Soil Phosphorus Dynamics in Response to Poultry Manure Amendment

Heidi Waldrip-Dail, Zhongqi He, Susan M. Erich, and Wayne C. Honeycutt

Abstract: Manure amendments are an excellent source of phosphorus (P) for crop production; however, animal manures differ in P availability. Poultry manure (PM) contains more stable mineral-associated P than many manures and may act as a longer-term P source when used in crop production. We used sequential fractionation and enzyme hydrolysis to evaluate the short-term effects of incorporating 0, 100, and 200 mg PM kg⁻¹ of soil into two Maine soils. Results indicated that most PM P was present in the H₂O- and HCl-soluble fractions (1936 and 5956 mg P kg⁻¹ manure, respectively), and that a large portion of stable organic P was present in the HCl fraction (3288 mg kg⁻¹). Poultry manure application resulted in only a transient increase in H₂O-P, implying rapid transfer to other fractions. A transformation of Pᵣ from the NaHCO₃ to the NaOH fraction was observed at Day 84 of the incubation with all treatments, indicating that soil properties influenced PM P dynamics. In the HCl fraction, some organic P became hydrolyzable and a portion was converted to other fractions. Comparing these data with those of a complementary study indicated that P from PM interacted differently with soil than did P from dairy manure. The observation of active interchange of P in different fractions during the incubation indicated that soil amendment with moderate levels of PM does not lead to accumulation of stable P forms and that the large HCl-P fraction (31.1% of total P) unique to PM could act as a source of plant-available P in a short term (e.g., a growing season).

Key words: Aerobic incubation, enzyme hydrolysis, phosphorus, poultry manure, sequential fractionation


Phosphorus (P) is an essential nutrient for plant growth. Animal manure contains P and other nutrients, and crop production can benefit from land application of manure. However, bioavailability of applied manure P is related not only to total P content but also to particular P forms present and how they interact with the soil matrix (He et al., 2004b; 2006b; Toth et al., 2006). It is therefore important to understand the interaction among manure-derived P and soils as well as the interconversion between P species over time.

Previously, our laboratory (He et al., 2004b; 2006b) used a sequential fractionation procedure, coupled with enzymatic hydrolysis, to monitor and compare the short-term (108 days) interchange of P forms during aerobic incubation of two Maine soils amended with inorganic fertilizer P or dairy manure (DM). This research demonstrated that when DM was applied to soils based on a target N application rate that bioavailable P (inorganic P and enzymatically hydrolyzable organic P in H₂O and NaHCO₃ fractions) was linearly related to applied P in a manner similar to that of chemical fertilizer; however, it is not clear whether this conclusion is applicable to PM. As much as 80% of DM P can be present in relatively soluble inorganic and organic forms (He and Honeycutt, 2001; He et al., 2004a). The distribution pattern of labile and stable P in PM differs from that of DM, with the H₂O and HCl fractions representing 16% to 41% and 22% to 58% of total P, respectively (He et al., 2006c). Significant amounts of HCl-P have been reported in numerous studies on P distributions of PM (Codling, 2006; Dail et al., 2007; Dou et al., 2003; He et al., 2006d). Furthermore, He et al. (2006c; 2006d) reported that a considerable amount of this HCl-P fraction was organic P (Pᵣ). Indeed, concentrations of Pᵣ are even greater than Pᵢ in many HCl fractions of PM, accounting for as much as 80% of total P in the HCl fraction (Ajiboye et al., 2007; He et al., 2008; Turner and Leytem, 2004).

Repeated annual soil amendment with PM can lead to elevated levels of water-soluble and Mehlich 1 P when fertilizing to meet crop P needs (Maguire et al., 2008). Despite the high concentrations of stable organic P in PM, it does not appear to result in soil buildup of HCl-P after long-term application, indicating that this fraction is undergoing some transformation to other forms or fractions upon entry into the soil P cycle. He et al. (2008) found that 20 years of repeated PM applications to pastureland did not lead to significant accumulation of hydrolyzable Pᵣ in soil HCl fractions, indicating that stable acid-extractable manure Pᵣ in PM must have been converted in soil to other P forms. The transformation of stable Pᵣ forms could be an important mechanism for maintaining a long-term balance between labile and immobile P in soils.

Therefore, we hypothesized that the high proportion of stable organic P in PM would result in different short-term P dynamics than observed with DM amendment and that the stable HCl-P would be transformed into other forms and fractions during incubation. To our knowledge, no such assessment of the short-term impact of PM on soil P dynamics by aerobic incubation coupled with sequential fractionation has been performed. Insight into the PM P dynamics in soils could be helpful in estimating bioavailable P in PM to meet crop P need in a short growing season.

MATERIALS AND METHODS

Soils and Manures

Soils were collected from the USDA-ARS research sites at Newport (sandy loam, no established soil series designation; coarse-loamy, mixed, frigid, Typic Haplustalf) and Presque Isle (Caribou sandy loam, fine-loamy, mixed, frigid, Typic Haplorthod), Maine. Both soils were sieved (2 mm) while still field moist, air dried, and stored at room temperature for 2 months before experiment initiation. Selected soil properties are listed in Table 1. Newport soil was P limited, and Caribou soil was Na limited. Selected soil properties are listed in Table 1.

Table 1. Newport soil was P limited, and Caribou soil was Na limited. Selected soil properties are listed in Table 1.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Clay (%)</th>
<th>Organic Matter (%)</th>
<th>pH (H₂O)</th>
<th>Exchangeable Ca (cmol(+) kg⁻¹)</th>
<th>Exchangeable Mg (cmol(+) kg⁻¹)</th>
<th>Exchangeable K (cmol(+) kg⁻¹)</th>
<th>Exchangeable Na (cmol(+) kg⁻¹)</th>
<th>Exchangeable Al (cmol(+) kg⁻¹)</th>
<th>Bulk Density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport Sandy Loam</td>
<td>19.2</td>
<td>4.5</td>
<td>6.3</td>
<td>15.6</td>
<td>5.8</td>
<td>7.6</td>
<td>9.4</td>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td>Caribou Sandy Loam</td>
<td>21.4</td>
<td>3.8</td>
<td>6.0</td>
<td>16.2</td>
<td>6.5</td>
<td>7.8</td>
<td>9.6</td>
<td>28</td>
<td>1.5</td>
</tr>
</tbody>
</table>
TABLE 1. Selected soil properties of Caribou and Newport soils

<table>
<thead>
<tr>
<th>Property</th>
<th>Caribou</th>
<th>Newport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, %</td>
<td>51</td>
<td>42</td>
</tr>
<tr>
<td>Silt, %</td>
<td>41</td>
<td>52</td>
</tr>
<tr>
<td>Clay, %</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>pH (1:1)</td>
<td>5.7</td>
<td>5.9</td>
</tr>
<tr>
<td>CEC, Cmol kg⁻¹</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Total N, %</td>
<td>0.17</td>
<td>0.2</td>
</tr>
<tr>
<td>Total C, %</td>
<td>2.19</td>
<td>2.52</td>
</tr>
<tr>
<td>Soil Pₐ, mg kg⁻¹</td>
<td>6.24</td>
<td>3.13</td>
</tr>
<tr>
<td>Soil Kᵢ, mg kg⁻¹</td>
<td>109</td>
<td>143</td>
</tr>
</tbody>
</table>

Values are for modified Morgan extracts.

Sequential Extraction, Dilution, and pH Adjustment

This procedure was based on previous reports for animal manure and manure-amended soil (He et al., 2004a; 2006b; 2006c). Briefly, 1.0 g of moist soil sample was removed from the incubation vessel, placed in a 50-mL tube with 25 mL of deionized H₂O, and shaken on an orbital shaker (250 r.p.m.) for 2 h at 22 °C. The solution was centrifuged at 23,700g for 30 min at 4 °C. Supernatants were then passed through a 0.45-μm filter and stored at −20 °C until analysis. As previously mentioned, storage of manures may result in slight changes in the P distribution, with the potential for increased labile P in stored soil/manure incubation tubes and P in extracted supernatants. Using the same procedure, soil residues were then sequentially extracted by 0.5 M NaHCO₃ (pH 8.5), 0.1 M NaOH, and 1.0 M HCl for 16 h each. To dilute samples and to prepare them for enzymatic hydrolysis at pH 5.0, the extracts were treated as follows: bicarbonate extracts were diluted 1:2 by slowly adding 1.28 mL of 2.5 M acetic acid and 3.72 mL of water to 5 mL of extract and then were set aside with loose caps for 1 to 2 h to allow excess carbonic acid (CO₂) to escape. Hydroxide extracts were diluted 1:5 by slowly adding 0.14 mL of 2.5 M sodium acetate, 0.10 mL of 0.1 M EDTA, 1.66 mL of 0.4 M sodium acetate-buffer (pH 5.0), and 6.1 mL deionized water to 2.0 mL of extract. Hydrochloric acid extracts were diluted 1:10 with 8.0 mL unbuffered 0.4 M NaAc and 1.0 mL deionized water to 1.0 mL extract.

Enzymatic Hydrolysis

Acid phosphatase (EC 3.1.3.2) type IV-S from potato (5.2 U mg⁻¹ solid) and 3-phytase (EC 3.1.3.8) from Aspergillus ficuum (1.1 U mg⁻¹) were obtained from Sigma (St Louis, MO). Each incubation mixture (0.5 mL) contained 0.3 mL of a pH-adjusted extract and 0.2 mL of enzyme-buffer solution (final activities, 0.25 U units each of 3-phytase and acid phosphatase). All enzymatic incubations were carried out at 37 °C for 1 h in a shaking incubator at 250 r.p.m. Controls were included whereby either the enzyme or samples (substrates) were omitted (He et al., 2006c). All incubations were performed in triplicate.

Phosphorus Determination

Inorganic orthophosphate (Pᵢ) concentration of the pH-adjusted extracts, both with and without enzymatic hydrolysis, was quantified by a molybdate blue method suitable for investigating enzymatic hydrolysis of organic phosphates (He and Honeycutt, 2005). Total P was determined using the same method, after H₂SO₄ potassium persulfate digestion and adjustment to pH 5.0 (He et al., 2006c). Organic P (P₀) was estimated as the difference between total P and Pᵢ. The proportion of organic P that was enzymatically hydrolyzable (Pₒₑ) was estimated as the difference between Pᵢ and Pₒₑ in incubation mixtures in the presence and absence of phosphatases. Organic P that was resistant to enzymatic hydrolysis (Pₒₑ) was estimated as the difference between total P and Pᵢ + Pₒₑ.

Statistical Analysis

All data are presented as the average of three replicates. One-way analysis of variance was computed to examine the effects of manure addition and incubation. Significance of differences among treatments was determined by mean separation using Fisher least significant difference test.

RESULTS

P Composition of PM

The freeze-dried manure contained a total of 19.0 g kg⁻¹ P on a dry-matter basis. Using sequential fractionation, we were
able to extract 10.3 g P per kg\(^{-1}\) manure, accounting for 54.2% of total manure P. The distribution of PM P in the four sequentially extracted fractions is shown in Figure 1. Specifically, the distribution P\(_i\) was 1268, 1093, 238, and 2668 mg kg\(^{-1}\) in \(\text{H}_2\text{O}\), NaHCO\(_3\), NaOH, and HCl fractions, respectively. Organic P was present at 668, 633, 471, and 3288 mg kg\(^{-1}\) in the same respective fractions. Although soil incubations with DM were not performed in the current experiment, we have included DM data from an earlier study in our laboratory (He et al., 2004a) for comparative purposes (Fig. 1). Unlike DM, PM contained relatively equal amounts of labile P (extracted by \(\text{H}_2\text{O}\) and NaHCO\(_3\)) and stable P (extracted by NaOH and HCl). Most organic P\(_i\) was present as enzymatically hydrolyzable forms. Table 2 shows the overall breakdown of P forms as distributed into soil per 100 mg total P kg\(^{-1}\) of soil.

**Inorganic P**

Water-soluble P\(_i\) in unamended samples was (average ± S.D.) 1.2 ± 0.1 and 6.8 ± 0.2 mg P kg\(^{-1}\) in Newport and Caribou soils, respectively. Application of PM strongly influenced H\(_2\)O P\(_i\) in both soils at Day 0 (Figs. 2A and B, H\(_2\)O P\(_i\)). Soils amended with PM100 and PM200 averaged 6.2 and 8.4 mg P kg\(^{-1}\) (Newport) and 10.7 and 16.5 mg P kg\(^{-1}\) (Caribou). These initial increases were less than the H\(_2\)O P\(_i\) portion of PM applied to soil (Table 2), indicating that a rapid transformation via soil adsorption and/or microbial immobilization of manure-derived H\(_2\)O P\(_i\) occurred during the time required to set up the experiment (approximately 2 h), freezing, and extraction (1 day). However, H\(_2\)O P\(_i\) in amended soils increased between Days 7 and 14, apparently caused by transformation of P from other fractions and/or forms to H\(_2\)O P\(_i\). By Day 108, H\(_2\)O-P\(_i\) was essentially the same in control and amended Newport soil. Caribou soil amended with PM200 had slightly higher concentrations than control and PM100 at the end of the incubation.

Bicarbonate-extractable P\(_i\) was higher at Day 0 in amended than in unamended samples, with 62.3, 74.7, and 81.1 mg P kg\(^{-1}\) in control Newport soil and that amended with PM100 and PM200, respectively (Fig. 2A and B, NaHCO\(_3\) P\(_i\)). Caribou soil contained 92.8, 107, and 114 mg P kg\(^{-1}\) for unamended, PM100, and PM200 samples (Fig. 2B, NaHCO\(_3\) P\(_i\)). These increases were quantitatively consistent with the input of 8.5 and 17 mg kg\(^{-1}\) NaHCO\(_3\)-extractable P from PM100 and PM200, respectively (Table 2). The overall impact of PM application on NaHCO\(_3\)-extractable P\(_i\) was small because of the relatively high indigenous content of this fraction in both soils. There were no significant differences between the treatments after Day 0 in Newport soil, whereas in Caribou soil, control samples had higher NaHCO\(_3\) P\(_i\) than amended soil up to Day 42. An increase of greater than 2.5-fold was noted from Day 0 to Day 28 in NaHCO\(_3\) P\(_i\) in all samples, including control. After Day 28, NaHCO\(_3\) P\(_i\) concentrations were relatively stable until Day 84. There was a sharp decrease in NaHCO\(_3\) P\(_i\) content from Day 84 to Day 108, averaging 94 (Newport) and 147 mg P kg\(^{-1}\) (Caribou).

Concentrations of indigenous NaOH P\(_i\) were high in both soils, averaging 591 and 712 mg P kg\(^{-1}\) for Newport and Caribou unamended samples (Figs. 2A and B, NaOH P\(_i\)). Whereas little P\(_i\) was found in NaOH fractions of PM (Table 2). Thus, manure amendment resulted in virtually no change in NaOH P\(_i\) concentrations other than a slight increase at Day 0 in Newport PM200 (694 mg P kg\(^{-1}\)). Overall, NaOH P\(_i\) concentration decreased over the course of the incubation up to Day 84. From Day 84 to Day 108, increases averaging 120 (Newport) and 166 mg P kg\(^{-1}\) (Caribou) were observed in all samples, similar in magnitude to decreases in NaHCO\(_3\) P\(_i\), indicating that the P gains in NaOH P\(_i\) originated as NaHCO\(_3\) P\(_i\). Transformation of P from one fraction to another has been previously described and could be a result of physicochemical and/or biological processes (He et al., 2004b; Ochwoh et al., 2005).

The HCl fractions contained the largest concentration of total P in PM (Table 2), and PM amendment markedly increased the HCl P\(_i\) pool in both soils over the course of the incubation (Figs. 2A and B, HCl P\(_i\)). At Day 0, both PM100 and PM200 were significantly higher in HCl P\(_i\) content than control in Newport soil, with values averaging 103, 143, and 145 mg P kg\(^{-1}\) for control, PM100, and PM200, respectively. There was no significant difference in amended and unamended Caribou soil treatments at Day 0. At the end of the incubation, PM200-treated samples of both soils had significantly higher HCl P\(_i\) than PM100 and control, thus indicating that whereas moderate addition of manure does not increase HCl P\(_i\), the addition of high levels of PM can lead to buildup of stable soil P.

**Organic P**

Poultry manure contained relatively small amounts of water-soluble P\(_o\), supplying 5.2 and 10.4 mg P kg\(^{-1}\) soil for PM100 and PM200, respectively (Table 2), and PM200 amendment increased this P pool at only two sampling dates in the Newport soil and three sampling dates in the Caribou soil (Figs. 3A and B, H\(_2\)O P\(_o\)). The initial pattern of H\(_2\)O P\(_o\) change over time was similar to that of H\(_2\)O P\(_i\) in both soils, with decreases observed after initial increases, suggesting soil sorption and/or microbial immobilization of both H\(_2\)O P\(_i\) and H\(_2\)O P\(_o\). The concentrations of H\(_2\)O P\(_o\) extracted from soil incubations were too low for analysis via enzymatic hydrolysis.

![Table 2: Phosphorus forms in PM to be applied to soil (per 100 mg total manure P kg\(^{-1}\) soil)](image)

<table>
<thead>
<tr>
<th></th>
<th>H(_2)O</th>
<th>NaHCO(_3)</th>
<th>NaOH</th>
<th>HCl</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P (mg kg(^{-1}) soil)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic P(_i)</td>
<td>9.8</td>
<td>8.5</td>
<td>1.9</td>
<td>20.7</td>
</tr>
<tr>
<td>Hydrolyzable P(_o)</td>
<td>1.7</td>
<td>3.1</td>
<td>2.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Unhydrolyzable P(_o)</td>
<td>3.5</td>
<td>1.8</td>
<td>1.2</td>
<td>4.9</td>
</tr>
</tbody>
</table>

\(^{1}\)Data were calculated based on the relative abundance of PM P in the four fractions shown in Fig. 1.
All subsequent extracted $P_e$ was separated into fractions that were enzymatically hydrolyzable ($P_{oe}$) or nonenzymatically hydrolyzable ($P_{ne}$). Initial levels of bicarbonate-extractable total organic $P$ ($NaHCO_3 P_0$) were low for both control and amended soils (averages of 9.11 and 10.3 mg $P$ kg$^{-1}$ for Newport and Caribou, respectively) (data not shown). The concentration of $NaHCO_3 P_{ne}$ remained low (average 16.3 and 17.6 mg $P$ kg$^{-1}$ for Newport and Caribou, respectively) and relatively stable throughout the incubation, with little differences between control and amended soils (Figs. 3A and B, $NaHCO_3 P_{ne}$). Nonhydrolyzable $P_e$ ($P_{ne}$) was initially very low in both soils; however, it increased 10-fold from Days 3 to 14, with 91.7 (Newport) and 114 mg $P$ kg$^{-1}$ (Caribou), followed by a similar decrease at Day 28 (Figs. 4A and B, $NaHCO_3 P_{ne}$). By Day 108, $NaHCO_3 P_{ne}$ concentrations were similar to the negligible initial values, with no difference between treatments.

Manure amendment did not significantly change the amount of total $P_e$ that was hydroxide extractable ($NaOH P_0$) (data not shown). Initial $NaOH P_0$ values averaged 57.4 (Newport) and 60.6 mg $P$ kg$^{-1}$ (Caribou). Most of the organic $P$ in this fraction was enzymatically hydrolyzable, with Newport soils having a slightly higher average for all treatments and time points (53.5 mg $P$ kg$^{-1}$) than Caribou (44.3 mg $P$ kg$^{-1}$; Figs. 3A and B, $NaOH P_{ne}$). Both soils exhibited an early spike in $NaOH P_{ne}$ similar to that seen with $NaHCO_3 P_{ne}$ followed by a return to initial low concentrations (Figs. 4A and B, $NaOH P_{ne}$). There was no change with amendment for $NaOH P_{ne}$ and significant differences on only one date for each soil for amended $NaOH P_{ne}$.

Despite the large amount of $PM P$ that was present as $HCl P_0$ (25.2 and 50.4 mg $P$ kg$^{-1}$ soil supplied with PM100 and PM 200, respectively; Table 2), manure amendment had little effect on the acid-extractable fraction in our two soils, except from Days 7 to 56, where PM200 amendment resulted in an increase in $P_{ne}$ in Newport soil (Fig. 4A, $HCl P_{ne}$). Overall, it appears that both $HCl P_0$ and $P_{ne}$ remain relatively stable or decrease over time with all treatments, and that the concentration of $P_{ne}$ tends to increase over time. This complementary pattern is considered an indicator of the interchange of $HCl$-extractable $P$ forms during incubation. For example, with PM200 at Day 0, the amounts of $P_{ne}$ were 62.5 and 91.8 mg $P$ kg$^{-1}$ for Newport and Caribou soils, respectively; and over the course of the incubation, this $P$ either disappeared from the $HCl$ fraction (Newport) or was converted to either $P_0$ or $P_{ne}$ (Caribou) (Figs. 2–4, $HCl$).

**DISCUSSION**

Laboratory incubation experiments have been used at our research facility to investigate short-term $P$ availability in soil...
from DM (He et al., 2004b; 2006b). These studies examined the dynamics of soil P from DM as compared with an inorganic fertilizer source applied to two Maine soils, one of which (Newport soil) was also used in the current study. He et al. (2004b) found that changes in H₂O-, NaHCO₃-, and NaOH-extractable P were similar for amended and unamended soils, indicating that soil properties played a major role in controlling P dynamics. A single application of DM impacted soil labile P primarily through an increase in the amount of P added, in a similar manner to fertilizer P in the form of potassium phosphate (He et al., 2006b). Dairy manure and fertilizer P may have behaved similarly in supplying P because most DM P is labile (inorganic and hydrolyzable organic) in H₂O and NaHCO₃ fractions (He et al., 2004a). Our current study suggests that conclusions based on DM are not applicable for PM probably because PM contains more stable P, and P₀ in the sequentially extracted HCl fraction (Fig. 1) (Dail et al., 2007; He et al., 2006c; 2006d).

The transient increase in H₂O P₀ in PM-amended soils implies that most water-extractable P in PM was rapidly transferred to other fractions. It has been reported that water-soluble P concentrations from PM amendment could be controlled by solid mineral P phases (immobilization-solubilization), whereas sorption-desorption processes may be responsible for soluble P release from DM-amended soil (Cooperband and Good, 2002). Cooperband and Good (2002) used chemical analysis and scanning electron microscopy of PM to reveal a higher Ca + Mg-to-P ratio in PM than DM, as well as the presence of mineral-like P-rich particles in PM.

The impact of PM on soil P₀ in NaHCO₃ and NaOH fractions was much less than that previously observed in DM, which was significantly increased with as little as 28 mg kg⁻¹ DM P (He et al., 2004a). A sharp decrease in NaHCO₃ P₀ content from Day 84 to Day 108 was similar to that in a sandy loam soil amended with DM by He et al. (2004b). Although we have no definitive explanation for this sudden increase after a period of steady-state conditions, we speculate that this change occurred as a result of a physiochemical or biological event resulting in transformation of this NaHCO₃ P₀ to be transformed into other forms and/or fractions. However, the coincident decrease in NaHCO₃ P₀ and increase in NaOH P₀ observed in all treatments, including unamended controls at the last sampling date suggested the interconversion of P₀ in the two fractions. During incubation, P₀ in the NaOH fraction increased, whereas P₀ in the NaHCO₃ fraction decreased. These observations support numerous short- and long-term studies suggesting that NaOH-extractable P acts in soil as a sink of and source for NaHCO₃ P (Beck and Sanchez, 1994; Buehler et al., 2002; Hao et al., 2004; 2008; He et al., 2004b). One possible explanation for
FIG. 4. Nonhydrolyzable organic P (P\textsubscript{oe}) in relation to incubation time for NaHCO\textsubscript{3}, NaOH, and HCl fractions extracted from Newport (A) and Caribou (B) soils with no P added (control), 100 mg PM P kg\textsuperscript{-1} dry soil (PM100), and 200 mg PM P kg\textsuperscript{-1} dry soil (PM200). Symbol * and ns indicate the statistical significant difference and no difference in the treatments at a sampling day (p > 0.05), respectively.

interconversion would be that anoxic conditions created during initial wetting of the soils caused the Fe(III) in the NaOH fractions to be reduced to more soluble Fe(II) (He et al., 2006a). The interchange of hydrolyzable organic P in the two fractions was generally similar to that of P\textsubscript{i}, species, although the pattern was not as readily apparent. Upon termination of the incubation, P\textsubscript{i} concentrations in both fractions had returned to near-initial values. Transformation of native bioavailable P (P\textsubscript{i} and P\textsubscript{oe}) could be associated with rewetting of dried soils and accompanying biological, chemical, and physical activities during preincubation (Nguyen and Marschner, 2005; Oehl et al., 2001). High levels of PM increased HCl P\textsubscript{i} to an extent even greater than the amount of P\textsubscript{i} in HCl fractions of the applied PM. Fluctuation of P\textsubscript{i}, levels in this fraction of amended soil did not mirror the pattern of P\textsubscript{i} in the control soil, as observed in NaHCO\textsubscript{3} and NaOH fractions (Fig. 2). The impact of DM amendment on P\textsubscript{i} in HCl fractions of soil was not reported in the previous work (He et al., 2004b; 2006b) because of negligible P concentrations in the DM HCl fraction, implying that DM amendment has a greater impact on HCl-extractable P\textsubscript{i} in soil than DM (He et al., 2004a; 2006d). Nonhydrolyzable P\textsubscript{oe} from the HCl pool of poultry litter did not accumulate in the soil HCl fractions (Fig. 4, HCl P\textsubscript{oe}), whereas P\textsubscript{oe} concentrations remained relatively stable or increased (Fig. 3, HCl P\textsubscript{oe}). During the incubation, HCl P\textsubscript{oe} might have been transformed to HCl P\textsubscript{i} by soil phosphatase activity (Crouse et al., 2002; Parham et al., 2002; Senwo et al., 2007) or converted to forms that are nonextractable or unhydrolyzable. Phytate, the major organic P form in the HCl fraction of PM, is prone to form complexes with soil components, such as Fe and Al (Cell et al., 1999; Dao, 2003; Guan et al., 2005; He et al., 2006a). The consistent increase in H\textsubscript{2}O P\textsubscript{i} and P\textsubscript{oe} in NaHCO\textsubscript{3} and NaOH fractions between Days 7 and 14 could be at least partly explained by the decrease of P\textsubscript{oe} in the HCl fraction during this same period.

Overall, PM amendment affected the soil P status primarily in the H\textsubscript{2}O and HCl P\textsubscript{i} fractions. As seen with DM, soil properties, including soil mineral phase and sorption-desorption processes, were key factors in controlling P dynamics in soils amended with PM. Changes in P\textsubscript{i} forms in PM-amended soils during the incubation followed the same patterns as control soils, particularly in NaHCO\textsubscript{3} and NaOH-extractable P. However, unlike the DM amendment, applied PM P did not additively increase extractable P concentrations. With up to 58% of extractable PM P in the HCl fraction and having relatively equal amounts of P\textsubscript{i} and P\textsubscript{oe}, the P\textsubscript{i} fraction remained relatively stable in amended soils over the course of the incubation, whereas P\textsubscript{oe} rapidly became enzymatic hydrolyzable, with a portion remaining in the HCl fractions and some transformed to other fractions. This observation indicated the transformation of PM from stable HCl-extractable forms to more labile forms during the incubation period, which is similar to the short growing season in Maine. Thus, we believe that such transformation could make stable HCl-extractable P become labile and constantly available throughout a growing season, although further field research is needed to confirm it.

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REFERENCES


