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Manures behave similar to superphosphate in phosphorus accumulation in long-term field soils

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Abstract

Repeated application of manures to agricultural soils could cause the accumulation of phosphorus (P) in soils. However, it is unclear if manure P can behave similar to P in soluble fertilizers in accumulation Olsen-P (0.5 mol L^{-1} $NaHCO_3$ at pH 8.5) in soils. A long-term wheat-maize rotation experiment was conducted to investigate the effects of repeated application of manures on P accumulation in soils. The results showed that excessive or residual P in soils led to increase of Olsen-P in soils, which could be predicted accurately by initial concentration of Olsen-P in soils, P fertilization rate, crop yield, soil pH and cultivation time. The effects of application of K fertilizers or maize straw to soils or replacement of maize with soybean in wheat cropping systems were not significant on soil Olsen-P accumulation. The accumulation rates of soil Olsen-P were governed by P application rates of soluble P fertilizers and/or manures. Similar trend of Olsen-P accumulation was found in soils with soluble P fertilizers only or plus manures P, which supplied evidence that behaviour of manure P in long-term field soils is similar to inorganic P fertilizers and are helpful for the best management of soil P in agricultural production and environment protection.

Keywords: Phosphorus; Accumulation; Long-term; Soil.

Introduction

The intensive and excessive use of phosphorus (P) fertilizers has resulted in the accumulation of P in many soils and possibly in risk of freshwater eutrophication through P runoff (Benke et al., 2008; Ma et al., 2009) if P concentrations in surface water reach above 0.02 mg L^{-1} for total P and above 0.01 mg L^{-1} for inorganic P (Daniel et al., 1998). The accumulation of P in soils can occur through the excessive application of both P chemical fertilizers and organic manures to soils (Selles et al., 1995; Aulakh et al., 2007). Ma et al. (2009) studied the accumulation of P in soils using the long-term winter wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) crop rotation experiments at five sites differing

geographically and climatically in China and developed a model that the accumulation of Olsen-P in soils could be described using application rates of P chemical fertilizers, crop yield and soil pH. For manures, generally, their amounts applied to soils are estimated based on N-requirements by crops, so that they often supply P more than that required by the crops (Liebhardt, 1976; Edwards and Daniel, 1992; Sims and Wolf, 1994), because the ratio of N:P in manures is lower than that in plant uptake (Benke et al., 2008). It was well documented that repeated application of P-rich manures at N-based application rates could lead to the accumulation of P in soils that greatly exceed agronomic optimums (Sharpley et al., 1984; Motavalli and Miles, 2002; Sims and Kleinman, 2005; Benke et al., 2008). Certainly, behaviour and fate of manure P in soils are governed mainly by the forms of P in manures compared to soluble P fertilizers (i.e. superphosphate), therefore there are many studies on the forms of P in manures (Hedley and McLaughlin, 2005). Gerritse and Vriesema (1984) found most of P in animal waste slurries from chickens, pigs and cows was in inorganic form in the solid phase. Toor et al. (2005) studied the speciation of P in manures using a combination of chemical fractionation and synchrotron X-ray absorption near edge structure (XANES) spectroscopy and also found that broiler litters were rich in dicalcium phosphate (65-76%), followed by aqueous phosphate (13-18%), and phytic acid (7-20%), although the distribution P species in manures depended on the sources of manures, even the P forms in feeds (Turner and Leytem, 2004). Therefore, the behaviour of the manure P in soils depends on the P amounts in inorganic forms in manures (Sharpley and Moyer, 2000; Eghball, 2003; Eghball et al., 2005). However, it is unknown if manure P can behave similar to soluble P fertilizers, such as superphosphate, in the status or accumulation of Olsen-P in field soils, especially in long-term field experiments. Such information is useful for predicting Olsen-P dynamics in soils and optimal P-fertilization in cropping systems.

The objectives of this study were: (i) to quantify the P accumulation rates in response to manure application to soils; and (ii) to model the effects of long-term manure application on Olsen-P accumulation in soils in a wheat-maize rotation system in a Fluvo-aquic soil in China; (iii) to validate the model independently using the data published in the literature.

Materials and Methods

Soil properties and experimental design

The long-term experimental site was located in Zhengzhou, Henan Province in China (34° 47'N, 113° 41'E) with a temperate monsoonal climate. The experiment was set up in 1990. The experimental site, soil properties and climate conditions were reported in details by Tang et al. (2008) and by Wang et al. (2010). They are briefly described again here. The average annual rainfall from 1991 to 2005 at the site was 646 mm, mean annual temperature was 14.8 °C and frost-free period was 224 days. The soil texture is a light loam with clay content (<0.002 mm) of 12.8%. The soil was classified as Calcaric Cambisol (FAO classification) or Fluvo-aquic soil (China classification). The main soil properties and N/P/K status in plough layer (0-20 cm) prior to the experiment were as follow: soil pH (water: soil=1:1) 8.3; organic matter 10.1 g kg^{-1}; total N 0.65 g N kg^{-1}; total P 0.64 g P kg^{-1}; total K 16.9 g K kg^{-1}; Alkaline hydrolysable N 76.6 mg N kg^{-1}); Olsen-P 6.5 mg P kg^{-1} and NH$_4$OAc-K 74 mg K kg^{-1}.

A wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) cropping rotation was used in the experiment for every cropping year for all the treatments of fertilizer/manure applications. Summer maize was sown in early June and harvested in mid September; winter wheat was sown in early October and harvested in early June. During the growing season, hand weeding was done to control weeds and fungicide and insecticide were applied when needed.

Each experimental plot was 400 m^2 (16×25 m). Treatments were randomly assigned to the plots. Seven treatments from the experiment were used in the present study: CK (unfertilized), NP (nitrogen and phosphorus), NPK (NP plus potassium), NPKSt (NPK plus return of maize straw), NPKM (NPK plus manures), 1.5NPKM (1.5 times of fertilizer amounts of NPKM) and NPKM2 (only difference with NPKM is wheat-soybean cropping rotation). The amounts of fertilizers applied to the soils with different treatments were shown in Table 1. When the nutrient was included in the treatment, the application rates of N, P and K for wheat were 165 kg N ha^{-1} year^{-1}, 36 kg P ha^{-1} year^{-1} and 68.5 kg K ha^{-1} year^{-1}, respectively. For maize, the application rates of N, P and K were 165 kg N ha^{-1} year^{-1}, 36 kg P ha^{-1} year^{-1} and 68.5 kg K ha^{-1} year^{-1} in 1991 and 187.5 kg N ha^{-1} year^{-1}, 41 kg P ha^{-1} year^{-1} and 78 kg K ha^{-1} year^{-1} from 1992 to 2005. All P fertilizers were in the form of superphosphate, N fertilizers in the form of urea, and K fertilizers in the form of potassium sulphate. All P and K, and 50-70% of N fertilizer were applied as base fertilizers at sowing. The remaining N fertilizer was applied as top-dressing at stem elongation stage. Organic manures (for NPKM and 1.5NPKM treatments), as well as maize straw (for NPKSt treatments), were applied as base fertilizers before sowing for wheat. The types of organic manures, amounts applied and nutrient concentrations in the manures were shown in Table 2. The application amounts of manures and straw were calculated based on the concentration of N in manures and straw in order to maintain equal total N input to mineral N treatments and keep the ratio of N in manures or straw to mineral N as 7:3 except that the amounts of applied straw was changed to that produced in the treatment of NPKSt from 2003-2005. The crop residue in all the other treatments was taken away from the field. Usually, wheat was irrigated twice at sowing and stem elongation stage, each around 75 mm of water, while maize was irrigated once with 75 mm of water at sowing. No replicates were designed in the experiment, but soil samples were taken from five randomly selected locations in each treatment to get average values.

Soil and plant sampling and analysis

Soil samples were collected annually from each treatment after about15 days after maize was harvested. An auger with 5 cm internal diameter was used to take soil samples in the plough layer (0-20 cm) at five randomly selected locations for each plot. The fresh soil samples were mixed completely, air-dried and sieved through a 2.0 mm sieve and stored for nutrient analysis. Soil samples were analysed for Olsen-P using 0.5 mol L^{-1} NaHCO$_3$ (pH 8.5) and total soil P following Page et al. (1982). The crop samples (grains and straws) were harvested. After drying, the crop samples were ground to pass 0.15 mm sieve. To determine the total P content, the plant samples were digested with H$_2$SO$_4$-H$_2$O$_2$ and concentration in the digesting solution was measured using the molybdenum-blue colorimetric method (Page et al., 1982).

Table 1. Total amounts of nutrients (N, P, and K) applied to soils in different treatments through chemical fertilizers and manures (M) or straw (St) from 1991 to 2005 in the long-term experiments.

Treatments	Wheat (kg ha⁻¹)			Maize (kg ha⁻¹)		
	N	P	K	N	P	K
CK	0	0	0	0	0	0
NP	2475	540	0	2790	610	0
NPK	2475	540	1028	2790	610	1160
NPKSt	743+1732[a]	540+200	1028+4008	2790	610	1160
NPKM	743+1732	540+1019	1028+1385	2790	610	1160
1.5NPKM	1114+1599	810+1529	1542+2078	4185	915	1740
NPKM2[b]	743+1732	540+1019	1028+1385	2790	610	1160

[a] Indicates the nutrients coming from manures or straw.
[b] In the treatment of NPKM2, the cropping rotation is wheat-soybean cropping rotation, which was different from all other treatments with wheat-maize cropping rotation.

Table 2. The concentrations of N, P, and K in manures applied to soils from 1990 to 2005.

Time (year)	Manure	Amount applied[a] (kg ha⁻¹)	Nutrient content in manure (g kg⁻¹)		
			N	P	K
1990	Horse	7857	14.7	5.4	8.8
1991	Horse	5397	21.4	7.7	14.9
1992	Horse	8684	13.3	6.5	15.9
1993	Horse	8309	13.9	7.9	10.2
1994	Horse	9957	11.6	9.8	6.0
1995	Horse	13916	8.3	5.8	4.5
1996	Horse	9094	12.7	5.7	9.8
1997	Horse	8684	13.3	3.4	6.6
1998	Horse	13750	8.4	3.0	10.3
1999	Horse-cattle	18333	6.3	6.8	8.0
2000	Barnyard	50217	2.3	2.3	4.4
2001	Barnyard	11000	10.5	5.6	5.4
2002	Cattle	18960	6.1	4.4	2.3
2003	Cattle	6047	19.0	9.4	12.2
2004	Cattle	7598	15.2	9.2	7.6
2005	Cattle	9625	12.0	4.9	6.4

[a] The normal application amounts of manures were calculated based on the concentration of N in manures and equal total N input to mineral N treatments. In the calculation the ratio of N in manures to mineral N was kept to be 7:3.

Modelling and validation

The average of Olsen-P and crop yield every four years was calculated in order to minimize their variation. A predictable model was developed by Ma et al. (2009) using P fertilization rate, crop grain yield and time (year) from long-term experiments with wheat-maize rotation systems at five sites differing geographically and climatically in China. The change of Olsen-P in soils with P fertilization was described by the following equations:

$$\text{Olsen-P} = \text{Olsen-P}_i + \frac{D}{pH} \sum_{1}^{t} (P_t - C_t \times Y_t) \qquad (1)$$

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

where Olsen-P_i is the initial concentration of Olsen-P (0.5 mol L^{-1} $NaHCO_3$ at pH 8.5) in soils (mg kg^{-1}), D is an constant, pH is soil pH, 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 (tonne ha^{-1}), 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 could be estimated as follows:

$$Rate_{ac} \ (mg \ kg^{-1} \ year^{-1}) = \frac{D}{pH} \ (P_m - C_m \times Y_m) \tag{3}$$

The model was parameterized using the dataset of Olsen-P in different treatments with manures, and then the parameterized model was compared with the model developed from soils applied with soluble P fertilizers (i.e. superphosphate) in order to find the different behaviour between manure P and soluble P fertilizers (i.e. superphosphate). Finally, the model of accumulation of Olsen-P developed for the soils with manure application was validated by all independent data from field sites for similar wheat-maize rotation which were found in literature.

Results

Accumulation of P in soils applied with organic manures

It was found that the concentrations of total P in soils were increased significantly in the manure treatments, such as NPKM, 1.5NPKM, and NPKM2 (Figure 1). There were no significant difference between NP, NPK and NPKSt. Also the trend of total P in soils was similar between the two cropping rotations (NPKM with wheat-maize rotation and NPKM2 with wheat-soybean rotation), As expected high application rates could cause high concentrations of total P in soils, such as 1.5NPKM treatments, in which the increasing rate of total soil P was found to be 0.0226 g/kg per year (R^2=0.99) when total input P was 214 kg ha^{-1} on average (114.9 kg ha^{-1} from superphosphate and 99.1 kg ha^{-1} from manures). In the treatment of NPKM, the increasing rate of total soil P was 0.0172 g/kg per year (R^2=0.96) when total input P was 214 kg ha^{-1} on average (77 kg ha^{-1} from superphosphate and 66.1 kg ha^{-1} from manures). The accumulation of total P in soils is because of high application rates and low recovery by crops in these treatments. The mean P recovery efficiency by crops (the proportion of total P taken up by crops (grain and straw) with applied P fertilizers (kg P ha^{-1}) to amount of P fertilizers applied to soils) was 64-70% for NP, NPK and NPKSt treatments, 39% for NPKM and NPKM2, and 29% for 1.5NPKM treatment, respectively. The P recovery efficiency decreased with P application rates in soils.

The excessive or residual P in soils led to increase of Olsen-P in soils (Figure 2). The results showed that the concentration of Olsen-P in soils applied with superphosphate and manures increased linearly and with cultivation time significantly (Table 3). Except for CK treatment, in which Olsen-P in soils decreased with cultivation time, the increasing rates of Olsen-P in soils were 1.42, 3.22 and 5.14 mg kg^{-1} $year^{-1}$) for NPK, NPKM and 1.5NPKM treatments, respectively. As similar as total P, the change of Olsen-P for NP and NPKSt was similar to NPK, which suggested that application of maize straw to soils had no significant effects on the change of Olsen-P in soils because of relatively low P amounts

applied by maize straw. Also like total P, the trend of Olsen-P in soils was similar between the wheat-maize rotation (NPKM) and wheat-soybean rotation (NPKM2), which indicated that soybean replacing maize in wheat cropping system did not affect the trend of Olsen-P in soils. Importantly, the accumulation rate of Olsen-P in soils was related to P application rates. In the long-term experiment, the change of Olsen-P could be generally divided into four groups: (1) decrease in CK; (2) slowly increase in NP, NPK, and NPKSt; (3) increase in NPKM and NPKM2, (4) quick increase in 1.5NPKM. Also, the relationship between the increase of Olsen-P (ΔOlsen-P) versus surplus P (amount of fertilizer applied in excess of removal by crops) in soils was shown in Figure 3. The results showed that the trend of accumulation of Olsen-P in soils is linearly related to surplus P in soils and suggested that 100 kg surplus P ha^{-1} could increase about 3.3 mg kg^{-1} Olsen-P in soils. When the treatments were divided into two groups: (1) soluble P fertilizers (NP and NPK), and (2) soluble P fertilizers with manures and straw (NPKM, 1.5NPKM, NPKM2 and NPKSt), the slopes of ΔOlsen-P (mg kg^{-1}) to surplus P (kg ha^{-1}) in the treatments with soluble P fertilizers only (NP and NPK) and plus manures and straw were found to be 0.039 (95% confidence intervals from 0.027 to 0.051) and 0.033 (95% confidence intervals from 0.031 to 0.034), respectively, which were not significantly different between them within the precision of the long-term experiments.
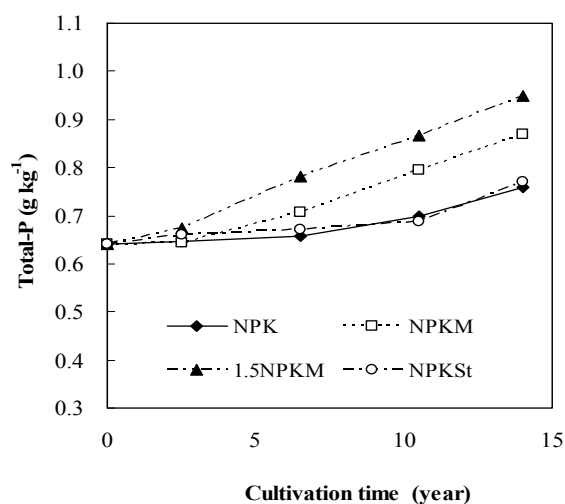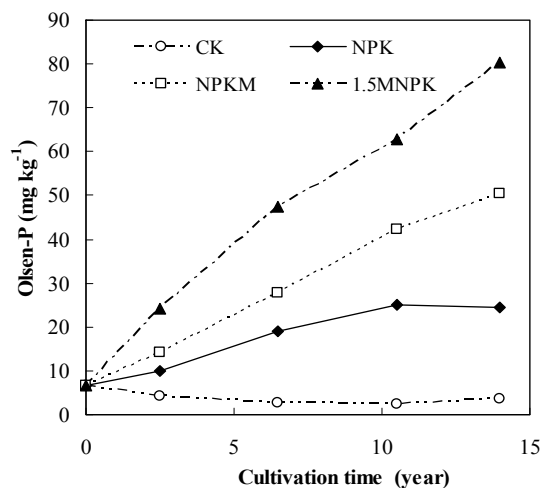

Figure 1. The change of total P with cultivation time (year) in the soils with different treatments (the NP treatment was similar to NPK and NPKM2 was similar to NPKM, which were not shown).

Table 3. The parameters derived from fitting linear relationships between accumulation of Olsen-P (mg kg-1) in soils applied with P fertilizers and cultivation time (year).

Treatment	Intercept (mg kg^{-1})	Slope (mg kg^{-1} year^{-1})	R^2
NP K	7.52	1.42	0.92[**a]
NPKM	6.59	3.22	0.99[***]
1.5NPKM	9.80	5.14	0.99[***]

[a, **] and [***] indicate significance at the 0.01 and 0.001 levels, respectively.

Figure 2. The change of Olsen-P with cultivation time (year) in the soils with different treatments (the NP treatment was similar to NPK and NPKM2 was similar to NPKM, which were not shown).
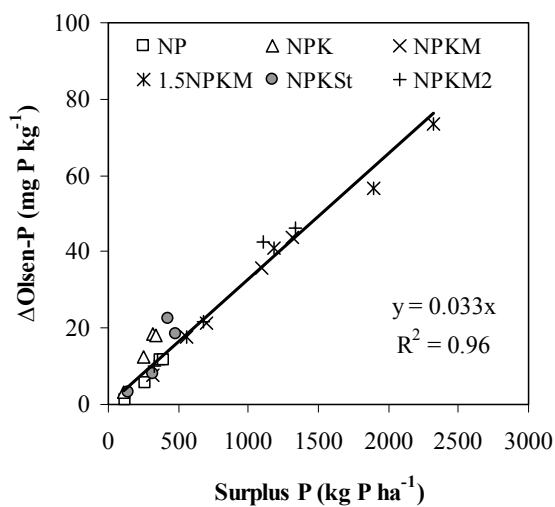

Figure 3. The increase of Olsen-P (ΔOlsen-P) in response to surplus P (amount of fertilizer applied in excess of removal by crops) in soils with P fertilization treatments.

Modeling and validation

The parameterized model for soluble P fertilizers (i.e. superphosphate) developed by Ma et al. (2009) is as below:

$$\text{Olsen-P (mg kg}^{-1}\text{)}= \text{Olsen-P}_i + \frac{0.238}{pH}\ (P_m - 2.78 \times Y_m) \times t \tag{4}$$

where Olsen-P_i is the initial concentration of Olsen-P in soils (mg kg^{-1}), the parameter of 0.238/pH (mg kg^{-1}·ha kg^{-1}) is ΔOlsen-P in soils (mg kg^{-1}) led by one unit of surplus P (kg ha^{-1}) in soils, P_m is the average of application rate of P fertilizer (kg P ha^{-1}), t is cultivation time (year), Y_m is the total grain yield of wheat and maize per year (tonne ha^{-1}), the parameter of 2.78 g P kg^{-1} crop yield is apparent concentration of P in grains of wheat and maize (*C*) which was very closed to the average of P concentration measured in wheat and maize grains (2.75 g P kg^{-1}) (Tang et al., 2008). When this model was used to predict the change of Olsen-P in soils applied with manures, the ratio of measured to estimated Olsen-P values was found to be 1.06 (95% confidence intervals from 1.01 to 1.11) with R^2=0.98. In other words, the accumulation of Olsen-P in soils could be increased more in the soil applied with manures compared to the soils applied with superphosphate when amounts of applied P were equal between them. However, the difference between superphosphate and manures was found to be only 6% in accumulation of Olsen-P in soils.

When the dataset from treatments of manures was used to optimize the parameters by minimizing the sum of the squares of the residual variation of the datum points from the model, the parameterized model for soils applied with manures was found to be as follows:

$$\text{Olsen-P (mg kg}^{-1}) = \text{Olsen-P}_i + \frac{0.252}{pH}\ (P_m - 2.84 \times Y_m) \times t \qquad (R^2=0.98, n=20) \qquad (5)$$

The measured and predicted Olsen-P values in soils applied with manures are shown in Figure 4. The ratio of measured to estimated Olsen-P values was equal to 1.00 (95% confidence intervals from 0.96 to 1.05), which suggested that the change of Olsen-P in soils applied manures could be predicted by P input and crop yield. Also, the parameter of 0.252/pH (mg kg^{-1}·ha kg^{-1}) in the model for the soils applied with manures was lower than the parameter of 0.238/pH (mg kg^{-1}·ha kg^{-1}) in the model for the soils applied with superphosphate, which also suggested that ΔOlsen-P in soils (mg kg^{-1}) led by one unit of surplus P (kg ha^{-1}) was more in the soils applied with manures than that in the soils applied with superphosphate. Another parameter of 2.84 g P kg^{-1} crop yield in the model for the soils applied with manures is higher than 2.78 g P kg^{-1} crop yield in the model for the soils applied with superphosphate, which was in good agreement with measured values. Although the accumulation of Olsen-P in soils could be increased more in the soil applied with manures compared to the soils applied with superphosphate when equal P amounts were applied, there was no significant differences between the parameterized models for soluble P fertilizers (such as superphosphate) (Equation 4) and for manures (Equation 5).

The measured Olsen-P values in soils applied with manures in literature were in good agreement with those predicted by the model of Equation 5 (Table 4), with difference between measured and predicted values being less than 24%. The correlation coefficient between the measured and the predicted Olsen-P was 0.85 (P<0.05). The accumulation rates of Olsen-P in soils applied with NPK plus manures were estimated from 1.5 to 3.6 mg kg^{-1} year^{-1}, which mainly depended on P fertilization rate, especially the amounts of manures and P concentrations in the manures applied to soils. The results indicated that the model can be used to predict the concentrations and accumulation rates of Olsen-P in soils applied with manures using P fertilization rate, crop yield and soil pH.
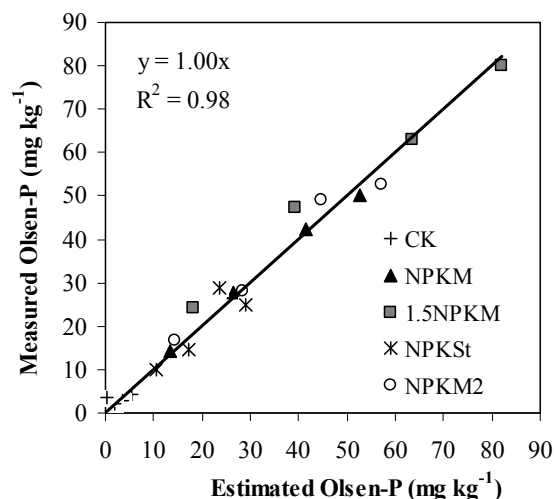
Figure 4. The measured Olsen-P and the Olsen-P estimated by the model of accumulation of Olsen-P in the soils with P fertilization with different cultivation time (Equation 5).

Table 4. The measured Olsen-P (Olsen-P_m) in literature and the predicted Olsen-P (Olsen-P_p) using the model (Equation 5) in one long-term experiments with naked oats (one crop each year) in Hebei, China from 1991-1998 (Liu et al., 2006) and another long-term experiment with wheat-maize-cowpea rotation in Ludhiana, India from 1970 (Biswas and Benbi, 1997; Benbi and Biswas, 1999).

Site	Treatment[a]	Duration (year)	Added P[b] (kg ha⁻¹ year⁻¹)	Soil pH	Yield (tonne ha⁻¹)	Olsen-P_i[c] (mg kg⁻¹)	Olsen-P_m (mg kg⁻¹)	Olsen-P_p (mg kg⁻¹)	Rate$_{ac}$[d] (mg kg⁻¹ year⁻¹)
Ludhiana, India	NPKM	22	83+12.5	8.2	11.4	4.1	44.1	46.7	1.96
Hebei, China	N1PM1	7	39.3+29.5	7.1	2.03	4.5	22.5	20.1	2.26
Hebei, China	N2PM1	7	39.3+29.5	7.1	2.36	4.5	21.1	19.9	2.23
Hebei, China	N1PM2	7	39.3+59	7.1	2.04	4.5	28.2	27.5	3.32
Hebei, China	N2PM2	7	39.3+59	7.1	1.98	4.5	36.5	27.8	3.33

[a] In the treatment of NPKM from Ludhiana, India the application rates of N and K fertilizers were 320 kg N ha⁻¹ and 110 kg K ha⁻¹ plus form yard manure every year. The Olsen-P in Ludhiana, India (mg kg⁻¹) is converted from kg P ha⁻¹ supposing soil bulk density of 1.3 g cm⁻³. Yield (average of total crop yield per year) in Ludhiana, India was extracted from Figure 2 in the paper of Biswas and Benbi (1997). In the experiment from Hebei, China, the application rates of N fertilizer were 60 (N1) or 120 (N2) kg N ha⁻¹, plus 22.5 (M1) or 45 (M2) t ha⁻¹ organic manures containing N 4.5, P 1.3 and K 5.0 mg kg⁻¹.
[b] The data of added P to soils was expressed as P from soluble fertilizers (such as superphosphate) (the former) plus from manures (the latter).
[c] Olsen-P_i is the initial concentration of Olsen-P in soils before the trials commenced.
[d] Rate$_{ac}$ is accumulation rate of Olsen-P in soils.

Discussion

It was found that there was a linear relationship between the accumulation of Olsen-P in soils and surplus P in soils with P fertilization (Figure 3), which is similar to those reported by Johnston and Poulton, (1992) and Tang et al. (2008) in long-term experiments. However, the

proportion of P extracted by a bicarbonate reagent decreases as the buffering capacity of the soil for phosphate increases (Barrow and Shaw, 1976). Therefore, the linear relationship between the accumulation of Olsen-P and surplus P in soils must be treated with some cautions for the soils with heavy applications of P fertilizers or with low buffering capacity for phosphate. In the present study, the linear relationships between the accumulation of Olsen-P and surplus P in the soils applied not only with soluble P fertilizers (such as superphosphate) but also with manures were not significantly different, which suggested that the manures behaved similar to superphosphate in P accumulation in long-term field soils.

In agricultural soils with normal P application rates (such as <100 kg P ha^{-1} year^{-1} from soluble P fertilizers and <100 kg P ha^{-1} year^{-1} from manures with wheat-maize rotation systems or similar, the concentrations of Olsen-P and accumulation rates would be predicted by initial concentration of Olsen-P in soils, P fertilization rate, crop yield, and soil pH, which was validated independently using the data found in literature (Table 4). Furthermore, the parameters were similar in the predictive models for the accumulation of Olsen-P in soils applied with soluble P fertilizer (such as superphosphate) (Equation 4) or with manure application (Equation 5). This supplied the evidence from the long-term field experiments that the behaviour of the manure P in field soils is similar to inorganic P fertilizers. This is in good agreement with the reported that the behaviour P in manures applied to soils is dominated mainly by the reactions of inorganic P (Gerritse and Vriesema, 1984; Toor et al., 2005) and the relative portion of organic P in manures, although in small percentage of total P in manures, could be mineralized into inorganic forms (Gerritse, 1981; He and Honeycutt, 2001; Crouse et al., 2002; Hedley and McLaughlin, 2005; Heidi et al., 2009). In other words, manure P can behave similar to soluble P fertilizers, such as superphosphate, in the accumulation Olsen-P in long-term field soils. On the other hand, the accumulation of Olsen-P in soils could be increased more in the soil applied with higher amounts manures compared to the soils applied with superphosphate when equal amounts P were applied to soils although the difference between superphosphate and manures was found to be only 6% in accumulation of Olsen-P in soils in the present study. Therefore, the models must be treated with some cautions for the soils with repeated heavy applications of organic manures (Whalen and Chang, 2001; Chang et al., 2005). Although there were small amounts of organic P in manures, which varied with the different sources of manures (He and Honeycutt, 2001; Turner and Leytem, 2004), the difference in contribution to Olsen-P accumulation in soils between application of superphosphate or manures to soils can be magnified at high manure application rates and high organic matter contents in soils induced by heavy manure applications (Griffin et al., 2003; Hao et al., 2008). Furthermore, as indicated by Ma et al. (2009), for different crop rotation systems, such as rice cropping rotation, the model must be parameterized using the data from the cropping rotation systems because of the uncertainty associated with the ratio of ΔOlsen-P to surplus P, the concentration of different plants and loss of soil P by leaching or erosion in the long-term experiments. Finally, from agricultural practice, farmers in China often applied soluble P fertilizers with manures to agricultural soils; therefore, the accurate prediction of accumulation rates of Olsen-P in soils applied soluble P fertilizers with manures is helpful for best management of P in soils for both agricultural production and environment protection. Also, application of models to predict the change of Olsen-P in soils can decrease the frequency of monitoring Olsen-P in soils and cut off the cost of soil testing (Ma et al., 2009).

Conclusions

Application of manures to soils could significantly increase the concentrations of total P in soils due to high amounts of P applied to soils and low P recovery efficiency by crops. The excessive or residual P in soils led to the increases of Olsen-P in soils, which could be predicted accurately by initial concentration of Olsen-P in soils, P fertilization rate, crop yield, soil pH and cultivation time in wheat-maize rotation systems in the soils applied not only with soluble P fertilizers but also with manures. The effects of application of K fertilizers or maize straw to soils or soybean replacing maize in wheat rotation system were not significant on the accumulation of Olsen-P in soils. Most importantly, the accumulation rates of Olsen-P in soils were governed by P application rates of soluble P fertilizers and manures. It is important to know that manure P can behave similar to soluble P fertilizers in the accumulation Olsen-P in field soils; therefore it is possible for the accurate prediction of accumulation rate of Olsen-P in soils with wheat-maize rotation systems, which is helpful for the best management of soil P in agricultural production and environment protection.

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References

Aulakh, M.S., Garg, A.K., Kabba, B.S., 2007. Phosphorus accumulation, leaching and residual effects on crop yields from long-term applications in the subtropics. Soil Use Manage. 23, 417-427.

Barrow, N.J., Shaw, T.C., 1976. Sodium bicarbonate as an extractant for soil phosphate III. Effects of the buffering capacity of a soil for phosphate. Geoderma. 16, 273-283.

Benbi, D.K., Biswas, C.R., 1999. Nutrient budgeting for phosphorus and potassium in a long-term fertilizer trial. Nutr. Cycl. Agroecosys. 54, 125-132.

Benke, M.B., Hao, X., Chang, C., 2008. Effects of long term cattle manure applications on soil, water and crops: Implications for animal and human health. In: Banuelos, G.S., Lin, Z.Q. (eds), Development and Uses of Biofortified Agricultural Products. CRC Press, Boca Raton, Florida, pp. 135-151.

Biswas, C.R., Benbi, D.K., 1997. Sustainable yield trends of irrigated maize and wheat in a long-term experiment on a loamy sand in semi-arid India. Nutr. Cycl. Agroecosys. 46, 225-234.

Chang, C., Whalen, J.K., Hao, X., 2005. Increase in phosphorus concentration of a clay loam surface soil receiving repeated annual feedlot cattle manure applications in southern Alberta. Can. J. Soil Sci. 85, 589-597.

Crouse, D.A., Sierzputowska-Gracz, H., Mikkelsen, R.L.A., Wollum, G., 2002. Monitoring phosphorus mineralization from poultry manure using phosphatase assays and phosphorus-31 nuclear magnetic resonance spectroscopy. Commun. Soil Sci. Plant Anal. 33, 205-1217.

Daniel, T.C., Sharpley, A.N., Lemunnyon, J.L., 1998. Agricultural phosphorus and eutrophication: A symposium overview. J. Environ. Qual. 27, 251-257.

Edwards, D.R., Daniel, T.C., 1992. Environmental impacts of on-farm poultry waste disposal-A review. Bioresource Technol. 41, 9-33.

Eghball, B., 2003. Leaching of phosphorus fractions following manure or compost application. Commun. Soil Sci. Plant Anal. 34, 2803-2815.

Eghball, B., Wienhold, B.J., Woodbury, B.L., Eigenberg, R.A., 2005. Plant availability of phosphorus in swine slurry and cattle feedlot manure. Agron. J. 97, 542-548.

Gerritse, R.G., 1981. Mobility of phosphorus from pig slurry in soils. In: Hucker, T.W.G., Catroux, G. (eds) Phosphorus in Sewage Sludge and Animal Waste Slurries. Reidel, Dordrecht, The Netherlands, pp. 347-369.

Gerritse, R.G., Vriesema, R., 1984. Phosphate distribution in animal waste slurries. J. Agric. Sci. (Cambridge), 102, 159-161.

Griffin, T.S., Honeycutt, C.W., He, Z., 2003. Changes in soil phosphorus from manure application. Soil Sci. Soc. Am. J. 67, 645-653.

Hao, X., Godlinski, F., Chang, C., 2008. Distribution of phosphorus forms in soil following long-term continuous and discontinuous cattle manure applications. Soil Sci. Soc. Am. J. 72, 90-97.

He, Z., Honeycutt, C.W., 2001. Enzymatic characterization of organic phosphorus in animal manure. J. Environ. Qual. 30, 1685-1692.

Hedley, M., McLaughlin, M., 2005. Reactions of phosphate fertilizers and by-products in soils. In: Sims, J.T., Sharpley, A.N. (eds) Phosphorus: Agriculture and Environment. American Society of Agronomy, Madison, Wisconsin, pp. 181-252.

Heidi, W.D., He, Z., Erich, S.M., Honeycutt, C.W., 2009. Soil phosphorus dynamics in response to poultry manure amendment. Soil Sci. 74, 195-201.

Johnston, A.E., Poulton, P.R., 1992. The role of phosphorus in crop production and soil fertility: 150 years of field experiments at Rothamsted, United Kingdom. In: Schultz, J.J. (ed.) Phosphate Fertilizers and the Environment, Proceedings of An International Workshop. International Fertilizer Development Centre, Tampa, Florida, pp. 45-64.

Liebhardt, W.C., 1976. Soil characteristics and corn yield as affected by previous applications of poultry manure. J. Environ. Qual. 5, 459-462.

Liu, J.L., Yang, F.C., Li, R.G., 2006. The yield responses of naked oats to phosphorus fertilizer and phosphorus behaviour in chestnut soil in a long-term experiment. Plant Nutr. Fert. Sci. 12, 201-207. (In Chinese with English abstract)

Ma, Y.B., Li, J.M., Li, X.Y., Tang, X., Liang, Y.C., Huang, S.M., Wang, B.R., Liu, H., Yang, X.Y., 2009. Phosphorus accumulation and depletion in soils in wheat-maize cropping systems: modeling and validation. Field Crops Res. 110, 207-212.

Motavalli, P.P., Miles, R.J., 2002. Soil phosphorus fractions after 11 years of animal manure and fertilizer applications. Biol. Fertil. Soils, 36, 35-42.

Page, A.L., Millar, R.H., Keeney, D.R., 1982. Methods of soil analysis: part 2. American society of Agronomy/Soil Science Society of America, Madison, Wisconsin.

Selles, F., Campbell, C.A., Zentner, P.R., 1995. Effect of cropping and fertilization on plant and soil-phosphorus. Soil Sci. Soc. Am. J. 59, 140-144.

Sharpley, A., Moyer, B., 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29, 1462-1469.

Sharpley, A.N., Smith, S.J., Stewardt, B.A., Mathers, A.C., 1984. Forms of phosphorus in soil receiving cattle feedlot waste. J. Environ. Qual. 13, 211-215.

Sims, J.T., Kleinman, P.J.A., 2005. Managing agricultural phosphorus for environmental protection. In: Sims, J.T., Sharpley, A.N. (eds) Phosphorus: Agriculture and Environment. American Society of Agronomy. Madison, Wisconsin, pp. 1021-1068.

Sims, J.T., Wolf, D.C., 1994. Poultry waste management: agricultural and environmental issues. Adv. Agron. 52, 1-83.

Singh, M., Tripathi, A.K., Reddy, K.S., Singh, K.N., 2001. Soil phosphorus dynamics in a Vertisol as affected by cattle manure and nitrogen fertilization in soybean-wheat system. J. Plant Nutr. Soil Sci. 164, 691-696.

Tang, X., Li, J.M., Ma, Y.B., Hao, X., Li, X.Y., 2008. Phosphorus efficiency in long-term (15 years) wheat-maize cropping systems with various soil and climate conditions. Field Crops Res. 108, 231-237.

Toor, G.S., Peak, J.D., Sims, J.T., 2005. Phosphorus speciation in broiler litter and turkey manure produced from modified diets. J. Environ. Qual. 34, 687-697.

Turner, B.L., Leytem, A.B., 2004. Phosphorus compounds in sequential extracts of animal manures: chemical speciation and a novel fractionation procedure. Environ. Sci. Technol. 38, 6101-6108.

Wang, Y.C., Wang, E., Wang, D.L., Huang, S.M., Ma, Y.B., Smith, C.J., Wang, L.G., 2010. Crop productivity and nutrient use efficiency as affected by long-term fertilisation in North China Plain. Nutr. Cycl. Agroecosyst. 86, 105-119.

Whalen, J., Chang, C., 2001. Phosphorus accumulation in cultivated soils from long-term annual applications of cattle feedlot manure. J. Environ. Qual. 30, 229-237.