SOIL CONSTITUENT FACILITATED TRANSPORT OF PHOSPHORUS FROM A HIGH-P SURFACE SOIL

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ABSTRACT

Mobile soil constituents such as soil colloidal matter and dissolved organic matter may affect the mobility of phosphorus (P) in soils. Phosphorus leaching of two fractions (colloidal and dissolved phosphorus) was studied in soil column experiments, using a surface loam soil from Higashi-hiroshima, Japan, with a high Olsen-P content (93 mg-P/kg). Repacked soil columns with or without artificial macropores were prepared. Artificial irrigation solution (0.085 mM NaCl + 0.015 mM CaCl<sub>2</sub> solution) was applied for 6 hrs at an intensity of 10 mm/hr or for 2 hrs at 30 mm/hr. Six irrigations were applied to each column with 42 hr intervals between irrigations. Colloidal phosphorus (CP) leaching showed a minor increase with time. Dissolved phosphorus (DP) leaching was almost constant. DP dominated total phosphorus leaching with a contribution of 81–86%. Higher CP and DP leaching at lower irrigation intensity and from soil without macropores were observed. A high correlation between DP leaching and dissolved organic matter (DOM) leaching was seen ($R^2 = 0.82 - 0.86$). Batch experiments were conducted to investigate P sorption and results showed that phosphorus was sorbed to or formed complexes with dissolved organic matter. This study shows that DOM-facilitated transport is likely to be a dominating process for phosphorus leaching from high-P surface soils.

Key words: colloidal matter, colloidal phosphorus, dissolved organic matter (DOM), dissolved phosphorus, DOM-facilitated transport, phosphorus sorption coefficient ($K_{pce}$) (IGC: B12)

INTRODUCTION

The understanding of transport and the fate of environmental impact chemicals (EICs) in soils is important for preservation and management of soil and groundwater resources. So far, only the transport of EICs dissolved in the soil water or as gaseous compounds in the soil air has been considered in soil and groundwater risk assessment models. The possibility of EIC transport in the form of EICs adsorbed onto mobile soil constituents, such as soil colloidal particles (e.g., soil minerals and organic coated clay minerals), has not been considered. Recently, however, great interest has arisen in understanding the mechanisms of colloid-facilitated transport of EICs in soils (Grollimund et al., 1996; Kretzschmar et al., 1999; McCarthy et al., 1989; Ouyang et al., 1996), with focus on EICs such as heavy metals (Jensen et al., 1999; Temminghoff et al., 1997), polycyclic aromatic hydrocarbons (PAHs) (Mackay et al., 2001; Magee et al., 1991; Totsche et al., 1997; Villholth et al., 1999), pesticides such as prochloraz (de Jonge et al., 1998), and nutrients such as phosphorus (Laubel et al., 1999). Colloid-facilitated transport processes should be included in the prediction of EICs behavior in soils, otherwise EIC transport may be underestimated.

Phosphorus is applied to agricultural soils as a fertilizer. During the irrigation process it will leach from surface soils to the lower soil horizons from where it can reach groundwater or tile-drains and subsequently surface waters. The elution of phosphorus to surface water causes eutrophication. Phosphorus input is a key factor in controlling eutrophication in freshwater systems, because P is often the single most limiting nutrient for growth of phytoplankton (Goltermann and de Oude, 1991; Heckrath et al., 1995). Since soils in general have a high P fixation capacity, vertical movement of P through the soil profile is generally considered of little importance (Cooke, 1976; Ryden et al., 1973), unless soils become P saturated following heavy manure applications (van Riemsdijk et al., 1973). Especially, it is likely that P losses through subsurface runoff will be enhanced once a certain plow layer concentration of sodium bicarbonate-extract-
able P (Olsen-P) is exceeded (Heckrath et al., 1995). Already more than a decade ago, studies have pointed out problems with P accumulation in some Japanese soils, especially upland field soils (JSSPN, 1990).

Transport of P through macropores in loamy soils may contribute to P loss via subsurface drainage systems (Bottcher et al., 1985; Skaggs et al., 1994). Moreover, P transport in the soil has been found to be very sensitive to irrigation intensity and volume (Grant et al., 1996; Hergert et al., 1981). The impact of macropore flow on the transport of the various forms of P therefore has to be taken into account when evaluating the impact in surface water eutrophication caused by P loss via subsurface drainage (Grant et al., 1996; Laubel et al., 1999).

The transport of eluted P from the plow layer may be facilitated by soil colloids and dissolved organic matters (DOM). Therefore, to preserve groundwater and surface water from contamination and eutrophication, greater attention should be paid to the colloid- and DOM-facilitated P transport. Colloid and dissolved organic matter leaching from surface soil has been documented by previous studies (Motoshita et al., 2001; 2002). In this study, phosphorus leaching and the relationship between phosphorus and three natural soil constituents, colloidal inorganic matter, colloidal organic matter and dissolved organic matter (DOM), were investigated in soil column and batch experiments. Soil with a high Olsen-P content was used in order to investigate potential P leaching problems from near P saturated surface soils. Phosphorus was fractionated into two fractions (colloidal and dissolved phosphorus; CP and DP) and the mobility and behavior of both fractions were investigated.

MATERIALS AND METHODS

Phosphorus leaching experiments were conducted with repacked loam soil columns. Loam soil was taken from the surface (0-20 cm) of an agricultural field that had not been recently cultivated, located in Higashihiroshima city. The inner diameter and length of each column were 20 cm by 30 cm, and the actual soil layer depth was 20 cm (Fig. 1). Three cm layers of glass beads (diameter size: 2.79-3.96 mm) were placed at both the top and the bottom of the soil layer in order to disperse homogeneously the applied solution into the soil matrix and prevent collapse of particles and aggregates at the bottom of the layer. Soil properties and texture are shown in Table 1. The total porosity of all repacked soil columns was 0.49 cm³/cm³. Each experiment was carried out with duplicate column to confirm the accuracy of the results.

Experimental Conditions

Phosphorus leaching behavior was investigated under various conditions. An overview of experimental conditions is given in Table 2. In the experiment with artificial macropores (Exp. 2), a 5-mm stainless steel bar was carefully pushed vertically through the soil layer at 4 discrete positions to create 4 continuous and equally spread macropores. The soil columns in the two other experiments (Exp. 1 and 3) did not contain artificial macropores but differed with respect to irrigation intensity, i.e. a three times higher irrigation intensity was applied in the second half of Exp. 3 (4th–6th irrigations).

An irrigation solution (0.085 mM NaCl + 0.015 mM CaCl₂ solution) with an ionic composition close to that of natural rain was applied to each soil column for 6 hours (irrigation intensity: 10 mm/hr) or for 2 hours (30 mm/hr) after the first drop was collected from the bottom of the soil column. A total of 6 irrigations, with 42 hours flow interruption between each irrigation, were applied to each soil column. Effluent was collected at every 30 minutes (10 mm/hr) or 10 minutes (30 mm/hr). Subsequently, effluent samples were fractionated as described below.

Fractionation Procedure

The size range of colloidal particles is generally said to be from 1 nm to 1 μm (Ranville et al., 1998). Collected effluent samples were therefore fractionated in three steps: (1) raw sample; (2) colloidal and dissolved phase sample; and (3) dissolved phase sample. The raw sample,
Table 2. Experimental and water flow conditions in the soil columns during each experiment

<table>
<thead>
<tr>
<th></th>
<th>Irrigation rate (mm/hr)</th>
<th>Outflow rate $V_{outflow}$ (mm/hr)</th>
<th>$\theta_{pore}$ (cm³ H₂O/cm³ soil)</th>
<th>Time for water breakthrough (min)</th>
<th>Pore-water velocity $u$ (mm/hr)</th>
<th>Macropore water velocity (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 1 (0MP)</td>
<td>Column no. 1</td>
<td>7.9 ± 1.1</td>
<td>0.47</td>
<td>20.8 ± 1.3</td>
<td>16.8</td>
<td>577</td>
</tr>
<tr>
<td></td>
<td>Column no. 2</td>
<td>8.3 ± 2.0</td>
<td></td>
<td>17.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exp. 2 (4MP)</td>
<td>Column no. 1</td>
<td>8.4 ± 0.7</td>
<td>0.46</td>
<td>11.0 ± 1.3</td>
<td>18.3</td>
<td>1091</td>
</tr>
<tr>
<td></td>
<td>Column no. 2</td>
<td>8.3 ± 0.6</td>
<td></td>
<td>18.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exp. 3 (0MP)</td>
<td>Column no. 1</td>
<td>18.1 ± 5.0</td>
<td>0.48</td>
<td>10.0 ± 0.5</td>
<td>37.7</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>Column no. 2</td>
<td>17.3 ± 4.7</td>
<td></td>
<td>36.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The interval between irrigations was in all cases 42 hrs. MP means macropore. The water outflow rate, time for water breakthrough and pore-water velocity are given as the average values for the 4th-6th irrigations. Numbers after ± are standard deviations, calculated from 36 measurements for $V_{outflow}$ and 3 measurements for water breakthrough time.

Fig. 2. Schematic diagram of fractionation procedure and the constituents of each leachate sample with respect to natural soil constituents and phosphorus

Fig. 2. Schematic diagram of fractionation procedure and the constituents of each leachate sample with respect to natural soil constituents and phosphorus.

containing particulate, colloidal and dissolved matters, was filtrated through a 1 μm glass-fiber filter (GA-100, ADVANTEC CO.) and the filtrate was defined as the colloidal and dissolved phase sample, containing colloidal and dissolved matters. The colloidal and dissolved phase sample was then centrifuged with proper centrifugation gravity and time (4110G, 18 min). The supernatant in the centrifugation tube was defined as the dissolved phase sample, containing only dissolved matters. To determine the proper centrifugation gravity, effluent samples were centrifuged with various gravities. Subsequently, the organic carbon and phosphorus concentrations of the supernatants were measured. At centrifugation gravities <4110G (18 min), the concentrations of organic matter and phosphorus in the supernatant decreased with an increase of centrifugation gravity, while the concentrations were at an almost constant level at centrifugation gravities >4110G. This suggests that the supernatant collected after centrifugation at 4110G for 18 min included only dissolved matters. A schematic diagram of the fractionation procedure and P and soil matter constituents of each phase sample is shown in Fig. 2.

Measurement Procedure

The content of organic matter and phosphorus in loam soil (sieved to <2 mm) used for both column and batch experiments were measured. Total organic matter contained in the soil was measured by loss-on-ignition (Brain et al., 1974). Total phosphorus contained in the soil was measured by the vanado-molybdo phosphoric acid method (Kitoson et al., 1944). Soil samples were also extracted with 0.5 M NaHCO₃ for Olsen-P measurement, closely following the procedure by Olsen et al. (1982).

Concerning analysis of effluent leached from soil columns, each fractionated sample (raw sample, filtrated sample and dissolved phase sample) was used for the analysis of turbidity, organic carbon concentration and phosphorus concentration. Turbidity is often used to evaluate colloid concentration in the solution. Our previous study investigated the correlation between turbidity and concentration of colloids for the same loam soil as used in the present study (Motoshita et al., 2002). According to the results, turbidity and concentration of colloids were significantly correlated ($R^2 = 0.83$) and the conversion coefficient from measured turbidity (NTU: The turbidity of mixed solution of hydrazine sulfate (5 g),
hexamethylenetetramine (50 g) and distilled water with total volume 1 L is 4000 NTU) into concentration (mg/L) was 0.90. Therefore, turbidity in the colloidal and dissolved phase sample was measured and converted to concentration of colloids using this conversion coefficient. Then, colloidal inorganic matter concentration was calculated from the difference between total colloid concentration and colloidal organic matter concentration (determined from the method described below).

Total organic carbon concentration in each of the three fractionated samples was measured (TOC-5000, SHIMADZU CO.). Particulate organic carbon and colloidal organic carbon concentration were calculated from the differences between raw sample and colloidal plus dissolved phase sample, and between colloidal plus dissolved phase sample and dissolved phase sample, respectively. Subsequently, organic carbon concentrations were converted into organic matter concentrations by multiplying by 1.72 (Brain et al., 1974).

Before phosphorus measurement, each fractionated sample (raw sample, colloidal plus dissolved phase sample, dissolved phase sample) was autoclaved (120°C, 30 min) with an addition of potassium peroxodisulfate to decompose all phosphorus into orthophosphoric acid. Subsequently, phosphorus concentrations in autoclaved samples were measured by the molybdate acid method (Japan Sewage Works Association, 1984) using a spectrophotometer (UV2500, SHIMADZU CO.). Particulate and colloidal phosphorus concentrations were determined in the same way as the organic carbon concentra-

\[
K_{sp} \text{ (mg-P/g soil constituent)} = \frac{\text{Colloidal or dissolved P concentration in the phase (mg-P/L)}}{\text{Colloidal or dissolved matter concentration in the phase (g/L)}}
\] (1)

Phosphorus sorption coefficients for the column experiments were estimated from the slope of regression lines between accumulated colloidal (or dissolved) phosphorus leaching and accumulated colloidal (or dissolved) matter leaching. In the 1st irrigation, soil conditions would be very unstable due to mixing of irrigation water and resident soil-water. Therefore, \(K_{sp}\) values were separately estimated for 1st irrigation and 2nd-6th irrigations.

For the batch experiments, the \(K_{sp}\) values for commercial humic acid were estimated as the slope of regression lines between phosphorus concentration and colloidal or dissolved matter concentration in the solution containing commercial humic acid with the added initial concentrations of 10, 20, or 30 mg/L.

RESULTS AND DISCUSSION

Water Flow Conditions in the Soil Columns

The water outflow rate from each column was fairly constant among irrigations. Table 2 shows the mean values of measured outflow rates during the last half of each experiment (4th-6th irrigations). The outflow rate in Exp. 3 was only two times that of Exp. 1–2 despite a three times higher irrigation rate, suggesting significant water storage in the columns. Since water ponding was observed at the soil surface during Exp. 3, the 17–18 mm/hr outflow rate is likely to be close to the saturated hydraulic conductivity of the soil. All experiments as expected took place at near water-saturated conditions since the final volumetric soil-water content after the last irrigation (\(\theta_{final} = 0.46–0.48\) cm³/cm³, Table 2) corresponds to 94–98% of the soil total porosity. The calculated mean pore-water velocities (\(u = V_{outflow}/\theta_{final}\)) showed a water movement with an average velocity between 1.7–3.8 cm per hour (Table 2). To evaluate the presumably rapid water movement in the large soil pores and the artificial macropores, the macropore water velocity was estimated accordingly to Jacobsen et al. (1997), as the length of the soil column divided by the time from start of irrigation to breakthrough of water. This yielded macropore water velocities between 58 and 120 cm/hr (Table 2). Much higher macropore water velocities took place in Exp. 2 (with artificial macropores) and Exp. 3 (higher irrigation rate).
compared to Exp. 1, supporting the idea that both macropores and higher irrigation rate can stimulate rapid preferential water flow.

Leaching Behavior of Each Fraction

Figure 3 shows temporal leaching behavior of colloidal inorganic matter, organic matter (colloidal and dissolved) and phosphorus (colloidal and dissolved) for the duplicate soil column in Exp. 1. It is interesting that each fraction has very different leaching behavior. Colloidal inorganic matter concentrations were high and increased with time during the first irrigation. During the subsequent 5 irrigations, the level of colloidal inorganic matter concentration decreased and approached a fairly constant low level, yielding similar and slow increase leaching curves for the 2nd–6th irrigations (Fig. 3(a)). Colloidal organic matter concentrations were slightly fluctuating but almost constant and generally low (Fig. 3(b)). Dissolved organic matter (DOM) concentrations were much higher than colloidal organic matter concentrations, and DOM concentrations slowly but markedly approached a constant level with time, as seen during the 3rd–6th irrigations (Fig. 3(b)). As also seen for organic matter, dissolved phosphorus (DP) concentrations were much higher than colloidal phosphorus concentrations during the 2nd–6th irrigations, and DP also approached a constant concentration level with time (Fig. 3(c)). Colloidal phosphorus (CP) showed increasing concentrations during the 1st irrigation followed by constant or slightly increasing concentrations with time during 2nd–6th irrigations (Fig. 3(c)).

Leaching behaviors of colloidal matter (inorganic and organic) and colloidal phosphorus seem to be very similar (Figs. 3(a), (b), (c)). This suggests that colloidal matter (inorganic and organic) may influence colloidal phosphorus leaching. The same hypothesis may also be valid in the relation between dissolved organic matter and dis-
solved phosphorus leaching because of similar leaching behaviors of those two fractions (Figs. 3(b), (c)). Correlations among these fractions are discussed below. Only results from Exp. 1 are shown in Fig. 3 but the results from Exp. 2 and 3 (data not shown) showed the same general trends as discussed for Exp. 1.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Phosphorus leaching (%)</th>
<th>Natural soil constituent leaching (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Colloidal P</td>
<td>Dissolved P</td>
</tr>
<tr>
<td>Exp. 1</td>
<td>8.6±6.3</td>
<td>84.8±8.2</td>
</tr>
<tr>
<td>Exp. 2</td>
<td>6.9±5.7</td>
<td>86.4±9.5</td>
</tr>
<tr>
<td>Exp. 3</td>
<td>5.0±7.0</td>
<td>91.4±8.7</td>
</tr>
</tbody>
</table>

The values shown in this table are (mean value of two duplicate columns)±(variation). The ratio of phosphorus leaching of each fraction to total phosphorus leaching (Particulate P (> 1 μm) + Colloidal P + Dissolved P) is shown. Natural soil constituent leaching ratio to total soil constituent leaching (Colloidal matter + Dissolved matter) is also shown.

**Table 3. The mass balance of phosphorus and natural soil constituent leaching during the 3 column experiments for 2nd-6th irrigation (Exp. 1-3)**

**Mass Balance of Phosphorus for Each Fraction**

The results of phosphorus leaching experiments were also used for estimating the mass balance of phosphorus leaching. The mass balance for phosphorus of each fraction (colloidal, dissolved) and accumulated leaching of each soil constituent are shown in Table 3. However, the data during the 1st irrigation was omitted in order to exclude the effect of soil disturbance. Only amounts of colloidal and dissolved soil constituents and P are shown in Table 3, since amounts of particulate soil constituents were insignificant and since particulate P only contributed to 3.6–6.8 (%) of total phosphorus leaching. The results revealed that the average contribution of dissolved phosphorus to total phosphorus leaching reached 81–86% after 6 irrigation events (excluding the 1st irrigation from the results as mentioned). Table 3 suggests that phosphorus leaching is dominated by dissolved phosphorus.

**Influences of Irrigation Intensity and Macropores on Phosphorus Leaching**

Figures 4 and 5 show the influences of irrigation intensity and macropores on accumulated colloidal and dissolved phosphorus leaching. Figure 4 shows a tendency
for higher P leaching in the soil columns without macropores. This may be due to better contact between the soil matrix and the infiltrating water if rapid macropore flow does not occur (Motoshita et al., 2001). For the 2nd–6th irrigations, accumulated dissolved phosphorus leaching in soil with 4 macropores seemed to be lower than for soil without macropores. However, this is partly due to the low phosphorus leaching during the 3rd irrigation that does not follow the trend of the other irrigations.

Irrigation intensity largely affected colloidal and dissolved phosphorus leaching. Both colloidal and dissolved phosphorus showed markedly higher leaching for smaller irrigation intensity (10 mm/h) than for larger irrigation intensity (30 mm/h) (Figs. 5(a), (b)). At higher irrigation intensity, the water will preferentially flow through the larger pores of the soil system (as previously discussed in relation to Table 2). Thereby, there will be diminished contact between the mobile water and phosphorus in the smaller and medium pores of the soil matrix. Also, the diffusion distance for P in immobile water regions to reach mobile water regions will be larger, reducing the possibility of sorption of dissolved P to DOM or colloidal matter in the mobile (flowing) water. Furthermore, dissolved phosphorus in the pore water will have reduced time to attach to the colloids suspended in the pore water or DOM due to the shorter residence time in the column at higher irrigation rate (Motoshita et al., 2002). These combined factors may have resulted in the lower colloidal and dissolved phosphorus leaching for larger irrigation intensity.

**Correlation between Accumulated Leaching of Phosphorus and Soil Constituent Fractions**

As described above, strong relations between colloidal phosphorus and colloidal inorganic matter and between dissolved organic matter and dissolved phosphorus seemed to exist. In this section, the correlations between the accumulated leaching of phosphorus fractions and the accumulated leaching of the soil constituent fractions will be examined and discussed.

As shown in Fig. 6, there seems to be a positive but low correlation between colloidal phosphorus leaching and total colloidal matter leaching for 2nd–6th irrigation ($y = 0.0044x, R^2 = 0.47$). It is noted that for the 1st irrigation in Exp. 1 leached colloidal phosphorus leaching concentrations were significantly higher than for the other two experiments (Exp. 2 and 3). The likely reason is that colloidal phosphorus leaching from the packed soil columns during the 1st irrigation was strongly affected by disturbance of soil packing (Motoshita et al., 2001), and that soil packing was slightly different among experiments with respect to soil homogeneity. The correlations between accumulated colloidal phosphorus leaching and the colloidal soil constituent fractions (total colloidal matter (Fig. 6), colloidal inorganic matter and colloidal organic matter) were generally not high. Thus, both colloidal inorganic and colloidal organic matter probably contribute to colloidal P transport. The inorganic colloidal matter leached at high concentrations (Fig. 3(a)) but likely has a low P sorption capacity while the colloidal organic matter leached at low concentrations (Fig. 3(b)) but likely has a high P sorption capacity. Furthermore, the colloidal organic matter showed a fluctuating leaching behavior (Fig. 3(b)). These combined factors could explain the lack of a high correlation between accumulated colloidal P leaching and either of the colloidal soil constituent fractions. Finally, no correlation between accumulated colloidal P leaching and DOM was seen.

Grant et al. (1996) investigated drainage water loss of phosphorus from four artificially drained, loamy soil, arable catchments in Denmark over a 1-yr period. They reported that at all arable catchments the concentrations of particulate phosphorus (mg-P/L) and particulate matter (mg/L) in the drainage water were significantly linearly correlated. The slope of the regression lines ranged from $y = 0.0028x$ to $y = 0.0070x$ (Fig. 6). In the present study, the best-fit regression line for the 2nd–6th irrigations yields $y = 0.0044x$ (Fig. 6), and is thus in between the regression lines of Grant et al. (1996). Further, more than half of the data points in the present study are in between the regression lines of Grant et al. (1996) and the rest are not far outside. Thus, the two studies compare well but, as mentioned, particulate P leaching only constituted a minor part of total P leaching in the present study.

Good correlations between dissolved phosphorus (DP) and dissolved organic matter (DOM) leaching for both the 1st irrigation ($R^2 = 0.69$) and the 2nd–6th irrigation ($R^2 = 0.86$) were obtained (Fig. 7) and the slopes of the two correlation lines are very similar. Phosphorus has a strong sorption affinity to soil solids. Therefore, the
leached concentration of dissolved phosphorus from the soils should be low theoretically. However, in this study the leached concentration of dissolved phosphorus was high (around 3 mg-P/L) and, in addition, good correlation between DP and DOM was seen. These results suggest that dissolved phosphorus may adsorb on or form complexes with dissolved organic matter and that DP subsequently is leached through DOM-facilitated transport.

Comparison with Other Leaching Studies on High-P Soils

The dissolved phosphorus concentrations leached from the soil columns in this study were extremely high (around 3 mg-P/L). In most other studies, the concentrations of phosphorus in drainage water from surface soil have been reported to be lower than 1.0 mg-P/L (Bottcher et al., 1985; Cooke, 1976; Sharpley and Menzel, 1987). However, Heckrath et al. (1995) reported that concentrations of phosphorus in drainage water higher than 1.0 mg-P/L were detected at some plots during investigations of P leaching from 20 field plots with silt loam soil at the Rothamsted experimental station in the U.K. Furthermore, they found that a high phosphorus concentration was detected from the site with a high concentration of Olsen-P and there was a change point (around 60 mg-P/kg) in the relation between phosphorus concentration in drainage water and Olsen-P extracted from the soil. Phosphorus concentration in drainage water showed a steep increase with the increase of Olsen-P (>60 mg-P/kg) and the highest concentration (2.8 mg-P/L) was found on the plot where the soil had the highest average Olsen-P concentrations (97 mg-P/kg). This is in good agreement with our study where the loamy soil has an Olsen-P of 93 mg-P/kg and a leached DP concentration of around 3 mg-P/L. Further, both Culley et al. (1983) (clayey soil) and Heckrath et al. (1995) found that dissolved leaching P contributed to between 62 and 86% of total P leaching, also in agreement with our study. These three studies show that for surface soils with high Olsen-P contents, high concentration of P in the leachate water and drainage water will likely occur, and a high percentage of the leached P will be in the form of dissolved (reactive) P.

Batch Experiment Results

The results of the column experiments implied a good correlation between dissolved P and dissolved organic matter leaching and suggested the sorption of phosphorus on dissolved organic matter (or complex binding between P and DOM). To confirm this, the effect of commercial organic matter (humic acid) concentration in the soil solution on phosphorus desorption behavior from soil to aqueous phase was examined in batch experiments. Characteristics of the added humic acid solution are shown in Table 4.

Figure 8 shows the change of dissolved phosphorus concentration in aqueous phase with the increase of dissolved organic matter concentration in aqueous phase. Dissolved phosphorus concentration increases with the increase of dissolved organic matter concentration in aqueous phase. This tendency agrees with the result of column experiments. In summary, the results of batch experiments support that a sorption (or complex binding)
Table 5. Estimation of phosphorus sorption coefficient ($K_{psc}$) with respect to dissolved organic matter (DOM) and total colloidal matter (TCM) estimated from column and batch experiments

<table>
<thead>
<tr>
<th>Column</th>
<th>DOM</th>
<th>TCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st irrigation</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>2nd-6th irrigation</td>
<td>330</td>
<td>4.4*</td>
</tr>
<tr>
<td>Batch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humic acid</td>
<td>7.7</td>
<td>23.7</td>
</tr>
<tr>
<td>Natural soil matter</td>
<td>220</td>
<td>n.e.**</td>
</tr>
</tbody>
</table>

*Excluding data from Exp. 1, 1st irrigation.
**Not calculated since TCM was not measured.

of phosphorus on dissolved soil organic matter will occur.

Estimation of Phosphorus Sorption Coefficients

The results of both column and batch experiments indicate that phosphorus can adsorb on or form the complexes with both colloidal matter and dissolved organic matter, and that dissolved phosphorus mainly adsorbed on or formed the complex with DOM. Based on this, phosphorus sorption coefficients ($K_{psc}$) were estimated from the results of both column and batch experiment, and estimated $K_{psc}$ values are given in Table 5.

The $K_{psc}$ value for P sorption onto total colloidal matter (TCM) was 4.4 in column experiments (2nd-6th irrigation) and 23.7 in batch experiments. The $K_{psc}$ was estimated with respect to both colloidal inorganic and organic matter but in column experiment only for colloidal organic matter in batch experiment. This accounts for the different $K_{psc}$ estimated from column and batch experiments, and supports that colloidal inorganic and organic matter will have different sorption capacity for phosphorus.

For P sorption onto DOM, $K_{psc}$ in the column experiments was 330 (2nd-6th irrigation) compared to only 7.7 (for commercial humic acid) in batch experiments. However, $K_{psc}$ for P sorption onto natural soil DOM was 220 in batch experiment and thus in reasonable agreement with the column experiments. The differences in $K_{psc}$ values indicate that the degree of phosphorus sorption onto DOM will depend on the properties of DOM and natural soil organic matter has high sorption capacity of phosphorus compared to commercial humic acid.

These results from column and batch experiments suggest that phosphorus will adsorb on or form the complex with organic matter, and that the sorption behavior of phosphorus might be affected by the type of organic matter. In future studies, phosphorus sorption for different types of soil organic matter covering both agricultural urban and forest soils as well as groundwater sediments must be investigated in more detail.

Estimation of Phosphorus Leaching Potential from High-P Surface Soil

Based on the above results, the phosphorus leaching potential was roughly calculated to assess the potential impact of DOM-facilitated phosphorus transport on the subsurface and groundwater environments. Concentrations of DOM in the leachate from column experiments during the last two (5th-6th) irrigations were used to represent stable soil conditions. DOM concentrations in the column experiments during the 5th-6th irrigation were around 4-6 mg/L. The $K_{psc}$ value for P sorption onto DOM in the column experiments was 330 (mg-P/gDOM) as shown in Table 5. A value of 1500 mm/year (mean precipitation from 19 years survey in Higashihiroshima area) was assumed as mean, yearly net precipitation corresponding to a net infiltration of 15000 m^3 per hectare (10000 m^3). Using these data, potential DOM leaching for one year was calculated as 60-90 (kgDOM/hectare/year), and potential DOM-facilitated P transport to groundwater for one year as 20-30 (kgP/hectare/year). This calculation indicates that natural DOM can enhance very significant amounts of phosphorus leaching from surface soils with high Olsen-P content.

CONCLUSIONS

In this study, colloidal and dissolved phosphorus leaching was investigated by column and batch experiments. In the column experiments, colloidal phosphorus showed an almost constant or slightly increased leaching behavior during multiple irrigation events, and dissolved phosphorus leaching was nearly constant after the initial soil disturbance (1st irrigation). Total phosphorus leaching was dominated by dissolved phosphorus with a contribution of more than 80%.

Both colloidal and dissolved phosphorus leaching were higher for smaller irrigation intensity (10 mm/hr) than for larger irrigation intensity (30 mm/hr). This suggests that irrigation intensity will affect both colloidal and dissolved phosphorus leaching. Only small differences in P leaching between soil columns with and without macropores were seen.

Positive correlation between accumulated dissolved phosphorus leaching and accumulated dissolved organic matter leaching was seen. Furthermore, in the batch experiments, dissolved phosphorus concentration increased with the increase of dissolved organic matter concentration in aqueous phase. Both facts support the hypothesis of a strong P binding to DOM.

Dissolved phosphorus leaching from the Japanese loam soil with high Olsen-P was very high. This is in accordance with studies on loamy and clayey soils from North America and the U.K. (Culley et al., 1983; Heckrath et al., 1995), suggesting that phosphorus leaching will be very high from surface soils with high Olsen-P. Maximum phosphorus leaching potential by DOM-facilitated transport to groundwater in a year was estimated to be 20-30 (kgP/hectare/year) for the Japanese loam soil with high Olsen-P based on the results from the column experiments.

In this study, a strong correlation between phosphorus mobility and DOM mobility was seen in both column and
batch experiments. Although column and batch experiments do not finally prove that most dissolved phosphorus will adsorb on or form complexes with DOM in natural soil conditions, both types of experiments implied that organic matter strongly affects the behavior and mobility of phosphorus, and that DOM-facilitated transport can be a dominating process for phosphorus transport through surface soils with high Olsen-P content.

ACKNOWLEDGEMENT

This study was in part funded by MON-BUKAGAKUSHO (Ministry of Education, Culture, Sports, Science and Technology), project no. 14550545 on "Remediation methods for polluted soils as related to colloid- and dissolved organic matter-facilitated transport".

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