Organic Phosphorus Fractions in Organically Amended Paddy Soils in Continuously and Intermittently Flooded Conditions

Changming Yang,* Linzhang Yang, and Lee Jianhua

ABSTRACT

Soil organic phosphorus (SOP) can greatly contribute to plant-available P and P nutrition. The study was conducted to determine the effects of organic amendments on organic P fractions and microbiological activities in paddy soils. Samples were collected at the Changshu Agro-ecological Experiment Station in Tahu Lake Basin, China, from an experiment that has been performed from 1999 to 2004, on a paddy soil (Gleysols). Treatments consisted of swine manure (SM), wheat straw (WS), swine manure plus wheat straw (SM + WS), and a control (chemical fertilization alone). Organic amendments markedly increased soil total organic phosphorus (TOP) and total organic carbon (TOC), especially in continuously flooded conditions. Based on the fractionation of SOP, organic amendments significantly increased soil labile organic phosphorus (LOP), moderately labile organic phosphorus (MLOP), and moderately stable organic phosphorus (MSOP) compared with the control. For SM and SM + WS treatments, LOP in continuously flooded soils decreased by 30.1 and 36.4%, respectively, compared to intermittently flooded soils. In organically amended soils, continuous flooding showed significantly lower microbial biomass phosphorus (MBP) and alkaline phosphatase activities (APA) than intermittent flooding. In intermittently flooded conditions, incorporating organic amendments into soil resulted in greater P uptake and biomass yield of rice than the control. In the intermittently flooded soils, APA (P < 0.05) and MBP (P < 0.01) were significantly and positively related to TOP, LOP, MLOP, and MSOP, whereas in continuously flooded soils, there was a significant (P < 0.05) negative relationship between MBP, TOP, and MSOP. Based on soil organic P fractions and soil enzymatic and microbiological activities, continuous flooding applied to paddy soils should be avoided, especially when swine manure is incorporated into paddy soil.

Phosphorus (P) has been one of the major nutrients limiting agricultural production in many regions of the world, and certainly this is the case in China, where soils deficient in P account for one-third of the cultivated land (Lu, 1989). Soil organic phosphorus (SOP) plays a significant role in P nutrition of crops especially in high-P-fixing calcareous soils (Taraifar and Claasson, 1988). The SOP can constitute a significant portion of total phosphorus (TP), ranging from 20 to 80% in most mineral soils (Stevenson, 1982), and can contribute substantially to plant-available P through mineralization (Sharpley, 1985). It is essential to include inorganic and organic P in soil P fertility tests to better predict plant responses (Sharpley, 1985). However, soil total organic phosphorus (TOP) might not be sensitive to changes in soil management practices in a relatively short time (Chater and Mattingly, 1980).

Because SOP is a heterogeneous mixture of organic substances, the different forms or fractions of SOP might have different effects on soil fertility and quality. Phosphorus fractionation has proven useful in identifying bio-geochemical soil P pools in various ecosystems (Hedley et al., 1982; Tiessen et al., 1983; Crews et al., 1995). The sequential technique of extraction developed by Bowman and Cole (1978) has proved very useful in quantifying soil organic P pools of different availability and is widely used to study effects of cropping, fertilizer, and management practices on the soil P status in long-term field experiments (Richards et al., 1995; Schmidt et al., 1996; Zhang and Mackenzie, 1997). According to Bowman and Cole (1978), SOP is separated into four distinct fractions based on stability: labile organic phosphorus (LOP), moderately labile phosphorus (MLOP), moderately stable organic phosphorus (MSOP), and highly stable organic phosphorus (HSOP). Zhang et al. (1994) suggests that the LOP and MLOP determined by Bowman and Cole’s method is a very useful index of whether a particular soil is rich in available organic P.

Soil organic P must first be hydrolyzed by soil phosphatases to inorganic forms such as H$_2$PO$_4^-$ and HPO$_4^{2-}$ before it can be utilized and taken up by plant roots from the soil solution (Tate, 1984; Marshner, 1995; He et al., 2004). Soil phosphatase activity can be a good indicator of the organic P mineralization potential and biological activity of soils (Chen, 2003). Soil microbial biomass, as a major sink and source of plant-available P, also plays a key role in the biochemical transformation process of SOP (Stewart and Tiessen, 1987). The immobilization of P in the microbial biomass is an important factor in maintaining and controlling the rate of P cycling through soils (Rodríguez and Fraga, 1999; Kramer and Green, 2000).

Paddy soil, as an anthropogenic soil, is an important soil resource in China, accounting for 20% of the total arable land. Pedogenesis of paddy soil is greatly affected by agricultural management such as cultivation, irrigation, and fertilization (Zhang and Gong, 2003). Due to continuous flooding and application of high rates of exclusively mineral fertilizers, the paddy soils in China are undergoing degradation of soil physical, chemical, and biological properties (Yang and Yang, 2005), which...
adversely affects rice plant growth and sustainable local agricultural development. Thus, adoption of appropriate and integrated nutrient and water management is of paramount importance in sustainable use of paddy soil.

The effects of agricultural management practices on paddy soil inorganic P supply are well documented (Gill and Mcelu, 1982; Campbell et al., 1991; Muhammad et al., 1992; Soon, 1998; Singh et al., 2001; Kalbasi and Karthikeyan, 2004). Most of the previous research focused on the influences of fertilization treatments on the dynamics of paddy soil P. However, there has been very little research so far on the effects of agricultural water management practices on organic P fractions and microbial and enzymatic activities involved in organic cycling and transformation in a manured anthropogenic soil from lacustrine deposit.

The objective of this study was to determine the relative effectiveness of combined application of inorganic and organic fertilizers on organic P fractions and microbiological and enzymatic activities involved in P transformation and cycling in continuously and intermittently flooded paddy soils. The goal was to establish a foundation for integrated and sustainable paddy soil management systems.

MATERIALS AND METHODS

Experimental Site Descriptions

This field experiment was initiated in 1999 at the Changshu Agro-ecological Experiment Station (CAES), Chinese Academy of Sciences, situated in Changshu City, Jiangsu province of China (31°33′ N, 120°42′ E, and altitude of 15 m). The region is part of Taihu Lake Basin in a subtropical and humid monsoon climate with average annual temperature of 15.5°C and precipitation of 1038 mm. The paddy soils under investigation is part of Taihu Lake Basin in a subtropical and humid monsoon climate with average annual temperature of 15.5°C and precipitation of 1038 mm. The paddy soils under investigation are developed on lacustrine deposits, and belong to Gleysols according to FAO (1998). Selected soil physical and chemical properties are given in Table 1.

Experimental Design and Soil Fertilization and Water Treatments

The experiment was laid out in a randomized complete block design using four replications. Plot size was 5 × 6 m. Four treatments were as follows: (i) swine manure applied at the rate of 15 Mg ha⁻¹ (SM), (ii) wheat straw added at the rate of 25 Mg ha⁻¹ (WS), (iii) swine manure plus wheat straw (SM + WS), each added at the rate of 10 Mg ha⁻¹ and 20 Mg ha⁻¹, respectively, and (iv) chemical fertilization with no organic amendments added (CK). Each plot received equal 150 kg N ha⁻¹, 45 kg P ha⁻¹, and 60 kg K ha⁻¹. Amounts of the N, P, and K were determined for swine manure and wheat straw. The remaining required N, P, and K was provided by chemical fertilizers. The P and K fertilizers were applied as superphosphate and potassium sulfate, respectively, as basal application when transplanting. Chemical N fertilizer was split into three applications: one-half was as NH₄HCO₃ at transplanting, one-fifth, and the remainder as urea, at tillering and booting, respectively. Swine manure was obtained from an intensive pig rearing farm near CAES. Swine waste biosolids consisted of feces, hair, and corn meal feed and were composted before application. Swine manure and wheat straw were chopped and incorporated into paddy soil 2 wk before transplanting each year. Total C, N, P, and K (g kg⁻¹) of swine manure were 368 ± 59.7, 19.3 ± 3.56, 9.87 ± 2.18, and 8.65 ± 1.34 g kg⁻¹, respectively; wheat straw contained 402 ± 67.8 g kg⁻¹ C, 7.15 ± 1.21 g kg⁻¹ N, 1.67 ± 0.34 g kg⁻¹ P, and 17.82 ± 3.16 g kg⁻¹ K, respectively. A common rice cultivar (Oryza sativa L. cv. Suõx 821) was transplanted in mid June with spacing of 15 × 15 cm and population density of 444000 plants ha⁻¹.

Two soil water regimes included: (i) continuous flooding, which involved flooding of plots to a depth of approximately 3 to 5 cm throughout the rice growth period, and (ii) intermittent flooding, which involved flooding (approximately 3 to 5 cm above the soil surface) for 3 wk after transplanting, followed by alternate 2-wk periods of drainage, then re-flooding. Plots were kept under intermittently flooded conditions until rice harvested. When drying, plots were maintained at field capacity to ensure that plants did not suffer any water stress.

Soil Sample Collection and Analysis

Soil Sampling

Soil samples were randomly collected from each plot in October 2004 using a 5.8-cm-diameter core tube inserted to a depth of 20 cm. Each sample consisted of five subsamples, which were mixed and homogenized to obtain a composite sample. Soil samples were processed by sieving through a 4.75-mm sieve at field moisture content. The subsamples for biological and biochemical analysis were directly stored at 4°C for 4 to 6 wk before analyses. Part of each sample was subsequently air-dried and finely ground (<2 mm) for chemical analysis.

Soil Organic Phosphorus Fractioning

Soil organic phosphorus (SOP) was separated into four fractions using a modified sequential extraction procedure developed by Bowman and Cole (1978) and modified by Fan et al. (1999). A flow diagram for the soil organic P fractionation procedure is given in Fig. 1. Highly stable organic phosphorus (HSOP) is derived from the difference between stable organic P and moderately stable organic phosphorus (MSOP). The MSOP and HSOP represent fulvic and humic acid P, respectively. The P concentration in all extracts was determined colorimetrically according to the method of Murphy and Riley (1962).

Soil Samples Analysis

Total phosphorus (TP) in the paddy soil samples was digested in a tri-acid mixture (HNO₃, HClO₄, and H₂SO₄ at a 3:1:1 ratio). The P concentration in the digest was determined colorimetrically using the vanado-molybdate-yellow color

Table 1. Selected physical and chemical characteristics of the surface soil (0–20 cm) used in this study.

<table>
<thead>
<tr>
<th>Clay</th>
<th>Sand</th>
<th>pH (H₂O 1:1)</th>
<th>OM†</th>
<th>Total N</th>
<th>Total P</th>
<th>Available P‡</th>
<th>Available K</th>
<th>CEC§</th>
<th>Feox¶</th>
<th>Alox¶</th>
</tr>
</thead>
<tbody>
<tr>
<td>467</td>
<td>154</td>
<td>7.85</td>
<td>32.1</td>
<td>1.88</td>
<td>0.62</td>
<td>8.3</td>
<td>120</td>
<td>16.9</td>
<td>13.2</td>
<td>5.47</td>
</tr>
</tbody>
</table>

† Organic matter.
‡ 0.5 M NaHCO₃ extraction (Olsen et al., 1954).
§ Cation exchange capacity; 1 M NH₄OAc method (Thomas, 1982).
¶ The subscript ox denotes acid ammonium oxalate extraction (Hodges and Zelazny, 1980).
method (Jackson, 1973). Soil total organic phosphorus (TOP) was determined after combustion at 550°C and extraction with 4 M H2SO4 (Anderson, 1960). Olsen P was analyzed by using the colorimetric molybdenum blue method following extraction with 0.5 mol NaHCO3 L⁻¹ (Olsen et al., 1954). Soil total organic carbon (TOC) was analyzed by means of dry combustion with an automatic nitrogen and carbon analyzer–mass spectrometer (ANCA–MS). Kjeldahl N content as total nitrogen was determined by digestion in H2SO4 followed by colorimetric analysis with the indophenol blue method, using a spectrometer (Nelson and Sommers, 1980).

Soil microbial biomass carbon (MBC) was estimated by fumigation of the sample with ethanol free CHCl₃ and extraction with 0.5 mol L⁻¹ K₂SO₄ using a conversion efficiency \((k_c)\) of 0.35 (Vance et al., 1987). Soil microbial biomass phosphorus (MBP) was determined by the fumigation–extraction method (Brookes et al., 1982). Microbial biomass phosphorus (MBP) was calculated as NaHCO₃–extractable inorganic P in the fumigated soil minus that extracted from unfumigated soil, divided by a conversion efficiency \((k_P)\) of 0.40.

Alkaline and neutral phosphatase activities (APA and NPA, respectively) in the soil samples were assayed using a modified disodium phenyl phosphate method (Alef and Nannipieri, 1995). Briefly, soil subsamples (5 g) were mixed with 10 mL of disodium phenyl phosphate solution (25 g L⁻¹) as substrate and thereafter incubated for 12 h at a temperature of 37°C in pH 10.0 acetate buffer for APA estimation or pH 7.0 citric-phosphate buffer for NPA. For the analyses, the buffer was diluted with sterile distilled water to 100 mL and released phenol was determined at 578 nm. Phosphatase activities were

![Flow diagram for soil organic P fractionation procedure](image-url)
Table 2. Total P and organic P as affected by organic amendments in intermittently and continuously flooded paddy soils.

<table>
<thead>
<tr>
<th>Water regime</th>
<th>Treatment†</th>
<th>TOC‡</th>
<th>TP‡</th>
<th>TOP‡</th>
<th>TOC to TOP ratio</th>
<th>TOP to TP ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermittently flooded</td>
<td>SM</td>
<td>15.9 ± 2.1 d</td>
<td>1.06 ± 0.17 a</td>
<td>180 ± 27.1 b</td>
<td>88.8</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>19.4 ± 4.2 e</td>
<td>1.09 ± 0.25 a</td>
<td>156 ± 24.3</td>
<td>125.2</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>SM + WS</td>
<td>17.7 ± 1.8 c</td>
<td>0.98 ± 0.21 a</td>
<td>175 ± 35.1 b</td>
<td>101.7</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>CK</td>
<td>10.2 ± 1.2 e</td>
<td>1.02 ± 0.23 a</td>
<td>105 ± 21.5 d</td>
<td>103.9</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>SM</td>
<td>19.8 ± 3.4 b</td>
<td>1.04 ± 0.36 a</td>
<td>201 ± 43.0 a</td>
<td>88.4</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>26.7 ± 6.7 a</td>
<td>1.08 ± 0.23 a</td>
<td>163 ± 23.9 c</td>
<td>161.3</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>SM + WS</td>
<td>21.5 ± 4.1 b</td>
<td>0.97 ± 0.17 a</td>
<td>185 ± 32.1 bc</td>
<td>110.5</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>CK</td>
<td>11.3 ± 1.4 e</td>
<td>1.00 ± 0.24 a</td>
<td>108 ± 17.2 d</td>
<td>109.5</td>
<td>0.11</td>
</tr>
<tr>
<td>Continuously flooded</td>
<td>SM</td>
<td>4.58 ± 0.62 c</td>
<td>0.29 ± 0.07 e</td>
<td>3.78 ± 0.03 e</td>
<td>5.24</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>3.87 ± 0.97 c</td>
<td>0.33 ± 0.17 b</td>
<td>3.43 ± 0.43 c</td>
<td>3.78</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>SM + WS</td>
<td>3.34 ± 0.97 c</td>
<td>0.26 ± 0.21 e</td>
<td>3.34 ± 0.03 e</td>
<td>2.87</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>CK</td>
<td>4.12 ± 0.62 a</td>
<td>0.41 ± 0.17 b</td>
<td>4.12 ± 0.03 e</td>
<td>4.21</td>
<td>0.11</td>
</tr>
</tbody>
</table>

† The terms SM, WS, SM + WS, and CK indicate swine manure, wheat straw, swine manure plus wheat straw, and chemical fertilization treatments, respectively.
‡ TOC, total organic carbon; TP, total phosphorus; TOP, total organic phosphorus.
§ Values are means ± SE; means followed the same letter are not significantly different ($P < 0.05$) by Duncan’s multiple range test.
LOP, MLOP, and MSOP in the organically fertilized soils increased by 131, 107, and 91%, respectively, compared to the control. The extent of the increases in soil LOP and MLOP due to incorporation of organic manure into the plots was significantly ($P < 0.01$) larger for SM$_1$WS treatment followed by SM treatment. There was no significant ($P > 0.05$) difference in highly stable organic phosphorus (HSOP) between chemically and organically fertilized paddy soils (Table 3). Continuous flooding increased MSOP, but significantly ($P < 0.05$) decreased the content of labile organic P in the paddy soil for all the organic treatments. The differences in LOP and MLOP between the two water regimes were more pronounced for SM$_1$WS treatment. In continuously flooded soils, for instance, the content of LOP for SM, WS, and SM$_1$WS declined by 30, 27, and 36%, respectively, compared to intermittently flooded soils. This demonstrates that continuously flooding markedly weakened the effectiveness of organic treatments in increasing soil labile organic P.

### Effect of Nutrient and Water Regimes on the Paddy Soil Microbial Biomass Carbon and Phosphorus

Soil microbial biomass phosphorus (MBP) for all the treatments with organic materials increased significantly ($P < 0.05$) compared to the control (Fig. 2a). In intermittently flooded soils, MBP values for SM, WS, and SM + WS treatments were, respectively, 108, 80, and 154% higher than that of the control. Continuously flooded conditions showed significantly ($P < 0.05$) lower MBP in the paddy soils fertilized by organic manure compared with intermittently flooded conditions (Fig. 2a). In continuously flooded soils, MBP values for SM, WS, and SM + WS treatments decreased by 30.6, 21.6, and 33.6%, respectively, compared to continuously flooded soils. Soil MBC followed a pattern similar to MBP, and was also significantly affected by fertilization treatments with the exception that the addition of wheat straw showed higher soil MBC relative to swine manure (Fig. 2b). The intermittently flooded condition enhanced the soil MBC, especially for the fertilization treatments with organic amendments (Fig. 2b).

### Effect of Nutrient and Water Regimes on the Paddy Soil Phosphatase Activity

Organic amendments significantly ($P < 0.05$) increased soil phosphatase activities, especially alkaline phosphatase activity, regardless of water regimes (Fig. 3). The differences in soil APA between organic and chemical fertilization treatments were considerably greater in

![Fig. 2. Microbial biomass P (a) and microbial biomass C (b) as affected by fertilization treatments in intermittently (■) and continuously (□) flooded paddy soils, respectively. The terms SM, WS, SM + WS, and CK indicate swine manure, wheat straw, swine manure plus wheat straw, and chemical fertilization treatments, respectively. Bars represent standard errors.](image-url)

![Fig. 3. Alkaline phosphatase activity (a) and neutral phosphatase activity (b) as affected by fertilization treatments in intermittently (■) and continuously (□) flooded paddy soils, respectively. The terms SM, WS, SM + WS, and CK indicate swine manure, wheat straw, swine manure plus wheat straw, and chemical fertilization treatments, respectively. Bars represent standard errors.](image-url)
intermittently flooded conditions than in continuously flooded conditions. In intermittently flooded soils, for example, the APA values for SM, WS, and SM + WS treatments were, respectively, 154, 141, and 170% greater than that of the control, whereas in continuously flooded soils, the increases were, respectively, 124, 127, and 124% (Fig. 3a). Very similar results were obtained from the determination of soil neutral phosphatase (NPA), but the differences between fertilization and water treatments were much smaller relative to APA (Fig. 3b).

**Table 4.** Linear correlations of soil phosphatase activities and microbial biomass P to soil organic P fractions.

<table>
<thead>
<tr>
<th>Water regime</th>
<th>Measured variable†</th>
<th>TOP</th>
<th>LOP</th>
<th>MLOP</th>
<th>MSOP</th>
<th>HSOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermittently flooded</td>
<td>APA</td>
<td>0.617**</td>
<td>0.782**</td>
<td>0.628**</td>
<td>0.589**</td>
<td>0.427</td>
</tr>
<tr>
<td></td>
<td>NPA</td>
<td>0.524**</td>
<td>0.689**</td>
<td>0.589**</td>
<td>0.522**</td>
<td>0.355</td>
</tr>
<tr>
<td></td>
<td>MBP</td>
<td>0.673**</td>
<td>0.894**</td>
<td>0.782**</td>
<td>0.613**</td>
<td>0.487</td>
</tr>
<tr>
<td>Continuously flooded</td>
<td>APA</td>
<td>-0.417</td>
<td>0.589†</td>
<td>0.412</td>
<td>-0.476</td>
<td>-0.127</td>
</tr>
<tr>
<td></td>
<td>NPA</td>
<td>-0.221</td>
<td>0.458</td>
<td>0.378</td>
<td>-0.229</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td>MBP</td>
<td>-0.575†</td>
<td>0.769**</td>
<td>0.523†</td>
<td>-0.603*</td>
<td>-0.231</td>
</tr>
</tbody>
</table>

† Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
†† The terms APA, NPA, and MBP indicate alkaline and neutral phosphatase activity and microbial biomass phosphorus, respectively.
‡ TOP, total organic phosphorus; LOP, labile organic phosphorus; MLOP, moderately labile phosphorus; MSOP, moderately stable phosphorus; HSOP, highly stable organic phosphorus.

were those between MBP and LOP and MLOP with the coefficients ($r$) of 0.89 and 0.71, respectively, in intermittently flooded soils. APA, NPA, and MBP were poorly correlated with the highly stable organic phosphorus (HSOP) in the paddy soil, irrespective of the water regimes.

**Plant Biomass Yield and Phosphorus Uptake by Rice Plants**

In general, incorporating swine manure or wheat straw into the paddy soil significantly ($P < 0.05$) increased rice biomass yields at harvest (Table 5). The SM + WS treatment, especially, showed 14 and 18% higher straw and grain yields, respectively, than the control, on average across water regimes. Continuous flooding decreased straw and grain yields of rice plants for organic treatments compared to the intermittent flooding, when organic amendments were incorporated into paddy soils (Table 5).

In terms of P uptake by rice straw and grain, significant differences were noted between organic and inorganic treatments (Table 5). The differences were more prominent in intermittently flooded conditions than in continuously flooded conditions. The intermittently flooded conditions showed a higher average total P uptake, relative to the continuously flooded conditions, especially for SM and SM + WS treatments (Table 5). In the intermittently flooded conditions, for example, P uptake by rice grain for the SM, WS, and SM + WS treatments was, respectively, 19, 13, and 27% higher than the control, whereas in the continuously flooded conditions, the increases were only 5.1, 3.2, and 12%, respectively.

**Table 5.** Effect of organic amendments on plant biomass and P uptake by rice straw and grain in intermittently and continuously flooded paddy soils, respectively (mean of 5 yr).

<table>
<thead>
<tr>
<th>Water regime</th>
<th>Treatment †</th>
<th>Rice biomass yield</th>
<th>P uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Straw kg ha⁻¹</td>
<td>Grain kg ha⁻¹</td>
</tr>
<tr>
<td>Intermittently flooded</td>
<td>SM</td>
<td>6245.5 ± 87.95 b‡</td>
<td>7985.7 ± 687.2 b</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>5825.4 ± 712.8 c‡</td>
<td>7623.3 ± 912.4 c</td>
</tr>
<tr>
<td></td>
<td>SM + WS</td>
<td>6677.7 ± 852.9 a‡</td>
<td>8475.8 ± 878.7 a</td>
</tr>
<tr>
<td>Continuously flooded</td>
<td>CK</td>
<td>5539.6 ± 678.2 a‡</td>
<td>6791.1 ± 812.3 f</td>
</tr>
<tr>
<td></td>
<td>SM</td>
<td>5962.5 ± 783.5 bc</td>
<td>7041.2 ± 534.6 e</td>
</tr>
<tr>
<td></td>
<td>WS</td>
<td>5715.1 ± 856.4 c‡</td>
<td>7284.3 ± 489.7 d</td>
</tr>
<tr>
<td></td>
<td>SM + WS</td>
<td>6445.5 ± 713.8 b‡</td>
<td>7934.5 ± 856.7 b</td>
</tr>
</tbody>
</table>

† The terms SM, WS, SM + WS, and CK indicate swine manure, wheat straw, swine manure plus wheat straw, and chemical fertilization treatments, respectively.
‡ Values are expressed as means ± SE; means followed the same letter are not significantly different ($P < 0.05$) by Duncan’s multiple range test.
DISCUSSION

Organic P, as the main source of plant-available phosphorus in agricultural soils, attracts more attention than soil total P, especially with the development of organic and sustainable farming systems. The relative distribution of SOP in different fractions may be influenced by soil type (Tiessen et al., 1983), climate, and agricultural management practices. The fractionation of SOP can help us better understand the dynamics of the soil organic P pool in the short term. Some fractions of SOP have been found to be more sensitive to contrasting agricultural management practices and to seasonal variations than the TOP (Margid and Nielsen, 1992). Sharpley (1985) demonstrated that moderately labile organic P was most responsible for the change in SOP due to manure application. Zhang et al. (1994) suggested that combined incorporation of inorganic P fertilizers and cellulose into soil greatly increased soil LOP, MLOP, and MSOP. Greater labile organic P fractions and total P in animal manure–treated soils than in inorganic P–treated soils have also been reported by Motavalli and Milles (2002) and Reddy et al. (2000). Our present study illustrates that MLOP and MSOP contributed to the increase in soil organic P due to organic amendments. However, continuous flooding considerably weakened the effectiveness of organic manure to increase SOP fractions, especially labile organic P fractions (Table 3). Though labile organic P fractions represent only a small proportion of the total organic matter, they are very dynamic, and play a key role in the P cycling and transformation. Strong correlation between soil APA, MBP, and LOP demonstrates that soil LOP fractions more effectively maintain soil enzymatic and microbiological activities involved in organic P cycling in intermittently flooded conditions than in continuously flooded conditions.

The phosphatase activities of soil indicate the biological activities from the soil microorganism or plant roots and also the organic P mineralization potential (Dick and Tabatabai, 1993). The susceptibility of SOP to phosphatase hydrolysis is potentially a constraint for plant P acquisition (Hayes et al., 2000). The significantly greater activities of phosphatase in the organically fertilized soils (Fig. 3) may be not only ascribed to enhanced microbial activity, but also to fine root growth of rice plants due to organic amendments (Yang et al., 2004). The results from the present study showed that the APA and NPA followed a very similar pattern to microbial activity, which in turn is influenced by a combination of factors including fertilization, soil type, and environmental conditions (Chen et al., 2004). Regardless of the water regimes, SM + WS had the highest MBP and phosphatase activities, as well as showing the highest LOP fractions in the paddy soils (Table 3 and Fig. 2 and 3). It is possible that the ratio of soil total organic carbon (TOC) to total phosphorus (TP) in the combined substrates is more favorable for microbial growth, compared to swine manure or wheat straw alone. The relatively high ratio of TOC to TP may have stimulated soil microbiological and enzymatic activities involved in soil organic P cycling and transformation (Shackle et al., 2000). Baum et al. (2003) found that soil phosphatase activity was affected by the TOC to TP ratio and that a smaller TOC to TP ratio was accompanied by a lower phosphatase activity.

However, present results showed a considerable decline in alkaline and neutral phosphatase in the manured soils under the continuously flooded conditions compared to the intermittently flooded conditions (Fig. 3). This is probably because anaerobic conditions, especially when organic manure is incorporated into paddy soil, lead to strongly reduced environments, where molecular oxygen is depleted, and Fe(III), Mn(IV), and SO$_4^{2-}$ in soil with high ferrous and manganese compounds are chemically reduced (Ponnamperuma, 1972). Consequently, the concentrations of reduced substances are greatly promoted in the paddy soil. Some toxic products such as Fe$^{2+}$, Mn$^{2+}$, organic acids, and hydrogen sulfide (H$_2$S) are produced by microorganisms as they decompose organic substrates, and are highly accumulated in soils when organic manure is incorporated into continuously flooded paddy rice fields (Yu, 1985; Narteh and Sahrawat, 1999; Imbellone et al., 2001; Gao et al., 2002). As a result, continuous flooding may have inhibited microbiological and root activity, and consequently decreased root phosphatase activities and suppressed soil organic P mineralization processes, which favored a buildup of stable organic P in paddy soil.

Huguenin-Elie et al. (2003) suggested that, in the flooded soil, P uptake was greater than that in the flooded then moist soil, which was confirmed only in chemically fertilized paddy soils in our present study. In organically amended paddy soils, intermittently flooded conditions showed higher P uptake by rice, as compared to continuously flooded conditions. In our study, the investigated paddy soils were characterized by high amounts of Fe- and Mn-oxides and low cation exchange capacity and are prone to accumulate soluble ferrous and iron and manganese after flooding, which are toxic to rice growth (Olayeye et al., 2001). Incorporation of swine manure into paddy soils resulted in more strongly reduced conditions and an increase in free Fe$^{2+}$ and S$^{2-}$, which can inhibit root growth and impair nutrient uptake (Sahrawat, 2000; Yang et al., 2004). Temporary loss of soil-water saturation during crop growth may limit rice yield, due to the decrease in phosphorus availability (Seng et al., 1999). However, organic amendment can improve the soil environment and root activity, and ameliorate the growth reduction of lowland rice caused by a temporary loss of soil-water saturation (Seng et al.,...
2004; Yang et al., 2004). Our present study demonstrates that, in organically amended paddy soils, the intermittently flooded conditions not only did not bring the reduction of rice growth, but improved rice biomass and P uptake.

Nitrogen nutrition also affects rice growth and P uptake. Different fertilizer and water management can change nitrogen cycling and budget in paddy soils (Kanwar et al., 1985). Losses of nitrate from applied urea can be high from rice fields as they are in flooded condition for most of the growing season (Dhyani and Mishra, 1993). When urea is applied in flooded water, it is converted to ammonium (NH₄⁺) through urea hydrolysis and nitrate (NO₃⁻) through nitrification (Awasthe and Mishra, 1987). Nitrate is soluble and moves with the water percolating through the soil and is not adsorbed to soil particles, which will inevitably result in losses of nitrogen from flooded paddy soils (Chowdary et al., 2004). In addition, organic manure incorporated into flooded paddy soil created a strongly reduced soil environment and high soil organic matter that promoted N losses through denitrification (Kanwar et al., 1985). Differential losses of N due to leaching and denitrification from continuously and intermittently flooded paddy soil with different fertilized treatments may account for the differences in rice yields and microbial biomass production in our present study. However, this hypothesis should be confirmed by future investigation and research.

Based on the complexity of factors controlling the dynamics of soil organic P fractions and microbiological and enzymatic activities involved in soil P transformation and cycling, more and longer term investigations are essential. Future study should focus on evaluating differences in biological and biochemical processes and their effects on organic P fractions in continuously and alternately flooded paddy soil amended with organic manure.

CONCLUSIONS

Based on the results obtained from a 5-yr field experiment, we concluded that paddy soil organic P fractions are considerably influenced by both fertilization and water regimes. In the combined application of chemical fertilizers and swine manure or wheat straw or both, continuous flooding markedly increased total soil organic carbon and organic P, but significantly altered the transformation of organic materials into labile organic P fractions. In the intermittently flooded conditions, incorporation of organic materials, especially swine manure plus wheat straw for 5 yr, not only increased the content of soil LOP fractions, but also soil phosphatase activities and microbial biomass C and P, compared to continuous flooding. Under the intermittently flooded conditions, organic treatments showed greater increase in plant biomass and P uptake by rice plants. The continuous flooding resulted in a lack of clear relationship between soil phosphatase activities and microbial biomass P and soil total organic P and its fractions. Based on soil organic P fractionation and soil enzymatic and microbiological activities involved in organic P cycling and transformation, continuous flooding applied to paddy soils should be avoided, especially when swine manure is incorporated into paddy soil.

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