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Phosphorus status and its sorption-associated soil properties in a paddy soil as affected by organic amendments

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Abstract
Purpose Yet the transformation and contribution of amorphous aluminum and iron which are usually indicated as oxalate-extractable forms (Al_{ox} and Fe_{ox}) to phosphorus (P) sorption in paddy soils, under long-term organic amendments combined with alternating flooding and draining, were not fully understood. The aim of this study was to investigate the effects of organic amendments on P status and P sorption-associated attributes including Al_{ox} and Fe_{ox} in a paddy soil.
Materials and methods We selected 26 study sites that varied in three fertilization regimes (i.e., MF, straw, and manure) and three management histories (i.e., 2, 8, and 13 years) in the experiment station. Soil samples were assayed for (1) P accumulation status including total P, Olsen-P, oxalate-extractable (P_{ox}) and degree of soil saturation with P (DPS), and (2) soil properties associated with P sorption including pH, soil organic matter (SOM), Al_{ox}, and Fe_{ox}.
Results and discussion Manure application presented significantly greater values for DPS (16.3 %, $P<0.01$), Olsen-P/TP ratio (4 %, $P<0.01$), and Olsen-P/P_{ox} ratio (6.8 %, $P<0.01$). Moreover, it increased the contents of Al_{ox} and Fe_{ox} in the paddy soil, especially the content of Al_{ox}. Phosphorus accumulation in the paddy soil was not significant in straw treatment vs. MF treatment. Both Al_{ox} ($P<0.01$) and Fe_{ox} ($P<0.05$) exhibited significantly linear relationships with SOM, suggesting that the organo-Al(Fe) complexes might widely generate in the paddy soil, which have strong affinity to P. In comparison with Fe_{ox}, Al_{ox} showed greater correlation coefficients with soil P forms (varying from 0.56 to 0.81) and higher predictability for DPS of the paddy soil (R^2=0.3679, $P<0.01$).
Conclusions These results suggest that Al_{ox} is the primary soil property associated with P sorption in the paddy soil under long-term organic amendments and repeated redox circulations.

Keywords Manure · Paddy soil · Phosphorus status · Straw incorporation

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1 Introduction

Organic amendments, such as application of manure and compost, and the incorporation of crop residues are effective methods to improve soil fertility and productivity (Zhu et al. 2010). Recently, the incorporation of crop residues to the soil is highly advocated in China, since the burning of residues in situ by farmers, as usually did, is causing a serious waste of nutrient resources besides contributing to air pollution. In the Taihu Lake region of the Yangtse River Delta, a typical area with rice cultivation in China, organic amendments are widely practiced to benefit soil fertility and productivity. However, long-term intensive fertilizer and/or manure application that often exceeds seasonal plant nutrient uptake has resulted in a significant phosphorus (P) accumulation and loss in this area, becoming a potential source of eutrophication in the Taihu Lake (Zhang et al. 2004, 2005; Shan et al. 2005).

Phosphorus sorption capacity, a measure of the maximum amount of P that a soil can retain, can provide valuable information for proper P management in order to minimize the transport of P from soil to water. Among the soil properties associated with soil P sorption, aluminum and iron extracted by ammonium oxalate (Al_{ox} and Fe_{ox}, respectively) are known to play predominant roles in controlling P retention in soils subjected to flooding and draining for rice cultivation (Yan et al. 2013). There are numerous studies reporting that flooding can significantly influence the precipitation and transformation of Al_{ox} and Fe_{ox} in wetland soils (e.g., Darke and Walbridge 2000; Schönbrunner et al. 2012). During soil flooding, the ferric (Fe) phosphates are solubilized when Fe(III) is reduced to Fe(II) (Ponnamperuma 1972); thus, it seems that Al_{ox} might be particularly important as an agent of P retention in paddy soils.

Additionally, soil organic matter (SOM) tends to accumulate in paddy soils as a result of long-term organic amendments, since anaerobic conditions associated with flooding impede the decomposition of SOM. The increased SOM could enhance the formation of organo-Al(Fe) complexes in paddy soils, which has strong affinity to P (Kang et al. 2009) and, in turn, benefit soil P sorption. In contrast, there are evidences that suggest that organic anions also can reduce P sorption capacity of existing oxides by competing with phosphate ions for binding sites (Guppy et al. 2005; Hua et al. 2008). This points the need to investigate the net effect of long-term organic amendments on P sorption capacity of paddy soils.

Although there are several studies with respect to P accumulation and movement in the paddy soils in Taihu Lake region (e.g., Zhang et al. 2004; Shan et al. 2005), these studies mainly focus on potential environmental risk of paddy soil to aquatic system without regarding soil P sorption capacity. Actually, P sorption capacity associated with amorphous Al and Fe contents could affect the P loss from the soil. Yet the transformation and contribution of Al_{ox} and Fe_{ox} to P sorption in paddy soils, under long-term organic amendments combined with flooding and draining rotation, were not fully understood (Yan et al. 2013). The main objectives of this study were to investigate the effects of long-term organic amendments on P status and P sorption capacity, associated with Al_{ox}, Fe_{ox} and SOM, of the paddy soils in Taihu Lake region. We hypothesized that under long-term organic material input, the contents of Al_{ox} and Fe_{ox} in the paddy soil will increase and that Al_{ox} may be more important in determining P sorption in the paddy soil compared with Fe_{ox}.

2 Materials and methods

The paddy soils (0–15 cm) with different fertilization regimes and cultivating histories were collected from Changshu Agroecological Experiment Station of the Chinese Academy of Sciences (31° 32′ 45″ N, 120° 41′ 57″ E), Jiangsu, China. This station is located in Taihu Lake region, where the cropping system is paddy rice and upland winter wheat rotation. Under the northern subtropical humid marine monsoon climate, this location had an average annual precipitation of 1, 200 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 and has a Ap1/Ap2/Bhg/Cg horizon (represented plough/plough pan/hydragric/gleyic horizons) as a result of long-term rice–wheat rotation (Gong et al. 1999).

2.1 Experiment design

We selected 26 study sites that varied in three fertilization regimes, i.e., (i) MF, mineral fertilizer only; (ii) straw, rice/wheat retained in addition to mineral fertilizer; and (iii) manure, swine manure in addition to mineral fertilizer, and three management histories (i.e., 2, 8, and 13 years) in the experiment station. Phosphorus source, input, and management history for each site are listed in Table 1. Mineral P applied for all the study sites was single superphosphate [$Ca(H_2PO_4)_2$, SSP]. Fifteen sites were selected for the MF treatment, which only received SSP at rates ranging 30–90 kg P ha^{-1} $year^{-1}$. Five sites were selected for the straw treatment, in which three sites received 30 kg ha^{-1} $year^{-1}$ of mineral P combined with rice/wheat straw equivalent to 2–5 kg P ha^{-1} $year^{-1}$, and the other two sites incorporated 45 kg P ha^{-1} $year^{-1}$ as SSP and 3–15 kg P ha^{-1} $year^{-1}$ as rice/wheat straw. Six sites were selected for the manure treatment, which had swine manure application equivalent to 30–80 kg P ha^{-1} $year^{-1}$ along with mineral P application of 45 kg P ha^{-1} $year^{-1}$. On average, the SSP used in our study contained 61.1 g P kg^{-1}; the swine manure contained 400 g C kg^{-1}, 9.3 g N kg^{-1}, 9.6 g P kg^{-1}, and 8.8 g K kg^{-1}; the wheat straw contained 441 g C kg^{-1}, 4.0 g N kg^{-1}, 0.4 g P kg^{-1}, and 51 g K kg^{-1}; and the rice straw

Table 1 Outline description for the fertilization scenarios and management histories of the sites studied

	Number soil samples	P source	*P* input (kg ha^{-1} $year^{-1}$)	Duration (years)
MF	3	SSP	45	8
	4	SSP	30	13
	4	SSP	60	13
	4	SSP	90	13
Straw	3	SSP+straw	30, 2–5	2
	2	SSP+straw	45, 3–15	8
Manure	3	SSP+manure	45, 30–40	8
	3	SSP+manure	45, 60–80	8

SSP single superphosphate, *MF* mineral fertilizer, *straw* rice and/or wheat straw retained after harvested plus mineral fertilizer, *manure* swine manure plus mineral fertilizer contained 400 g C kg^{-1}, 7.2 g N kg^{-1}, 1.6 g P kg^{-1}, and 36 g K kg^{-1}.

Crop cultivation and field management were performed according to local farming practice. Generally, the rice-growing season lasts from early June to middle October, whereas the wheat-growing season lasts from November to May of next year. Soils are typically submerged in water during the rice-growing season except a short drying period (5–7 days) in the late tillering stage of rice to control the disabled tillering, as well as to provide favorable conditions for rice growth. Otherwise, the paddy field was drained for cultivation of upland wheat.

2.2 Soil sampling and analysis

Soil samples which consisted of five separate cores (5-cm diameter) were collected from 0 to 15 cm from each plot after the harvest of rice in October 2011. The samples were air-dried, ground to pass a 2-mm sieve, and stored at low humidity prior to analyses.

Soil pH was measured in a 1:2.5 (soil/water ratio, w/v) mixture using a glass electrode, and SOM was determined using the potassium dichromate sulfuric acid oxidation method (Nelson and Sommers 1982) by a conversion factor of 1.724. Total P was determined by perchloric acid digestion (Kuo 1996). Briefly, 1 g of soil was treated with concentrated H_2SO_4 (8.00 ml) and ten drops of $HClO_4$ and digested at 200 °C until almost white sands 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 (Olsen and Sommers 1982). After filtration, the P concentration in the extracts mentioned above was determined colorimetrically by the method of Murphy and Riley (1962). Ammonium oxalate-extractable P, Al, and Fe were determined by shaking 1:40 (w/v) soil/ammonium oxalate extracting solution (pH 3.0) for 2 h, centrifuging at 5,000 rpm 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 degree of P saturation (DPS) was obtained for all the samples using the equation: $\mathrm{DPS} = \frac{P_{ox}}{Al_{ox}+Fe_{ox}} \times 100$, where the P_{ox} was oxalate-extractable P expressed in mmol kg^{-1}, and Al_{ox}+Fe_{ox} was the sum of oxalate-extractable Fe and Al which was also expressed in mmol kg^{-1}.

2.4 Statistical analysis

The results were statistically analyzed using one-way analysis of variance tests (ANOVA), correlation analysis, simple linear regression, and multiple linear regression using "stepwise" procedure. The differences between means were analyzed with least significant difference (LSD) analysis at P=0.05. The interaction effects of fertilization and management history on soil attributes were not obtained since two-way ANOVA could not be performed due to the relatively insufficient samples in our study, but this was not the main objective of our study. The statistical analyses were performed using SAS 8.2 software (SAS Institute 2001).

3 Results

3.1 Phosphorus accumulation

Total P, extractable P forms (Olsen-P and P_{ox}), and DPS, were significantly affected by the fertilization pattern (P<0.01, Table 2). Manure application had the highest soil P accumulation, interpreted by significantly higher DPS value and greater contents of various soil P forms (TP, Olsen-P, and P_{ox}; P<0.01), while the straw treatment did not significantly increase soil P accumulation compared with the MF treatment (P>0.05). To eliminate the influence of P application rates and management histories among the three fertilization treatments, we used the proportions of extractable P forms to TP (i.e., Olsen-P/TP and P_{ox}/TP) to better understand P accumulation in the paddy soil. No significant difference was observed for P_{ox}/TP among the three fertilization treatments (P>0.05). The mean values of Olsen-P/TP ratio and Olsen-P/P_{ox} ratio of the manure treatment were 3.99 % (±0.17 % SE) and 6.81 % (±0.91 % SE), respectively, which were significantly higher than those of the other treatments (P<0.01, Table 2), suggesting that there was a greater accumulation of labile P with long-term manure application in the paddy soil.

3.2 Changes in soil properties associated with P sorption

Organic amendments exerted various influence on soil pH, and the contents of SOM, Al_{ox}, and Fe_{ox} which play a role in P sorption. In accordance with the changes in soil P accumulation, the manure treatment had significantly higher Al_{ox} and SOM contents and pH (47.56 mmol kg^{-1}, 42.24 g kg^{-1}, and 7.22, respectively, P<0.05, Table 2). By contrast, no significant difference in Fe_{ox} was observed when compared among fertilization treatments (P>0.05, Table 2), although the mean value of Fe_{ox} for the manure treatment was greater than that of Al_{ox} (95.16 vs. 47.56 mmol kg^{-1}).

3.3 Soil properties effects on P status

Soil organic matter, Al_{ox}, and Fe_{ox} were the determining factors in influencing P status in the paddy soil studied. The three soil attributes were significantly correlated with Olsen-P and

Table 2 Phosphorus status and associated soil properties for the paddy soil under different fertilization patterns

Soil property	MF (8 and 13 years)			Straw (2 and 8 years)			Manure (8 years)			*P* value
	Range	Mean	S.E.	Range	Mean	S.E.	Range	Mean	S.E.	
Olsen-P [mg kg^{-1}]	5.53–33.18	18.37 b	2.61	12.67–24.55	17.76 b	2.73	32.63–58.58	45.88 a	4.79	**
P_{ox} [mg kg^{-1}]	234–724	449 b	43	272–495	365 b	36	364–1007	724 a	101	**
TP [g kg^{-1}]	0.59–1.10	0.79 b	0.04	0.48–0.87	0.66 b	0.09	0.95–1.38	1.14 a	0.08	**
Olsen-P/TP [%]	0.85–3.69	2.19 b	0.23	2.24–2.84	2.68 b	0.11	3.44–4.52	3.99 a	0.17	**
P_{ox}/TP [%]	26.39–76.40	55.84	3.55	41.69–69.46	57.02	4.49	36.92–80.48	62.96	6.93	NS
Olsen-P/P_{ox} [%]	1.53–6.25	4.01 b	0.38	3.68–6.82	4.85 b	0.54	4.28–10.85	6.81 a	0.91	**
SOM [g kg^{-1}]	36.85–43.69	40.21 ab	0.48	33.68–42.73	37.73 b	2.06	37.67–45.62	42.24 a	1.23	*
pH	6.49–7.52	6.92 b	0.06	6.88–7.06	6.95 b	0.03	6.76–7.48	7.22 a	0.11	*
Al_{ox} [mmol kg^{-1}]	26.78–49.07	39.58 b	1.51	28.61–38.19	33.59 b	1.79	37.01–63.10	47.56 a	3.72	**
Fe_{ox} [mmol kg^{-1}]	48.52–108.76	80.48	4.19	71.94–92.71	84.86	4.40	52.31–134.25	95.16	10.97	NS
DPS [%]	8.75–17.75	11.80 b	0.73	8.35–12.21	9.88 b	0.68	12.41–20.84	16.29 a	1.63	**

Means with different letter in the same row have significantly different at $P<0.05$

Olsen-P $NaHCO_3$ extracted P, *TP* total P, *SOM* soil organic matter, *DPS* degree of P saturation, calculated as $P_{ox} \times 100A/(Al_{ox}+Fe_{ox})$, *$P_{ox}$, Al_{ox}, and Fe_{ox}* ammonium oxalate extracted P, Al, and Fe, respectively, *NS* not significant

** $P<0.01$; * $P<0.05$

TP ($P<0.05$) except the correlation between Fe_{ox} and TP (Table 3). Moreover, the correlation coefficients for Al_{ox} and soil P forms were higher than those for Fe_{ox}. Correlation analysis results indicated that there was no significant correlation for the pH and P status in the paddy soil (Table 3).

Soil properties associated with P accumulation (i.e., SOM, Al_{ox}, and Fe_{ox}) were significantly interrelated ($P<0.05$), for which the correlation coefficients varied from 0.41 to 0.79 (Table 3). Soil organic matter was able to explain roughly 27 % of the $Al_{ox}+Fe_{ox}$ variability ($P<0.05$, Fig. 1). For individual parameter, the linear regression *R*-square for Al_{ox} and SOM was greater than that for Fe_{ox} (0.49 vs. 0.17). Stepwise multiple regression suggested that SOM, Al_{ox}, and Fe_{ox} can provide a reliable prediction for DPS of the paddy soil ($R^2=0.3851$, $P<0.05$), in which Al_{ox} played the predominant role for the prediction ($R^2=0.3697$, $P<0.01$, Table 4).

Table 3 Pearson correlation coefficients of soil P forms and associated soil attributes at 0–15 cm depth in the paddy soil

	Olsen-P	P_{ox}	TP	SOM	pH	Al_{ox}	Fe_{ox}
Olsen-P	1						
P_{ox}	0.86**	1					
TP	0.93**	0.83**	1				
SOM	0.44*	0.58**	0.56**	1			
pH	NS	NS	NS	NS	1		
Al_{ox}	0.56**	–	0.60**	0.70**	NS	1	
Fe_{ox}	0.41*	–	NS	0.41*	NS	0.79**	1

SOM soil organic matter, *TP* total phosphorus, *P_{ox}, Al_{ox}, and Fe_{ox}* ammonium oxalate extracted P, Al, and Fe, respectively, *NS* not significant; – not available because P_{ox} was not independent of Al_{ox} and Fe_{ox}

** $P<0.01$; * $P<0.05$

4 Discussion

4.1 Effects of organic amendments on P-related properties

Wen et al. (2014) suggested that long-term organic fertilization could influence the transformation of Al fractions, converting exchangeable Al to organically bound and other amorphous patterns. By contrast, Pizzeghello et al. (2011, 2014) reported that some calcareous soils treated with mineral fertilizer showed higher values of Fe_{ox}/Fe_t (total Fe) and Al_{ox}/Al_t (total Al) ratios compared with soils treated with organic amendments. It is known that the oxalate extract dissolves both noncrystalline and organically bond Fe and Al forms. The observation that the paddy soil treated with organic amendments had relatively higher content of Al_{ox} was presumably due to the enhanced formation of organo-Al complexes, as SOM increased through organic fertilization. There was a significant positively linear regression between SOM and Al_{ox} ($R^2=0.49$, $P<0.01$, Fig. 1). Additionally, the presence of organic matter can inhibit mineral crystallization which, in turn, enables the formation of poorly crystalline oxides (Börling et al. 2001). Given that organic amendments may contain Al and/or Fe (e.g., Li et al. 2014), the organic materials incorporated in soils can also directly impact soil Al and/or Fe content. Further investigation of the apparent balance of Al and Fe in the paddy soil for

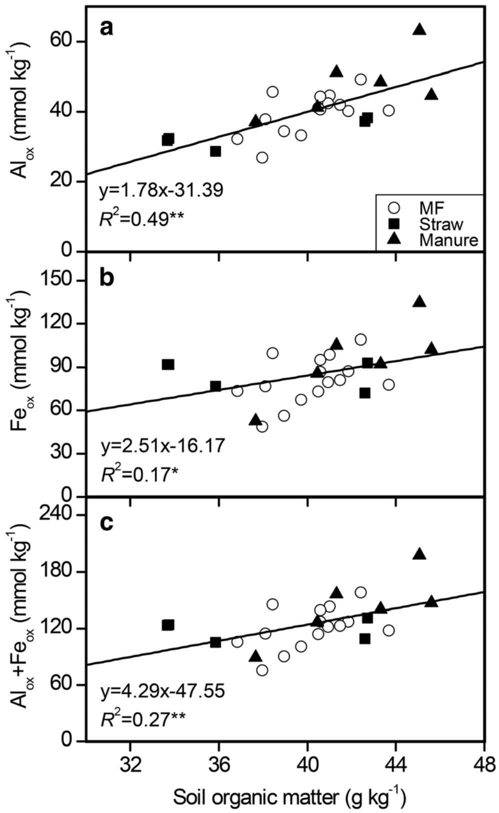

Fig. 1 Relationships between soil organic matter and **a** oxalate extracted Al (*Al_{ox}*), and **b** oxalate extracted Fe (*Fe_{ox}*), and **c** the summation of Al_{ox} and Fe_{ox} (*$Al_{ox}+Fe_{ox}$*). *MF* mineral fertilizer, *straw* rice and/or wheat straw retained after harvested plus mineral fertilizer, *manure* swine manure plus mineral fertilizer. $^{*}P<0.05$; $^{**}P<0.01$

organic treatments will benefit our understanding of Al_{ox} and Fe_{ox} increment.

Long-term manure application in the paddy soil resulted in increased soil pH which is the most important factor in regulating P retention ($P<0.05$, Table 2). A considerable amount of calcium (Ca), as a result of the Ca–P additives in the diet, along with initial higher pH value in swine manure may contribute to the increased soil pH (Li et al. 2014). On the other hand, Ca input via swine manure to the paddy soil could impact soil P status, thus more attention needs to be paid to soil Ca–P (e.g., noncrystalline Ca–P) in the manure treatment.

4.2 Effects of organic amendments on soil P sorption capacity

Al_{ox} and Fe_{ox} have been widely used to assess P sorption capacity of noncalcareous soils (Van der Zee and Van Riemsdijk 1988; Maguire et al. 2001). Although the content of Al_{ox} was less than that of Fe_{ox}, Al_{ox} exhibited greater correlation coefficients with soil P forms than Fe_{ox}, suggesting that Al was more important to P accumulation in the paddy soil (Table 2). This could be due to interaction between Fe and other minerals, or a preference of P sorption onto certain Al minerals. In contrast to Fe, in flooded environments, the Al chemistry is not affected by the changes redox potentials, and its dynamics is controlled by the tendency of Al to form complexes with the SOM (Darke and Walbridge 2000). Similar results were also reported by Penn et al. (2005) that Fe oxides and/or amorphous Fe (ammonium oxalate extracted) showed weaker correlation with soil P retention than amorphous Al. Eriksson et al. (2015) used X-ray absorption near edge spectroscopy (XANES) to characterize P speciation and found that P was adsorbed mostly to Al (hydr)oxides in soils after fertilization whereas preferred for sorption to Fe in unfertilized soils.

Degree of P saturation is considered as a useful indicator for proper P management to minimize the transport of P from soil to water (Beauchemin and Simard 1999; Kleinman and Sharpley 2002). We conducted multiple linear regression to determine the best fitting model for DPS and to identify the crucial soil properties associated with DPS. As expected, SOM, Al_{ox} and Fe_{ox} could desirably predict the DPS of the paddy soil. Moreover, consistent with the results of correlation analysis, the regression *R*-square of Al_{ox} was much greater than that of Fe_{ox}, indicating Al_{ox} was the crucial element in predicting DPS of the paddy soil (Table 4). Long-term organic amendments are of great benefit to SOM buildup, thereby enhancing the generating of ogano-(Fe, Al) complexes that control the P sorption capacity in the paddy soil (Fig. 1). Our results showed that organic amendments enhanced P sorption capacity of the paddy soil since SOM, Al_{ox}, and Fe_{ox} were increased due to organic treatments (Table 2). Therefore, the DPS of the paddy soil treated by organic

Table 4 Multiple linear regression formulae describing the relationship between soil properties and degree of phosphorus saturation (DPS) for the 26 paddy soils

Response	Independent variables	Equation	*R*-square	*P* value
DPS vs. SOM, Al_{ox} and Fe_{ox}				
DPS	SOM, Al_{ox}, and Fe_{ox}	$DPS=-3.73+0.169(SOM)+0.265(Al_{ox})-0.015(Fe_{ox})$	0.3851	0.0121
	Al_{ox}	$DPS=1.038+0.28374(Al_{ox})$	0.3697	0.001
DPS vs. SOM, Alox+Feox				
DPS	SOM and $Al_{ox}+Fe_{ox}$	$DPS=-9.55+0.399(SOM)+0.048(Al_{ox}+Fe_{ox})$	0.3397	0.0085

SOM soil organic matter, *Al_{ox} and Fe_{ox}* ammonium oxalate extracted Al and Fe, respectively amendments was, in part, alleviated compared with that treated with mineral fertilizer only if they had equivalent P input.

4.3 Effects of organic amendments on soil P accumulation

Our results indicated that manure application in paddy soil made a more vigorous accumulation of P, in terms of active P (Olsen-P), compared with straw application (Table 2). This is probably because the majority of P components in swine manure are H_2O- and $NaHCO_3$-extractable P fractions which are weakly bounded and susceptible to lose (Li et al. 2014). No significant difference in soil P accumulation was observed when compared between straw and MF treatments, probably because P content in straw was relatively lower compared with the P in manure. Zhu et al. (2010) also reported that, in an 8-year field experiment, chemical fertilizers plus straw incorporation did not significantly increase soil TP and Olsen-P contents in subtropical region of China compared with chemical fertilizer application.

Phosphorus accumulation in soil under a certain fertilization treatment or P budget usually exhibited a linear correlation with management history (Whalen and Chang 2001; Messiga et al. 2010; Ciampitti et al. 2011). In our study, the effect of management history on P accumulation in paddy soil was not fully elucidated due to the insufficient samples for each field monitoring period (Table 1), as this was not the main purpose of our study. The observation that 8-year managing history, but not 13 years, made the highest soil P accumulation (data not shown), was likely due to the fact that the nutrient source for all the samples of 8-year management was mainly manure application, of which the P input was relatively higher (Table 1).

5 Conclusions

Results of this study showed that P status and its sorption-associated soil properties of the paddy soil was differentiated by fertilization patterns. Manure application having more P surplus made the most vigorous accumulation of P in terms of active P, which presented significantly greater value for the ratios of Olsen-P/TP (P<0.01) and Olsen-P/P_{ox} (P<0.01). Phosphorus accumulation in the paddy soil treated by mineral fertilizer plus straw incorporation was not significant, as compared with applied chemical fertilizers alone. In addition, long-term swine manure application increased the contents of amorphous Al and Fe (i.e., Al_{ox} and Fe_{ox}) in the paddy soil, especially the content of Al_{ox}. Both Al_{ox} and Fe_{ox}, Al_{ox}, in particular, exhibited significantly linear relationships with SOM (P<0.05), suggesting that the possible formation of organo-Al(Fe) complexes, having strong affinity to P, occurs in the paddy soil. However, Al_{ox} showed greater correlation coefficients with soil P forms compared with Fe_{ox}.

Empirical results of this study suggested that Al_{ox} was the crucial soil property associated with P sorption in the paddy soil under long-term organic amendments and repeated redox circulations. To Al_{ox}, however, the specific mechanisms of the relatively stronger affinity with P was not well investigated in this study. Further research will stress on the specific reactions among Al, Fe, P, and SOM in the paddy soil under long-term organic amendments and repeated redox circulations.

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