Soil Phosphorus and Vegetation Influence on Wetland Phosphorus Release after Simulated Drought

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Phosphorus enrichment of marsh soils can act as an internal source of nutrients to the water column, continuing to drive existing wetland eutrophic conditions even after external sources have been terminated. The goal of this study was to determine the effects of soil P concentration and flood intolerant vegetation presence on initial (1–10 d) and extended (10–38 d) P release rates from the soils after reflooding. Intact soil cores were collected from P enriched and unenriched areas of the Blue Cypress Marsh in east-central Florida. Initial P release was greater in soils with higher soil total P concentrations and containing vegetation. Soil P enrichment resulted in the final water column P concentrations in the enriched cores to be 50% higher than those in the P unenriched cores. A single drawdown and reflood event led to ~6% of the total soil P released to the water column from the P enriched vegetated treatment compared with a ~1% of total P released from the P enriched non-vegetated treatment. Initial P release rates from the enriched, vegetated treatment were five times greater than the enriched, non-vegetated treatment. Episodic growth of flood intolerant plants under drawdown conditions was shown to be a significant mechanism for nutrient release in episodically flooded P enriched wetland systems. Episodic flooding and drying cycles could therefore mobilize P over the long-term from P enriched to P unenriched areas.

Management of P in nutrient limited wetlands is essential in preventing eutrophication. Regulation of external nutrient sources can only control the amount of P entering the system. However, it does not address internal P pools already present, which could potentially become mobile. Phosphorus accumulation in wetland soils/sediments can act as an internal source of nutrients to the water column, continuing to drive existing eutrophic conditions even after external sources have been terminated (Fisher and Reddy, 2001; Malecki et al., 2004). Decades of nutrient loading have been shown to result in significant P accumulation in the organic soil fractions (DeBusk et al., 1994; Mitsch et al., 1995; Vaithiyanathan and Richardson, 1997; Fennessy and Mitsch, 2001) and can affect the biogeochemical cycling of other nutrients (White and Reddy, 1999, 2000, 2003; DeBusk and Reddy, 2003).

Natural episodic drops in water levels (droughts) can lead to oxidation of wetland soils, increasing soil organic matter decomposition rates (Reddy, 1983; Fabre, 1988; Martin et al., 1996; Olila et al., 1997; Watts, 2000b; James et al., 2001; White and Reddy, 2001; DeBusk and Reddy, 2003). Organic soils therefore have the potential to release P to the water column on reflooding. Also, P retention capacity of soils that have undergone drawdown have been shown to diminish on reflooding compared with continually flooded soils (De Groot and Van Wijck, 1993; Qiu and McComb, 1994; Baldwin, 1996; Mitchell and Baldwin, 1998; Watts, 2000a; Klotz and Linn, 2001). However, little research has focused on the effect of initial soil P concentrations on water quality on reflooding in wetlands outside of the heavily studied Florida Everglades ecosystems (Newman and Pietro, 2001; Corstanje and Reddy, 2004).

Many P flux studies on soils or sediments have been conducted on intact soil cores devoid of vegetation (Holdren and Armstrong, 1980; Olila et al., 1997; Moore et al., 1998; Fisher and Reddy, 2001). However, vegetation is a key component in wetland ecosystems and community shifts are often seen as a result of water level fluctuations and soil nutrient concentrations (Yarbro, 1983; Gerritsen and Greening, 1989; Urban et al., 1993; Wu et al., 1997). Research has shown high soil P concentrations can result in vegetation shifts, leading to a concomitant loss of indigenous species (Davis, 1991, 1994; Föllmi, 1996). This vegetation can act as short-term P storage, which can rapidly release 35 to 75% of the total plant-associated P during senescence, potentially increasing water column P concentrations (Richardson, 1985; White et al., 2004; 2006; Corstanje et al., 2006).

The hypothesis of this study is that initial soil P (internal P load) and the presence of flood intolerant vegetation will increase P release to the water column after a drawdown/reflooding event. Specific objectives of this study were to: (i) compare P release rates from P enriched and unenriched soils, (ii) determine the P release rates for cores containing soil only and soil colonized with mature standing vegetation, and (iii) compare various pools of soil P.

Abbreviations: BCMCA, Blue cypress marsh Conservation Area; SRP, soluble reactive P; TDP, total dissolved P; TP, total phosphorus; TPI, total inorganic P; TPo, total organic P.
MATERIALS AND METHODS

Study Area

The Blue Cypress Marsh Conservation Area (BCMCA), Florida is an 8000-ha freshwater marsh located in the headwaters of the St. Johns River Basin (Fig. 1). The surface hydrology of the system follows a south to north gradient. Surface flow is also influenced by the presence of levees, which direct water from the enriched regions (northeast) toward the unenriched area (northwest). Fluctuations in water levels occur naturally in this system, with standing water present for 9 to 10 mo of the year, dependent on precipitation. A 4-mo drought occurred during the Spring/Summer of 2001, resulting in the loss of standing water and soil aeration to a depth of at least 30 cm. This allowed the introduction of the pioneer species *Eupatorium sp.* (dog fennel), which subsequently senesced once the marsh reflooded.

Water management structures (levees) were constructed in the 1950s to divert surface water away from the wetland for agricultural use (cattle ranching and crop production), resulting in approximately 65% of the St. Johns River floodplain being drained. Nutrient enriched surface runoff from the surrounding agricultural lands was channeled into the NE region of the marsh. After ∼40 yr, surface inflows to the system were terminated in the early 1990s as part of a St. Johns River Water Management District restoration project.

Previous studies documented the existence of a P gradient starting from the NE corner decreasing toward the interior of the marsh (Fig. 2) (Olila and Reddy, 1995). Higher soil total P (TP) levels (618 mg kg⁻¹) were found closest to the inflow point of agricultural runoff along the NE levee. The Northwest (NW) region of the marsh has remained relatively unaffected by past surface water inputs with an average soil TP of 444 mg kg⁻¹ (0–10 cm soil interval). Predominant and native vegetative species within the marsh are *Cladium sp.* stands and *Panicum sp.* flats, now located primarily in the unenriched region. *Typha latifolia* encroached on *Cladium sp.* in the enriched region of the marsh, similar to trends documented in the Florida Everglades (Davis, 1991, 1994).

Experimental Design

Intact soil cores were collected from the P enriched and unenriched areas of BCMCA on 5 to 6 Dec. 2001 (Fig. 1). To maintain a uniform vegetation community, monotypic *Cladium sp.* stands, which were present in both the P enriched and unenriched regions, were sampled. The samples were collected between mature *Cladium sp.* stands to eliminate the influence of large root masses. Three vertical intact soil sections were taken from each area by cutting through the peat with a serrated knife and then advancing the tube (i.d. = 30 cm) into the soil to obtain a minimum depth of 25 cm for each soil section. This procedure resulted in minimal soil compaction. These soil sections were transported to a temperature controlled greenhouse (mean air temperature = 25°C) and allowed to dry out by evaporation for 142 d. The drawdown/simulated drought was intended to mimic the 2001 summer drought event that occurred in the marsh, and resulted in the colonization of the pioneer species *Eupatorium sp.* This plant thrives in moist but not saturated soils, rapidly germinating under drawdown conditions (Tobe et al., 1998, p. 308–309).

Following the simulated drought, the intact soil sections (30 cm i.d.) were subsampled using eight smaller cores (7 cm id) with four containing mature standing vegetation (vegetated, *Eupatorium sp.*) and four having no visible emergent vegetation (non-vegetated) for each of the P enriched and unenriched sites. Vegetated cores were collected by isolating individual plants in the center of each core. The core was
then extracted by using a serrated knife and advancing the core tube down to minimize soil compaction. Both vegetated and non-vegetated cores contained belowground biomass and no roots were removed to minimize soil disturbance and to mimic field conditions. An additional three cores from each site were taken and sectioned to determine soil characteristics before reflood. All cores were then reflooded with filtered (0.45 μm) site water to produce an overlying water column of 30 cm. Water column P concentrations were corrected for repeated sampling and replacement of column water by filtered (0.45 μm) site water. Overlying water columns were maintained to a depth of 30 cm to prevent the overestimation of P concentrations due to increasingly reduced water column volume (Moore et al., 1998). Site water P concentrations were not found to differ significantly between the two sites, with 0.012 and 0.025 mg L\(^{-1}\) for soluble reactive P (SRP) and TP, respectively. The reflooded cores were placed in a water bath with a mean temperature of 23°C. At termination of the experiment, there was insufficient plant biomass remaining in the vegetated treatment for determination of nutrient content due to decomposition processes, 38 d after the reflood.

**Laboratory Analyses**

**Water Column**

Water samples (40 mL) were taken from the mid-depth of the water column of each core on Days 0, 1, 2, 5, 10, 20, 30, and 38 after reflooding and analyzed for SRP. Total P was determined on all water samples except those taken on Days 20 and 30. Soluble reactive P samples were filtered through a 0.45-μm membrane filters and immediately frozen. The TP water samples were digested with 5.5 M (11 N) H\(_2\)SO\(_4\) before colorimetric analysis (Method 365.1, USEPA, 1993). Filtered (0.45 μm) site water of known P concentration was added to the cores, equal to the amount removed at each sampling (40 mL), to maintain a consistent water column of 30 cm over the incubation period (Moore et al., 1998). The removal and addition of site water was accounted for in the calculation of the P flux rates.

**Soil**

At the end of the 38-d flux study, the top 0 to 10 cm of each soil core was removed and analyzed for the following physicochemical properties: moisture content as a percentage of total wet soil mass (constant weight, 70°C); dry-weight bulk density and pH (1:1 ratio). Total N (TN) and moisture content as a percentage of total wet soil mass (constant weight, 70°C); dry-weight bulk density and pH (1:1 ratio). Total N (TN) and total C after flooding. Data shown are means and one standard deviation (\(n = 3\)).

### Table 1. Mean soil physicochemical characterization of the 0- to 10-cm soil layers comparing P enriched and P unenriched and vegetation (vegetated and non-vegetated) effects for moisture content, bulk density, pH, total N, and total C after flooding. Data shown are mean values and one standard deviation (\(n = 3\)).

<table>
<thead>
<tr>
<th>Soil characteristics</th>
<th>P enriched</th>
<th>P unenriched</th>
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</thead>
<tbody>
<tr>
<td>Moisture content, %</td>
<td>14 ± 4.9</td>
<td>31 ± 8.5</td>
</tr>
<tr>
<td>Bulk density, Mg m(^{-3})</td>
<td>0.16 ± 0.03</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>pH</td>
<td>6.1 ± 0.07</td>
<td>5.9 ± 0.1</td>
</tr>
<tr>
<td>Total N, g kg(^{-1})</td>
<td>30.3 ± 1.0</td>
<td>28.0 ± 2.8</td>
</tr>
<tr>
<td>Total C, g kg(^{-1})</td>
<td>490 ± 7.8</td>
<td>474 ± 4.5</td>
</tr>
<tr>
<td>Total P, mg kg(^{-1})</td>
<td>618 ± 50.3</td>
<td>499 ± 48.2</td>
</tr>
</tbody>
</table>

a 1 M HCl extraction (Reddy et al., 1998) with total organic P (TPo) calculated as the difference between TP and TPC.

Microbial biomass P (MBP) was calculated as the difference in TP between fumigated (CHCl\(_3\)) and non-fumigated samples following a 0.5 M NaHCO\(_3\) reagent. The residual fumigated samples were sequentially extracted following the P fractionation scheme developed by Ivanoff et al. (1998) to determine moderately labile, non-labile, and residual organic P pools. An inorganic P fractionation scheme determined inorganic P forms representing the readily exchangeable (1.0 M KCl), Fe/Al bound (0.1 M NaOH) and Ca/Mg bound P (0.5 M HCl) extractable pools (Reddy et al., 1998).

**Data Analysis**

Phosphorus flux rates from intact cores were calculated by regressing concentration over two time intervals (1–10 and 10–38 d) due to the biphasic nature of the concentration vs. time curves. Water column and soil characteristics were contrasted by analysis of variance to determine the effect of soil P concentrations and vegetation presence on soil P forms. Tukey-Kramer adjustment was used for the multiple comparison of means (\(\alpha = 0.05\)) among all the groups. Water column and soil characteristics were contrasted by ANOVA to determine the effect of soil P concentrations and vegetation presence on soil P forms. Tukey-Kramer adjustment was used for the multiple comparison of means (\(\alpha = 0.05\)) among all the groups.

The overall experimental design consisted of a fully randomized two way ANOVA, with a site and plant effect, resulting in the general form:

\[
y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha \times \beta)_i j + \epsilon_{ijk}
\]

where \(y_{ijk}\) equals response measure for \(i\)-th site, \(j\)-th plant treatment and \(k\)-th rep; \(\mu\) equals overall mean; \(\alpha_i\) equals effect due to the \(i\)-th site effect, and assumed to be normally distributed with mean zero and standard deviation \(\sigma_{\alpha_i}\); \(\beta_j\) equals effect due to the \(j\)-th plant effect, and assumed to be normally distributed with mean zero and standard deviation \(\sigma_{\beta_j}\); \(\epsilon_{ijk}\) equals residual effect, assumed to be normally distributed with mean zero and standard deviation \(\sigma_{\epsilon_{ijk}}\).

The model generates treatment effect estimates for site (\(df = 1\)), plant (\(df = 1\)), and the plant x site interaction (\(df = 1\)), with LSD’s for the pair wise comparisons. Residual Maximum Likelihood (REML) mixed effects models were used in all analyses (MIXED procedure in SAS, Version 9.0, 2003, SAS Institute, Inc., Cary, NC).

**RESULTS AND DISCUSSION**

**Soil Characteristics**

Significantly higher soil TP concentrations were found in the 0- to 10-cm layer of the P enriched soils (618 ± 50.3 mg kg\(^{-1}\)) compared with the unenriched soils (444 ± 48.2 mg kg\(^{-1}\)). The dried, preflood soils from the enriched and unenriched regions had mean moisture contents of 14 ± 4.9 and 31 ± 8.5%, which increased to 74 ± 1.3 and 76 ± 1.6%, respectively, after reflooding (Table 1). Bulk densities of the dried soils were similar at 0.16 Mg m\(^{-3}\) in both the enriched and unenriched soils. Total N was not significantly different between the (i) drawdown and reflooded soils, (ii) P enriched and unenriched soils nor vegetated and non-vegetated treatments. The soil P within BCMCA consisted primarily of organic P, accounting for >85% of the soil TP in both
regions with no significant differences as a result of initial soil P or vegetation effects (Table 2).

After flooding, bulk densities of the vegetated and non-vegetated cores varied little with mean values of 0.18 ± 0.027 and 0.17 ± 0.016 Mg m⁻³, respectively. Bulk densities of the P enriched and unenriched soils were also not significantly different at 0.18 ± 0.016 and 0.16 ± 0.010 Mg m⁻³, respectively. Total C values in the P enriched (490 ± 7.78 g kg⁻¹) soils were greater than the P unenriched soils (474 ± 4.53 g kg⁻¹).

All inorganic P soil fractions (readily available P, Fe/Al bound P, or Ca/Mg bound P) were not significantly different between the P enriched and unenriched soils, nor vegetated and non-vegetated (Table 3). The differences in TP between the soils therefore, can be assumed to be in the organic fractions. There was no significant difference in the microbial biomass vs. the vegetation and non-vegetated treatments due to large variability, which was likely due to the fact that non-vegetated cores also contained roots from surrounding vegetated areas. As mentioned in the methods, we did not remove any roots to both prevent disturbance and to maintain the experiment close to field conditions where roots would be present under bare soil. In this fashion, any difference in P flux would be primarily a result of release from the aboveground biomass.

Phosphorus Flux Rates

There was a significant interaction term of soil P enrichment and vegetation treatment. This interaction indicates that the presence of vegetation in soils containing elevated TP concentrations showed a significant increase in the amount of P released to the water column. Whereas, plants present in the P unenriched soil did not lead to a mobilization of P to the water column. It has been demonstrated that a single plant species grown under low and high nutrient conditions led to lower nutrient biomass under the low nutrient condition (Güsewell and Koerselman, 2002). The vegetation in both the P enriched and P unenriched treatments was similar (Eupatorium sp.). Reflooding of the cores resulted in the senescence of the flood intolerant vegetation and therefore resulted in P release. The significantly higher rates of P release from the P enriched treatment with vegetation vs. the P unenriched vegetated treatment was presumably due to higher P uptake by the plants, reflecting P availability in the soil.

Soluble Reactive Phosphorus Release

Soluble reactive P accounted for the majority of P released to the water column (Fig. 3). In the non-vegetative treatment, this was equivalent to 98.5 and 100% of TP for the P enriched and unenriched non-vegetated treatment. In the vegetative treatment, SRP concentrations equated to 65 and 98.5% for the P enriched vegetated and P unenriched soils, respectively.

Water column soluble reactive P ranged from 1.41 ± 0.56 mg L⁻¹ in the unenriched, non-vegetated soil to 2.03 ± 0.87 mg L⁻¹ in the enriched soil at Day 38. In response to the higher labile P fraction in the soil, the SRP concentrations rapidly increased over the first 10 d after reflood to 1.91 mg L⁻¹ in the enriched, vegetated treatment (Fig. 3A) while the SRP concentrations remained relatively low at 0.33 mg L⁻¹ in the P unenriched, vegetated treatment (Fig. 3B).

A significant increase in SRP was seen over the first 10 d after reflood followed by a period of steady concentrations between Day 10 and Day 38. The data were therefore divided into two phases. An initial, first release phase (1–10 d) calculated the initial P release rates directly after reflood. The second phase release rates (10–38 d) were determined for water samples taken after an extended period of reflood. There was an initial spike in SRP concentration between Day 0 and Day 1 in all the cores, presumably as a result of soil suspension during reflooding, which occurs on rehydration of the dry, organic soils. The SRP concentrations stabilized after 24 h and therefore the release rates were calculated from Day 1.

Initial SRP release rates were significantly lower from the P enriched non-vegetated treatment, at 9.25 ± 1.80 mg SRP m⁻² d⁻¹. These rates were in comparison with the higher release rate from the P enriched non-vegetated treatment (13.4 ± 4.88 mg SRP m⁻² d⁻¹) (Table 4). The second phase (10–38 d) of SRP release was lower with rates of 7.05 ± 2.30 and 12.7 ± 4.57 mg m⁻² d⁻¹ for the unenriched, non-vegetated and enriched, non-vegetated soils, respectively. This differential release led to final SRP concentrations in the water column in the P enriched soil only

<table>
<thead>
<tr>
<th>Soil P treatment</th>
<th>P Enriched</th>
<th>P Unenriched</th>
<th>Vegetated</th>
<th>Non-vegetated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microbial Biomass P (0.5 M NaHCO₃)</td>
<td>55.3 ± 4.5</td>
<td>65.0 ± 20.8</td>
<td>52.7 ± 25.9</td>
<td>54.4 ± 17.9</td>
</tr>
<tr>
<td>Labile P (0.5 M NaHCO₃)</td>
<td>21.9 ± 6.63</td>
<td>21.8 ± 3.00</td>
<td>31.3 ± 9.18</td>
<td>22.2 ± 6.10</td>
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<tr>
<td>Fulvic acid-P (0.5 M NaOH)</td>
<td>93.2 ± 15.0</td>
<td>83.2 ± 21.6</td>
<td>96.2 ± 5.88</td>
<td>91.3 ± 19.7</td>
</tr>
<tr>
<td>Humic acid-P (0.5 M HCl)</td>
<td>40.2 ± 13.3</td>
<td>41.2 ± 17.4</td>
<td>41.7 ± 9.93</td>
<td>46.0 ± 15.4</td>
</tr>
<tr>
<td>Residual P (ashing)</td>
<td>114 ± 21.4</td>
<td>96.9 ± 24.5</td>
<td>126 ± 20.2</td>
<td>108 ± 27.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil P effects</th>
<th>P Enriched</th>
<th>P Unenriched</th>
<th>Vegetated</th>
<th>Non-vegetated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readily Available Pₗ (1.0 M KCl)</td>
<td>7.17 ± 4.34</td>
<td>4.31 ± 2.48</td>
<td>11.2 ± 8.55</td>
<td>7.70 ± 4.40</td>
</tr>
<tr>
<td>Fe/Al bound Pₗ (0.1 M NaOH)</td>
<td>21.4 ± 2.72</td>
<td>19.4 ± 3.64</td>
<td>22.6 ± 4.04</td>
<td>20.0 ± 2.99</td>
</tr>
<tr>
<td>Ca/Mg bound Pₗ (0.5 M NaOH)</td>
<td>20.3 ± 2.30</td>
<td>18.2 ± 3.25</td>
<td>21.5 ± 4.09</td>
<td>19.1 ± 2.61</td>
</tr>
<tr>
<td>Residual P (ashing)</td>
<td>222 ± 35.5</td>
<td>166 ± 73.5</td>
<td>221 ± 47.9</td>
<td>218 ± 31.2</td>
</tr>
</tbody>
</table>

Table 3. Sequential fractionation of the soil (0–10 cm) inorganic P pools for the P enriched and unenriched and the vegetated and non-vegetated treatments for readily available P, Fe/Al bound P, Ca/Mg bound P, and residual P fractions. Data shown are means and one standard deviation (n = 3).
treatment to be double the concentration than the P unenriched soil only treatment (Fig. 3A and 3B).

The enriched vegetated treatment showed an initial mean release rate of 43.0 ± 12.5 mg SRP m\(^{-2}\) d\(^{-1}\), which was significantly higher than the 13.4 ± 4.88 mg SRP m\(^{-2}\) d\(^{-1}\) for the non-vegetated soils (Table 4). The release rates equated to a three-fold difference as a result of vegetative presence in these enriched soils. These data suggest that the presence of vegetation can lead to significant mobilization of P from P enriched soil through uptake by the plant and subsequent leaching from the plant tissue during senescence. Therefore, plant growth during dry periods in wetlands can play an important role in internal P cycling in wetlands. A decrease in SRP release rates was found during the second phase, with 3.68 ± 5.82 and 12.7 ± 4.57 mg m\(^{-2}\) d\(^{-1}\) in the vegetated and non-vegetated P enriched soils, respectively (Table 4).

Fluctuations in SRP concentrations were observed in the P enriched, vegetated treatment, beginning on Day 5 and with a decrease in SRP concentrations from Day 10 to Day 30. The SRP concentration curve took on an S-shape in the vegetated cores only, while the non-vegetated treatment release remained linear (Fig. 3A). Since this oscillation in P concentration was only seen in the vegetated treatment, it is possible this artifact may be a result of epiphytic microorganisms present on the stems and leaves of plants (Preece and Dickinson, 1971; Collins, 1976; Blakeman, 1981; Morris et al., 1996).

Water column SRP concentrations in the P-enriched, vegetated treatment were significantly lower than those observed for non-vegetated cores, for four of the eight sampling events (Fig. 3B). The first phase (1–10 d) release rates in the vegetated cores averaged 5.74 ± 3.60 mg SRP m\(^{-2}\) d\(^{-1}\). The non-vegetated treatment was not significantly different at 9.25 ± 1.80 mg SRP m\(^{-2}\) d\(^{-1}\) (Table 4). Therefore, the growth of vegetation in P-unenriched soils did not lead to an increase in SRP release to the water column on reflooding so plant colonization alone was not a single factor in P release, but rather the interaction of plant colonization and P enriched soils led to this mobilization (Fig. 3B and 3D).

These results have important ramifications for wetlands with regions of P enriched soils. In the P enriched soil, SRP was mobilized by the plants on reflooding released into the water column. Conversely, the vegetated, unenriched soil released no significant amounts of SRP on reflood. Therefore, plant colonization during dry periods in P enriched soils is a significant mechanism for P release from the soil and this process could result in the remobilization and redistribution of soil P from the P enriched to P unenriched sections of the wetland when water flow is restored.

Table 4. Initial (1–10 d) and extended (10–38 d) release rates of soluble reactive P, total dissolved P and total P showing effects of P enrichment (Enriched and Unenriched) and vegetation (Vegetated and Non-vegetated). Values shown are means and one standard deviation (n = 4).

<table>
<thead>
<tr>
<th>Treatment (n = 4)</th>
<th>Soluble reactive P</th>
<th>Total P</th>
<th>1–10 d</th>
<th>10–38 d</th>
<th>1–10 d</th>
<th>10–38 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>P unenriched vegetation</td>
<td>5.74 ± 3.60</td>
<td>9.43 ± 3.65</td>
<td>9.40 ± 3.40</td>
<td>8.00 ± 3.85</td>
<td></td>
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<tr>
<td>P unenriched non-vegetated</td>
<td>9.25 ± 1.80</td>
<td>7.05 ± 2.30</td>
<td>9.16 ± 1.71</td>
<td>6.99 ± 2.56</td>
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</tr>
<tr>
<td>P enriched vegetation</td>
<td>43.0 ± 12.5*†</td>
<td>−3.68 ± 5.82†</td>
<td>26.6 ± 18.0*</td>
<td>0.89 ± 7.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P enriched non-vegetated</td>
<td>13.4 ± 4.88*†</td>
<td>12.7 ± 4.57</td>
<td>8.69 ± 4.80</td>
<td>12.7 ± 4.13</td>
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</tr>
</tbody>
</table>

* Indicates significant difference at an α = 0.05 between the vegetated and non-vegetated cores within sites.
† Indicates significant difference at an α = 0.05 between the 1 to 10 d and the 10 to 38 d rates for each treatment within sites.
column TP concentrations rapidly increased over the first 10 d to 2.47 mg L\(^{-1}\) in the P enriched, vegetated treatment, with four times more TP released (26.6 ± 18.0 mg TP m\(^{-2}\) d\(^{-1}\)) compared with the P enriched, non-vegetated treatment (8.69 ± 4.80 mg TP m\(^{-2}\) d\(^{-1}\)) (Fig. 3C, Table 4).

Total P release from the P enriched, non-vegetated treatment cores continued to increase after Day 10 with a second phase release rate of 12.7 ± 4.13 mg TP m\(^{-2}\) d\(^{-1}\), demonstrating a continual, consistent release of P over the 38 d incubation (Fig. 3C). Cores from P enriched, vegetated treatments showed a significant drop in P release rates to 0.891 ± 7.51 mg m\(^{-2}\) d\(^{-1}\) 10 d post reflood. This decline in release rates suggests the rapid release of P may have reduced the P concentration gradient between the water column and soil, thereby reducing flux out of the soil. The presence of vegetation significantly increased the initial release of TP in the P enriched soils only. This P flux is likely a result of P leaching from the plant, similar to the observed higher release rates of SRP from the vegetated, P enriched soils and includes some dissolved and particulate P fractions which comprise the difference between the final water column concentrations of SRP and TP concentrations (Fig. 3A and 3C).

Water column TP concentrations in the non-vegetated and vegetated, unenriched treatments, were not significantly different (Fig. 3D). The first phase (1–10 d) TP release rate in the vegetated cores was 9.40 ± 3.40 mg m\(^{-2}\) d\(^{-1}\) while the non-vegetated cores released TP at a rate of 9.16 ± 1.71 mg m\(^{-2}\) d\(^{-1}\). This finding further demonstrates that there was no significant effect of vegetation on release of TP, as was seen for SRP in P unenriched soils. After the initial phase, the vegetated and non-vegetated P unenriched treatments followed similar trends with 10 to 38 d release rates of 8.00 ± 3.85 and 6.99 ± 2.56 mg m\(^{-2}\) d\(^{-1}\), respectively (Table 4).

While nutrient enriched wetland soils show a propensity for P release following a drawdown/reflood event, the unenriched wetland soils did not. These results also suggest that flood intolerant plant colonization and growth during periods of low water/drought do not lead to mobilization of soil P in all cases. Where soil P is elevated due to historic external loading, the presence of flood intolerant vegetation can increase P release on refloodding. For similar wetland peat soils, we have observed that vegetation significantly increased the initial release of P from the nutrient enriched soils, rates that can be significantly increased by the presence of vegetation. Regarding the overall distribution of P, release from P enriched soils would have the effect of decreasing the soil P concentrations in enriched areas while increasing the soil P concentrations in others (unenriched), eventually elevating the overall baseline soil P concentrations of the entire system. These results have serious consequences for any marsh restoration if the restoration goal is to attain pre-impact soil P concentrations or to prevent further eutrophication of the marsh. These goals might not be attainable without the physical removal of the P enriched soil from the system to prevent the continual spread of P into pristine marsh area.

CONCLUSIONS

Desiccation of organic soils resulted in the release of P to the water column after refloodding. The P release rates were dependent on the soil TP concentration and the presence/absence of flood intolerant vegetation. Soil P characteristics at the 0- to 10-cm soil layer did not change as a result of the drawdown/reflood treatment. However, soil TP concentrations across regions were comparable at the end of the experiment. Phosphorus release to the overlying water column occurred rapidly within the first 10 d after reflood, with the majority (>99%) of P as SRP in both non-vegetated P enriched and unenriched soils. There was also significantly higher TP release from soil with higher initial TP concentrations. The quantity of P released by vegetation was found to be dependent on soil nutrient content, with greater P release in the nutrient enriched region compared with the nutrient unenriched region.

Since the termination of external nutrient inputs to BCMCA, internal nutrient dynamics have become an important regulator of the system’s recovery. In this study we have shown that a drawdown and subsequent reflood can result in significant fluxes of P from the nutrient enriched soils, rates that can be significantly increased by the presence of vegetation. Regarding the overall distribution of P, release from P enriched soils would have the effect of decreasing the soil P concentrations in enriched areas while increasing the soil P concentrations in others (unenriched), eventually elevating the overall baseline soil P concentrations of the entire system. These results have serious consequences for any marsh restoration if the restoration goal is to attain pre-impact soil P concentrations or to prevent further eutrophication of the marsh. These goals might not be attainable without the physical removal of the P enriched soil from the system to prevent the continual spread of P into pristine marsh area.

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