Phosphorus accumulation in soils in rice-rice cropping systems with chemical fertilizer application: modeling and validation

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Abstract
Phosphorus (P) accumulation in paddy soils was studied by a long-term experiment (over 25 years) with rice-rice rotation system in Qiyang, Hunan province, China. Fertilizer application rates were 145 kg N/ha/year, 112.6 kg P_2O_5/ha/year, 67.6 kg K_2O/ha/year.The results showed that the increases of soil Olsen-P were closely related to fertilizer application rates, rice yield and cultivation time. A model of Olsen-P accumulation was established by soil pH, initial soil Olsen-P, fertilizer application rate, yield, and cultivation time. The accumulation rate of Olsen-P could be estimated with 1.32 mg/kg/year on average. Also Olsen-P accumulation rate could be estimated with different fertilizer application rates. The model was validated well by another three independent long-term experiments with the acceptable differences between the measured and estimated Olsen-P (from 0.1 to 9.9 mg/kg). Each 100 kg P/ha surplus in paddy soils with rice-rice rotation system would increase the Olsen-P by 7.0 mg/kg. The findings will be very helpful to understand phosphorus accumulation and management in paddy soils.

Key Words
Phosphorus, accumulation, long-term, paddy soil, rice-rice rotation.

Introduction
Rice is first staple crop in the world as well as in China (Maclean et al., 2002). Application of phosphorus fertilizer is one of the most important for higher crop yields (Löbermann et al., 2007). In pursuit of higher yields, farmers resorted to using higher than the recommended levels of fertilizers in many areas in China. However, the phosphorus accumulation in cultivated soils is a concern for non-point environmental pollution and for efficiency of phosphorus resources because of excessive phosphorus input (Zhang et al, 2004). The purposes of this study are to develop a model for prediction of phosphorus accumulation in soils in rice-rice cropping systems with chemical fertilizer application using long-term experiments and to validate the model by other independent experiments in order to manage P in paddy soils rationally.

Methods
Soil properties and experimental design
The long-term experiment with rice-rice system was conducted in 1981 in Qiyang Red Soil Experimental Station, Hunan province, China (E111º52′23″, N26º45′12″). Soil in the station derived from quaternary period red soil. The soil properties prior to the experiment were as follows: pH 8.0, organic matter19.8 g/kg, total N 1.48 g/kg, total P 0.48 g/kg, total K 14.2 g/kg, alkaline hydrolysable N 158 mg/kg, Olsen-P 8.0 mg/kg and NH_4OAc-K 14.2 mg/kg. The NPK treatment in the experiment was used. The application rates of NPK inorganic fertilizers every year were 145 kg N/ha as urea, 112.6 kg P_2O_5/ha as super-phosphate, and 67.6 kg K_2O/ha as potassium chloride. There were three replications in the experiments.

Sampling and analysis
Grain yields and straw biomass were recorded. The samples of the grains and straw were collected after every harvest time, and soil samples were collected at the top 0-20 cm soil at the same time with late rice harvest. Samples were mixed thoroughly, air-dried, ground and stored for analysis. Soil Olsen-P was extracted by 0.5 mol/L $NaHCO_3$ (pH 8.5) solution and analysed using a molybdenum-blue colorimetric method, and total P in plant samples were digested by tri-acid mixture (HNO_3:$HClO_4$:H_2SO_4 at 3:1:1 ratio) and measured by a molybdenum-blue colorimetric method.

Modeling and validation
The change of Olsen-P in soils with long-term application of phosphorus fertilizer was described by following equation (Ma et al., 2009):

Olsen-P = Olsen-P_i + (D/pH) × (P_m - C_m×Y_m) × t (1)

where Olsen-P is P concentration extracted by 0.5 mol/L $NaHCO_3$ (pH 8.5) in the soil (mg/kg), Olsen-P_i is the initial concentration of Olsen-P in the soil (mg/kg) prior to the experiment, t is the cultivation time (year), D is constants, P_m is fertilizer application rate yearly on average (kg/ha), Y_m is rice yield (t/ha) yearly on average, C_m is the apparent concentration of P in rice plants on average (g/kg), pH is soil pH. The parameters were optimized by data processing system (Tang and Feng, 2007). The accumulation rate ($Rate_{ac}$, mg/kg/year) of Olsen-P in soils could be estimated as follows:

$Rate_{ac}$ = D/pH × (P_m - C_m×Y_m) (2)

The models of accumulation of Olsen-P in soils were validated by all independent data from field sites for rice-rice system which were found in literatures.

Result

Change of Olsen-P with time in paddy soils with long-term chemical P fertilization

The trend of Olsen-P in soils was increasing and the accumulation of Olsen-P was linearly related to the fertilization time (year) and rice yield. The slope of Olsen-P versus fertilization time was 1.32, which indicated that the accumulation rate of Olsen-P in the experiment was about 1.32 mg/kg per year.

Predictable P accumulation model and validation in paddy soils with long-term chemical P fertilization

The parameterized model is as below:

Olsen-P = Olsen-P_i + (0.425/pH) × (P_m–3.23 × Y_m) × t (R^2 = 0.95, n = 10) (3)

The estimated and measured Olsen-P values in soils were shown in Figure 1. Soil pH in paddy soil was 6.1 on average, thus each 100 kg P/ha surplus in soil would increase the Olsen-P by 7.0 mg/kg/year. The accumulation rate of Olsen-P in paddy soil is higher than that in upland soils with wheat-maize rotation (Ma et al., 2009).

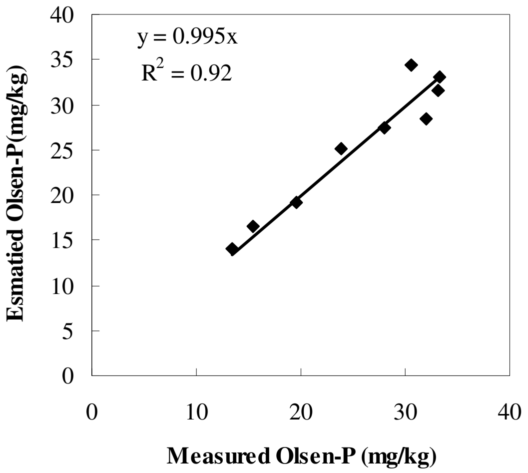

Figure 1. The measured and estimated Olsen-P by the model (Equation 3) in soils with chemical P fertilization

Model validation by three independence long-term experiments

The model (Equation 3) was validated by published data in another three long-term experiments in literatures. The first long-term experiment started in 1983 was located in Nanchang, Jangxi province, China. The treatments were PK, NP and NPK, the application rates of N and K fertilizers were of 330 kg N/ha/year, 52.4 kg P/ha/year and 300 kg K_2O/ha/year. The second long-term experiment started in 1981 was located in Wangchang, Hunan province, China. The treatments were NP, NPK and NPKCa. The fertilizer application rates were 330 kg N/ha/year, 78.6 kg P/ha/year (before 1991), and 39.3 kg P/ha/year (after 1991), 240 kg K_2O/ha/year, lime 2025 kg/ha/year. The third long-term experiment started in 1990 was located in Hangzhou, Zhejiang province, China. The treatments were NP and NPK. The application rates of N and K fertilizers were 315 kg N/ha/year, 68.8 kg P/ha/year and 157 kg K_2O/ha/year. All the three experiments were with rice-rice rotation every year. The details for the three long-term experiments were described as Table 1. There was closely linear relationship between the measured and estimated Olsen-P with R^2 0.92 ($p<0.001$) (Figure 2) although the predicted Olsen-P was generally 8% lower than the measured Olsen-P. The difference between the estimated and measured Olsen-P was found from 0.1 to 9.9 mg/kg (Table 1), which was considered to be acceptable because of the variation of soil sampling for Olsen-P measurement.

Table 1. The measured Olsen-P (Olsen-P_m) in literature and the predicted Olsen-P (Olsen-P_p) using the model (Equation 3) in three long-term experiments with rice-rice rotation every year in Wangcheng - Hunan, Nanchang - Jingxi, and Hangzhou – Zhejiang, China (Xu et al., 2006).

Site	Treatment	Time (Year)	Added P (kg/ha/year)	Soil pH	Yield (t/ha)	Olsen-P_i (mg/kg)	Olsen-P_m (mg/kg)	Olsen-P_p (mg/kg)	$Rate_{ac}$ (mg/kg/year)
Jangxi	PK	10	52.4	6.4	7.11	20.8	39.8	40.4	2.0
Hunan	PK	20	52.4	5.4	7.91	20.8	61.0	63.1	2.1
China	NP	10	52.4	6.8	9.20	20.8	41.0	35.0	1.4
	NP	20	52.4	5.8	9.25	20.8	61.8	53.9	1.7
	NPK	10	52.4	6.2	11.35	20.8	39.8	31.6	1.1
	NPK	20	52.4	5.7	11.32	20.8	51.6	44.5	1.2
Wangcheng	NP	10	78.6	5.8	9.64	10.2	50.2	45.2	3.5
Hunan	NP	19	39.3	5.4	9.42	10.2	26.2	28.2	0.7
China	NP	24	39.3	5.1	9.46	10.2	25.3	23.5	0.8
	NPK	10	78.6	5.6	11.54	10.2	41.5	41.8	3.2
	NPK	19	39.3	5.6	11.04	10.2	23.7	15.9	0.3
	NPK	24	39.3	5.1	11.05	10.2	18.2	18.1	0.3
	NPKCa	10	78.6	6.3	11.65	10.2	48.0	38.1	2.8
	NPKCa	19	39.3	5.7	11.07	10.2	24.5	15.7	0.3
	NPKCa	24	39.3	5.7	11.07	10.2	20.3	17.1	0.3
Hangzhou	NP	5	68.8	6.8	12.16	32.5	44.3	41.9	1.9
Zhejiang	NP	10	68.8	6.8	12.34	32.5	55.2	50.8	1.8
China	NP	14	68.8	7.3	11.56	32.5	60.8	58.8	1.9
	NPK	5	68.8	7.0	12.36	32.5	42.2	41.4	1.8
	NPK	10	68.8	6.7	12.65	32.5	52.9	50.5	1.8

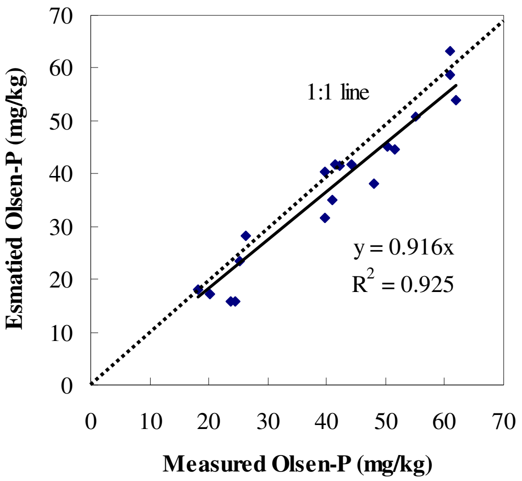

Figure 2. The validation of the model (Equation 3) by independent data from three field sites for rice-rice system published in literatures.

Conclusion

Accumulation of Olsen-P in paddy soils was closely related to P fertilization rate, rice yield, cultivated time, and soil pH. The model of Olsen-P accumulation in paddy soils was developed and validated by other independent long-term experiments in paddy soils. The model can be used to predict the accumulation of Olsen-P in paddy soils according to P fertilization rate, rice yield, cultivated time, and soil pH, and also used to identify the amounts and years of excess P application that would be required to build the Olsen-P level to the critical concentration of Olsen-P in soils. The finding was significant for P management and environmental protection in paddy soils.

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