Kang et al., 2009). Zhang et al. (2005) showed that clay, organic C, Al_{ox}, and Fe_{ox} were significantly correlated with S_{max} in a simple correlation analysis,

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[*] Corresponding author. Tel.: +86 25 86881253; fax: +86 25 86881000.
E-mail address: djwang@issas.ac.cn (D. Wang).

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http://dx.doi.org/10.1016/j.agee.2013.05.009

but only Al_{ox} and Fe_{ox} had significant direct effects on S_{max}. Kang et al. (2009) investigated soils from the Coastal Plain region of North Carolina, U.S., and found that clay, Al_{ox}, and Fe_{ox} had significant direct effects on S_{max}, and the S_{max} was highly influenced by the indirect effect of Al_{ox} and Fe_{ox} through OM content.

Continuous fertilization and straw incorporation can result in changes of soil properties including OM, pH, and some biological properties (Eghball, 2002; Kanchikerimath and Singh, 2001; Zhu et al., 2010), which might in turn affect P sorption capacity of soils. However, the effects of the changed soil properties due to fertilization on P sorption capacity of the paddy soil in Taihu Lake region are still not well studied. Since these soil properties reported could exert influences together on P sorption capacity of the soil, we employed path analysis to identify their direct and indirect effects on P sorption. The objectives of this study were (i) to investigate the effects of organic amendments on P accumulation and soil properties in the paddy soil, and (ii) to determine the crucial soil properties associated with S_{max} in the paddy soil.

2. Materials and methods

2.1. Experimental site and design

The experiment started in 2003 at Changshu Agroecological Experiment Station of the Chinese Academy of Sciences (31°32′45″ N, 120°41′57″ E), Jiangsu, China. This site is located in Taihu Lake region, where paddy rice and upland winter wheat are planted in rotation. Under the northern subtropical humid marine monsoon climate, the location had an average annual precipitation of 1200 mm and an annual mean temperature of 16.0 °C in the past 10 years. The soil therein is Hydragric Anthrosols (IUSS Working Group WRB, 2007) developed from the lacustrine deposit. Under long-term wet cultivation of rice, there was an anthraquic horizon with an underlying hydragric horizon in the soil profile (Gong et al., 1999). Soil samples from the first 15 cm of the Ap1 horizon had a silt loam texture (clay 242 g kg^{-1}, silt 680 g kg^{-1}, and sand 78 g kg^{-1}) and initial pH (H_2O) 7.4, OM 40 g kg^{-1}, total nitrogen (N) 2.13 g kg^{-1}, total P 0.77 g kg^{-1}, Olsen-P 13.1 mg kg^{-1}, and ammonium acetate extractable potassium (K) 89.4 mg kg^{-1}.

There were four fertilization treatments in the experiment: (1) control (CK, chemical fertilizers only), (2) rice/wheat straw retained in addition to chemical fertilizers applied in CK (S_{ret}), (3) 7.5 t ha^{-1} y^{-1} wet pig manure in addition to chemical fertilizers applied in CK (M7.5), and (4) 15 t ha^{-1} y^{-1} wet pig manure in addition to chemical fertilizers applied in CK (M15). The plots were completely randomized in the experimental field, and each treatment (8 m × 8 m in size) was replicated three times. The cropping system in the experiment was rice and winter wheat rotation. For all treatments, chemical fertilizers were applied with the rates of N, P, and K of 180–15–90 kg ha^{-1} for rice and 150–30–60 kg ha^{-1} for winter wheat. The basal fertilizer applications for both rice and winter wheat were made to supply 40%, 100% and 50% of the total N, P and K, respectively. And the remainder of N and K was top dressed during panicle forming stage. The pig manure was only used as basal in rice season and all harvested crop straw was chopped and incorporated in the S_{ret} treatment while removed from the field for the other three treatments. On average, the pig manure (based on dry weight) contained 400 g C, 9.3 g N, 9.6 g P and 8.8 g K kg^{-1}; the wheat straw contained 441 g C, 4.0 g N, 0.4 g P and 51 g K kg^{-1}; and the rice straw contained 400 g C, 7.2 g N, 1.6 g P and 36 g K kg^{-1}. Crop cultivation and field management were performed according to local farming practice. Generally, the wheat growing season lasts from November to May of next year, whereas the rice growing season lasts from early June to middle October, during which soils are typically submerged in water. In the late tillering stage of rice, however, a short drying period lasting from five to seven days was allowed to control the disabled tillering and to provide favorable conditions for rice growth. Then, the paddy field was resubmerged. The typical Eh value of the rooting zone during rice growing season ranged from −200 mV to −30 mV, while pH value in the floodwater varied approximately between 6 and 9 (Wang et al., 2012). The pe + pH value ranged approximately 4.5–6.5 at seedling stage, 5.0–6.0 at tillering stage, and 6.0–7.5 at panicle stage of the rice growing season depending on fertilization patterns (calculated based on Wang et al., 2012).

2.2. Soil sampling and analyses

Soil samples consisted of five separate cores (5 cm diameter) were collected from 0 to 15 cm mostly in the Ap1/Ap2/Bhg/Cg horizon (represented plough/plough pan/hydragric/gleyic horizons) from each plot after the harvest of rice in October 2011. 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) mixture using a glass electrode and soil OM was determined using the dichromate oxidation method (Walkley and Black, 1934). Total P was determined by perchloric acid digestion (Kuo, 1996). For the digestion, one gram of soil were treated with concentrated H_2SO_4 (8.00 mL) and 10 drops of $HClO_4$, and digested at 200 °C until almost white sand are obtained (Pizzeghello et al., 2011). After cooling, the mixture was diluted with distilled water to 100 mL. Olsen-P was obtained by shaking 2.5 g of soil with 50 mL of 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) for 30 min (modified from Olsen and Sommers, 1982). Water extractable P was determined in a soil/water ratio of 1:10 (w/v) at 23 °C for 1 h (Börling et al., 2004). After filtration, the P concentration in the extracts was determined colorimetrically by the method of Murphy and Riley (1962). Ammonium oxalate extractable P, Al, and Fe were determined by shaking 1:40 soil/ammonium oxalate extracting solution (pH 3.0) for 2 h, centrifuging at 5000 r min^{-1} for 10 min (Schoumans, 2000). After filtration, the supernatant was analyzed for P, Al, and Fe by an Optima 8000 ICP-OES spectrometer (PerkinElmer, USA).

2.3. Degree of P saturation

The DPS was obtained for all the samples using the relationship:

$$\mathrm{DPS} = \frac{\text{Extractable P}}{\text{P sorption capacity}} \times 100 \qquad (1)$$

where the extractable P was oxalate extractable P expressed in mmol kg^{-1}, and P sorption capacity of the soil was the sum of oxalate extractable Fe and Al which also expressed in mmol kg^{-1}.

2.4. Phosphorus adsorption isotherm

Phosphorus adsorption isotherms were determined according to the method of Graetz and Nair (2000). Two and half gram of soil sample was equilibrated in 50 mL centrifuge tubes with 25 mL of 0.01 mol L^{-1} $CaCl_2$ solution containing 0, 3, 5, 7, 9, 12, 18, 24, 30, 40 and 50 mg P L^{-1}. Three drops of chloroform were added to each tube to inhibit microbial activity. Then the tubes were shaken for 24 h on an end-over-end shaker at 150 oscillations per min, and the supernatants were filtered through 0.45 μm membrane filters. The P in solution was then analyzed colorimetrically using the molybdate blue method (Murphy and Riley, 1962). Duplicate analyses were conducted on all samples.

The total amount of P sorbed by the soil (S) was calculated by

$$S = S_0 + S' \qquad (2)$$