WETLANDS, Vol. 27, No. 4, December 2007, pp. 1025–1035

SOIL PHOSPHORUS RELEASE FROM A RESTORATION WETLAND, UPPER KLAMATH LAKE, OREGON

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Abstract: Many wetland restoration projects are initiated with phosphorus (P) retention as a primary objective. While undisturbed wetlands often are net sinks for P and other nutrients, there is evidence that newly flooded restoration wetlands on former agricultural land initially release P to surface waters. The objectives of this study were to: 1) measure P release from soils to overlying surface waters that would occur when re-flooding agricultural fields to restore a lake fringe wetland connected to Upper Klamath Lake, Oregon; and 2) identify management strategies to abate nutrient release from soils during restoration to minimize P loading to Upper Klamath Lake. We simulated the process of re-flooding soils using mesocosms in a laboratory experiment. The soils were flooded with lake water, and the water was replenished on a weekly basis. The net P flux from soils to surface water was estimated by measuring differences in P concentrations between water that had been in the mesocosms and the lake water used for replenishment. After the flooding experiment, we measured the concentrations of four forms of soil P using a modification of the Hedley procedure, to examine relationships between soil P chemistry and P release. The majority of P was released in the first two days of the experiment, and all detectable P was released by the end of the second month. We estimated that 1–9 g P/m^2 were released from the soils to the water column over the course of the experiment, which amounted to 1%–16% of total soil P. Scaling up to the entire wetland, this totals approximately 64 tons P released over 3,000 ha. We did not find any statistically significant relationships between any of the four forms of soil P and the amount of P released in the flooding experiment. Even though we demonstrate here that P is released while undertaking wetland restoration projects on former agricultural land, it is likely to be a temporary process, and once the wetland begins to resume more natural hydrological and biogeochemical functions and vegetation structure, it will re-start the process of soil accretion and P sequestration.

Key Words: eutrophication, phosphorus retention, soil phosphorus fractionation, water quality, wetland restoration

INTRODUCTION

Wetlands have become increasingly altered on a global scale, resulting in measurable losses of ecosystem services (Millennium Ecosystem Assessment 2005, Zedler and Kercher 2005). Wetland restoration is an important strategy in the conservation toolbox to restore these lost services. These ecosystem services include water purification, where wetlands remove nutrients, toxins, and sediments from the water column. Phosphorus retention, for example, is a valuable ecosystem service in many watersheds because this element often limits freshwater primary productivity. When it is present in excess, it can lead to surface water eutrophication by stimulating cyanobacterial and algal blooms. Phosphorus retention can occur in many wetland types, and wetlands frequently are used world-wide for semi-natural wastewater treatment (Mitsch et al. 1995, 2000, Kadlec and Knight 1996).

It is unlikely, however, that a wetland, either natural or restored, has limitless capacity to filter soluble and sediment-bound P from the water column (Fisher and Acreman 2004). Annual cycles of primary productivity and hydrologic regimes cause many surface water-driven wetlands to oscillate temporally between releasing and sequestering P (Corstanje and Reddy 2004, Novak et al. 2004, Qiu et al. 2004), and the timing of these retention and release cycles can influence downstream water quality. For example, P release that occurs during the growing season may produce cyanobacterial blooms that are more likely to be detrimental to water quality in receiving waters than if releases occur at other times of year.

Phosphorus retention in wetlands is controlled by several factors that vary depending upon whether the P is particulate or soluble. Retention of soil-bound particulate P is controlled by physical processes, such as sediment deposition (White et al. 2000). Retention of soluble P involves a suite of geochemical and biological mechanisms, although the former are thought to be responsible for greater quantities of P retention (Walbridge and Struthers 1993, Novak et al. 2004). Geochemical mechanisms include soluble P forming complexes in the soil with Fe and Al hydroxides and with Ca. Previous studies demonstrated that soil P sequestration is greater when there is a lower P loading rate, greater availability of soil sorption sites, a greater wetland surface area, longer water residence time, and greater wetland water depth (Novak et al. 2004, Hansson et al. 2005). Biological mechanisms include microbial, periphyton, and macrophyte uptake (Dodds 2003, Hansson et al. 2005). These are thought to account for less long term or gross P retention than abiotic ones, because microbial uptake saturates and turns over relatively quickly and because plant P uptake is a short-term storage compartment (Walbridge and Struthers 1993).

Wetland P release is controlled by a related series of mechanisms. Decomposition of soil organic matter or litter can release P to the water column (Mayer et al. 1999, Fisher and Reddy 2001, Olde Venterink et al. 2002, Qiu et al. 2004). Cycles of soil wetting and drying tend to release P, either because of microbial cell lysis following osmotic shock (Turner and Haygarth 2001, Wright et al. 2001, Van Dijk et al. 2004, Chacón et al. 2005), or because of increased organic matter decomposition associated with changes in water availability, pH, or redox (Mayer et al. 1999, Fisher and Reddy 2001, Olde Venterink et al. 2002, Austin et al. 2004, Chacón et al. 2005). Soil-bound P also can be released from sorption sites via anion exchange (Wright et al. 2001).

Wetland restoration projects often are implemented with nutrient (P)-sequestration as a goal, thus understanding whether the wetland sequesters or releases P is an important management issue where restoration is used to improve downstream water quality. The Upper Klamath Basin of south-central Oregon, USA, is a watershed plagued by poor water quality. As much as 66% of the original 20,000 ha of wetlands surrounding Upper Klamath Lake have been diked, ditched, and drained for agricultural production over the last century (Boyd et al. 2002). The value of these lost wetlands is now apparent, because the lake has become hypereutrophic, experiences annual blooms of the cyanobacteria *Aphanizomenon flos-aquae*, and wetland restoration projects are ongoing in an effort to reduce external P loads to the lake. However, recent research confirms that re-flooding previously drained and tilled soils may release P to surface waters, at least in the short term (Aldous et al. 2005). What has not been documented, either from this watershed or more generally in the scientific literature, is the magnitude and timing of the P release and the relative contribution of the release to the annual P load of a hypereutrophic lake.

The primary objective of this study was to measure the amount and timing of P that would be released from (or taken up by) soils as a restoration wetland is re-flooded. We used soil cores that were flooded over a period of four months to estimate the net flux of P between the soils and the water column by measuring changes in water P concentrations. We compared the forms and amounts of P in four soil P fractions after the flooding experiment to help explain site differences in P releases from the soils. These data will guide restoration management of this and other restoration projects. They will enable improved planning efforts for: 1) the timing of restoration activities to minimize the deleterious effects of re-flooding; and 2) testing mitigation measures prior to restoration to minimize P release.

METHODS

Site Description

The Williamson River Delta (42°29′41″N, 121°58′22″W) was a 3,000 ha wetland along the northern shore of Upper Klamath Lake along the last five km of the Williamson River, including the mouth (Figure 1). Historically, it was an emergent marsh with organic peat soils along the lake fringes and mineral alluvial soils closer to the river floodplain. In the 1940s, it was isolated hydrolog-

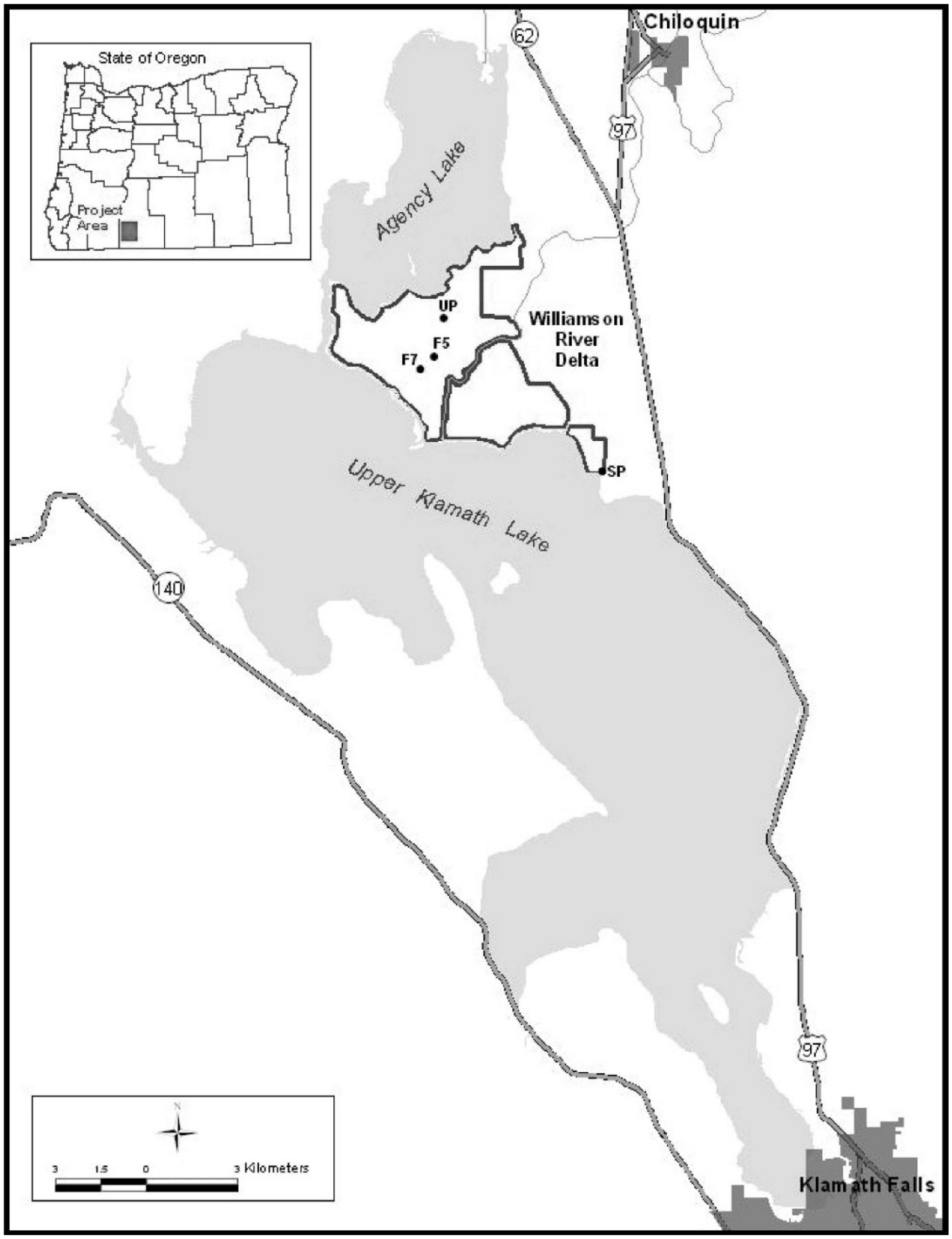

Figure 1. Map of the study area and sampling sites.

ically from the lake by levees, drained, and converted to cropland, which caused significant organic matter losses from oxidation and erosion and thus soil subsidence. The property was purchased by The Nature Conservancy between 1996 and 1999. Agricultural activities in different portions of the property were successively terminated and restoration activities, such as levee breaching, flooding to promote the growth of wetland vegetation, and river channel restoration, are ongoing. The wetland ultimately will be reconnected to Upper Klamath Lake, at which point the hydrologic regime will be under river and lake level control. We refer to this project as a restoration wetland, rather than a restored wetland, to reflect the ongoing nature of the restoration activities (Aldous et al. 2005).

Soils used in these experiments were taken from four locations (Figure 1) designed to represent four zones of the restoration wetland that had been separated from Upper Klamath Lake by levees. They are predominantly histosols. Fields 5 and 7 are from the Lather series (Coprogenous, euic Limnic Borohemists), and South Marsh and Upper Wetland are from the Tulana series (medial, nonacid, mesic Mollic Andaquepts) (Cahoon 1985). These soils consist of a combination of peat, volcanic ash, and

Table 1. Agricultural activities in each of the fields to be converted to wetland. Each site was selected as representative of one zone of the restoration wetland, based on soil properties, proximity to lake and river, and past agricultural activities.

Site	Area of zone represented by each sample (ha)	Type of agricultural activity	Soil type	Years agriculture terminated/ flooding initiated
Field 5	437	row crops	Lather series	1996/1998
Field 7	283	row crops	Lather series	1996/1998
South Marsh	69	grazing	Tulana series	1998/1999
Upper Wetlands	1,422	row crops	Tulana series	1996/1999

alluvial and lacustrine deposits. Samples at the Upper Wetland site were taken in an area that received riverine deposits during frequent out-of-bank flooding prior to cropland conversion, thus these soils were more mineral in nature. Soils at the four sites differed also in past water and crop management, and time since agricultural activities were halted (Table 1).

P Flooding Experiment

In July 2003, six replicate cylindrical soil cores were collected from each of the four locations described above for use in the P flooding experiment. The first core was taken from a random location, and each successive core was taken within 1 m of the initial core. Cores were collected using 15 cm tall and 10 cm diameter PVC tubes, each with a beveled end that was pushed into the soil. A bread knife was used to cut into the soil around the core to minimize compaction. The bottom of the core was cut flush with the bottom of the tube. Any wetland vegetation was clipped to 3 cm from the surface of the core. Each core was inserted into an 80 cm long PVC tube, also 10 cm diameter, and the bottom of the core was sealed with a fitted PVC cap using non-leachable glue approved for drinking water. An additional core was collected at the South Marsh site for monitoring temperature, DO, and pH during the flooding experiment. The cores were transported to an unheated lab for the experiment.

In the lab, the cores were positioned randomly in a rack, and 4.15 L of water was added slowly to each core to prevent soil disturbance. This gave a depth of approximately 75 cm, which will be the estimated average water depth in the emergent wetlands after the levees are breached and hydrologic connection is reestablished. Water from Upper Klamath Lake was used for the incubation to mimic the water that will flood the wetland soils once the restoration activities are completed. A small diameter flexible PVC tube attached to an aquarium bubbler was inserted into the water column of each core 10 cm above the soil surface to simulate wind mixing and prevent the development of anoxia. The additional core from the South Marsh site was treated in the same manner, except that it had a Hydrolab Quanta (2002) with DO, pH, and temperature sensors inserted to 15 cm above the soil surface, which took measurements on a 30-minute interval, and then recorded them to a data logger.

The first day of the experiment was day 0, and water from the water column was sampled on days 1, 2, 6, 14, 21, 34, 49, 62, 76, 91, 105, 118, and 133 after they were initially flooded. Sampling was performed by turning off the bubbler and inserting a flexible PVC tube attached to a peristaltic pump to 10 cm above the soil surface. Two 100 ml samples were taken from each of the six replicates. Samples were chilled and analyzed within 48 hours (Aquatic Research Inc., Seattle, Washington, USA). Analyses of digested total P were done using the automated ascorbic acid reduction method, which involves the formation of a molybdenum-phosphate complex which is reduced by ascorbic acid and analyzed colorimetrically.

The water column was replaced weekly to simulate the constant renewal of water over the restoration wetlands. This was done by pumping the water column down to slightly above the soil surface using a peristaltic pump and replacing it with water collected that same day from Upper Klamath Lake. Thus, the soil cores were flooded with water that had seasonal variation in P concentrations throughout the experiment from July to November. The lake water used for replenishment also was sampled for total P using the same methods described previously.

To determine the net flux of P between soils and water column, we calculated the difference between the total amount of P added (in lake water) and the total amount of P removed (when the tubes were drawn down) throughout the experiment. Total P added was the product of the concentration of P in the lake water and the volume of lake water added every two weeks after the water column was drawn down. Total P removed was the product of the volume of water pumped out of the tubes every two weeks and the concentration of P in each of the tubes.

Soil Core Analysis

We measured four P fractions at the end of the P flooding experiment to determine if there was a soil P chemistry indicator that could be used to estimate potential P release from other restoration wetlands around Upper Klamath Lake. Three soil cores were selected randomly from the six replicates for analysis. The choice of P fractions was based on a previous study where relationships were found between P fluxes and the following fractions: labile inorganic P (P_i), total Fe- and Al- bound P_i, calcium-bound P_i, and residual P (Aldous et al. 2005). The P fractions were extracted sequentially from field moist soils using a modification of the Hedley procedure (Hedley et al. 1982, Qualls and Richardson 1995). Labile inorganic P (P_i) was extracted with 0.5 M $NaHCO_3$. Total Fe- and Al-bound P_i was extracted using 0.1 M NaOH followed by NaOH + sonication to extract occluded Al- and Fe-bound P_i. Calcium-bound P_i was extracted with 1 M HCl. The remaining soil residue was oven dried at 70°C, ground, and digested with nitric and perchloric acid to estimate residual P. It should be noted that, in addition to residual forms of organic P that account for most of the organic P in soils, labile forms of organic P, including microbial P, are recovered in the digestion. Total P also was measured by nitric and perchloric acid for comparison with the sum of the four P fractions measured. All P extracts were analyzed colorimetrically using the ascorbic acid method (APHA 1998).

A subsample of soil was oven-dried at 70°C, weighed, ground, and sieved through a 2-mm mesh screen for analysis of total C, N, and P. Total P was determined by nitric and perchloric acid digestion (Sommers and Nelson 1972). Total C and N were measured using a Perkin-Elmer 2400 CHN analyzer. Bulk density was calculated by weighing the field moist soil sample then applying a moisture correction factor determined by drying a subsample at 70°C then weighing it to correct for its water content.

Statistical Analyses

We used mixed model ANOVA to compare total P release among sites using the soil P fractions as covariates (SAS Institute 2003). To examine temporal patterns in P release, we used a repeated measures MANOVA. To test for significant differences among sites for each P fraction, we used Student-Newman-Keuls tests for multiple comparisons. All tests of significance were made at $\alpha = 0.05$.

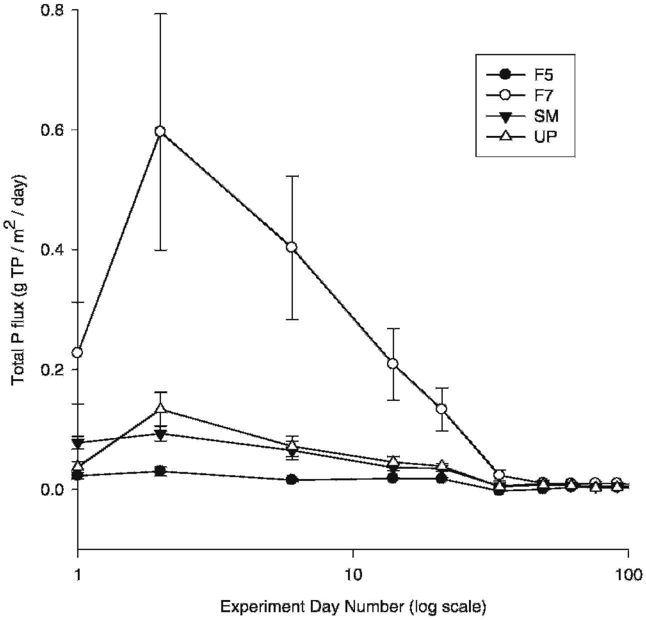

Figure 2. Flux of total P between soil core and water column for the 133 days of the flooding experiments. Values are means of six replicates ± standard errors. Positive values indicate release of P from soils to water, and negative values indicate soil uptake of P. F5 = Field 5; F7 = Field 7; SM = South Marsh; UP = Upper Wetlands.

For the soil P fractions, all statistical analyses were performed on the fractions calculated per mass of soil (μg P/g) as well as per volume (μg P/cm^3). Even though the bulk densities were significantly different, there were no differences in the direction or magnitude of results for the soil P fractions. Therefore, discussion of data and results are based on the P fractions per volume (μg P/cm^3).

RESULTS

Flooding Experiment

The majority of P released from the soils occurred within the first 48 hours of the experiment (Figure 2). Both the time and site*time effects were significant in the repeated measures analysis of variance ($p < 0.05$), confirming that the amount of P release changed over time for each site. Total P release from Field 7 was significantly greater than all other locations ($p < 0.001$), which were not different from each other. After the initial pulse, P release declined and stabilized for the remainder of the

Table 2. Measured total phosphorus release over 134 days of the flooding experiment. Values are means of six replicates (± standard error). P release estimates for each zone were calculated using the zone areas in Table 1. Values that do not share a small case superscript are statistically different at $p < 0.05$ with a Student-Newman-Keuls test of multiple comparisons.

	Phosphorus released (g P/m^2)	Phosphorus released (tons P/zone)
Field 5	0.94 (0.26)^b	4.14
Field 7	8.61 (1.68)^a	24.42
South Marsh	2.42 (0.41)^b	1.68
Upper Wetlands	2.37 (0.33)^b	33.79
SUM		64.04

experiment. Although the net P flux was from the soils to the water column for the remainder of the experiment, this was not significantly different from 0 after day 62 ($p > 0.05$ for all sampling dates).

From the flooding experiment, we estimated that between 1 and 9 g P/m^2 was released from the cores to the surface water over the 134 days of the experiment (Table 2). Field 7 total P release was significantly greater than from the other three fields ($p < 0.001$). Scaling up to the field, with each zone of the restoration wetland represented by one set of samples, the total load for the first year of reconnection is predicted to be approximately 64 tons of P (Table 2).

Water temperature ranged from 9–28°C, which reflects air temperature in the unheated facility. The pH ranged from 7.1–9.9. Large spikes in pH through July and August, and declines in September, October, and November can be attributed to the weekly water change. In the summer months, lake water daytime pH is high due to cyanobacterial photosynthesis, and it drops as production declines in the fall. The weekly mean pH was 8.2 and remained more or less constant throughout the experiment. This is slightly lower than 8.7, which is the mid-summer average for the restoration area (The Nature Conservancy, unpublished data). The concentration of dissolved oxygen (DO) ranged from 2.8–9.5 mg/L. The weekly water change caused the DO to drop from July through October, and spike in November. This was an artifact of the lake water DO concentration, which is low in the summer when cyanobacterial respiration is high, but declines through the fall as cyanobacterial production and decomposition decline. The weekly mean DO was 6.4 mg/L, which is slightly lower than 9.0 mg/L, the midsummer average for the restoration area (The Nature Conservancy, unpublished data).

Soil Cores

Residual P made up the bulk of the P fractions (Table 3), and was significantly greater than all other fractions ($p < 0.001$). In this study, residual P consists largely of recalcitrant organic P with small amounts (< 10%) of labile organic P and microbial P, based on previous work by Graham et al. (2005) in other restoration marshes around Upper Klamath Lake. The Ca-bound pool made up the second largest fraction, but it was not statistically greater than the other pools ($p > 0.05$).

Fields 5 and 7 had the highest concentrations of humic organic P ($p < 0.001$). The more mineral Upper Wetland site consistently had the highest concentrations of labile inorganic P, Fe- and Al-bound P, Ca-bound P, and residual P (Table 3; $p < 0.002$ for all fractions). This could be attributed to the high mineral content of the volcanic soils, or potentially to greater fertilizer P inputs during the years of cultivation. The higher pH and greater concentration of Ca-bound P support this conclusion because lime amendments were frequently used at this site to correct for pH (Dan Renne, The Nature Conservancy, personal communication).

The amount of P released during the flooding experiment ranged from 1%–16% of the total P measured in the soil cores after the flooding experiment (Table 4). The percentage for Field 7 was approximately four times greater than the others ($p < 0.05$).

There were no statistically significant relationships detected between the amount of P released (as measured in the flooding experiment), and the soil P fractions after flooding (as measured by Hedley fractionations). However, because the data from Field 7 differed markedly from the other sites in P release, pH, %C, and %N (Table 5), we removed the Field 7 data and re-analyzed the data. In this second analysis, there were apparent positive relationships between P released and labile P_i and Fe- and Al-bound P (Figure 3), even though these relationships were not significant because of the small number of data points. However, because the soil cores were analyzed after the flooding experiment, it is possible that there might have been differences in soil P prior to flooding that were not

Table 3. Soil phosphorus fractions after the flooding experiment. All concentrations are in units of μg/cm^3. Values are means of three replicates (± standard error). Values that do not share a small case superscript are statistically different at $p < 0.05$ with a Student-Newman-Keuls test of multiple comparisons.

	Labile inorganic P	Fe- and Al-bound P	Ca-bound P	Humic Po	Residual P
Field 5	7.66 (2.70)^b	52.02 (17.02)^b	56.36 (9.97)^b	88.27 (3.60)^a	87.81 (5.54)^b
Field 7	4.99 (0.28)^b	52.66 (3.19)^b	58.25 (2.27)^b	97.19 (7.74)^a	101.53 (4.92)^b
South Marsh	9.71 (1.04)^b	71.37 (5.75)^b	23.96 (3.59)^b	56.58 (3.52)^b	66.87 (4.79)^b
Upper Wetlands	49.18 (4.52)^a	198.70 (21.57)^a	278.19 (28.72)^a	17.97 (4.01)^c	750.48 (69.39)^a

detected, which might have explained the differences in P release.

The soil chemistry data provide some clues about the historic wetlands found at the different sampling sites. In Fields 5 and 7, the lower pH, higher %C and %N, and lower bulk density ($p < 0.05$) (Table 5) indicate more organic soils. These areas likely were historically emergent marsh year-round. In contrast, the Upper Wetlands were closer to the river floodplain and probably received mineral-rich alluvial deposits, and thus have less C and N and greater bulk density. South Marsh historically was connected to Upper Klamath Lake, and was emergent marsh prior to agricultural conversion, yet the soils are more mineral with higher amounts of diatomite (The Nature Conservancy, unpublished data). Thus this area historically might have been lake bottom.

DISCUSSION

Soil P Release

All of the soils released P to the water column at the onset of the flooding experiment. Although the net P release declined after the first month, we never observed P uptake in the 133 days of the experiment. This was not unexpected. Phosphorus release associated with re-flooding wetland soils for restoration is known to occur in many wetlands types, including wet meadows with sandy peat in Sweden (Olde Venterink et al. 2002), emergent marshes with organic soils in Florida (Fisher and Reddy 2001), and lake fringe wetlands with sandy loams in Australia (Qiu et al. 2004). Although wetlands often sequester P once they have been saturated for some time, we found no studies that documented a net P uptake by soils upon re-flooding, including those conducted in relatively undisturbed ecosystems not undergoing restoration activities (e.g., Wright et al. 2001, Corstanje and Reddy 2004, Chacón et al. 2005).

Although there were no statistically significant relationships between P release to the water column and post-flooding soil P chemistry, two relationships were elucidated between soil P release and two mineral P fractions — labile inorganic P (P_i) and Fe/Al-bound P. We noted a positive relationship between P release and post-experiment labile P_i and Fe/Al-bound P when not including Field 7 data, which differed markedly in P release and soil chemistry (Figure 3). Because labile P_i would be flushed easily from the soils with flooding, it might be directly related to P release. Similarly, Fe-bound P is released under reducing conditions (Pant and Reddy 2003), which would have developed as the microbial community consumed O_2 in the pore spaces, leading to a rapid release of that inorganic P fraction.

Field 7 soils released much more P, including organic P, than soils collected from other fields, despite similar concentrations of all of the labile P fractions that we measured post-flooding. Field 7

Table 4. Total P release as a percent of soil total P after the flooding experiment. Total P release data from the flooding experiment are slightly different from the data reported in Table 2 because these data are means of only three replicates that were also analyzed for soil P, rather than all six replicates used in the flooding experiment. Soil total P values are derived by summing the soil total P after the flooding experiment and the amount of P released during the flooding experiment (i.e., values in the first column). All values are means of three replicates (± standard error). Values of % P released that do not share a small case superscript are statistically different at $p < 0.05$ with a Student-Newman-Keuls test of multiple comparisons.

	Total P Release (μg P/cm^3)	Soil Total P (μg P/cm^3)	P Released (%)
Field 5	3.39 (1.36)	295.50 (32.93)	1.11 (0.37)^b
Field 7	62.01 (17.38)	376.63 (21.95)	16.12 (3.78)^a
South Marsh	17.14 (2.31)	245.63 (19.47)	6.98 (0.82)^b
Upper Wetlands	19.45 (2.88)	1313.96 (103.75)	1.52 (0.31)^b

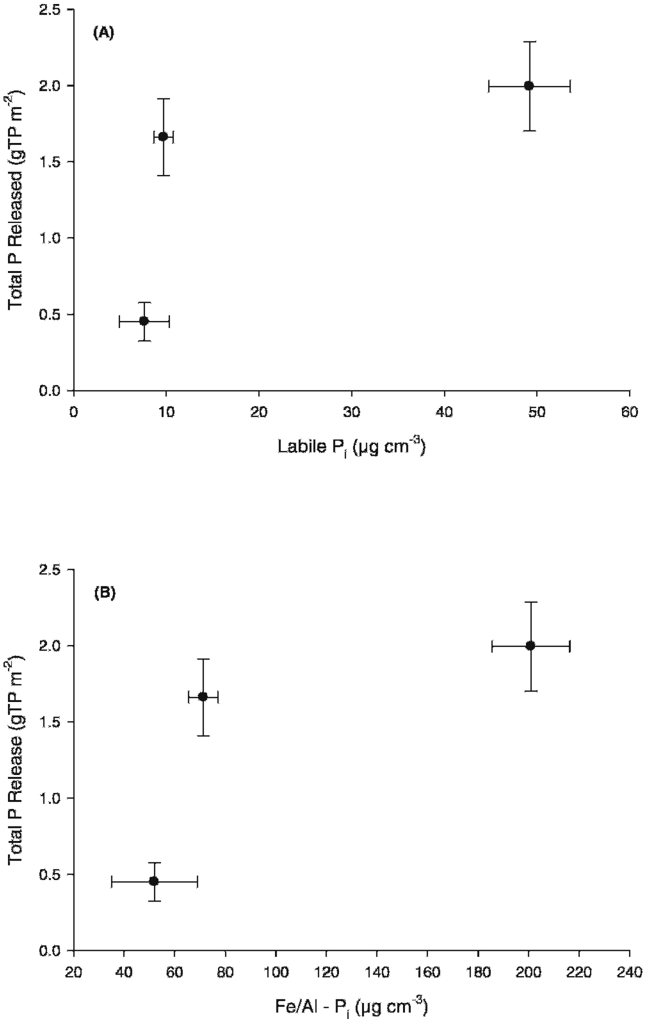

Figure 3. Relationship between total P release from the flooding experiments and A) Labile Pi and B) Fe- and Al-bound P. Field 7 data were omitted as described in the Results. F5 = Field 5; F7 = Field 7; SM = South Marsh; UP = Upper Wetlands.

also contained significantly more organic C and N than the other sites (Table 5). In addition to the chemical mechanisms for soil P release described above, we cannot rule out a microbial mechanism for P release, particularly at this site. The aforementioned chemical pathway involving inorganic P is an immediate response to anoxic conditions that probably developed over the first week of the experiment. The subsequent exponential decline in P flux over the course of the next 30 or so days may best be explained by microbial use of C and subsequent P release. Although we do not have pre-flooding data on soil organic P concentrations, Field 7 has substantial ground-water upwelling, and farmers were never able to completely drain it, although it was still farmed (D. Renne, The Nature Conservancy, personal communication). Longer saturated periods over the years of cultivation would have slowed decomposition in comparison to the soils from other sites, and so this site might have had more labile organic P prior to the experiment, as well as more and higher quality C, which could have supported greater microbial respiration and P release in our experiment.

Another hypothesis to explain the greater P release from Field 7 soils is that the wetter conditions led farmers to manage this field in subtly different ways that might have increased fertilizer P retention or reduced P losses. Again, this P fraction was not measured because the soils analyses were done after the flooding experiment.

Water Quality Implications

A release of 64 tons of P from soils to the water column — between 1% and 16% of the total soil P — estimated by our mesocosm experiment has significant implications for wetland restoration and lake water quality in general. A P budget constructed for Upper Klamath Lake for federal regulatory purposes estimated the annual P load to be 467 tons/year (internal load = 285 tons P/year + external load = 182 tons P/year) (Boyd et al. 2002). Our experiments indicate that restoring the hydrology in this emergent marsh will increase the annual P load to the lake by approximately 14% of the total load (35% of the external load). As a one-time release, this is reasonable in comparison to the 21–25 tons P that were released annually while the Williamson River Delta was still being farmed (Snyder and Morace 1997).

Table 5. Soil C and N and bulk density after flooding treatments. Data are means of three replicates (± standard error). Values that do not share a small case superscript are statistically different at $p < 0.05$ with a Student-Newman-Keuls test of multiple comparisons.

Site	pH	Carbon (%)	Nitrogen (%)	Bulk density (g/cm^3)
Field 5	7.63 (0.07)^{a,b}	11.02 (0.48)^{b}	0.95 (0.03)^{b}	0.417 (0.016)^{b}
Field 7	6.37 (0.21)^{c}	16.65 (0.50)^{a}	1.41 (0.02)^{a}	0.383 (0.031)^{c}
South Marsh	7.23 (0.01)^{b}	7.38 (0.18)^{c}	0.73 (0.02)^{c}	0.513 (0.015)^{b}
Upper Wetlands	7.89 (0.09)^{a}	5.24 (0.04)^{d}	0.30 (0.01)^{d}	0.800 (0.017)^{a}

It is not clear to what extent the release of P will be cyclic and reoccur on an annual basis as the soils dry and wet following lake water levels. In any given year, depending on annual precipitation and lake level management, between 810 and 1,215 ha of the wetland will be permanently flooded and between 640 and 1,165 ha will undergo wet-dry cycles typical of emergent marshes (The Nature Conservancy, unpublished data). The parts of the marsh undergoing a wet-dry cycle may continue to release P in subsequent years, assuming that P release is mediated by organic P mineralization and/or alternating oxidizing and reducing conditions that would promote Fe/Al-P uptake and release. However, the magnitude of the peak release is expected to decline substantially through the years for two key reasons. First, soils from the Williamson River Delta have elevated P concentrations in comparison to undisturbed lake fringe wetlands around Upper Klamath Lake (Graham et al. 2005). This may be a relict of the fertilizer used during farming operations. Assuming P in the restoration wetlands is highly susceptible to mineralization and release but that the Williamson River Delta ultimately resembles its undisturbed counterparts, a significant proportion of soil P eventually will be flushed off. A second cause of eventual decline in P release could arise from plant colonization. Established plant communities can build peat and mineral sediments that bind P and store them in non-labile forms. Furthermore, wetland vegetation also will decrease water velocities, which causes sediment deposition as well as increases the contact time between P in surface waters and the sediments and plants (Mitsch and Gosselink 2000, Cronk and Fennessy 2001).

It is another question entirely whether our calculations represent an accurate estimate of the P that will be released when the wetlands are reconnected to the lake and river. Soil core incubation experiments are known to be fraught with methodological problems, including soil disturbance during sampling, significant edge effects because of the high perimeter to edge ratio, relatively static water levels, etc. Furthermore, the soil cores used in this experiment were largely devoid of vegetation and periphyton. These organisms may mediate P release in the short term changing the rate of soil drying, contributing to P uptake, and slowing the rate of soil wetting, and in the long term by contributing to the formation of recalcitrant organic P, all of which are associated with P sequestration. Finally, the undisturbed lake fringe wetlands around Upper Klamath Lake have been accumulating P at a rate of 0.40–0.45 g P/m^2/year for 100 years or more (Graham et al. 2005), so once the restoration wetlands begin to function like the undrained marshes, they will hopefully act as net P sinks.

Our assumption that the P release will decline with successive flooding events is supported by previous research. In earlier experiments, we compared P fluxes from three restoration wetlands and three undisturbed wetlands, and showed that the restoration wetlands released much more P than their undisturbed counterparts (Aldous et al. 2005). Furthermore, in a series of repeated flooding experiments, Pant and Reddy (2003) showed a decline in P release with successive flooding cycles, even from the most P-enriched soils.

Adaptive Management

Our scaled-up estimates indicate that a large quantity of P (64 metric tons over 3,000 ha) could be released from the wetland soils following restoration activities. For Upper Klamath Lake, where annual P loading to the lake is very high, this amount still represents 14% of the total annual load. Thus restoration planning efforts have taken this negative side-effect into account. In other more nutrient-poor watersheds, accounting for P release may be even more important, if the pulse of P released dominates the annual P load and significantly contributes to future internal loading of receiving waters. Results from these experiments currently are guiding planning and execution of restoration at the Williamson River Delta in the following ways:

1) Most of the P was released during the first 48 hours of flooding at all sites, regardless of soil chemistry. Thus the restoration project is being designed to retain as much soil P within the wetland prior to hydrologically reconnecting the wetlands to Upper Klamath Lake. There are several possible strategies that could be implemented to improve soil P retention in wetlands. For example, we will complete all interior construction work (e.g., removing or breaching interior levees and filling interior drains) and flood the interior part of the wetland complex for at least one season before removing exterior levees that separate the delta from Upper Klamath Lake and the Williamson River. This will promote wetland vegetation establishment and minimize soil erosion before the wetland is connected hydrologically to surrounding water bodies. Our monitoring data indicate that wetland plants easily recolonize former wetland habitats once re-

flooded (The Nature Conservancy, unpublished data). Only after wetland vegetation has begun to establish and most bare soil is covered, will the exterior levees which separate the wetland areas from the Williamson River and Upper Klamath Lake be breached. Currently, we are planning more detailed *in situ* research projects to quantify the effectiveness of this strategy.

2) Blooms of the cyanobacteria *Aphanizomenon flos-aquae* occur in Upper Klamath Lake during mid-summer. Releasing P to the lake during these blooms probably will result in negative effects on water quality by facilitating more algal growth. We intend to do all reconnection activities during the fall of the year when cyanobacteria are less active. It is important to note that when farming activities occurred on this delta, the P released from agricultural return water was done in the spring, when the cyanobacteria are beginning to grow, compared to the fall timing of planned restoration activities.
3) We considered the idea of leaving the exterior levees intact and actively managing the wetland by pumping water on and off, to minimize P release to surrounding water bodies. However, this idea was rejected because one of the primary goals for wetland restoration in the Upper Klamath River watershed is to provide habitat for the larval life stages of two endangered fish species (*Deltistes luxatus* and *Chasmistes brevirostris*), which require connectivity between the wetland, river, and lake.
4) Results of this research demonstrated a negative side effect to wetland restoration. Additional research is needed to fully understand how, when, and where these initial nutrient releases are offset by nutrient sequestration. Nonetheless, we strongly advocate restoring these ecosystems to accomplish a variety of conservation and water quality objectives. First, there have been significant reductions in wetland habitat globally (Naiman and Turner 2000, Millennium Ecosystem Assessment 2005, Zedler and Kercher 2005) and efforts to reverse that conversion are urgently needed for all of the ecosystem services wetlands provide. Second, although there may be initial P releases, evidence from the literature and previous experimental work indicate that this will be a short-term phenomenon and that the wetland eventually will resume more natural functions and act as a net P sink.

ACKNOWLEDGMENTS

Larry Dunsmoor and Kris Fischer of the Klamath Tribes generously provided lab space and materials. Adrien Elseroad created Figure 1 and obtained some data used in area calculations. Mark Stern provided information associated with the purchase and restoration planning undertaken by The Nature Conservancy. Tammy Wood and Dan Snyder of USGS provided advice and commentary throughout the design and execution of the experiments. Jillian Bertram conducted the soil P fractionations. Karen Gleason and Martha Thompson formatted the manuscript for publication. Dan Renne provided insight from the years of agricultural production. The manuscript was significantly improved by comments from three anonymous reviewers.

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Manuscript received 25 October 2006; accepted 2 July 2007.