Relative Movement and Soil Fixation of Soluble Organic and Inorganic Phosphorus

Brandon H. Anderson and Frederick R. Magdoff*

ABSTRACT

There is considerable concern about pollution of surface waters with P. Although most of the research has focused on inorganic P in surface runoff, it has recently become possible to easily follow the fate of soluble organic P forms in soils and waters. Two experiments were performed to compare the relative mobility and soil fixation affinity of orthophosphate monoesters, orthophosphate diesters, and soluble inorganic P. We used three P substrates, 4-methylumbelliferyl phosphate (MUP), deoxyribonucleic acid (DNA), and KH$_2$PO$_4$ in (i) a soil column experiment and (ii) a soil P adsorption test tube experiment. Shortly after columns were prepared, approximately two pore volumes of 0.005 M CaCl$_2$ were passed through 25 cm length columns containing 10 cm of loamy sand amended with approximately 10 mg P as MUP, DNA, or KH$_2$PO$_4$ above 15 cm of nonamended loamy sand. The total net quantity of 757.8 µg P 2L$^{-1}$ of orthophosphate diesters in the leachate from the DNA columns exceeded the net quantity of orthophosphate monoesters in leachate from the MUP columns (4.6 µg P 2L$^{-1}$) and soluble inorganic P from the KH$_2$PO$_4$ columns (34.0 µg P 2L$^{-1}$). Adsorption of soluble organic and inorganic P in the test tube experiment yielded similar results: DNA, containing orthophosphate diesters, had a relatively low affinity for soils. In both experiments, high concentrations of other P compounds were identified in samples treated with organic P substrates, suggesting enzymatic hydrolysis by native soil phosphatase enzymes. These findings indicate that repeated application of organic forms of P could lead to significant leaching of P to ground water.

The USEPA describes N and P as the leading cause of pollution in lakes and estuaries and the third largest source of pollution in rivers (USEPA, 1995). However, the chemical, biological, physical, and hydrological factors controlling the fate of nonpoint sources of P pollution are still not completely understood. A vast body of research has been focused on better understanding the movement and availability of inorganic P, with organic P receiving little attention despite its substantial contributions to the total P content in most soils. The perception that soluble inorganic P is the main bioavailable form for plants and technical difficulties in the analysis of organic P have contributed to our limited understanding of the cycling and movement of organic P in ecosystems (Jansson et al., 1988; Turner and Haygarth, 2000). Organic P may constitute 29 to 65% of the total P in soil systems (Harrison, 1987) and upward of 90% of the total P in soil solution (Helal and Dressler, 1989; Shand et al., 1994; Turner and Haygarth, 2000), yet little is known about the fate and movement of this important P fraction in terrestrial systems. The variable chemical composition of organic inputs and differences in biological and chemical reactivity, as well as mobility of organic P compounds, create an exceedingly complex situation in soil. Organic P in environmental samples must be better classified and quantified to help us more fully understand the P cycle in soil environments. Ready identification of basic classes of organic P is critical to a deeper understanding of the factors controlling the fate of different organic P compounds. Without knowledge of these factors, it is impossible to adequately predict the influence of soluble organic P from soils on eutrophication of surface waters.

Researchers have used $^{31}$P NMR to identify the forms of organic P (Newman and Tate, 1980; Condron et al., 1990) and chromatographic techniques to determine concentrations of specific organic P compounds in water samples (Nanny et al., 1995) and soil solutions (Espinosa et al., 1999). The lengthy time required to analyze samples, use of expensive equipment, and poor sensitivity at low organic P concentrations are a few disadvantages of these techniques. Recent advances using phosphatase enzymes (Turner et al., 2002) have provided a quick and inexpensive way of quantifying and identifying organic P from a wide spectrum of environmental samples in soil, water, and runoff samples. In addition, commercially available phosphatase enzymes have high substrate specificity for organic P and using these enzymes allow detection of hydrolyzed soluble organic P in samples containing <10 µg L$^{-1}$ (ppb) of organic P.

Phosphorus transport by runoff and erosion has received the greatest amount of attention. Inorganic P losses from leaching have been considered to be of little importance (Sharpley and Menzel, 1987) and only relevant for specific environmental conditions such as deep sandy soils (Humphreys and Pritchett, 1971), high organic matter soils (Fox and Kamprath, 1971; Cogger and Duxbury, 1984), and soils receiving large quantities of P fertilizer (Sharpley et al., 1984, 1993; Eghball et al., 1996).

Humphreys and Pritchett (1971) found that all of the P applied as inorganic fertilizer to sandy soils (>93% sand) had leached below a depth of 50 cm. They reported substantial decreases in P leaching for finer-textured soils and those soils containing greater amounts of reactive Al. Fox and Kamprath (1971) and Cogger and Duxbury (1984) concluded that P leaching is primarily governed by the concentrations of Fe and Al sesquioxides and that the potential for P to leach in an organic soil is greater than a mineral soil. Transport of inorganic P through soils with histories of excessive fertilizer and manure applications has been measured (Sharpley et al., 1984, 1993; Eghball et al., 1996). Total soil organic

*Corresponding author (fmagdoff@uvm.edu). P through soils with histories of excessive fertilizer and

Vermont, Burlington, VT 05405. Received 24 Jan. 2005. *Corresponding

Abbreviations: DNA, deoxyribonucleic acid; MUP, 4-methylumbelliferyl phosphate; TSP, total soluble phosphorus.
P enrichment was quantified in soil profiles of sandy and silt loams amended with high rates of poultry manure (Sharpley et al., 1993) and organic P declined rapidly from the soil surface to a 30-cm depth in a clay loam with a history of heavy cattle manure applications (Sharpley et al., 1984). Eghball et al. (1996) found pronounced leaching of P in sandy loam soils that have received over 50 yr of feedlot manure and/or fertilizer P, with available (sodium bicarbonate–soluble) soil P levels at depths of 1.8 m for fields receiving manure applications comparable with that at 0.9 m for fields receiving only superphosphate. These authors concluded the organic P content of the manure contributed to the presence of P at the greater soil depths.

For the purpose of studying organic matter and P movement, leachate samples have been collected in field plots with lysimeters (Haygarth and Jarvis, 1997; Chardon et al., 1997; Haygarth et al., 1998; Turner and Haygarth, 2000), from tile drainage (Grant et al., 1996; Stamm et al., 1998), and soil columns (Bowman et al., 1967; Sawhney 1977; Weigand and Totsche, 1998). With the exception of Bowman et al. (1967) and Chardon et al. (1997), these studies did not examine the contribution of soluble organic P in the collected leachate samples. Bowman et al. (1967) used a miscible displacement technique to flush inositol phosphate through a sandy loam soil at 5 and 20°C. Inositol phosphate was reported to have a greater soil adsorption affinity than inorganic P. Twice as much of organic P was collected in the leachate of a column incubated at 5°C than an identical column incubated at 20°C and it was suggested that this was due to increased microbial activity at the higher temperature. Chardon et al. (1997) treated soil columns and field plots with animal manure and compared the differences in soluble organic P in the leachate. Although their method of defining organic P was highly simplified and nonspecific (total P minus molybdate-reactive P), they found organic P represented >90% of the total P in leachate from manure treated soil columns, and >70% of the total P in leachate collected from lysimeters in manure treated field plots.

Inositol phosphate has been studied more than any other form of soil organic P, in part due to its stability and persistence in the soil (Turner et al., 2002), high percentage of total organic P (Harrison, 1987; Condron et al., 1990), high fixation capacity (Celi et al., 1999; Anderson et al., 1974), and widespread occurrence in soils and natural waters (Harrison, 1987; Turner et al., 2002). Analytical obstacles with phytase active on inositol phosphate limit its routine analysis in soil, sediment, and water samples. Sample impurities of crude phytase obtained from Aspergillus ficuum (Turner et al., 2002) and wheat (Triticum aestivum L.) (Shand and Smith, 1997; Hayes et al., 2000) have caused unreliable results. Phytase purification techniques need to be refined before any future studies are preformed with this enzyme. It has been assumed that the adsorption capacity of organic P is governed by the amount of phosphate groups on the organic compound (Stewart and Tiessen, 1987). Inositol phosphate, with six phosphate groups (IP6), has a high charge density and therefore has a strong soil fixation capacity and a greater likelihood of accumulating in soil (Celi et al., 1999), particularly iron oxide-rich soils (Anderson et al., 1974). Although orthophosphate diesters contribute the greatest amount of organic P inputs to a soil, the amount of orthophosphate diesters found in soil is relatively small (Turner et al., 2002). Greaves and Wilson (1970) have suggested that the low charge density of orthophosphate diesters results in greater susceptability to enzyme hydrolysis, explaining the relatively low occurrence of orthophosphate diesters in soils compared with the relative abundance of inositol phosphate.

The purpose of this study was to examine the relative soil P adsorption potential of known quantities of selected P soluble substrates using a diversity of Vermont agricultural soils.

MATERIALS AND METHODS

Experiment I: Soil Columns

A sandy loam soil was used in this experiment because coarse-textured soils are more likely to leach phosphate than fine-textured soils (Humphreys and Pritchett, 1971; Tiessen et al., 1991). The Adams sandy loam (sandy, isotic, frigid Typic Haplorthods) was collected from an agricultural field in the Champlain Valley of Vermont. This site was in established grass for at least 7 yr. The soil was collected from the Ap horizon, passed through a 1.7-mm sieve, mixed thoroughly, and stored at 0°C. The soil had a pH of 5.0, 2% organic matter, and 6 mg P kg⁻¹, 62 mg Al kg⁻¹, 6 mg Fe kg⁻¹, 454 mg Ca kg⁻¹, and 45 mg Mg kg⁻¹ extracted by Modified Morgan solution. The soil was 81% sand, 6% silt, and 13% clay.

Each of four PVC columns (10.2 cm i.d., 25 cm length) was filled with moist soil in two parts—10 cm of soil (treatment well mixed with soil) above 15 cm of soil with no treatment added. The lower portion of each column was filled with 1.5 kg of moist soil (7.5% moisture), representing approximately 15 cm of column length. Each column was designated a single drip line using a five-channel Lachat model 2200-000 peristaltic pump calibrated to drip at a constant rate of 7 mL min⁻¹. The bottom 15 cm of soil in the column was continuously leached with distilled water until 40 mL of leachate was collected. Then, 100 mL of the following solutions were added to different plastic buckets containing 925 g (dry wt.) of moist soil: 0.005 M CaCl₂ (control), 101 µg P mL⁻¹ as DNA Type XIV–herring testes (Sigma no. D-6898), 98 µg P mL⁻¹ as MUP (Sigma no. M-8168), and 101 µg P mL⁻¹ as KH₂PO₄. Soluble organic P treatments (DNA and MUP) were selected because of their complete hydrolysis with the enzyme assay procedure (Turner et al., 2002). Each DNA molecule contains numerous diester bonds whereas each MUP contains only one monoester bond. Bucket contents were thoroughly mixed by hand and transferred to columns. Phosphorus additions per column were 10.1 mg P for DNA, 9.8 mg P for MUP, and 10.1 mg P for the KH₂PO₄ solution, and none for the control.

Soil-filled column pore volume was 908 cm³, volumetric pore space was 0.45 cm³ cm⁻¹, and leaching began within 0.5 h of adding the surface portion of soil to columns. Columns were leached once with 2 L of 0.005 M CaCl₂ solution over a period of approximately 5 h at a constant flow rate of 1.43 × 10⁻³ m s⁻¹. Twenty consecutive leachate samples were collected in 100 mL portions, each slightly more than one-tenth pore volume. Leachate samples were filtered through a 0.45-µm nylon syringe filter before the enzyme-based organic P analysis. The experiment was replicated three times, at weekly intervals. For each replicate, soil was discarded and replaced following the same mixing procedures. Mixing of substrates with soil occurred immediately before the leaching. Replicates...
of the measured soluble P in leachate were similar and the mean values of replicates are reported in this article.

**Experiment II: Soil Phosphorus Adsorption in Test Tubes**

Soils (Table 1) were selected from the Ap horizon of agricultural fields, located in the Champlain Valley of Vermont, and were selected based on their differences in texture, soil test P, and reactive Al levels (Table 1). Aluminum extracted by Modified Morgan solution is considered reactive Al because it is related to the amount of P fixed by soils (Magdoff et al., 1999). Soils were dried at 55°C. One gram of dry soil was added to 25 mL of treatment solution (MUP, DNA, KH₂PO₄, distilled water) in 40-mL centrifuge tubes. Solutions for each P source were prepared at 5 and 10 µg P mL⁻¹. Each soil × P concentration treatment was replicated three times. Capped centrifuge tubes containing the soil–solution treatment mixtures were shaken continuously for 12 h. Samples were then centrifuged at 10 000 × g for 15 min and filtered through a 0.45-µm syringe filter. Filtered solution was added to the phosphatase enzyme assay mixture described by Turner et al. (2002). Phosphorus was determined colorimetrically by the molybdate–stannous chloride method (Jackson, 1958). The total amount of soluble P (TSP) adsorbed by soil was determined as follows:

\[
TSP_{ads} = \frac{\text{Substrate} \: \mu \text{g P mL}^{-1} \text{soil} \: \text{sol} \: \mu \text{g P mL}^{-1} \text{treatment}}{1 \text{ g Soil} \: 25 \text{ mL}^{-1} \text{ solution}_{\text{water or treatment}}}
\]

**Table 1. Characteristics of soils used for the P adsorption experiment.**

<table>
<thead>
<tr>
<th>Soil type†</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>OM</th>
<th>pH</th>
<th>P</th>
<th>Al</th>
<th>Ca</th>
<th>K</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Silt loam</td>
<td>12</td>
<td>81</td>
<td>7</td>
<td>4.5</td>
<td>7.3</td>
<td>4.8</td>
<td>17</td>
<td>2192</td>
<td>63</td>
<td>156</td>
</tr>
<tr>
<td>2. Silty clay loam</td>
<td>23</td>
<td>42</td>
<td>35</td>
<td>5.6</td>
<td>7.2</td>
<td>6.4</td>
<td>11</td>
<td>3648</td>
<td>126</td>
<td>360</td>
</tr>
<tr>
<td>3. Loamy sand 1</td>
<td>85</td>
<td>10</td>
<td>5</td>
<td>2.1</td>
<td>6.8</td>
<td>3.4</td>
<td>138</td>
<td>927</td>
<td>92</td>
<td>84</td>
</tr>
<tr>
<td>4. Loamy sand 2</td>
<td>85</td>
<td>11</td>
<td>4</td>
<td>3.6</td>
<td>6.3</td>
<td>3.4</td>
<td>138</td>
<td>927</td>
<td>14</td>
<td>37</td>
</tr>
<tr>
<td>5. Loamy sand 3</td>
<td>80</td>
<td>15</td>
<td>5</td>
<td>3.1</td>
<td>5.5</td>
<td>1.5</td>
<td>244</td>
<td>178</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

† Nutrients extracted by Modified Morgan’s Solution (1.25 M ammonium acetate at pH 4.8).
‡ Classification of the soils follows: (1) Scantic fine, illitic, nonacid, frigid Typic Epiaquepts; (2) Vergennes very-fine, mixed, active, mesic Glossaquic Hapludalfs; (3) Adams sandy, isotic, frigid Typic Haplorthods; (4) Windsor mixed, mesic, Typic Udipsamments; (5) Windsor mixed, mesic, Typic Udipsamments.

Enzyme Assay and Phosphorus Analysis

Organic forms of soluble P were determined using the enzyme assay as described by Turner et al. (2002). Alkaline phosphatase–phosphomonoesterase (Sigma no. P-4252) and phosphodiestrase I (Sigma no. P-4506) were dissolved in 0.1 M tris-HCl buffers containing 2 mM MgCl₂ (activator of enzymes). The enzyme assay mixture consisted of 4.5 mL of filtered soil extract, 0.25 mL of 0.1 M NaN₃ (to prevent microbial interference), and 0.25 mL of enzyme solution (one of two enzymes in buffer, either mono- or di-phosphoesterase, and one check containing only tris-HCl to determine soluble inorganic P). The final 5-mL mixture was incubated at 37°C in sealed glass test tubes for 16 h overnight. After the 16 h incubation, samples were analyzed for P using the molybdate–stannous chloride method. Inorganic P was also determined in samples prepared as described for organic P, but without the addition of a phosphatase enzyme. Organic P hydrolyzed by the monoesterase and diesterase enzymes and inorganic P (no enzyme) were determined colorimetrically with a spectrophotometer set at 660 nm. The amount of monoester P hydrolyzed was determined by subtracting the amount of molybdate-reactive P (inorganic P) present without addition of an enzyme from the amount of molybdate-reactive P present following reaction with monoesterase. Likewise, the amount of diester P hydrolyzed was determined by subtracting the amount of molybdate-reactive P (inorganic P) present without addition of an enzyme from the amount of molybdate-reactive P present following reaction with diesterase.

**Statistical Analysis**

Soluble P in leachate samples was classified into three general categories: orthophosphate monooesters, orthophosphate diesters, and soluble inorganic P. The types of soluble P were compared among treatments (MUP, DNA, KH₂PO₄) using the general linear model procedure (SAS Inst., 1990). For all statistical analyses, a probability value of ≤0.05 was used to determine significance.

**RESULTS AND DISCUSSION**

**Experiment I: Organic and Inorganic Phosphorus in Soil Column Leachate**

Although the total amount of orthophosphate monooesters in the leachate from the MUP treatment columns was greater than the check treatment columns, 26.7 and 22.2 total µg P, respectively, the differences were not statistically significant (Fig. 1). On the other hand, the total orthophosphate monooesters collected in the DNA column leachate was significantly greater than the check column, representing a seven-fold difference. Only the leachate from the DNA columns contained significantly

![Fig. 1. Total soluble P collected in 2 L of leachate from check columns and those treated with KH₂PO₄, MUP, and DNA.](image-url)
greater amounts of orthophosphate diesters than the check column, 833.7 and 75.9 µg P in 2 L, respectively. Total soluble inorganic P in the leachate from KH$_2$PO$_4$, MUP, and DNA treatment columns were significantly higher than the total soluble inorganic P in the check column. The substantial recovery of soluble P forms that were not applied to the columns receiving DNA treatments (monoester and inorganic P), as well as large quantities of diester-P, indicate partial DNA hydrolysis and/or displacement of resident soil P. The similar amounts of organic and inorganic P leached from columns treated with MUP and KH$_2$PO$_4$, (Fig. 1) indicates that hydrolysis of monoester P in MUP may have been more complete than for DNA, although displacement of resident soil P by MUP may have also occurred. Considering that phosphatase enzymes are ubiquitous in soil, it is likely that some of the added MUP and DNA were susceptible to enzyme hydrolysis while in the soil. Dick and Tabatabai (1978) studied several organic P compounds in aerobic soils. Soils incubated for 1 d with added substrates resulted in the 20 to 90% hydrolysis depending on the soil. It is probable that the treatments of labile MUP and DNA were hydrolyzed to some extent within the soil during the experiment. Despite apparent partial enzyme hydrolysis of DNA within the soil columns, a greater amount of total soluble P leached from columns treated with this diester-rich P substrate.

The DNA treatment leachate contained more total soluble P for each category determined—diesters, monoesters, and inorganic P—than the other treatments (Fig. 1). If other soluble orthophosphate diesters behave similarly to DNA in soil, substances containing high concentrations of diesters may pose a greater risk of movement through a soil profile than substances high in orthophosphate monoester or inorganic P. Even though orthophosphate diesters are fairly labile and susceptible to hydrolysis, their demonstrated mobility indicates that they may directly contribute to P deep in the soil profile. The rapid mobility of soluble orthophosphate diester compounds may be substantial before the diester bonds become naturally hydrolyzed by native phosphatase enzymes in a soil. This may help explain the finding of Eghball et al. (1996), who showed that large annual applications of manure increased the content of P in a sandy soil profile to depths of 1.8 m. These authors concluded that organic P content of the manure contributed to the presence of P at the greater soil depths.

Compared with the check treatment, the total amount of P recovered was about 15% for the KH$_2$PO$_4$ and MUP treatments, but 375% greater for the DNA treatment (Fig. 1). Leaching began soon after mixing P with soil and filling columns and progressed for approximately 5 h, which should favor P leaching because of lack of time for added P to react with the soil. On the other hand, the amounts of P added to soil were relatively small, approximately 10 mg P kg$^{-1}$ soil, favoring more complete fixation by sites capable of reacting with P. On a surface area basis, based on P added per column surface area (10 mg P to a 10 cm i.d. column), approximately 12.5 kg P was added per hectare. Thus, the results of this column experiment might have relevance for field conditions because of the much higher rates of P commonly applied as fertilizer or manure commonly applied by farmers.

Of the leachate–treatment combinations that were statistically different from the check, the greatest P concentrations were found in the leachate collections between 0.3 and 0.9 pore volumes (Fig. 2). The rapid initial movement of soluble P, indicated by the steepness of the slope of the curves, is even more evident when the cumulative net P is expressed as a percentage of the total recovered (Fig. 3). Nearly 100% of the soluble organic P (monoesters and diesters) collected from the DNA treatment column was recovered within the first pore volume. In contrast, the cumulative net inorganic P recovered in the first pore volume of leachate from the DNA, MUP, and KH$_2$PO$_4$ treatment columns in the first pore volume were 88, 74, and 80% of the total recovered during the experiment, respectively. Even though the most rapid initial P leaching rate occurred with the KH$_2$PO$_4$ treatment, after 0.5 pore volume the trend of P recovery in leachate resembled the gradual leaching of inorganic P from the columns treated with organic substrates.
**Experiment II: Organic and Inorganic Phosphorus Adsorption–Desorption**

Solutions containing varying concentrations of P treatments (DNA, MUP, KH$_2$PO$_4$) were mixed with five soils representing a range of texture and chemical characteristics (Table 1). The amount of added P (organic or inorganic) adsorbed to a soil was assumed to be the difference between the starting concentration of P and the amount of P remaining in solution after shaking and centrifuging the soil–P treatment mixture. Based on charge density differences for the organic and inorganic P compounds, we expected the relative amounts of P to be adsorbed as follows: KH$_2$PO$_4$ > MUP > DNA.

This expected trend did occur for the average P adsorption by the four soils that adsorbed significant amounts of P from the 10 µg P mL$^{-1}$ solution (Soils 1, 2, 4, and 5), with mean TSP$_{ads}$ of KH$_2$PO$_4$ (199 mg P kg$^{-1}$ soil) > MUP (146 mg P kg$^{-1}$ soil) > DNA (72 mg P kg$^{-1}$ soil). These adsorption results are consistent with the leaching experiment in which significantly more P leached from soil treated with DNA than soil treated with either KH$_2$PO$_4$ or MUP. However, comparing P adsorption from different sources for individual soils, only Loamy Sand 2 and Loamy Sand 3 had significant differences that supported our hypothesis at the 10 µg P mL$^{-1}$ treatment concentration (Table 2). The silty clay loam and Loamy Sand 1 showed a significantly greater adsorption affinity for KH$_2$PO$_4$ treatment compared with the DNA treatment. However, there were no significant differences between TSP$_{ads}$ between silt loam treatments. The quantities of P adsorbed by individual soil samples from each of the initial solution P concentration treatments were related to P source treatments. For example, the soil that tended to adsorb little P from KH$_2$PO$_4$ (Loamy Sand 1, high in soil test P) also adsorbed little P from MUP and DNA solution treatments. The amount of TSP adsorbed from the MUP solution treatment was related to that adsorbed by DNA and KH$_2$PO$_4$ treatments as follows ($n = 20$ for each relationship):

\[
\text{TSP}_{ads}\text{MUP} = 0.8(\text{TSP}_{ads}\text{KH}_2\text{PO}_4) - 1.7, \quad r^2 = 0.97 \\
\text{TSP}_{ads}\text{DNA} = 0.4(\text{TSP}_{ads}\text{KH}_2\text{PO}_4) - 2.7, \quad r^2 = 0.68 \\
\text{TSP}_{ads}\text{DNA} = 0.6(\text{TSP}_{ads}\text{MUP}) - 3.6, \quad r^2 = 0.80
\]

**Table 2. Total soluble P adsorbed from solutions containing DNA, MUP, and KH$_2$PO$_4$**

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Conc. of P</th>
<th>Amount of P</th>
<th>Original solution</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µg P mL$^{-1}$</td>
<td>mg P kg$^{-1}$ soil</td>
<td>DNA</td>
<td>MUP</td>
</tr>
<tr>
<td>Silt loam 1</td>
<td>5.0</td>
<td>125</td>
<td>78</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>250</td>
<td>109</td>
<td>167</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>5.0</td>
<td>125</td>
<td>66</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>250</td>
<td>108</td>
<td>158</td>
</tr>
<tr>
<td>Loamy sand 1</td>
<td>5.0</td>
<td>125</td>
<td>27a</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>250</td>
<td>10a</td>
<td>5a</td>
</tr>
<tr>
<td>Loamy sand 2</td>
<td>5.0</td>
<td>125</td>
<td>53a</td>
<td>94b</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>250</td>
<td>50a</td>
<td>149b</td>
</tr>
<tr>
<td>Loamy sand 3</td>
<td>5.0</td>
<td>125</td>
<td>23a</td>
<td>85b</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>250</td>
<td>37a</td>
<td>125b</td>
</tr>
</tbody>
</table>

† Similar lowercase letters indicate no significant differences ($p < 0.05$) between treatment means for a given soil and P addition concentration. No letters for a soil–concentration combination indicates that there were no significant differences in total P adsorption among P treatments.

Beyond the significant linear fit of these regression models, the slopes of the lines provide further evidence of the differences in P adsorption between treatments. Comparisons among slopes indicate that more P was adsorbed from KH$_2$PO$_4$ than MUP and DNA, while more P was adsorbed from MUP solution treatments than DNA treatments. Soluble inorganic P has a greater soil adsorption affinity than soluble phosphon monoesters and diesters.

With only five soils used in this study, it is impossible to generalize about the relation of soil properties to the amount of P adsorption from the three treatment sources. However, the relatively high amount of P adsorbed from DNA and MUP treatments for Soils 1 and 2 (high in silt and clay) may be due to adsorption on fine soil particles being more important for soluble organic compounds than adsorption on reactive Al sites, apparently plentiful in Soils 3 and 5 (modified Morgan Al of 138 and 244, respectively). On the other hand, P adsorption from KH$_2$PO$_4$ was high in Soils 1, 2, 4, and 5, indicating that inorganic P was adsorbed easily by both the fine fractions and reactive Al sites.

Solutions from each soil–treatment combination were analyzed for three types of soluble P compounds—monoesters, diesters, and inorganic P. For example, in addition to the P form in the applied DNA compound, orthophosphate diesters, solutions from DNA treated soils were also analyzed for orthophosphate monoesters and inorganic P. If no physical, enzymatic, or chemical interactions occurred between the soil and added P treatment, the quantity of nonapplied P compounds should be negligible. However, there were elevated levels of nonapplied P compounds ranging from 25 to 87% of the P remaining in the MUP treatments (mainly inorganic P) and 7 to 70% of the P remaining in the DNA treatments (both monoester and inorganic P). No substantial amounts of orthophosphate diesters were identified in the MUP-treated soils (except Loamy Sand 1), nor were there any elevated concentrations of soluble organic P compounds in the KH$_2$PO$_4$-treated soils. Although there is no direct evidence in this experiment, it is likely that full or partial hydrolysis of the organic substrates occurred from interaction with resident soil phosphatase enzymes.

**CONCLUSIONS**

The DNA-treated soils had greater amounts of P in leachate (Experiment I) and solutions from the adsorption experiment (Experiment II) than soils treated with inorganic P or MUP. If other soluble orthophosphate monoesters and diesters behave similarly in a soil to MUP and DNA, respectively, orthophosphate diesters may have a greater likelihood of leaching through a soil than orthophosphate monoesters or soluble inorganic P. Organic soluble P forms (monoesters and diesters) identified in the leachate of the DNA treatment columns were leached more rapidly and in greater concentrations when compared with leachate from the control columns. The movement of organic P in treated soils was evaluated in this experiment following a single P application and single leaching regime. However, these results indi-
cate that repeated application of sources high in soluble organic P (such as animal manures) to agricultural soils may well provide a substantial source of organic P to ground water. In both experiments, elevated concentrations of nonapplied P forms after treatment with soluble organic P suggests either P exchange and/or full or partial hydrolysis of soluble organic P.

ACKNOWLEDGMENTS

This work was supported by USDA CSREES Hatch funding to the Vermont Agricultural Experiment Station, Project #VT-PS-01003.

REFERENCES


