Soil phosphorus flux from emergent marsh wetlands and surrounding grazed pasture uplands


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Phosphorus (P) release from wetland soils to overlying waters is important to consider when restoring wetland hydrology. Soil physicochemical characteristics influence P dynamics between underlying soil and overlying water. Our study initially characterized wetland and surrounding upland soils prior to flooding. Deep marsh wetland soils had greater moisture content, soil organic matter, nitrogen (N), P, and lower bulk density than surrounding upland pasture soils, which indicates a nutrient concentration gradient between wetland and upland soils. To determine the short-term P dynamics between soils and overlying water, we conducted four laboratory soil water core studies during a 15-month period. Surface soils (0-10 cm) collected October 2005, February 2006, October 2006 and December 2006 from wetlands and their surrounding uplands within cow-calf grazed pastures were flooded for 7 days, and we measured P release from soil to overlying water. Phosphorus release rates from wetland (deep marsh and shallow marsh) and upland soils were similar. Values ranged between 20 mg m⁻² d⁻¹ (retention) and 77 mg m⁻² d⁻¹ (release). There was a significant, although weak, negative linear relationship between P release from deep marsh soils and hydroperiod. Thus, it may be important for land managers to consider increasing hydroperiod of wetland soils to decrease P release and increase retention. In addition, there was a significant negative exponential relationship between P release and days since deep marsh soil inundation. This suggests that to decrease P release from soils, soils should be wet rather than dry for prolonged periods, prior to flooding. We found significant relationships between P release from upland soils and their nutrient content (N, P and carbon). Reducing nutrient content in upland soils may help reduce the magnitude of P release from soil.

1. Introduction

Nutrients exported from non-point sources such as agricultural pastures can contribute to eutrophication in downstream surface waters such as ditches, canals, wetlands, rivers, and lakes (Vadas et al., 2009). Therefore, water and phosphorus (P) management in grazed pastures and managed wetlands are important to reduce nutrient loading to downstream water bodies. Many agricultural management practices are implemented to reduce nutrient export by a combined approach of reducing and balancing inputs and outputs at field-, farm- and watershed-scales (Sharpley et al., 2001b). Practices often include reducing and/or limiting the use of phosphate fertilizers, reducing soil erosion and water runoff, and protecting riparian and wetland areas to buffer stormwater flows (Bottcher et al., 1995; McDowell et al., 2001; Sharpley et al., 2001a,b). However, while reducing nutrient export and the amount of P entering receiving water bodies, these practices often do not address the internal supply of nutrients present (Fisher and Reddy, 2001). In some instances, the internal supply of nutrients in receiving systems can be in excess of the external nutrient loading (Fisher and Reddy, 2001; Søndergaard et al., 2003; Bostic and White, 2007). This can occur due to sustained historical P loading, resulting in P accumulating in soils and sediments. For example, water flowing into historically loaded wetlands will have lower P concentrations because of improved management practices that have reduced P application and export from upland systems. This creates a P concentration gradient from the underlying soil, or sediment, to the incoming water, causing P to move from soil porewater to the overlying water column (Moore et al., 1998).

Phosphorus release from historically P loaded soil/sediment to overlying water is typically a result of a diffusion-controlled process due to a P concentration gradient between underlying soil and
overlying water (Reddy et al., 1999). However, P can also flux from soils to overlying water via advective processes. Advection P release can be caused by bioturbation, the feeding activities of invertebrates in underlying soil, and it is the bulk movement of soil pore water to the overlying water column (van Rees et al., 1996).

Several researchers report that the internal supply of nutrients in wetland and other flooded soils and sediments can result in nutrient release from soil to overlying water (Marsden, 1989; Fisher and Reddy, 2001; Aldous et al., 2007; Bostic and White, 2007). Release of P to overlying water depends upon various soil/sediment characteristics and environmental conditions such as pH (Moore and Reddy, 1994; Olila and Reddy, 1995); iron and aluminum content in underlying acidic soil (Richardson, 1985); calcium and magnesium concentrations in underlying alkaline soil (Froelich, 1988); soil and water temperature, which influences microbial activity (Malecki et al., 2004); P concentration in overlying water and underlying soil (Pant and Reddy, 2003; Novak et al., 2004); mineralization of soil organic P (Fisher and Reddy, 2001); oxygen content and ionic strength of overlying floodwater (Ryden and Syers, 1975); soil redox conditions (Patrick and Khalid, 1974; Liikanen et al., 2004); and antecedent soil hydrological conditions (Olila et al., 1997; Dunne et al., 2006; Aldous et al., 2005).

Hydrological factors such as flooding, drawdown and antecedent hydrological conditions can also significantly influence P dynamics (Pant and Reddy, 2003; Aldous et al., 2005; Dunne et al., 2006) between soil and water. Pant and Reddy (2003) observed that P release from P loaded soils decreased as the number of flooding cycles increased, whereas in another study, they suggested that drawdown periods of about 30 days prior to flooding reduced release rates, increased humification, and immobilized P by induced microbial activity (Pant and Reddy, 2001a).

The objectives of this study were to evaluate whether a nutrient concentration gradient exists between wetland and upland grazing pastures soils, determine P release from soils along a hydrological gradient from wetland to surrounding grazed upland improved pasture, and determine the relationships between physicochemical characteristics of wetland and upland soils and P release. This study is important as land managers are restoring the hydrology of historically hydrologically isolated wetland systems for the purposes of water and nutrient storage. Although wetland soils typically act as long-term sinks for nutrient storage, P release can occur in the short-term. We hypothesize that this short-term release of P from wetland soils is less than the P release from uplands soils, with this difference being influenced by soil physicochemical characteristics, such as soil organic matter and nutrient content. We also hypothesize that hydrologic factors such as hydroperiod and antecedent hydrologic conditions contribute to the P dynamics between underlying soil and overlying floodwater.

2. Methods

2.1. Site description

All soils were collected from four small (<2 ha) natural wetlands located in cow-calf grazing pastures in the Okeechobee Basin, South Florida (Dunne et al., 2007): two on Beaty Ranch (N 027° 24.665', W 080° 56.940'), and two on the Larson Dixie Ranch (N 027° 20.966', W 080° 56.465') (Fig. 1). Wetlands on the same ranch were less than 1 km apart. Cow-calf grazing pastures that surrounded wetlands were grazed at a cattle-stocking density of about 1 head/ha at Larson Dixie and about half this at Beaty Ranch. Cattle typically grazed in upland pasture year-round and were not restricted from grazing in or near wetland areas. Wetlands were unfenced and during summer periods, cattle used wetland areas as cooling ponds.

Prior to field sampling, vegetative communities and basin morphology were used to stratify the wetland and surrounding pasture upland into zones similar in vegetation community structure to Van der Valk (1989). The wetland center zone was categorized as “deep marsh.” These areas had open water present during wetland flooding. Typical vegetation species included Potentaria cordata var. lanceifolia (Muhl.) Torr., Bacopa monnieri (L.) Pennell, Panicum hemitomon Schult., Polygonum sp., and Ludwigia repens Forst. The second zone was a transition zone, “shallow marsh.” There was evidence of flooding, but this area was often dry during field sampling. A concentric ring of juncus effusus L demarcated the outer extent of this zone. Other species present included Eleocharis baldwinii (Torr) Chapm. Paspalum acuminatum Raddi, and Hydrochloa caroliniensis Beauv. The third zone was classified as “wet meadow” where P. acuminatum Raddi was very common. The final zone identified was the surrounding “pasture upland,” which was dominated by forage grass Paspalum notatum Flugge.

Wetlands at Larson Dixie were embedded in an upland pasture, which had soils classified as Siliceous, hyperthermic Spodic, Psammaquents (Basinger series). Upland pasture soils at Beaty Ranch were Sandy, Siliceous, hyperthermic Typic Humaquents (Placid series) (Lewis et al., 2001). All soils were formed from sandy marine sediments, were deep and poorly drained.

2.2. Hydrology

Each wetland was drained by a ditch that transported water off-site during high water events. However, these wetlands were historically hydrologically isolated from surrounding surface waters. In an overall water budget of the sites, Min et al. (2010) estimated that hydrologic inflow to the wetlands was 79% rainfall. Surface runoff from surrounding pasture and backflow contributed 19%. Groundwater recharge was dependent on ditch elevation and fluctuated between 5% and 57% of total outflows. Ten to forty-three percent of the total outflow was evaporation/transpiration, with the remainder being ditch flow out of the wetland.

The relative elevation of each soil sample location (n = 102) was measured during soil sampling events in October 2005, October 2006 and December 2006. These elevations were used to help calculate hydroperiod for a given soil sample location. Relative elevations were not measured for soil sample locations in February 2006. In addition, in December 2006, no elevations were taken at Beaty sites. Relative elevations were not taken on these dates due to field logistical difficulties. Measured relative elevations were referenced to a groundwater well in the deepest portion of each wetland to determine water depth and ultimately hydroperiod for each respective soil sample location (Dunne et al., 2007). Water depth was treated as the lower wetland boundary and the range of water levels was treated as the hydroperiod.

levels in groundwater wells at Larson Dixie were monitored from July 2003 until April 2006 and water levels in Beaty wells were monitored from December 2003 until March 2006. In addition to calculating hydroperiod for a given soil sample location, we also calculated the number of days a soil sample location was inundated, prior to sampling. We called these values “days since inundation” and used it as a proxy for antecedent soil hydrological conditions. The temporal nature of these wetlands was one of our justifications for undertaking a similar core study several times during a 15-month period, as sites became progressively dry. There was a prolonged drought in the Okeechobee Basin during 2005 and 2006.

2.3. Soil sampling

Soil samples collected on 7 October 2005 were characterized for a suite of soil physicochemical characteristics (described below). Intact soil cores (0-10 cm) were taken along three transects that extended from the center of each wetland, to surrounding pasture upland. Along each transect, 3 intact soil cores were taken in the wetland (deep marsh, shallow marsh, wet meadow) and one intact core was taken in the pasture upland. Therefore, 12 soil cores were taken at each site. Cohen et al. (2008) suggested that in similarly sized wetlands that soil samples collected within 30–60 m of each other had similar biogeochemical characteristics; therefore, samples were auto correlated in space. To ensure that our replicate samples per zone were independent of each other, we sampled soils along and between transects that were typically greater than 60 m apart. Polycarbonate tubes (7.5 cm internal diameter × 0.3 cm wall thickness × 15 cm in length) were sharpened at one end and hammered to a soil depth of 15 cm. Tubes were then removed from soil and extruded out of the core tube from the bottom up, using a ramrod. Soil was sectioned at a 10 cm depth from the surface, while the remaining 5 cm core was discarded. Each sample was placed into a pre-labeled zip lock bag and put on ice in a cooler. Soils were transported back to the laboratory, where they were stored at 4 °C until prepared for physicochemical analyses.

2.4. Experimental core studies

For experimental core studies, intact soil cores (0-10 cm) were collected on 7 October 2005, 2 February 2006, 20 September 2006, and 12 December 2006. During the 15-month period, there was a prolonged drought at all sites; therefore, as time increased, site moisture also decreased. During each sampling event, 9 intact soil cores were collected from each wetland and 3 soil cores were collected from the surrounding upland. Upon collection, tubes with intact soil cores were placed on ice, transported back to laboratory and stored at 4 °C for 1 week until laboratory experiments were conducted. Prior to undertaking experimental core studies, the cap covering the top of each intact core tube was removed. To prevent air and water leakage from the bottom of core tubes, the cap on the bottom of each tube was sealed with a metal clamp. Each soil core tube was then wrapped in aluminum foil to prevent soil exposure to light and algal growth. Soils in core tubes were initially wetted with Kissimmee River water until surface appeared saturated. Once saturated, soils were flooded with a volume of Kissimmee River water equivalent to a water depth of 15 cm. All soil core tubes were placed at random into glass aquariums. To maintain isothermal conditions and prevent water leakage from core tubes, the aquariums were filled with tap water until their water depth was equal to that of floodwaters in the core tubes. Temperature loggers iButton® (Dallas Semiconductor Corp., Dallas, Texas) were placed in the aquariums to record ambient water temperature.

Sampled wetlands were typically not flooded during sampling events; therefore, we could not collect site water to flood soils during laboratory core studies. Instead, at each time of sampling, Kissimmee River water was collected and used to flood cores. The Kissimmee River is near (~15 km) wetland study sites. Phosphorus concentrations were initially measured in Kissimmee River water, which was collected in October 2005; February 2006; September 2006; and December 2006. Sampled water was passed through a 0.45 μm disc filter into a 20 mL scintillation vial. Filtered water was analyzed for soluble reactive P (SRP) using an automated ascorbic acid method (Method 365.1; USEPA, 1993). Soluble reactive P concentrations in sampled floodwater was filtered and analyzed as previously described.

The areal mass of SRP in the water column was determined on each day of sampling as the product of the measured SRP concentration in water, multiplied by the volume of overlying water, divided by the underlying soil surface area. Sample volume of each sampling event was accounted for by subtracting the sampled volume from the overlying water volume. This was about 1% of the total water volume on each day of sampling and less than 5% during the 7 days.

Phosphorus release rate was determined similarly to Pant and Reddy (2003). Briefly, P flux (mg m⁻² d⁻¹) is the linear slope between the cumulative areal mass of SRP in the overlying water (mg m⁻²) on days 0, 1, 2, 5, and 7, y-axis, regressed against time (days 0, 1, 2, 5 and 7) on the x-axis.

2.5. Physicochemical characteristics of soils

The following soil physicochemical parameters were measured on soils collected in October 2005: pH, water content, bulk density, total P (TP), total nitrogen (TN), total carbon (TC), organic matter (as measured by loss on ignition [LOI]), inorganic P extracted with 1 M HCl, and water-extractable P (WEP). These characteristics were measured to physically and chemically characterize soils, as soil characteristics are important for soil water dynamics (Pant and Reddy, 2003). Soil pH was measured in a 1:2 soil to water ratio. A known mass of field moist soil was then dried for 72 h at 70 °C and the net percentage difference between wet and dry weights was quantified as soil moisture content. Soil bulk density was determined using a simplified coring method similar to Blake and Hartge (1986). Soil TP concentration was determined on 0.5 g of finely ground dry soil that was combusted at 550 °C in a muffle furnace for 4 h. Ash was then dissolved in 6 M HCl (Andersen, 1976) and digestate analyzed for P using the automated ascorbic acid method (Method 365.1; USEPA, 1993). Depending on soil textural components, 5–60 mg of dried finely ground soil was analyzed for TC and TN by dry combustion using a C–N–S analyzer (Carlo Erba Model NA-1500). To determine inorganic P, soils (0.5 g of finely ground and sieved to 2 mm) were extracted with 25 mL of 1 M HCl. Samples were then centrifuged for 10 min at 6000 rpm and filtered through 0.45 μm filter paper using a vacuum filtration system. Soluble reactive P was analyzed using an automated ascorbic acid method as previously mentioned. To quantify WEP, field moist soils were extracted with DDI water for 1 h at a soil to solution ratio of 2 g of dry, ground, and sieved soil to 20 mL of water.

Soil physicochemical characteristics of the different wetland zones (deep marsh, shallow marsh, and wet meadow) and surrounding pasture upland soils at Beaty ranch (BN = Beaty North; BS = Beaty South) and Larson Dixie ranch (LW = Larson West; LE = Larson East) and. Values represent a mean (± one standard deviation) (n = 3).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Site</th>
<th>Deep marsh</th>
<th>Shallow marsh</th>
<th>Wet meadow</th>
<th>Upland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (%)</td>
<td>BN</td>
<td>80.8 (3)</td>
<td>56.8 (8)</td>
<td>50.4 ND</td>
<td>35.0 (3)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>73.8 (3)</td>
<td>80.2 (0)</td>
<td>57.1 (13)</td>
<td>32.7 (5)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>57.6 (2)</td>
<td>42.4 (4)</td>
<td>26.9 (3)</td>
<td>32.9 (7)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>45 (6)</td>
<td>26.3 (6)</td>
<td>33.4 (11)</td>
<td>42.4 (2)</td>
</tr>
<tr>
<td>Bulk density (g cm$^{-2}$)</td>
<td>BN</td>
<td>0.345 (0.04)</td>
<td>0.840 (0.36)</td>
<td>0.646 ND</td>
<td>0.649 (0.22)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>0.329 (0.08)</td>
<td>0.278 (0.03)</td>
<td>0.649 (0.61)</td>
<td>0.866 (0.14)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>0.560 (0.11)</td>
<td>0.786 (0.18)</td>
<td>0.945 (0.15)</td>
<td>0.800 (0.17)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>0.759 (0.10)</td>
<td>0.962 (0.10)</td>
<td>1.013 (0.03)</td>
<td>0.667 (0.01)</td>
</tr>
<tr>
<td>Total P (mg kg$^{-1}$)</td>
<td>BN</td>
<td>546 (170)</td>
<td>315 (208)</td>
<td>404 ND</td>
<td>173 (5)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>408 (102)</td>
<td>825 (185)</td>
<td>376 (136)</td>
<td>226 (150)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>461 (171)</td>
<td>363 (105)</td>
<td>159 (60)</td>
<td>365 (261)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>432 (78)</td>
<td>221 (120)</td>
<td>250 (182)</td>
<td>288 (27)</td>
</tr>
<tr>
<td>TN (%)</td>
<td>BN</td>
<td>1.110 (0.28)</td>
<td>0.583 (0.22)</td>
<td>0.573 ND</td>
<td>0.369 (0.02)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>1.180 (0.60)</td>
<td>1.843 (0.37)</td>
<td>0.858 (0.33)</td>
<td>0.442 (0.12)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>1.256 (0.33)</td>
<td>0.818 (0.20)</td>
<td>0.439 (0.11)</td>
<td>0.629 (0.29)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>0.851 (0.22)</td>
<td>0.590 (0.23)</td>
<td>0.604 (0.36)</td>
<td>0.664 (0.13)</td>
</tr>
<tr>
<td>TC (%)</td>
<td>BN</td>
<td>18.373 (5.12)</td>
<td>8.080 (4.03)</td>
<td>9.800 ND</td>
<td>5.708 (0.03)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>18.216 (9.75)</td>
<td>27.969 (7.00)</td>
<td>12.583 (5.14)</td>
<td>6.174 (2.77)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>16.083 (4.52)</td>
<td>10.225 (2.81)</td>
<td>4.793 (1.38)</td>
<td>7.616 (4.55)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>10.920 (3.11)</td>
<td>6.522 (3.35)</td>
<td>6.744 (5.39)</td>
<td>9.603 (2.16)</td>
</tr>
<tr>
<td>WEP (mg kg$^{-1}$)</td>
<td>BN</td>
<td>1.25 (0.31)</td>
<td>1.57 (1.13)</td>
<td>0.16 ND</td>
<td>0.58 (0.36)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>4.22 (0.79)</td>
<td>2.53 (1.30)</td>
<td>1.33 (0.13)</td>
<td>0.89 (0.85)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>1.43 (0.24)</td>
<td>1.22 (0.26)</td>
<td>0.97 (0.48)</td>
<td>1.87 (2.30)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>1.91 (0.36)</td>
<td>2.75 (1.60)</td>
<td>2.38 (2.94)</td>
<td>0.47 (0.41)</td>
</tr>
<tr>
<td>1 M HCl P (mg kg$^{-1}$)</td>
<td>BN</td>
<td>84.57 (38.66)</td>
<td>43.87 (16.10)</td>
<td>68.47 ND</td>
<td>26.12 (7.31)</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>80.97 (22.23)</td>
<td>143.13 (38.06)</td>
<td>64.64 (16.89)</td>
<td>34.05 (18.27)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>76.04 (11.66)</td>
<td>55.82 (4.90)</td>
<td>24.25 (12.96)</td>
<td>81.50 (61.11)</td>
</tr>
<tr>
<td></td>
<td>LW</td>
<td>59.43 (10.97)</td>
<td>31.42 (20.84)</td>
<td>54.75 (29.99)</td>
<td>48.04 (5.82)</td>
</tr>
</tbody>
</table>

ND, not determined.

Samples were then centrifuged, filtered, and analyzed for SRP as previously described.

2.6. Statistical analyses

Data distributions were tested for normality. If data were not normally distributed prior to statistical analyses, they were log transformed to approximate normality. If data still did not approximate normality, then a non-parametric test (Kruskal–Wallis) was undertaken on non-transformed data. Statistically significant differences were determined at the p < 0.05, 0.01, and 0.001 levels. Soil physicochemical characteristics were compared to P release rates between sites (Larson Dixie and Beaty) using t-tests, and using ANOVAs we compared differences among the wetland zones. Relationships were also investigated between P release from the different zonal soils and their physicochemical characteristics. A Pearson product moment correlation coefficient quantified the strength of relationships. Of particular interest were the relationships between P release and hydroperiod, and the number of days a soil sample location was inundated for, prior to sampling. Regression analyses were used to investigate these relationships.

3. Results and discussion

3.1. Soil physicochemical characteristics

Beaty soils had greater moisture content, similar pH (average was 4.4 ± 0.4 pH units) and lower bulk density than soils collected from Larson Dixie (Table 1; t-test; p < 0.05) suggesting that Beaty soils were saturated for longer. In addition, the hydroperiod for Beaty soils was significantly greater than for Larson Dixie soils (Fig. 2; t-test; p < 0.05) confirming that Beaty sites were flooded for longer. When concentrations (mg kg$^{-1}$) (Table 1) and storages (g m$^{-2}$) (normalized for soil bulk density and soil sampling depth; data not shown) of TP, 1 M HCl P, WEP, TN and TC were compared between sites, concentrations and storages were similar.

Deep marsh soils had greater moisture content than all other soils (Table 1; ANOVA; p < 0.05). In addition, the hydroperiod for deep marsh soils was significantly greater (between 60 and 100 days) than the hydroperiod of all other soils (Fig. 2). Bulk density of deep marsh soils was about 30% less than upland soils, whereas wetland soil concentrations of TP, TN, and TC were about twice that of upland soils (Table 1; ANOVA; p < 0.05). Carbon is an important wetland soil characteristic for long-term P storage, since organic matter accretion controls long-term P storage (Bridgham et al., 2001; Reddy et al., 1999; Craft and Richardson, 1993). We found that wetland soils (deep marsh, shallow marsh and wet meadow) had greater concentrations of carbon relative to upland soils (t-test; p < 0.05). The gradients observed in our study were similar to the findings of Axt and Walbridge (1999). They reported that soil characteristics such as organic matter, bulk density, and clay content were significantly greater in palustrine forested wetlands, relative to their adjacent streambank and upland soils and these differences influenced soil P sorption.

Previous studies, Walbridge and Struthers (1993) suggested that when one compares across landscape type it is important to take into account soil characteristics like soil bulk density and sampling depth. Therefore, in our study we normalized soil nutrient concentrations with sampling depth and bulk density, which varies across wetland and upland zones. We found that there was no significant difference between soil zonal nutrient (TP, TN, and TC) storage on a mass per unit area (g m$^{-2}$) basis.
3.2. Short-term phosphorus release from wetland and upland soils

In general, the P release during the four experimental core studies (each study had a 7-day flooding period) was greatest from Larson Dixie soils (t-test; $p < 0.001$). When release for the four individual sites were compared, soils collected from Larson West released greatest amounts of P (ANOVA; $p < 0.05$) while, Larson East and Beaty South soils released similar amounts of P to overlying water. In October 2005, Beaty soils released less P than soils from Larson Dixie (t-test; $p < 0.001$). In fact, during October 2005 and February 2006 Beaty North wetland soils (deep marsh, shallow marsh, and wet meadow) tended to retain P, whereas upland soils tended to release P to overlying water (Fig. 3). Release of P throughout the study increased through time for all deep marsh soils, between October 2005 and December 2006 (Fig. 3; Kruskal–Wallis test; $p < 0.01$). During the July and December 2006 sampling, collected wetland soils were not inundated. We hypothesize that flooding these relatively dry, deep marsh soils provided suitable conditions for mineralized organic P to flux from soil into overlying water (Pant and Reddy, 2003). Mineralization of organic P to inorganic forms under aerobic conditions can contribute to increased P release from soils that are re-flooded (D’Angelo and Reddy, 1994; Olila et al., 1997). Our previous study (Dunne et al., 2007) suggested that most P in surface soils of Larson Dixie and Beaty wetlands was stored in organic P forms. Microbial biomass P was about 21% of soil total P, whereas fulvic acid bound P was greater, 33% of total P. Unavailable organic P (humic acid bound P) and recalcitrant residual P accounted for 26% of soil total P.

In contrast to deep marsh soils, there were no significant differences in P release rates through time from shallow marsh, wet meadow and upland soils (Fig. 3). This was not expected as nutrient concentrations in upland soils were much lower than nutrient concentrations in wetland soils. Further, as time progressed from October 2005 to December 2006 all sites became progressively drier (see later discussion). Our findings suggest that P release rates from soils to overlying water is more related to the areal storage of P ($g m^{-2}$), as areal storage was generally similar between wetland and upland soils.

In a land management context, these results suggest that if upland soils become flooded due to restoring hydrology of isolated wetlands for increased water and nutrient storage, an initial short-term P release from additionally flooded wetland and surrounding upland soils may be of similar magnitudes. However, we suggest that P release will be much less if soils are continu-
We hypothesized that as initial SRP concentrations in overlying water increased from 0.08 to 1 mg SRP L$^{-1}$, P release would decrease as the P concentration gradient decreases between soil porewater and overlying water (Reddy et al., 1999). However, we found that P release was similar between cores that were incubated at both 0.14 and 1 mg SRP L$^{-1}$. Release was also similar between cores incubated at initial P concentration of 0.08, and 0.16 mg SRP L$^{-1}$. However, there were significant differences between release rates for initial SRP concentrations of 0.14 and 1 mg SRP L$^{-1}$, and initial SRP concentrations of 0.16 and 1 mg SRP L$^{-1}$ (ANCOVA; p < 0.05). These findings suggest that other factors, possibly changes in environmental conditions are more important for P release from these soils.

In general, we believe that the rate of P release measured during the (short-term) 7-day flooding periods represents a maximum estimate of potential P release from soil to water, as release is typically greatest for the initial flooding period (Fisher and Reddy, 2001; Malecki et al., 2004; Aldous et al., 2007). Furthermore, during this period, release typically increased linearly. Pant and Reddy (2003) report that release tends to decrease with number of times a soil is flooded, with this decrease related to the reduced amount of available P stored in soil.

We suggest that soils could continue to release P under flooded conditions for about a year. This is based upon an average inorganic P (1 M HCl) wetland and upland soil storage (3.7 and 3.5 g m$^{-2}$, respectively) and our estimate of maximum P release for wetland and upland soils (9 and 11 mg m$^{-2}$ d$^{-1}$, respectively). However, the wetlands we studied were not permanently flooded and various processes at the ecosystem-scale determine whether a given wetland retains or releases P. These include P uptake by plants, microbes, and algae (Dodds, 2003), accumulation and accretion of organic material (Craft and Richardson, 1993) and water level management (Graham et al., 2005). Nonetheless, previous studies (Dolan et al., 1981; Dunne et al., 2007) suggest that the greatest nutrient storage in wetland ecosystems is in soils. Knowing magnitudes of potential internal P loading can help water managers determine its relative importance for nutrient budgets (Malecki et al., 2004).
3.3. Other P release studies

In our study, P release from wetland and upland soils ranged between a retention of 20 mg P m\(^{-2}\) d\(^{-1}\) and a release of 77 mg P m\(^{-2}\) d\(^{-1}\). Other P release studies in wetland, estuarine, lake, and improved pasture studies in central Florida have reported values from 0.4 mg m\(^{-2}\) d\(^{-1}\) P retained to 242 mg m\(^{-2}\) d\(^{-1}\) released (Moore et al., 1998; Pant and Reddy, 2003; Malecki et al., 2004; Dunne et al., 2006, 2007; Aldous et al., 2007; Tweel and Bohlen, 2008). In these studies, values vary dramatically depending on experimental approaches, sites, flooding duration, and initial soil and water P content, which often make it difficult to compare rates among studies. However, they do indicate the magnitude of potential release from different types of soils and sediments, which is of potential use to land and water managers, in determining its relative importance to nutrient loading.

3.4. Relationships between phosphorus release, soil characteristics and hydrological factors

Soil TC was positively related to soil water content (Pearson correlation; \(r = 0.57; p < 0.001\)). Total P, TN and 1 M HCl P were all significantly related to each other (\(r > 0.81\)). Inorganic P extracted with 1 M HCl accounted for between 14 and 24% of soil TP storage. The WEP fraction was weakly associated with TN (\(r = 0.36; p < 0.05\)), whereas WEP was not related to other soil P fractions such as 1 M HCl P or soil TP. This may be because the WEP storage fraction was less than 1% of soil TP storage (g m\(^{-2}\)). However, Kleinman et al. (2005) found a positive relationship between WEP and TP in animal manures. They also used WEP in soil to predict TP concentrations in surface runoff from manure applied pasture upland soils.

There were few relationships between deep marsh soil characteristics and P release. However, there were significant relationships between soil organic matter (\(r = -0.34\) and WEP (\(r = 0.35\)), and P release. When Moore et al. (1998) investigated flooded lake sediments they found no relationships between soil characteristics and P release. They suggested that redox conditions, which govern iron and P dynamics, were mostly responsible for P release in their study. They also cited decomposition and release of labile organic P could contribute to the lack of relationship between WEP and P release. Soils also have an extreme buffering capacity to changes in porewater P concentrations (Bridgham et al., 2001).

In shallow marsh soils of this study, P release was significantly correlated with bulk density (\(r = 0.28\)) and TC (\(r = 0.39\)), but in wet meadow soils, P release was significantly correlated only with WEP (\(r = 0.48\)). In contrast to wetland soil characteristics only having a few relationships between P release, P release correlated with numerous soil characteristics in upland soils. For example, P release was significantly correlated with TP (\(r = 0.33\)), TN (\(r = 0.34\)), and TC (\(r = 0.50\)).

Phosphorus release and hydroperiod in deep marsh zones were significantly negatively correlated (Fig. 4) suggesting that as hydroperiod increased, P release decreased. This has important implications for restoring hydrology to historically isolated wetlands, as we found that increasing duration (hydroperiods > 250 days) was concomitant with deep marsh soils retaining P.

When days since inundation for deep marsh soils were regressed against P flux, there was a negative exponential relationship (Fig. 5; ANOVA; \(p < 0.01\)). Phosphorus release was greatest when deep marsh soils were dry for longer periods (negative days since inundation), whereas when deep marsh soils were collected under flooded conditions, which only occurred in October 2005 (positive days since inundation) P release tended to be lower. Phosphorus release during dry conditions is probably due to increased rates of decomposition, which cause organic P to mineralize to inorganic forms during aerobic conditions. Phosphorus release rates also tended to increase and were more variable after soils were dry for about 200 days (Fig. 5). Previously, Dunne et al. (2006) observed that wetland soils at Larson Dixie, that were flooded for 28 days and then re-flooded for another 28 days, had lower P release rates relative to soils that were either saturated or dry for 28 days and then flooded for 28 days. In contrast, Aldous et al. (2005) observed that nutrient impacted wetland soils when re-flooded, released P at similar rates, irrespective of antecedent soil moisture conditions. However, they did suggest that undisturbed wetland soils, which were pre-dried, released P into water during flooding, while pre-flooded soils did not. Olila et al. (1997) found that when wetland soils were dried for 10 weeks and then re-flooded, P release was 334 mg Pm\(^{-2}\) d\(^{-1}\), whereas when soils were dried for 3 weeks and re-flooded, P release was much lower (32 mg P m\(^{-2}\) d\(^{-1}\)). The death of microbes and the availability of organic acids...
may have contributed to increased P release during longer periods of drying (Pant and Reddy, 2001b).

Significant relationships did not exist between P flux and days since inundation for shallow marsh soils; however, there was a weak, but significant relationship between flux from wet meadow soils and days since inundation ($r = -0.35$; $p = 0.03$). There was no relationship for uplands soils. The general lack of relationships could be due to the mineral nature of upland soils relative to deep marsh soils. Deep marsh soils had greater organic matter content ($33 \pm 10\%$) and soil TC ($16 \pm 6\%$) than the other zonal soils (ANOVA; $p < 0.05$).

4. Conclusions

Deep marsh soils were wetter, had greater amounts of organic matter and greater nutrient concentrations than surrounding pasture upland soils. However, when we compared nutrient storage on an areal basis across landscape position (deep marsh, shallow marsh, wet meadow and upland) storages were similar.

During the four, 7-day laboratory P core studies, short-term P release from soil to overlying water was similar across landscape position. We observed a significant negative linear relationship between P release from soil and hydroperiod in deep marsh soils indicating that as hydroperiod increased, P release decreased. Deep marsh soils that were wet for more than 250 days, tended to retain rather than release P, which supports water managers decisions to consider restoring hydrology to these historically isolated wetlands. In addition, P release from deep marsh soils increased, as the number of days since inundation tended to increase. This release was probably a result of organic P being mineralized during non-flooded conditions and subsequent release to overlying water during flooding.

In contrast to deep marsh soils, there was no relationship between P release and hydroperiod in upland soils. Phosphorus release in upland soils was significantly related to soil total nutrient (N, P and C) content. Therefore, we conclude that reducing nutrient content in upland soils could contribute to reducing P release from upland soils upon flooding.

Management practices targeted to increase water and P storage in historically isolated wetlands, which have been P impacted for many years, need to understand and consider potential short-term releases of P from both wetland and surrounding upland soils. Finally, we conclude that successful management to mitigate this release includes maintaining increased hydroperiod and reducing the frequency of drying deep marsh soils.

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