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Predictive Model for Phosphorus Accumulation in Paddy Soils with Long-Term Inorganic Fertilization

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Prediction of accumulation of available phosphorus (P) in paddy soils is crucial for the best management of P fertilizers. Based on the long-term double-rice rotation systems, a predictive model for accumulation rates of Olsen P in paddy soils with chemical fertilization was developed. In paddy soils with more than 40 kg applied P ha^{-1}, the accumulation of Olsen P in the soils could occur. With the target rice yield of 10 tons ha^{-1} per year, the increases in Olsen P in paddy soils were estimated by the model as 0.7, 2.2, and 3.8 mg kg^{-1} when P application rates are 40, 60, and 80 kg P ha^{-1}, respectively. The accumulation rate of Olsen P was relatively high in paddy soils. The predictive model can be used to predict accurately the concentrations of Olsen P in paddy soils based on initial Olsen P, P application rate, and crop yield and to optimize P fertilization for rice crop production and environmental protection.

Keywords Accumulation, long-term, paddy soil, phosphorus, rice

Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops in China, with 18.7% (29.2 × 10^6 ha) of harvested area and 28.6% (183 × 10^6 ha) of rice production in the world in 2006 (FAO 2009). Furthermore, the total consumption of phosphorus (P) fertilizers in China increased 4.77 times from 1980 (1.19 × 10^6 tons P) to 2006 (5.68 × 10^6 tons P) and reached about 31% of P consumption of the world (Lin and Li 2004; FAO 2009). Because of high fixing capacity of soils, the excessive use of P fertilizers has resulted in the accumulation of P in many soils (Barberis et al. 1995; Djodjic, Bergström, and Grant 2005) and possibly in the risk of freshwater eutrophication through P runoff (Sharpley et al. 1996; Daniel, Sharpley, and Lemunnyon 1998; Sims and Kleinman 2005). Of all farming practices and environmental protection, predicting and controlling P accumulation in soils

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becomes an important approach for rational fertilization to improve crop yield and secure water bodies (Zhang, Burghardt, and Yang 2005; Wang et al. 2008).

There are some long-term fertilizer field trials to monitor long-term changes in crop yield, soil fertility, and fertilizer–yield response for rice cropping systems (Tan et al. 1995; Dobermann et al. 1996; Dawe et al. 2000; Haefele et al. 2003; Shen et al. 2004). It has been shown that the recovery of P fertilizer (proportion of P uptake by crops to total P input by fertilization) by rice in soils with fertilization of nitrogen (N), P, and potassium (K) varied from 46% to 130% from in southeastern Asia and China (Dobermann et al. 1996; Shen et al. 2004; Zhao et al. 2009). However, the quantitative relationship between soil available P pool, P input, and P uptake by crops must be identified because the accumulation of available P in paddy soils is a big concern for nonpoint pollution, as well as for rational P management for agriculture. Ma et al. (2009) and Tang et al. (2008) studied the accumulation of P in soils using five long-term wheat–maize rotation experiments geographically and climatically differing in China and developed a model for the accumulation of Olsen P [soil P extracted by 0.5 mol L^{-1} sodium bicarbonate ($NaHCO_3$) at pH 8.5] in soils described by application rates of P chemical fertilizers, crop yield, and soil pH. It is unclear whether the behavior of P accumulation in rice cropping systems in paddy soils is different from that in wheat–maize cropping systems. Therefore, the objectives of the present study were (i) to quantify the P accumulation rates in response to P application rates and rice crop uptake in paddy soils, (ii) to develop a predictive model for P accumulation in paddy soils with long-term inorganic fertilization, and (iii) to validate the model independently using the data published in the literature.

Materials and Methods

Soil Properties and Experimental Design

Three long-term experiments in paddy soils with double-rice monoculture rotations in China were used in the present study. One was located in Qiyang of Hunan Province (S1-QY), which was to develop the predictive model for P accumulation in paddy soils with long-term inorganic fertilization. Others were located in Nanchang of Jiangxi Province (S2-NC) and in Wangcheng of Hunan province (S3-WC) as validation sites. All three experiments were set in 1981 at the main area of paddy soils to investigate the application of fertilizers on crop yield and soil fertility. Their exact location, soil properties, and climate characteristics are shown in Table 1.

The experimental treatments were CK (unfertilized), NP (N and P fertilizers), and/or NPK (NP plus K chemical fertilizers). Because P concentration in manures was not recorded in experimental periods, only the treatments involving chemical P fertilizers were used in the present study. The application rates of N, P, and K fertilizers, replication, and plot size in each site are shown in Table 2. Urea, superphosphate, and potassium chloride were the sources of fertilizers. The fertilization treatments arranged in a randomized complete block design. There was a concrete wall between each plot. Because the treatments differed with experimental sites, the exact treatments in different sites used in the present study can be found in Tables 3 and 4.

A double-rice monoculture rotation was used in these experiments. Seeding and transplanting were performed on about 1 April and 1 May for early rice and 27 June and 30 July for late rice each year, respectively. During the growing season, hand weeding

Table 1
Experimental location, soil properties, and climate characteristics of different experimental sites

Experimental site	S1-QY	S2-NC	S3-WC
Location (province-site)	Hunan-Qiyang	Jiangxi-Nanchang	Hunan-Wangcheng
Period (year)	1981–2002	1981–2000	1981–2004
Latitude	26° 45′ N	30° 29′ N	27° 58′ N
Longitude	111° 52′ E	114° 18′ E	122° 36′ E
Altitude (m)	120	12	50
Annual mean precipitation (mm)	1407	1300	1350
MAT (°C)[a]	18.1	16.8	17.5
Frost-free period (day)	300	239	275
Sunshine hours	1458	2079	1700
Soil classification in China	Paddy soil	Paddy soil	Paddy soil
Soil pH (water/soil 1/1)	6.2[b]	6.3	6.6
Organic matter (g kg^{-1})	19.8	27.4	35.5
Total N (g N kg^{-1})	1.48	1.80	2.05
Total P (g P kg^{-1})	0.48	1.00	0.66
Total K (g K kg^{-1})	14.2	30.2	14.1
Alkaline hydrolysable N (mg N kg^{-1})	158	150.4	151
Olsen P (mg P kg^{-1})	8.0	20.8	10.2
NH_4OAc-K (mg K kg^{-1})	14.2	98.5	62.3

[a]Mean annual temperature.
[b]pH in control soil in 2000.

was done to control weeds. Fungicides and insecticides were applied when needed. Rice was maintained according to the best management practice for the local area. Rice was harvested on about 27 July for early rice and 20 October for late rice each year, respectively.

Soil and Plant Sampling and Analysis

The rice yields of grains and straw were recorded, and the samples of grains and straw were collected after every harvest time. Soil samples were collected annually in the plow layer (0–20 cm) at five randomly selected locations for each plot after late rice harvest. The fresh soil samples were mixed completely, air dried, sieved through a 2.0-mm sieve, and stored for nutrient analysis. Soil samples were analyzed for Olsen P using 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) and a molybdate–antimony–ascorbic acid colorimetric method, and for soil total P using a sulfuric acid– perchloric acid (H_2SO_4-$HClO_4$) digestion and molybdate–antimony–ascorbic acid colorimetric method following Page, Millar, and Keeney (1982). To determine the total P content, the plant samples were digested with a mixture of nitric–perchloric–sulfuric acids ($HNO_3/HClO_4/H_2SO_4$ at 3:1:1 ratio), and the concentrations in the digesting solution were measured using a molybdate-blue colorimetric method (Page, Millar, and Keeney 1982). The values of soil pH were measured using soil extracts at 1:1 ratio of deionized water to soil.

Table 2
Crop rotation, fertilizer application rates when N or P or K are applied, and experimental design

Experimental site	S1-QY		S2-NC		S3-WC	
Location (province-site)	Hunan-Qiyang		Jiangxi-Nanchang		Hunan-Wangcheng	
Crop rotation cycle	1 year		1 year		1 year	
Crop rotation	Early rice	Late rice	Early rice	Late rice	Early rice	Late rice
Added N (kg/ha/year)	72.5	72.5	150	180	150	180
Added P (kg/ha/year)	24.6	24.6	26.2	26.2	39–19.7[a]	39–19.7[a]
Added K (kg/ha/year)	28	28	129.4	129.4	99	99
Plot area (m^2)	27		33		66.7	
Replications	3		3		3	

[a]The application rates of P were 39 kg P/ha/year for early rice and late rice separately from 1981 to 1990 and 19.7 kg P/ha/year for early rice and late rice separately in 1992, 1995–1997, and 2000–2004 in the S3-WC experimental site.

Table 3
Concentrations of measured soil Olsen P (Olsen P_m) and soil Olsen P (Olsen P_p) predicted by Eq. (4), soil pH, and rice grain yields (averaged since 1981) for NPK treatment in different years in the long-term experiment with a double-rice monoculture rotation (S1-QY)

Year	Soil pH	Rice grain yield (ton/ha)		Olsen P_m (mg/kg)	Olsen P_p (mg/kg)	$Rate_{ac}$[a] (mg/kg/year)
		Early rice	Late rice			
1986	5.06	5.93	4.82	13.4	14.2	1.24
1988	4.77	6.43	4.60	15.4	16.2	1.17
1990	4.99	6.25	4.49	19.6	19.2	1.24
1994	5.10	5.93	4.42	23.8	25.3	1.33
1996	5.64	5.67	4.26	28.0	29.4	1.43
1998	6.08	5.54	4.39	32.0	32.3	1.43
2000	6.14	5.38	4.29	33.2	36.3	1.49
2002	6.52	5.36	4.21	33.3	39.7	1.51

[a]$Rate_{ac}$ is accumulation rate of Olsen P in soils.

Modeling and Validation

A predictive model for wheat–maize rotation systems was developed by Ma et al. (2009) using P fertilization rate, crop grain yield, and time (year) from long-term experiments at five sites in China that geographically and climatically differ. The change of Olsen P in soils with P fertilization was described by the following equations:

Table 4

Measured Olsen P (Olsen P_m) in literature and the Olsen P (Olsen P_p) predicted by Eq. (4) in long-term experiments in Nanchang, Jiangxi (S2-NC) from 1983 to 2003 and Wangcheng, Hunan (S3-WC) from 1981 to 2004 (Xu et al. 2006) in China

Site	Treatment[a]	Duration (year)	Added P (kg/ha/year)	Soil pH	Yield (ton/ha)	Olsen P_m (mg/kg)	Olsen P_p (mg/kg)	$Rate_{ac}$[b] (mg/kg/year)
S2-NC	PK	10	52.4	6.4	7.11	39.8	44.1	2.33
S2-NC	PK	20	52.4	5.4	7.91	61.0	63.7	2.15
S2-NC	NP	10	52.4	6.8	9.20	41.0	39.2	1.84
S2-NC	NP	20	52.4	5.8	9.25	61.8	57.5	1.83
S2-NC	NPK	10	52.4	6.2	11.4	39.8	34.2	1.34
S2-NC	NPK	20	52.4	5.7	11.3	51.6	47.8	1.35
S3-WC	NP	10	78.6	5.8	9.64	50.2	47.6	3.74
S3-WC	NP	19	39.3	5.4	9.42	26.2	40.4	1.59
S3-WC	NP	24	39.3	5.1	9.46	25.3	44.2	1.42
S3-WC	NPK	10	78.6	5.6	11.5	41.5	43.2	3.30
S3-WC	NPK	19	39.3	5.6	11.0	23.7	33.2	1.21
S3-WC	NPK	24	39.3	5.1	11.1	18.2	35.3	1.05
S3-WC	NPKCa	10	78.6	6.3	11.7	48.0	42.9	3.27
S3-WC	NPKCa	19	39.3	5.7	11.1	24.5	33.0	1.20
S3-WC	NPKCa	24	39.3	5.7	11.1	20.3	35.2	1.04

[a]N, P, and K in treatments represent the application of N, P, and K fertilizers; NPKCa represents the application N, P, and K fertilizers plus lime.

[b]$Rate_{ac}$ is accumulation rate of Olsen P in soils.

$$\text{Olsen P} = \text{Olsen P}_i + D \times \sum_{1}^{t} (Pt - Ct \times Yt) \qquad (1)$$

$$\text{Olsen P} = \text{Olsen P}_i + D \times (P_m - C_m \times Y_m) \times t \qquad (2)$$

where Olsen P_i is the initial concentration of Olsen P in soils (mg/kg), D is the increase of Olsen P (ΔOlsen P, mg kg^{-1}) led by one unit of P surplus (kg/ha) in soils, P is application rate of P fertilizer (kg P ha^{-1}), t is cultivation time (year), C is the apparent concentration of P in grains of wheat and maize (g kg^{-1}), Y is the total grain yield of wheat and maize per year (tons ha^{-1}), and the subscript m denotes the average of P, C, and Y in the period of cultivation years, respectively. The accumulation rate ($Rate_{ac}$) of Olsen P in soil is estimated as follows:

$$Rate_{ac}\ (\text{mg/kg/year}) = D \times (P_m - C_m \times Y_m) \qquad (3)$$

In the present study, the model for paddy soils with a double-rice monoculture rotation system was parameterized by a data-processing system (Tang and Feng 2007) using the dataset of Olsen P change with different time in S1-QY and other field sites (S2-NC and S3-WC).

Results

Accumulation of P in Soils Treated with Chemical Fertilizers

The concentrations of Olsen P in soils, pH, and rice yields in different years in the long-term experiments are found in Table 3. The mean yields of early rice and late rice were found to be 5.4 and 4.2 tons ha^{-1} per year. The mean P recovery efficiency by rice crops (the proportion of total P taken up by rice crops (grain and straw) to amount of P fertilizers applied to soils) in S1-QY was found to be about 68.2% in the period of 1981–2002 with P surplus of about 15.6 kg ha^{-1} per year in soil with a rate of chemical P fertilization (49.2 kg P/ha/year). The excessive or residual P in soils led to increase of Olsen P in paddy soils. The results showed that the concentration of Olsen P in the paddy soils increased linearly and with cultivation time significantly [Olsen P (mg kg^{-1}) = 1.33t (year) – 7.32, n = 9, $R^2 = 0.98$, $P < 0.001$] if P application rate was constant. However, the accumulation rate of Olsen P in soils was related to the P application rate and crop yield (P amount of plant removal).

Modeling and Validation

The dataset including cultivation time, P application rates, soil pH, rice yields, and measured Olsen P in S2-NC and S3-WC is shown in Table 4. The predictive model was developed using P fertilization rate, grain yield of rice, and cultivation time (year). To increase the applicability, the predictive model was parameterized by all data from three sites, excluding the S3-WC, with cultivation time of 19 and 24 years (the reasons are discussed later). The parameterized predictive model was as follows:

$$\text{Olsen P (mg/kg)} = \text{Olsen P}_i + 0.0763 \times (P_m - 3.07 \times Y_m) \times t\ (R^2 = 0.95,\ n = 17) \qquad (4)$$

where Olsen P_i is the initial concentration of Olsen P in soils (mg/kg), the parameter of 0.0763 (mg/kg·ha/kg) is ΔOlsen P in paddy soils (mg kg^{-1}) led by one unit of P surplus (kg ha^{-1}) in paddy soils, P_m is the average of application rate of P fertilizer (kg P ha^{-1}), t is cultivation time (year), and Y_m is the total grain yield of rice per year (tons ha^{-1}). It was developed from three different soils in various locations; therefore, the predictive model had high applicability. Regression coefficient (R^2) for measured versus estimated Olsen P values in the paddy soils was 0.95 ($P < 0.001$). Also, the ratio of measured to estimated Olsen P values was equal to 1.00. The results showed that the predictive model of Eq. (4) could be used for prediction of Olsen P accumulation in paddy soils involving a double-rice monoculture rotation system with the difference between measured and predicted values being less than 20%, except for the values of Olsen P in S3-WC with cultivation time of 19 and 24 years (outliers in Figure 1). Because the P application rate in S3-WC decreased from 39 kg P/ha/year to 19.7 kg P/ha/year since 1990 (Table 2), the concentrations of Olsen P in soils decreased with cultivation time since 1990. For example, in NPK treatment, the concentrations of Olsen P in soils decreased from 41.5 mg/kg in 1990 to 23.7 mg kg^{-1} in 1999 and to 18.2 mg kg^{-1} in 2004. The outliers from the predictive model for S3-WC with cultivation times of 19 and 24 years were probably the result of the difference between the processes of accumulation and depletion of Olsen P in paddy soils. This also revealed that the model for Olsen P accumulation in paddy soils could not be used for depletion of Olsen P in soils. It is interesting that the predicted Olsen P was significantly less than that in S3-WC with cultivation times of 19 and 24 years, which suggested that the transformation of non-Olsen P to Olsen P was a slow process compared to the inverse process in field soils.

When P application rates ranged from 49.2 to 78.6 kg/ha in paddy soils with rice yields from 7.1 to 11.7 tons ha^{-1}, the accumulation rates of Olsen P in paddy soils were estimated to be from 1.2 to 3.7 mg/kg/year. The concentrations and accumulation rates of

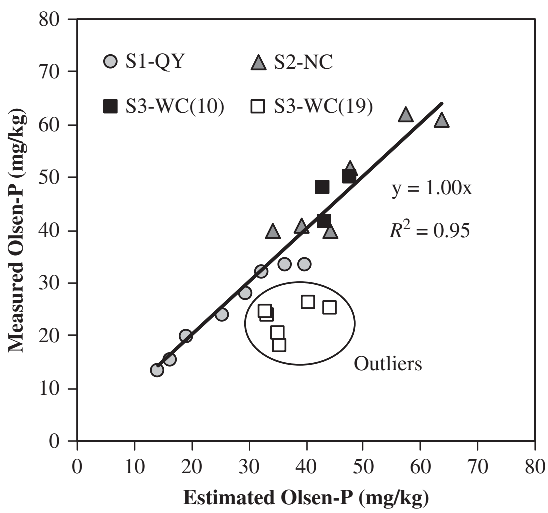

Figure 1. Measured Olsen P and Olsen P estimated by the predictive model of Olsen P accumulation in paddy soils with P chemical fertilization [Eq. (4)] in long-term experiments in Qiyang, Hunan (S1-QY), Nanchang, Jiangxi (S2-NC), and Wangcheng, Hunan (S3-WC). S3-WC(10) expressed as the data for cultivation time of 10 years and S3-WC(19) expressed as the data for cultivation times of 19 and 24 years (Table 4). The outliers were not included in the regression.

Olsen P in paddy soils with a double-rice rotation system could be predicted by P chemical fertilization rate, rice crop yield, and cultivation time. The predictive model can be used for the best management of P in paddy soils for agricultural production and environment protection.

Discussion

The ΔOlsen P in paddy soils (mg kg^{-1}) led by one unit of P surplus (kg ha^{-1}) in paddy soils) was found to be about 0.076 mg/kg·ha/kg, which means that for every 100 kg surplus P per ha in paddy soils, the Olsen P would be increased by about 7.6 mg kg^{-1} in paddy soils. In other words, about 21% of surplus P accumulated as Olsen P in paddy soils if soil bulk density was 1.4 g cm^{-1}, which was more than that in soils of arable land (Johnston and Poulton 1992; Aulakh, Garg, and Kabba 2007; Ma et al. 2009). For example, it was reported that only 8–13% of surplus P accumulated as Olsen P in the soils with wheat–maize rotation systems (Ma et al. 2009). The results indicated that the immobilization of P fertilizers added to paddy soils was generally less than that for the soils of arable land, which is in agreement with reports by Gasser and Bloomfield (1955), Bradley, Vimpany, and Nicholls (1984), and De Mello, Barrón, and Torrent (1998). Best management of P fertilizers is very important for paddy soils in a view of freshwater eutrophication. If the target yield of double rice was 10 tons ha^{-1}, the increase in Olsen P (ΔOlsen P) in paddy soils will be estimated by the model as 0.7, 1.5, 2.2, 3.0, and 3.8 mg kg^{-1} when P application rates are 40, 50, 60, 70, and 80 kg P ha^{-1}, respectively. A difference of 10 kg P ha^{-1} in P application rates will cause an Olsen P change of about 0.75 mg kg^{-1}. The optimal application rate in paddy soils depends on the initial Olsen P in paddy soils and the critical value for rice yield and threshold value for increasing P losses (Higgs et al. 2000).

The model of accumulation of Olsen P in paddy soils was validated independently in the soils with normal P application rates, such as 40–80 kg P/ha/year, in a double-rice rotation system with inorganic fertilizers as a phosphorus source (Figure 1). At high application rates (or low application rates at which the depletion of Olsen P may occur) for other rice-based rotation systems, such as rice–wheat or single rice rotation, the predictive model must be treated with some caution because of the uncertainty associated with the ratio of ΔOlsen P to P surplus. However, in paddy soils in the present study, there were insignificant effects of soil pH on ΔOlsen P increased by one unit of P surplus, which was probably because the pH range in the present study was still not wide enough. In addition, it is still unclear if the P in organic manures behaves similar to P in chemical fertilizers, and studies need to validate this if data from long-term experiments are available.

Conclusions

The accumulation of Olsen P in paddy soils occurred, and its rate was estimated from 1.2 to 3.7 mg/kg/year when P application rates ranged from 49.2 to 78.6 kg ha^{-1} in paddy soils with rice yields from 7.1 to 11.7 tons ha^{-1}. A predictive model for concentrations and accumulation rates of Olsen P in paddy soils with a double-rice rotation system was developed based on the initial Olsen P in paddy soils, P application rates, and crop yields. In paddy soils with applied P more than 40 kg P ha^{-1}, the accumulation of Olsen P in the soils may occur and will be accurately estimated by the predictive model. Furthermore, accumulation rate of Olsen P in paddy soils was quicker than that in soils of arable land and the best management of P fertilizers in paddy soils is crucial for freshwater eutrophication.

Finally, the predictive model can be used for optimal P fertilization for rice crop production and environmental protection.

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