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RESEARCH ARTICLE

Fate of low-molecular-weight organic phosphorus compounds in the P-rich and P-poor paddy soils

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Abstract

Continuous application of organic fertilizers can cause accumulation of organic phosphorus (P) in soil, especially in the low-molecular-weight organic phosphorus (LMWOP) forms. This organic P pool represents a potentially important source of P for both plants and microorganisms. To understand the effect of long-term fertilization (30 years) (P-rich soil) *vs*. fallowing (P-poor soil) on the bioavailability and fate of LMWOP in subtropical paddy soils, we determined the sorption and mineralization of ^{14}C-labeled adenosine, adenosine monophosphate (AMP), adenosine diphosphate (ADP), and adenosine triphosphate (ATP) in each soil. The contents of carbon, nitrogen, and P in the P-rich soil were more than two times greater than those in the P-poor soil. The mineralization rates of the LMWOP compounds were faster in the P-rich soil compared to the P-poor soil, and followed the order AMP>ADP>ATP. Using sterilized soil, all forms of adenosine-P were strongly sorbed to the solid phase and reached saturation in a short time, with the adsorbance increasing with the number of phosphate groups. We concluded that the mineralization of LMWOP compounds was repressed slightly by sorption to the solid phase, but only in the short term. Thus, LMWOP compounds serve as readily available sources of C for microorganisms, making P available for themselves as well as for the plants. However, P accumulation and the progressive saturation of the P sorption sites in highly fertile soils may increase the potential risk of P runoff.

Keywords: rice paddy, phosphatase, phosphorus cycling, microbial community

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1. Introduction

Phosphorus (P) is one of the most important nutrients for crops. The fate of the inorganic P pool, including its movement in the soil and its adsorption/desorption reaction, has been intensively studied (Kögel-Knabner *et al.* 2010; Yan *et al.* 2013, 2017). Organic forms of P comprise 20–80%

of the total P in the soils, and they represent a potential source of P for both plants and microorganisms (Chen *et al.* 2003; Fransson and Jones 2007; Zhang *et al.* 2014; Arruda *et al.* 2018; Hu *et al.* 2018). Fertile soils are generally rich in organic-P fractions, which are labile or moderately labile, including compounds such as nucleic acids, phospholipids, inositol phosphates, phosphoproteins, and P-containing metabolic compounds, such as adenosine phosphates (Lee *et al.* 2004; Fransson and Jones 2007). These compounds may represent up to 50% of the organic P pool in soils (Turner *et al.* 2003; Vats *et al.* 2005; Li *et al.* 2016). Thus, in order to develop sustainable agricultural systems by improving P utilization, it is essential to understand the factors that regulate the dynamics of the major forms of labile organic-P in soil.

Cycling of organic-P in soil is largely regulated by the activity of plant roots and microorganisms (Chen *et al.* 2003; Parham 2014; Yokoyama *et al.* 2017; Wei *et al.* 2019a), which produce enzymes to mineralize P-containing organic compounds (e.g., phosphatases), as well as being sources of these compounds (e.g., in root and microbial turnover). For instance, ATP is one of the dominant forms of P in plant tissues (i.e., ATP contents of pea shoots and roots are 113 and 98 mmol g^{-1}; Smyth and Black 1984) and microbial cells (i.e., ATP content in bacterial cells is 0.6–4.2 mmol L^{-1}; Yaginuma *et al.* 2014). ATP can be released from dead cells but is also excreted into the environment by Gram-positive and Gram-negative bacteria (Mempin *et al.* 2013) and by plant roots (from actively growing root regions where cell expansion is occurring; Kim *et al.* 2006; Ge *et al.* 2019). The role of the ATP released by living bacterial cells is still under discussion, but ATP is a possible source of nutrients or a signaling molecule for bacterial communities (Mempin *et al.* 2013). ATP contains not only C and P, but also N, therefore the products of its degradation can serve as sources of multiple nutrients for both microorganisms and plants.

The availability of P in the soil depends on a combination of environmental and biological factors, including: i) the amount and type of clay minerals, i.e., presence of gibbsite and goethite increases the sorption of inorganic P, making it unavailable for plants (Li *et al.* 2016); ii) oxygen content, i.e., frequent changes in soil moisture (pulse redox conditions) mobilizes labile forms of organic P (Yevdokimov *et al.* 2016; Gu *et al.* 2018; Wei *et al.* 2019b); and iii) pH conditions, i.e., the acidification of the rhizosphere by root exudates (i.e., by carboxylic acids) increases P availability (Bending 2017). The type of fertilizer applied also directly and indirectly affects soil microbial community composition and activity (Yao *et al.* 2016; Wei *et al.* 2017, 2019a; Yu *et al.* 2019), which in turn is responsible for P mineralization *via* the production of hydrolytic enzymes. However, it is still not clear what regulates the turnover of dissolved organic-P (DOP) in rice paddy soils, because: i) The Eh and pH are frequently fluctuating (Yan *et al.* 2017), ii) the contents of Al and Fe are high, and iii) these soils are always fertilized with either organics, mineral fertilizers, or a combination of the two (Lan *et al.* 2012; Dong *et al.* 2014). For low-molecular-weight compounds (sugars, carboxylic and amino acids), it is known that microbial utilization overcomes sorption on the mineral matrix (Fischer *et al.* 2010; Gunina *et al.* 2014). However, it is not clear whether the same patterns could be observed for organic-P compounds present in soil solutions in paddy environments.

Thus, the present research hypothesized that the sorption and mineralization of organic P substrates in soils will be affected by: i) the number of phosphate groups within the organic-P compound, because this part of molecule can be sorbed to the mineral phase, and ii) soil fertility level (contents of total carbon (C), nitrogen (N) and P), because it directly affects microbial activity. To test these hypotheses, the base compound (adenosine) with either 1, 2, or 3 phosphate groups — namely adenosine monophosphate (AMP), adenosine diphosphate (ADP), and adenosine triphosphate (ATP) (all labeled with ^{14}C) — were obtained, and their fates in P-rich (fertilized) and P-poor (fallow) paddy soils were studied in a short-term laboratory experiment.

2. Materials and methods

2.1. Soil samples

Soil samples were collected from the Changsha Research Station for Agricultural and Environmental Monitoring (113°19′52′′E, 28°33′04′′N) in Jingjin County, Hunan Province, China. Two soil samples were collected from: i) fertilized soil, as the P-rich soil from a site that was cultivated for rice (*Oryza sativa* L.) and fertilized with a combination of pig manure and inorganic fertilizer that contained 120 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1} in every growing season, and ii) a P-poor (control) soil, which was under fallow for the same period of time. Soil samples were collected from a depth of 0–20 cm in four replicates, sieved (<2 mm), and stored dry prior to analysis. The soil was a typical Stagnic Anthrosol developed from granitic red parent material, and had 6.1% clay, 61.1% silt, and 32.8% sand for the control, and 5.5% clay, 50.6% silt, and 43.9% sand for the P-rich soil. The main characteristics of the soils are presented in Table 1. Importantly, the Olsen-P content was significantly higher in the P-rich than in the P-poor soil (42.45 *vs*. 3.87 mg kg^{-1}).

2.2. Chemical analyses

The pH and electrical conductivity (EC) were determined

Table 1 Chemical characteristics for the P-rich and P-poor paddy soils at 0–20 cm depth[1)]

Paddy soil	pH	EC (μs cm^{-1})	TN (g kg^{-1})	SOC (g kg^{-1})	Olsen-P (mg kg^{-1})	TP (g kg^{-1})	DOC (mg kg^{-1})	MBC (mg kg^{-1})
P-poor	5.27±0.01	69.7±0.21 b	1.48±0.01 b	14.8±0.17 b	3.87±0.02 b	0.42±0.04 b	79.9±1.74 b	150.4±14.0 b
P-rich	5.04±0.01	138.7±0.21 a	2.44±0.08 a	29.8±0.83 a	42.5±1.34 a	1.03±0.02 a	118.3±6.16 a	175.9±8.56 a

[1)] EC, electrical conductivity; TN, total nitrogen; SOC, soil organic carbon; Olsen-P, available phosphorus; TP, total phosphorus; DOC, dissolved organic carbon; MBC, microbial biomass carbon.
Values represent mean±SE (n=4). Significant differences at P<0.05 level are shown by different letters within the same column.

with a standard electrode with a soil/water ratio of 1:2.5 (w/v). Soil moisture content was determined by drying at 105°C for 24 h, and total C and N were obtained by the dry combustion method (Vario MAX, Elementar Analysen System GmbH, Germany). Total P content in soil was measured by a molybdate blue method after the soil samples were digested in a mixture of nitric and perchloric acids. Olsen-P was extracted into 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) solution by shaking at 205 r min^{-1} for 30 min (Ding *et al.* 2012). Soil dissolved organic C (DOC) was extracted with K_2SO_4 (0.5 mol L^{-1}) and measured with a liquid-TOC analyzer (Phoenix-8000). Soil microbial biomass C (MBC) was determined by chloroform fumigation-extraction (Wu *et al.* 1990).

2.3. Organic-P mineralization

Five grams of dry soil was placed into a 50 mL centrifuge tube, hydrated to 50% of WHC, and later saturated to over 100% by placing a water table 1 cm above the soil surface, and pre-incubated for 2 weeks at 20°C. There were 20 tubes for each soil. After pre-incubation, 0.5 mL of a ^{14}C-labeled solution (0.2 kBq mL^{-1}) of either [8-^{14}C]-adenosine (Sigma-Aldrich Corp, USA), [U-^{14}C]-adenosine monophosphate (AMP; NEN-Dupont, USA), [8-^{14}C]-adenosine diphosphate (ADP; NEN-Dupont), or [8-^{14}C]-adenosine triphosphate (ATP; NEN-Dupont) were added to each soil type at five concentrations: 10, 50, 100, 500 and 1 000 μmol L^{-1}. To collect the $^{14}CO_2$ producted from mineralization of the added compounds, a 1 mol L^{-1} NaOH trap (1 mL) was placed inside the tube which was then tightly sealed and incubated in the dark at 20°C for 168 h. The NaOH traps were replaced after 1, 3, 6, 24, 48, 72 and 168 h. The amount of $^{14}CO_2$ captured was determined by liquid scintillation counting (Wallac EG & G, Milton Keynes, UK). After 168 h, 25 mL of 0.5 mol L^{-1} KH_2PO_4 was added to all samples and the tubes were shaken for 30 min in order to extract any free ^{14}C organic compounds still remaining in the soil. Subsequently, a 1 mL aliquot of the 0.5 mol L^{-1} KH_2PO_4 extract was removed and centrifuged (18 000×g for 5 min) to remove microorganisms/particles from the solution. The radioactivity of the solution was determined as described above.

2.4. Organic-P sorption

Sorption experiments were conducted using the soils sterilized by autoclave at 121°C for 30 min (Serrasolsas and Khanna 1993). The autoclaving eliminated microorganisms that could degrade the ^{14}C-labelled substrates and denatured any phosphatases that existed in the soil (Fransson and Jones 2007; Roberts *et al.* 2007). Solid phase sorption of each substrate was determined by shaking 2.5 g of soil with 5 mL of each ^{14}C-labeled compound for periods of up to 3 h. The same ^{14}C-labeled compounds listed above were used, namely: [8-^{14}C]-adenosine, [U-^{14}C]-AMP, [8-^{14}C]-ADP, or [8-^{14}C]-ATP. The ^{14}C-labeled solutions (0.2 kBq mL^{-1}) were added at five concentrations: 10, 50, 100, 500 and 1 000 μmol L^{-1} into the soil. After shaking for either 0.25, 1, 3, or 6 h, an aliquot of solution (350 μL) was removed from the soil suspensions. Aliquots were centrifuged at 18 000×g for 5 min and ^{14}C activity in the supernatant was determined as described above.

2.5. Statistical and data analysis

The mineralization of substrates is bi-phasic, with a rapid first phase followed by a second slow phase (Hill *et al.* 2011). The $^{14}CO_2$ efflux from the soil after the addition of ^{14}C-labelled substrates was best fitted to a first order double exponential decay equation (Hill *et al.* 2011):

$$y=\alpha_1\times(1-\exp^{-k_1\times t})+\alpha_2\times(1-\exp^{-k_2\times t}) \quad (1)$$

where k_1 and k_2 are the coefficients describing the fast and slow mineralization phases, respectively, and a_1 and a_2 describe the sizes of the pools. The $t_{1/2}$ of the soil solution substrate pool (a_1) was calculated as:

$$t_{1/2}=\ln(2)/k_1 \quad (2)$$

Freundlich isotherm was fitted to the data from the sorption experiment and the amount of sorbed compounds was calculated as follows:

$$S=\alpha\times ESC^b \quad (3)$$

where S is the amount of sorbed (μmol g^{-1}) compounds, a and b are empirically derived parameters (Roberts *et al.* 2007), ESC is the equilibrium solution concentration at the end of the experiment (μmol L^{-1}), The partition coefficient (K_d) was calculated as follows:

$$K_d=S/ESC \quad (4)$$

All data represented the means of four replicates with their standard errors. The analysis of significant differences was performed by one-way ANOVA at the 95% confidence level (P<0.05). Residuals were checked for normality and homogeneity. All analyses were conducted with SigmaPlot 10.0 (SPSS Inc., Chicago, IL).

3. Results

3.1. Soil characteristics

The two paddy soils used in the experiments differed significantly in their chemical characteristics (Table 1). The EC, and total N, C, and P in the P-rich soil were *ca*. two times higher compared to those in the P-poor soil, whereas Oslen-P was 11 times higher.

3.2. Mineralization of substrates

Mineralization curves of adenosine and the three organic P substrates showed a biphasic $^{14}CO_2$ evolution (Fig. 1). The total amount of ADP mineralized in the P-rich soil was 1.5 times greater than in the P-poor soil (Fig. 1) with similar values being observed for adenosine, AMP, and ATP. Generally, less than 1% of the initially applied ^{14}C was recovered in a 0.5 mol L^{-1} K_2SO_4 extract at the end of a 7-day incubation period, which suggested a nearly complete utilization of all compounds by the microbial community.

There was a significant divergence in mineralization rates among the substrates during the initial utilization phase

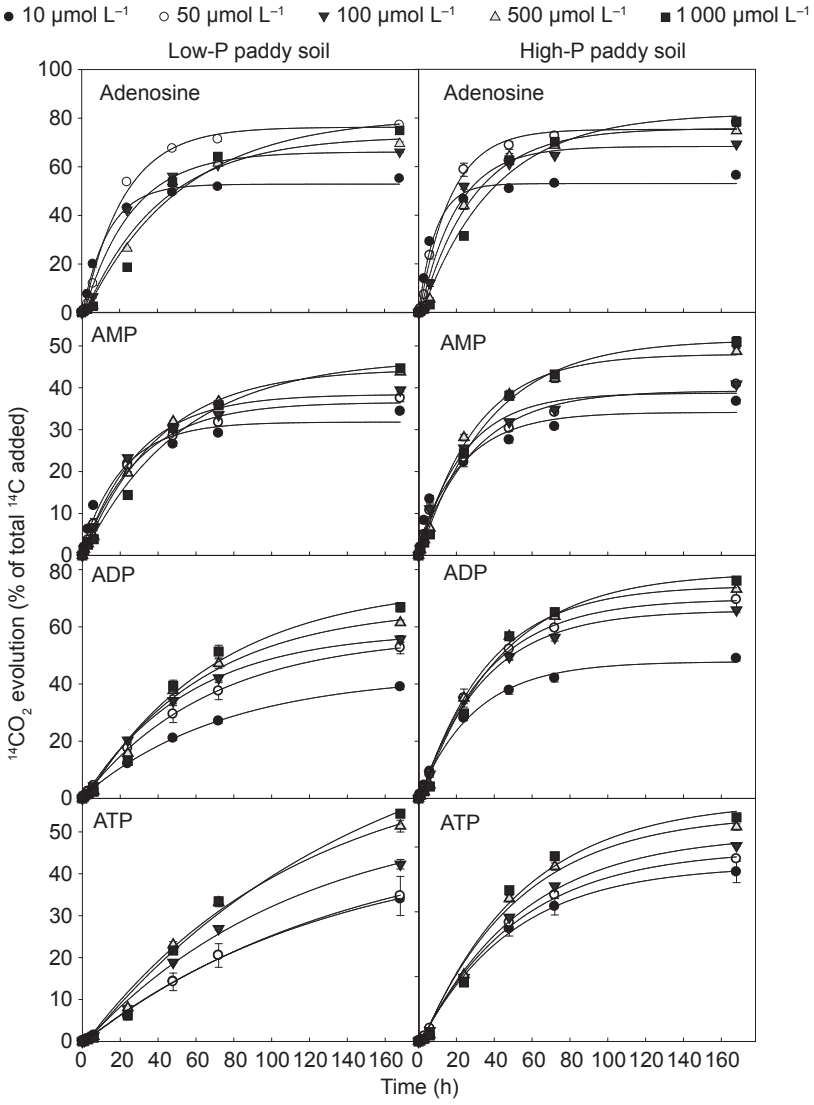

Fig. 1 Time-dependent mineralization of ^{14}C-labeled adenosine, AMP, ADP and ATP at concentrations ranging from 10 to 1 000 μmol L^{-1} in P-rich and P-poor paddy soils in comparison to their non-phosphorylated counterparts (10 to 1 000 μmol L^{-1} of adenosine). Values represent mean±SE (n=3).

(first 48 h): for the first hour, mineralization rates followed the order AMP>ADP>adenosine>ATP in both paddy soils (Fig. 2). After 48 h, the mineralization rates followed a different trend: adenosine>ADP>ATP>AMP in both soils (Fig. 2). Moreover, the mineralization rates increased for adenosine and ATP, but decreased for AMP in both soils. These results indicated that the soil microorganisms utilized the AMP and ADP as C or P sources first, and then adenosine and ATP. Moreover, the mineralization rate of P-containing substrates was always higher in the P-rich soil than in the P-poor soil as a function of incubation time.

3.3. Half-life of adenosine substrate-derived C in soil

The half-life ($t_{1/2}$) of C derived from each adenosine substrate increased with increasing the applied concentration in both soils (Table 2). The $t_{1/2}$ of the adenosine substrates increased to 3–10 times with increasing the number of phosphate groups for both soils depending on the concentration (Table 2). The $t_{1/2}$ of ADP- and ATP-derived C was 1.5 and 3 times slower in the P-rich soil than in the P-poor soil, whereas $t_{1/2}$ of AMP-C and adenosine-C was the same in both soils. Thus, the increasing $t_{1/2}$ of adenosine compounds with increasing the number of phosphate groups can reflect the effect of sorption on the mineral matrix, which can partially affect microbial mineralization. The faster $t_{1/2}$ of the studied compounds in the P-rich soil indicated higher microbial activity than in the P-poor soil.

3.4. Sorption of organic-P compounds

The sorption of the ^{14}C-labeled adenosine compounds to the solid phase was time-dependent and followed the same pattern in both paddy soils: ATP=ADP>AMP>adenosine (Fig. 3). The sorption was very fast for all compounds and reached the maximum after 15 min. The Freundlich sorption isotherm showed that saturation was not reached over the applied concentration range of the substances (10 to 1 000 μmol L^{-1}) (Fig. 4). The Freundlich parameter *a* increased with the number of phosphate groups, whereas parameter *b* decreased in both paddy soils (Table 3). The solid-to-solution partition coefficients K_d for AMP, ADP, and ATP were concentration-dependent and decreased with substrate concentration in both soils, but there was no dependency for adenosine (Table 3). Moreover, the K_d increased with an increasing number of phosphate groups from adenosine to ATP. Additionally, K_d was always greater for ATP in the

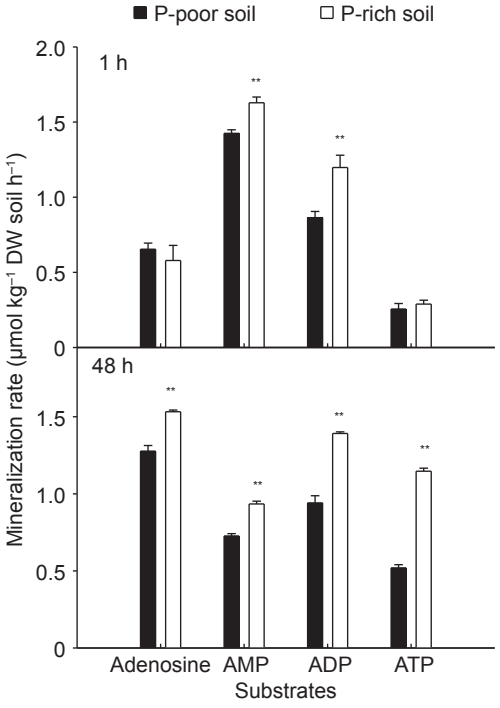

Fig. 2 Mineralization rates of ^{14}C-labeled adenosine, AMP, ADP, and ATP at a concentration of 1 000 μmol L^{-1} after 1 h and 48 h of incubation in the P-rich and P-poor paddy soils. Values represent mean±SE (n =4). ** represent significant differences of same substrate between two paddy soils at the P<0.01 level.

Table 2 Half-life ($t_{1/2}$) of ^{14}C-labeled adenosine, AMP, ADP and ATP in P-poor and P-rich soils[1)]

Paddy soil	Concentration (μmol L^{-1})	Adenosine		AMP		ADP		ATP	
		$t_{1/2}$ (h)	R^2	$t_{1/2}$ (h)	R^2	$t_{1/2}$ (h)	R^2	$t_{1/2}$ (h)	R^2
P-poor	10	9.7±0.6	0.99	15.1±1.0	0.97	51.7±1.8	0.99	91.6±1.5	0.99
	50	15.0±0.3	0.99	21.1±2.5	0.99	49.5±6.4	0.99	78.6±4.5	0.99
	100	17.6±0.6	0.99	20.3±0.3	0.99	38.4±1.1	0.99	78.6±4.5	0.99
	500	28.1±0.3	0.98	27.8±0.6	0.99	43.4±1.6	0.99	79.3±3.2	0.99
	1 000	35.4±1.2	0.98	35.7±0.9	0.99	48.2±1.8	0.98	105.1±7.5	0.99
P-rich	10	6.4±0.3	0.99	16.7±2.9	0.96	20.6±0.5	0.99	33.7±0.6	0.99
	50	12.3±0.6	0.99	20.5±2.1	0.98	24.6±1.4	0.99	35.9±1.0	0.99
	100	13.4±0.6	0.99	16.9±0.5	0.99	23.7±0.8	0.99	37.3±0.5	0.99
	500	19.3±0.7	0.99	20.6±0.5	0.99	24.7±0.7	0.99	37.3±0.5	0.99
	1 000	26.6±0.3	0.99	25.8±1.6	0.99	29.2±0.5	0.99	37.1±0.7	0.98

[1)] The R^2 coefficients represent the goodness of fit of a double first-order kinetic decay model to the experimental data. Values represent mean±SE (n=4).

P-poor soil than in the P-rich soil, except when ATP was applied at concentrations above 500 μmol L^{-1}. The results showed that organic P sorption increased with the number of phosphate groups and decreased with increased nutrient availability.

4. Discussion

Long-term fertilization can improve soil fertility of paddy surface soils (Abdi *et al.* 2014; Yan *et al.* 2017; Liu *et al.* 2019; Wang *et al.* 2019; Zhang *et al*. 2019) by increasing the total C, N, and P contents, as well as increasing the size of the microbial biomass (Table 1). Mineralization of organic-P compounds in both paddy soils was similar for the fast stage (0–24 h) followed by a slower mineralization stage (24–168 h), which was consistent with the report of a previous study (Fransson and Jones 2007). The results indicated that high rates of phosphatase activity and dephosphorylation of the added compounds occur almost immediately, which makes adenosine available for uptake by soil microbes (Fransson

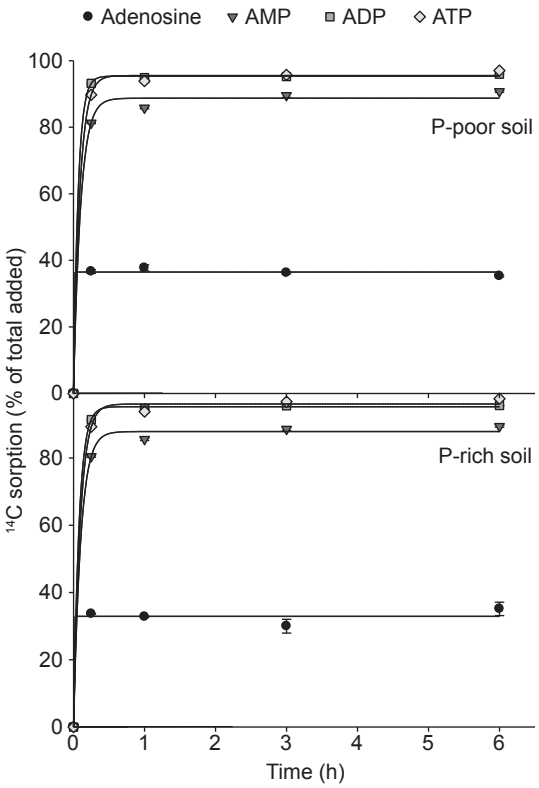

Fig. 3 Sorption of ^{14}C-labeled adenosine, AMP, ADP, and ATP in P-poor and P-rich paddy soils. The initial concentration was 500 μmol L^{-1}. Values represent mean±SE (n=3).

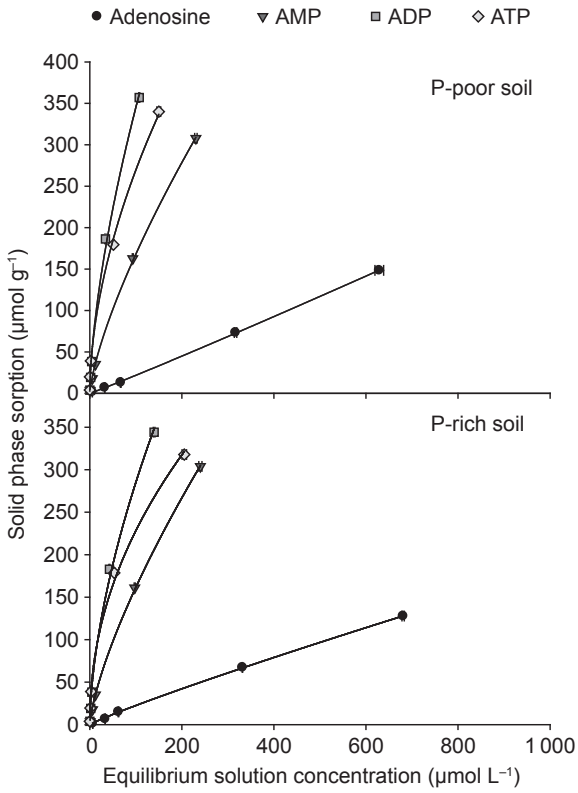

Fig. 4 Sorption isotherms for ^{14}C-labeled adenosine, AMP, ADP, and ATP in P-poor and P-rich paddy soils. Values represent mean±SE (n=3).

Table 3 Parameters of Freundlich sorption isotherm fits to the sorption of different ^{14}C-labeled substrates to the solid phase at different concentrations in P-poor and P-rich soils[1)]

Paddy soil	Substrate	a	b	K_d for various substrate concentrations				
				10 μmol L^{-1}	50 μmol L^{-1}	100 μmol L^{-1}	500 μmol L^{-1}	1 000 μmol L^{-1}
P-poor	Adenosine	0.18±0.02	1.05±0.02	0.32	0.22	0.19	0.23	0.24
	AMP	5.82±0.45	0.73±0.02	4.57	3.15	2.83	1.74	1.34
	ADP	18.81±3.28	0.63±0.04	14.43	10.18	9.40	5.47	3.32
	ATP	21.36±3.66	0.55±0.04	160.70	85.82	17.23	3.49	2.27
P-rich	Adenosine	0.35±0.041	0.91±0.02	0.22	0.20	0.24	0.20	0.19
	AMP	5.74±0.45	0.73±0.02	3.62	2.98	2.85	1.65	1.26
	ADP	18.11±3.27	0.60±0.04	12.38	8.98	8.53	4.28	2.46
	ATP	25.43±3.56	0.48±0.03	36.49	15.61	13.62	3.34	1.55

[1)] The a and b values are empirically derived parameters for calculation of the amounts of sorbed compounds, and K_d is the solid-to-solution partition coefficient for adenosine compounds for the various substrate concentrations.

and Jones 2007). The adsorption capacity of organic P is closely related to the number of phosphate groups (Condron 2005). Consistent with our first hypothesis, the K_d was the lowest for adenosine, followed by AMP and ADP, and the highest for ATP. Higher adsorption leads to lower microbial accessibility (Cabrita *et al.* 2002; Giannecchini *et al.* 2005; Tozzi *et al.* 2006). As a result, the mineralization rates of organic P substrates decreased with the increasing number of phosphate groups, regardless of soil fertility. The mineralization rates of ADP and ATP were accelerated over time, potentially indicating that phosphatase activity was increased with prolonged incubation times.

As expected by our second hypothesis, the mineralization rates of added LMWOP compounds were profoundly affected by soil fertility, which was significantly higher in the P-rich than P-poor soil. Many studies have found that the addition of exogenous nutrients or increasing of the soluble orthophosphate concentration in soil could potentially increase phosphatase activity and accelerate the mineralization process of organic P (Fox and Comerford 1992; Marklein and Houlton 2012; Wei *et al.* 2018). The results most likely attributed to the stimulatory effect of increased P availability on phosphatase activity. In additional, the LMWOP was much more accessible to microorganisms in P-rich soil, supported by the greater K_d of LMWOPs in P-poor soil than in P-rich soil (Table 3). Also, organic matter accumulation could compete with P for absorption sites, therefore decreasing P adsorption capacity and increasing P availability in soil (Mikutta *et al.* 2006; Lindegren and Persson 2009; Pavinato *et al.* 2009; Fink *et al.* 2016). In our study, the SOC in P-rich soil was 2 times higher than that in P-poor soil (Table 1). Consequently, P sorption in the P-rich soil was smaller than in the P-poor soil (the strongest for ATP) (Table 3). However, long-term fertilization in soil enhances P accumulation and decreases the soil P saturation capacity (Wang *et al.* 2012; Yan *et al.* 2013, 2017). This can also have a negative consequence for highly fertile paddy soils, leading to an increased risk of P runoff during rice cultivation (Zhang *et al.* 2003; Shan *et al.* 2005; Wang *et al.* 2012; Yan *et al.* 2017).

The sorption of organic-P on the solid phase was largely completed within 15 min (Fig. 3). The sorption did not greatly interfere with the mineralization of AMP, especially at the low substrate concentrations where sorption to the solid phase was the strongest (Table 3). These results were consistent with previous findings (Fransson and Jones 2007), which showed that microorganisms can promote desorption of adenosine compounds from the mineral matrix and utilize them. P-solubilizing microorganisms are common in soil, which produce organic acids and H^+ during the metabolism of organic C (Alori *et al.* 2017). The $t_{1/2}$ of ADP- and ATP-derived C were two times faster in the P-rich soil than in the P-poor soil. However, a small variation for $t_{1/2}$ of both compounds between the applied concentrations was found (Table 2). These observations indicated that phosphatase activity was high in both soils, with an additional increase in the production of phosphatases in the P-rich soil. The $t_{1/2}$ of AMP-C was even higher at some of the applied concentrations, which suggested that phosphatase activity did not limit the utilization of LMWOP compounds if only one phosphate group was present (Fransson and Jones 2007).

5. Conclusion

Long-term fertilization of paddy soils not only increased the contents of essential nutrients (C, N, and P) but also improved LMWOP mineralization. Mineralization rates of adenosine phosphates were the highest for AMP and the lowest for ATP in both soils, indicating that the number of phosphate groups can partially affect this process. However, the microbial activity was higher in the P-rich than P-poor soil, as indicated by the faster mineralization rates of ADP and ATP. The sorption of AMP was lower than ADP and ATP, and each respective adenosine phosphate showed the same sorption trend in both soils. Thus, these results suggested that on the one hand soil fertilization can improve the capacity of the microbial community to mineralize LMWOP, and thus promote plant nutrition; but on the other hand, it can increase the risk of P runoff.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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