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Influence of hydrologic regime and vegetation on phosphorus retention in Everglades stormwater treatment area wetlands

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Abstract:

The Florida (USA) Everglades ecosystem has been impacted due to increased loading of nutrients, in particular phosphorus (P), primarily from adjacent agricultural areas. Consequently, restoration measures involve the establishment of stormwater treatment areas (STAs) comprising a series of constructed wetlands. A series of mesocosms were established at the inflow of the Everglades Nutrient Removal Project wetland, the first such STA constructed. These mesocosms were designed to mimic STAs, as they operated as flow-through systems and were packed with native soil. The objective of the study was to determine the effects of vegetation and hydrologic fluctuations on P retention/release by the wetland soil and on effluent water quality. Four treatment combinations consisted of continuously flooded with emergents (*Typha*), intermittently flooded with emergents, continuously flooded with no emergents, and intermittently flooded with no emergents. Intermittently flooded treatments underwent two 1 month drawdown events during the year. Soils were collected to determine the various pools of P and surface water samples were collected twice weekly to determine mass P flux in and out of the mesocosms. Results showed that the majority of the P was stored in the calcium- and magnesium-bound fraction, as well as the refractory pool in the soil. Approximately 91% of the inflow soluble reactive P (SRP) mass was retained within the mesocosms for the continuously flooded treatment, and 80% was retained in the treatments subjected to periodic drawdown events, regardless of vegetation type. There was a net annual flux of dissolved organic P (DOP) out of the mesocosms for the drawdown treatments, whereas the net reduction in the DOP concentrations for the continuously flooded treatments was just 17%. These results demonstrate that, although these wetland systems perform well in reducing surface water SRP, additional research may need to focus on improving the reduction of DOP in order to reduce further the P loads to the nutrient-sensitive Everglades system. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS constructed wetland; nutrients; water quality

INTRODUCTION

Phosphorus (P) retention by wetlands may include surface adsorption on soil minerals (Zurayk *et al*., 1997), precipitation (Reddy *et al*., 1987), microbial immobilization (Newbold *et al*., 1983), and plant uptake (Reddy *et al*., 1995). These processes may be combined into two distinct P retention pathways for wetlands: sorption and burial (Reddy *et al*., 1999). P sorption includes both adsorption and precipitation reactions as mechanisms for the removal of phosphate from the soil solution to the solid phase. When plants senesce, some of the P contained in detrital tissue is recycled within the wetland, and released into the water column. The remaining refractory detrital tissue may eventually become incorporated as organic matter in the wetland soil profile.

Accretion of organic matter has been reported as a major sink for P in wetlands (Craft and Richardson, 1993; Reddy *et al*., 1993). Wetlands tend to accumulate organic matter due to the production of detrital

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material from biota and relatively low rates of decomposition under flooded conditions (DeBusk and Reddy, 1998). Soil accretion rates for constructed wetlands are of the order of millimetres per year, although accretion rates in productive natural systems such as the Florida (USA) Everglades have been reported as high as 1 cm or more per year (Reddy *et al*., 1993). Over time, productive constructed wetland systems will accumulate organic matter that has different physical and biological characteristics than the original pre-construction soil. Eventually, this new material settles and compacts to form new soil that may exhibit a different P removal capacity than the original soil. P accretion increases with P loading to the wetland (Reddy *et al*., 1993). However, an increase in accretion does not assure low surface water outflow P concentrations, especially for intermittently flooded wetland systems.

The State of Florida in partnership with the US Federal Government has initiated a set of restoration measures to lessen the impact of surface water nutrient loads on the Everglades system. The Everglades Agricultural Area (EAA), a vast agricultural area (240 000 ha) immediately north of the Everglades system, is primarily used for sugar cane production with some intensive row crop management. Construction of six stormwater treatment wetlands totalling over 16 700 ha has been completed to remove nutrients from surface waters prior to release into the northern Everglades. The Everglades Nutrient Removal (ENR) Project wetland was the first of these systems constructed and began operation in 1994. An interim water quality standard for total P is currently in place at 0·050 mg l^{-1} for surface waters entering the northern Everglades and a more stringent standard, which may be as low as 0·010 mg l^{-1}.

Recently, concern has arisen that peat material accreted during flooded conditions can be oxidized during dry periods, resulting in decreased net P retention by the stormwater treatment areas (STAs). Periodic drawdown and resulting aerobic conditions may cause rapid oxidation of the labile organic pool. This oxidation can result in the conversion of organic P into labile inorganic P, which can be subsequently released into the water column (Olila *et al*., 1997; Pant and Reddy, 2001). Depending on soil characteristics, drawdown may consolidate the detrital material and increase the stability of inorganic P through precipitation reactions. In addition, flooded soils in previously farmed areas may release P to the overlying water column as a result of solubilization of residual fertilizer P stored in the soil (D'Angelo and Reddy, 1994). However, many of these studies have involved drawdown and reflooding of intact cores in carefully controlled conditions, shielded from sunlight and barren of vegetation. Additionally, these previously investigated systems were never maintained as flow-through systems characteristic of constructed wetland systems.

The objective of this study was to determine the interactive effects of vegetation and periodic hydrologic fluctuations on the P retention/release characteristics of ENR Project soils and on surface water quality.

MATERIALS AND METHODS

Experimental design

Twelve mesocosms were established at the north end (inflow) of the ENR Project (STA-1W) and designed to simulate the STAs, as they consisted of either macrophyte-dominated or open-water habitats and were operated as flow-through systems at hydraulic and P loading rates typical of the STAs (Figure 1). Each mesocosm was 8·0 m long, 1·0 m wide, and 1·0 m deep. Each was plumbed to allow continuous control of the flow of surface water. Each mesocosm was filled with 30 cm of peat soil. The surface water had a mean hydraulic retention time (HRT) of 15 days while maintaining a 40 cm floodwater depth during flooding treatments. The hydraulic loading rate was kept constant during the year. Therefore, any changes in mass loads over time were a direct result of changing concentrations in the inflow waters.

There were three replicates for each of four treatments of: continuously flooded with macrophytes, intermittently flooded with macrophytes, continuously flooded with no macrophytes, intermittently flooded without macrophytes. In mesocosms with emergent macrophytes, natural colonization of cattails and other macrophytes was allowed after the initial planting of 32 mature cattail (*Typha*) plants in each of the six vegetative treatment tanks, whereas the remaining set of mesocosms was maintained free of emergent

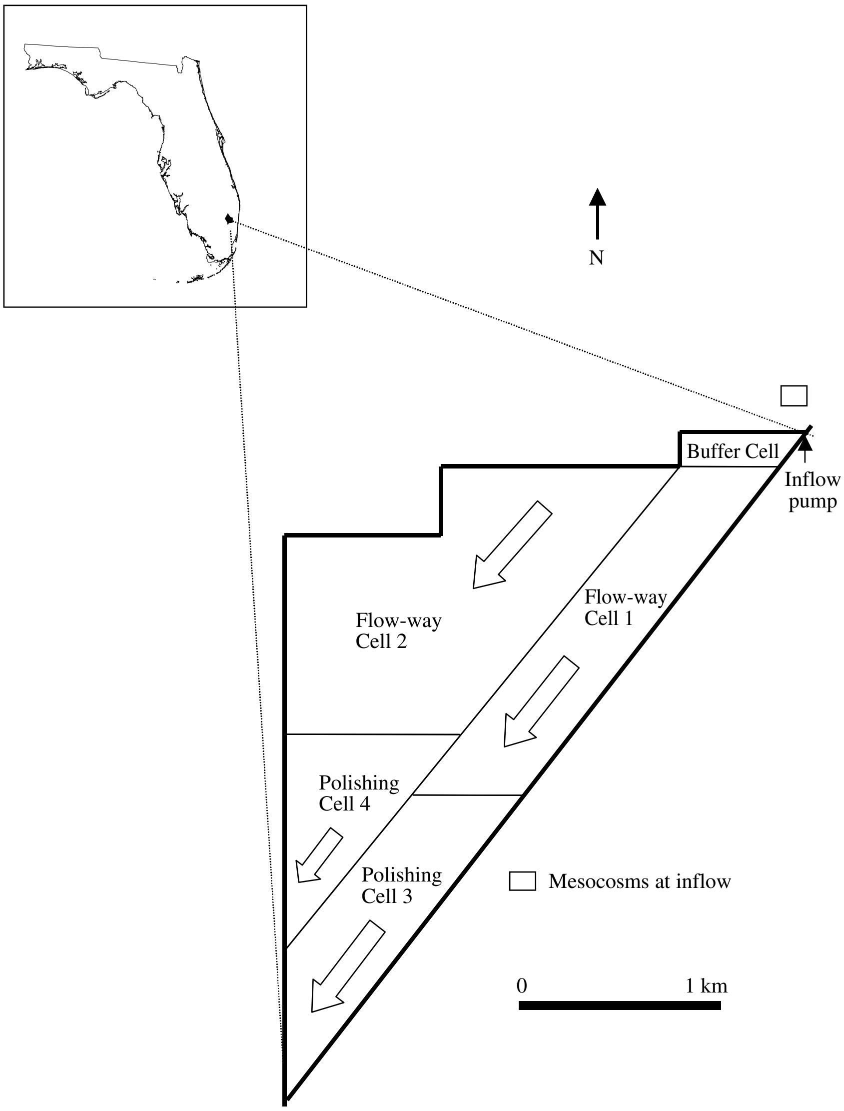

Figure 1. Study site depicting location of the mesocosms proximal to the inflow of the Everglades Nutrient Removal Project wetland. Arrows depict direction of water flow

macrophytes. However, the growth of algae (periphyton) and submerged aquatic vegetation was permitted in these mesocosms.

There were two 1 month drawdown periods scheduled during the first year. After an initial 3 month stabilization period under flooded conditions, the floodwater was drained for 1 month, reflooded for 4 months, the floodwater drained again for an additional month and then reflooded for another 4 months. Continuously flooded mesocosms underwent no hydrologic manipulations during the 1 year study, except to maintain the floodwater at a depth of 40 cm. The two drawdown periods were selected to represent the summer and winter conditions. The design of the experiment was to determine the fate of water-column P under each of the aforementioned treatments. Resource managers will apply these data to determine the best hydrologic management of these constructed wetlands, in order to reduce further the P loading to the northern Everglades.

Water sampling and analyses

The hydraulic loading rate was monitored and surface water samples were collected at the inflow and outflow of each mesocosm twice each week. Filtered samples were collected for soluble reactive P (SRP) and total dissolved P (TDP) determinations, and unfiltered samples were collected for total P (TP) determinations. SRP was determined colorimetrically (Method 365·1; USEPA, 1993). Water samples for TDP and TP were analysed colorimetrically (Method 365·1; USEPA, 1993) after autoclave digestion. Particulate P (PP) was determined by subtracting TDP from TP and dissolved organic P (DOP) was determined by subtracting SRP from TDP.

Macrophyte and algae/periphyton sampling and analyses

The density of macrophytes was low at the experiment outset. Therefore, only one plant was sampled from each mesocosm that contained emergents (*Typha*) as a treatment at time zero. No algae were established at the onset of the experiment. After 1 year, the density of macrophytes and algae was high and continuous across the mesocosms and, therefore, a 0·25 m × 0·25 m quadrat was used to collect the vegetation. The plant material was dried, weighed, cut into 1 cm pieces, and then finely chopped. A sub-sample was taken and ground finer in a ball-mill grinder to be analysed for total carbon (C), total nitrogen (N), and TP.

The dried, finely ground macrophyte and algae material was analysed for total C and N content using a Carlo-Erba NA-1500 CNS Analyzer (Haak–Buchler Instruments, Saddlebrook, NJ, USA). TP was determined from a Kjeldahl digestion and analysed colorimetrically for P (Method 365·1; USEPA, 1993).

Soil sampling and analyses

A total of 12 bulk soil samples were collected from the mesocosms at time zero and again after 1 year. Soils were sampled by driving a 10 cm diameter aluminium tube to the bottom of each tank, collecting the entire 30 cm profile. The depth of the soil was noted and the soil sample was immediately extruded into a labelled plastic bag. The samples were weighed, homogenized, and transferred to 2 l polyethylene storage containers and refrigerated at 4 °C until analysis. The entire soil profile (0–30 cm) was collected in order to calculate the mass balance of P from the mesocosms.

Moisture content was determined by weight percent change of the initial soil and samples dried at 70 °C until constant weight. Bulk density was calculated for each soil core on a dry weight basis. TP concentrations were determined on sub-samples by ashing at 550 °C in a muffle furnace followed by sulphuric acid digestion (Anderson, 1976), and analysis by an automated ascorbic acid method (Method 365·1; USEPA, 1993). The soil pH was determined by 1 : 1 soil : distilled water slurry measured with a Fisherbrand Accument AR50 pH meter.

The soils were also analysed for various inorganic P fractions following the sequential inorganic P fractionation scheme developed for histisols (Reddy *et al.*, 1998). The P fractions described below were determined from field moist soils (0·5 g dry weight equivalent).

KCl-extractable P (*KCl-*P_i). P in soil extracted with a 1 M KCl solutions (soil to solution ratio of 1 : 100) represents the readily available pool of P (water soluble plus exchangeable pool). Soil suspensions were equilibrated for a period of 1 h by continuously shaking on a mechanical shaker, followed by centrifugation at 100 *g* for 10 min. Supernatant solutions were filtered through a 0·45 µm membrane filter and the filtrates were acidified to pH 2. Solutions were analysed for SRP. The residual soil sample was then used in the following sequential extraction scheme.

NaOH-extractable P (NaOH-P_i *and NaOH-*P_o*).* The residual soil obtained from the KCl extraction was treated with 0·1 M NaOH to obtain a soil to solution ratio of 1 : 100. Soil suspensions were allowed to equilibrate for a period of 17 h by continuously shaking on a mechanical shaker, followed by centrifugation at 4000 *g* for 10 min. The supernatant solution was filtered through a 0·45 µm membrane filter and the residual solution was used in the following sequential extraction. Filtered solutions were analysed for both SRP and TP, and these fractions are referred as NaOH-P_i and NaOH-TP respectively. NaOH-P_i represents iron/aluminium-bound P. Extraction with 0·1 M NaOH also removes the P associated with humic and fulvic acids. The difference between NaOH-TP and NaOH-P_i is organic P (NaOH-P_o) associated with fulvic and humic acids.

HCl-extractable P (*HCl-P_i*). The residual soil obtained from the NaOH extraction was treated with 0·5 M HCl to obtain a soil to solution ratio of 1 : 100. Soil solutions were allowed to equilibrate for a period of 24 h by continuously shaking on a mechanical shaker, followed by centrifugation at 100 *g*. The supernatant solution was filtered through a 0·45 μm membrane filter and the residual soil was discarded. Filtered solutions were analysed for SRP. This fraction will be referred to as HCl-P_i, representing calcium-bound P. The P extracted with acid represents the P tied up in apatite minerals, essentially as calcium phosphate. P can also be present in transitional forms, such as monocalcium, dicalcium and octacalcium phosphate. Under most soil conditions, apatite P does not readily desorb, except under very acidic conditions.

Residual-P. The P not extracted in any of the above fractions is termed Residual-P. This fraction was calculated as follows:

$$\text{Residual-P} = \text{TP} - (\text{KCl-P}_i + \text{NaOH-TP} + \text{HCl-P}_i)$$

The Residual-P fraction was assumed to represent both refractory organic P and any other mineral P fractions not extracted with KCl, NaOH, or HCl reagents.

Redox measurements

A mesocosm was randomly selected from each of the four treatment combinations and fitted with two permanently installed platinum-tipped electrodes in order to monitor redox potential E_h at 5 and 10 cm soil depths. Readings were taken using a portable 313 Corning (Corning, NY) millivolt reader and a Fisherbrand (Pittsburg, PA) calomel reference electrode.

RESULTS

Water analyses

SRP. The inflow SRP concentration averaged 0·065 mg l^{-1} and the outflow SRP concentration for both the continuously flooded treatments (with and without macrophytes) was consistently low, averaging 0·006 mg l^{-1} (Figures 2 and 3). The average annual outflow SRP concentrations for both drawdown treatments (with and without macrophytes) were over twice the continuously flooded treatments, averaging 0·013 mg l^{-1} (Table I).

There was no net P export at any time during the year for the continuously flooded treatments (with and without macrophytes). There was a net P release for both the macrophytes and the no emergent macrophyte treatments immediately after the reflooding from first drawdown cycle (Figures 2 and 3). The net P release occurred for up to 4 weeks after reflooding. After this point, the mass of P-in was greater than the mass of P-out for the remainder of the 52 week data record. There was no net export of P during the reflooding period after the second drawdown, suggesting that some factor may have affected the release of P from the soil during the first drawdown period.

A mean annual reduction of 85% of the influent SRP load for all treatments was seen, although the percentage reductions were 91% for the continuously flooded treatment while averaging 80% for the drawdown treatments.

TDP. The results for TDP are similar to those observed for SRP. There was no net P export from the continuously flooded treatments during the 52 week record, with TDP outflow averaging 0·0125 mg l^{-1}.

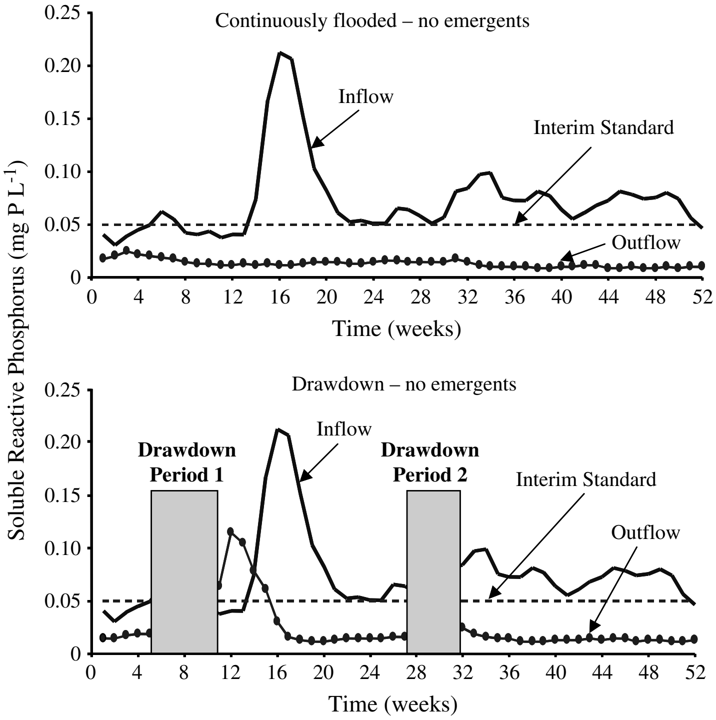

Figure 2. SRP concentrations for the continuously flooded and drawdown treatments with no emergents for the mesocosm study. Outflow concentrations are mean values of three replicate mesocosms

Again, there was a net P release for both the macrophytes and the no macrophytes treatments, which underwent hydrologic manipulations with an average outflow TDP concentration of 0·0235 mg l^{-1}. The net release of P occurred for up to 4 weeks after the reflooding period after the first drawdown period.

The removal rates for TDP from the water column for the continuously flooded treatments were higher than the drawdown treatments on a mass or annual areal basis. This difference was due to the net export of P that occurred immediately after the first drawdown period. On average, there was an 83% reduction of TDP load in the continuously flooded treatments with a lower mean reduction of 67% for the drawdown treatments on an annual basis.

The percentages of the forms of P were different in the inflow and outflow water. The average concentration for TDP in the inflow water was 0·072 mg l^{-1} and comprised 87% SRP and 13% DOP. The average outflow TDP concentration for all treatments was 0·018 mg l^{-1} and was broken down into 51% SRP and 49% DOP. Therefore, there was much greater removal efficiency for SRP than for DOP in these systems.

TP. There was a net reduction in the concentration of TP for the continuously flooded treatments, from a mean of 0·113 mg l^{-1} for the inflow water to a mean value of 0·021 mg l^{-1} for the outflow, resulting in an 81% reduction in concentration (Table I and Figures 4 and 5). The reduction was lower for the drawdown treatments, with a mean outflow concentration of 0·033 mg l^{-1} for a 71% reduction. The performance of both these hydrologic treatments meets or exceeds the current interim standard of 0·05 mg l^{-1} for TP currently imposed on surface waters flowing to the Everglades.

Soil analyses

Soils were characterized by low dry weight bulk densities (0·21–0·23 g cm^{-3}) and high dry weight percentage moisture contents (73–77%). Soil pH values, determined on slurries, were slightly above neutral

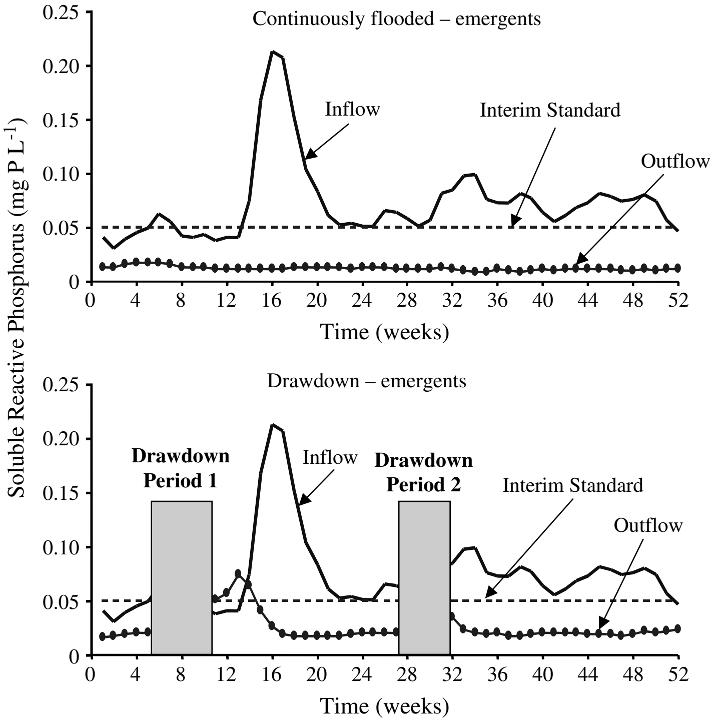

Figure 3. SRP concentrations for the continuously flooded and drawdown treatments with emergents for the mesocosm study. Outflow concentrations are mean values of three replicate mesocosms

Table I. Mean (±1 standard deviation) of inflow and outflow concentrations for various P fractions for the mesocosm study at the ENR Project during year 1

Hydrologic regime		Phosphorus (mg l^{-1})				Reduction from inflow concentration (%)			
		SRP	DOP	PP	TP				
	Inflow	0·065 ± 0·039	0·008 ± 0·005	0·040 ± 0·030	0·113 ± 0·052				
Continuously flooded	Outflow	0·006 ± 0·002	0·006 ± 0·003	0·009 ± 0·003	0·021 ± 0·005	90·8	17·0	77·5	81·4
Intermittently flooded[a]	Outflow	0·013 ± 0·013	0·009 ± 0·007	0·011 ± 0·011	0·033 ± 0·027	80·0	−116	72·5	71·0

[a] Two 1 month long drawdown periods.

($\mu = 7{\cdot}24 \pm 0{\cdot}078$). These values are typical for the organic soils found in the south Florida–Everglades region (White and Reddy, 2000). There were no statistically significant differences in bulk density, pH or moisture content across the treatments.

Soil total C and total N analyses revealed mean total C contents of 352 g kg^{-1} and a mean total N value of 19·1 g kg^{-1} (Table II). On average, the TP of the soil was higher in the treatments containing emergents (393 mg kg^{-1}) than the no-emergent treatment (364 mg kg^{-1}); however, this difference was not statistically significant (Table II). The total C and N contents were not significantly different from time zero and were typical of south Florida peat soils. The TP values are typical of those found in unimpacted areas of the northern Everglades (Reddy *et al*., 1993; White and Reddy, 2000).

There was approximately a 52% inorganic and 48% organic split when comparing the summed inorganic fractions (KCL-SRP_i + NaOH-P_i + HCL-P_i) with the summed organic fractions (NaOH-P_o + Residual-P)

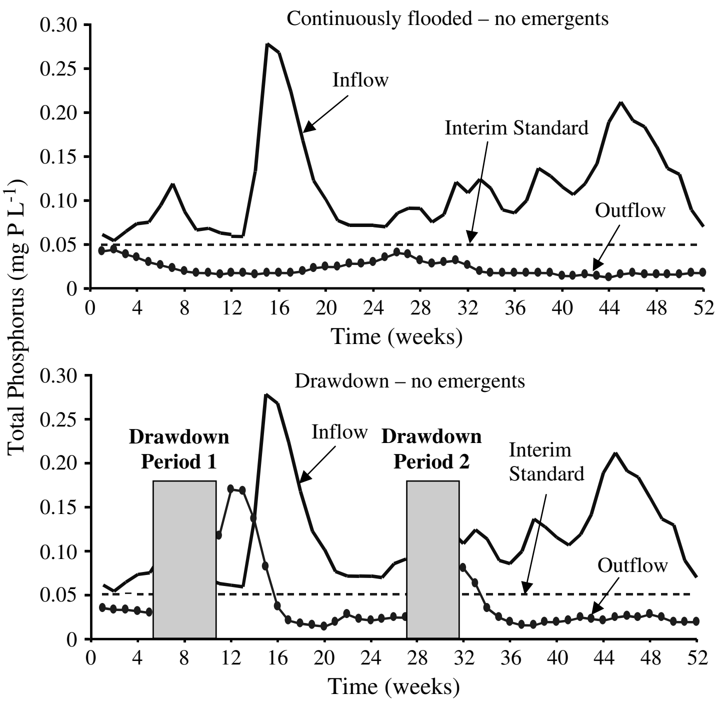

Figure 4. TP concentrations for the continuously flooded and drawdown treatments with no emergents for the mesocosm study. Outflow concentrations are mean values of three replicate mesocosms

in the soil. There were no significant differences detected among the treatments. The KCL-P_i fraction was relatively small, averaging 2·99 mg kg^{-1}, whereas the NaOH-P_i was less than half of the NaOH-P_o (20·9 mg kg^{-1} and 51·0 mg kg^{-1} respectively). The two largest components of soil TP were the HCL-P_i and the Residual-P_o fractions. The HCL-P_i fraction, at 161 mg kg^{-1}, was the largest soil P component and Residual-P_o averaged 116 mg kg^{-1} (Tables III and IV). The HCL-P_i fraction of the soil is relatively stable under the circum-neutral to basic pH values found in this system. A relatively large HCL-P_i pool has also been documented in the surficial detrital/floc layer of the ENR Project wetland at stations closest to the surface water inflow point (White and Reddy, unpublished data). The iron–aluminium-bound fraction (NaOH-P_i) was small (<5%). The iron-bound fraction was likely released upon initial flooding of the mesocosm at the low E_h values seen in the soil and, therefore, this component was likely not responsible for the P flush seen after reflooding of the drawdown events.

Macrophyte and algae/periphyton analyses

The vegetation in the emergent treatment consisted primarily (>95%) of cattail (*Typha*). The coverage of the emergent vegetation was consistent across the mesocosms. The material was collected in a 0·25 m × 0·25 m randomly located quadrat. Average dry weights of the emergent plant material collected at the end of the year were $4{\cdot}16 \pm 0{\cdot}38$ g m^{-2} for the continuously flooded and $3{\cdot}79 \pm 0{\cdot}91$ g m^{-2} for the intermittently flooded or drawdown treatment. For the no-emergent treatments, $1{\cdot}39 \pm 0{\cdot}76$ g m^{-2} dry weight of algae/periphyton was collected from the continuously flooded treatment and $1{\cdot}05 \pm 0{\cdot}28$ g m^{-2} dry weight collected from the drawdown treatment.

The nutrient content of the macrophytes and algae differed. The dried macrophyte tissue averaged C and N contents of 429 g kg^{-1} and 5·35 g kg^{-1} respectively, yielding a C : N ratio of 80. The algae/periphyton tissue

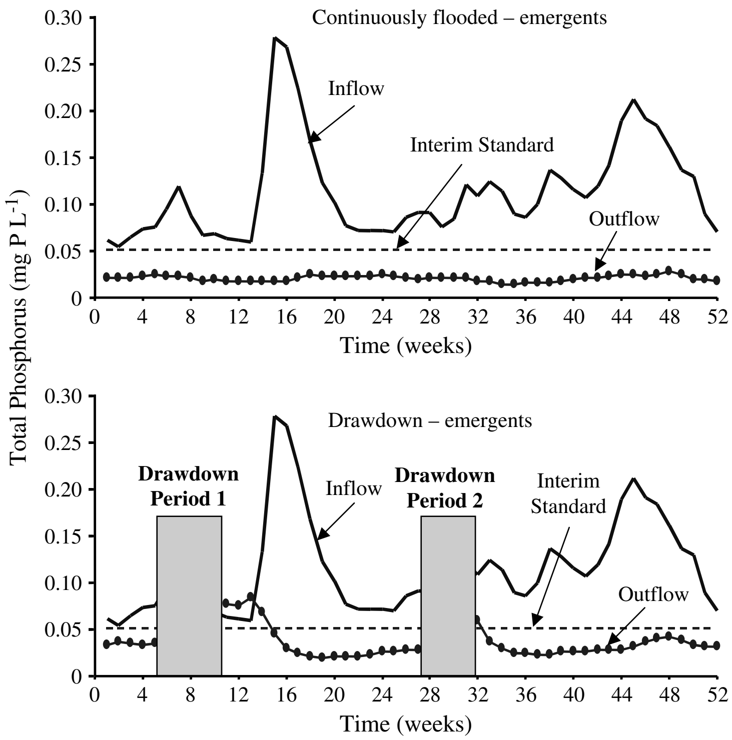

Figure 5. TP concentrations for the continuously flooded and drawdown treatments with emergents for the mesocosm study. Outflow concentrations are mean values of three replicate mesocosms

Table II. Total carbon, nitrogen and phosphorus of soil collected from the mesocosms after 1 year. Depicted are mean ($n = 3$) values ±1 standard deviation

Treatment		Total C	Total N	TP
Hydrology	Vegetation	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})
Continuously flooded	No emergents	343 ± 10·8	19·7 ± 0·81	366 ± 39·4
Intermittently flooded[a]	No emergents	351 ± 10·4	19·7 ± 0·87	361 ± 55·4
Continuously flooded	Emergents	345 ± 16·3	17·7 ± 1·31	386 ± 44·7
Intermittently flooded[a]	Emergents	368 ± 14·9	19·1 ± 1·1	399 ± 109

[a] Two 1 month long drawdown periods.

averaged C and N contents of 218 g kg^{-1} and 9·2 g kg^{-1} respectively, yielding a C : N ratio of 24. TP values averaged 697 g kg^{-1} for the macrophyte tissue and 1295 g kg^{-1} for the algae/periphyton tissue (Table V).

Redox measurements

Data on redox of the soils for the continuously flooded treatments were stable over the year with a corrected mean value of −148 ± 33·4 mV at the 5 cm depth and −141 ± 38·0 mV at the 10 cm depth. The redox for the flooded period of the intermittently flooded treatments was −145 ± 51·7 mV for the 5 cm depth and −129 ± 60·4 mV for the 10 cm depth, with no significant difference between depths for both sets of data.

Table III. Mean values of inorganic P components of the soil from the mesocosms from the ENR Project after 1 year. Depicted are means ($n = 3$) ± 1 standard deviation (KCl-P_i represents the readily available pool; NaOH-P_i represents the iron–aluminium-bound pool; HCl-P_i represents the calcium–magnesium-bound pool)

Treatment		KCl-P_i (mg kg^{-1})	NaOH-P_i (mg kg^{-1})	HCl-P_i (mg kg^{-1})	Total P_i (mg kg^{-1})
Hydrology	Vegetation				
Continuously flooded	No emergents	5·59 ± 0·86	20·6 ± 4·15	148 ± 16	171 ± 12
Intermittently flooded[a]	No emergents	2·32 ± 1·26	15·8 ± 5·51	137 ± 29	155 ± 32
Continuously flooded	Emergents	2·79 ± 1·27	23·7 ± 4·83	167 ± 34	195 ± 37
Intermittently flooded[a]	Emergents	1·28 ± 0·51	23·3 ± 5·89	190 ± 78	217 ± 84

[a] Two 1 month long drawdown periods.

Table IV. Mean values of organic P components of the soil from the mesocosms from the ENR Project after 1 year. Depicted are means ($n = 3$) ± 1 standard deviation (NaOH-P_o represents the fulvic and humic acid pool; Residual-P represents refractory organic P and any other mineral P not extracted with the extractants)

Treatment		NaOH-P_o (mg kg^{-1})	Residual-P (mg kg^{-1})	Total P_o (mg kg^{-1})
Hydrology	Vegetation			
Continuously flooded	No emergents	51·9 ± 6·2	119 ± 4·9	171 ± 1·8
Intermittently flooded[a]	No emergents	40·7 ± 21	110 ± 7	151 ± 27
Continuously flooded	Emergents	48·9 ± 18·8	104 ± 13·4	153 ± 32
Intermittently flooded[a]	Emergents	63·3 ± 21·9	130 ± 34	194 ± 56

[a] Two 1 month long drawdown periods.

Table V. Total carbon, nitrogen and phosphorus of vegetation collected from the mesocosms from the ENR Project after 1 year. Depicted are mean ($n = 3$) values ±1 standard deviation

Treatment		Total C (g kg^{-1})	Total N (g kg^{-1})	TP (g kg^{-1})
Hydrology	Vegetation			
Continuously flooded	No emergents	226 ± 20	13 ± 2·25	1390 ± 289
Intermittently flooded[a]	No emergents	209 ± 7·6	10·7 ± 1·75	1200 ± 277
Continuously flooded	Emergents	434 ± 16	5·4 ± 1·24	593 ± 155
Intermittently flooded[a]	Emergents	423 ± 21	5·3 ± 0·58	801 ± 194

[a] Two 1 month long drawdown periods.

The redox values for the drawdown periods were significantly higher than the continuously flooded periods (Figure 6). The first drawdown period (April) had a mean redox of 395 ± 151 mV at the 5 cm depth and 408 ± 193 mV at the 10 cm depth. The second drawdown period (September) had lower average values of 154 ± 179 mV and 101 ± 209 mV for the 5 cm and 10 cm depths respectively. The higher redox values during the drawdown corresponded with the net release of SRP and TDP from the mesocosms (Figures 2 and 3).

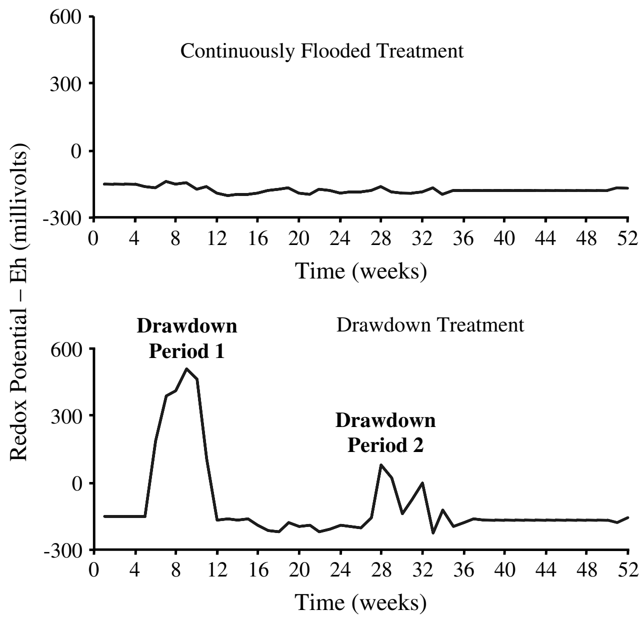

Figure 6. Redox potential for the 5 cm depth of the continuously flooded and drawdown treatments of the mesocosm study

DISCUSSION

The greatest influence on the retention/release of P from these wetland mesocosms was related to hydrologic manipulations, in particular the drawdown events. Data demonstrated that the second drawdown redox values (<200 mV) were significantly lower than those from the first drawdown (>300 mV). This difference was attributed to increased rainfall during the second drawdown maintaining the soils at higher moisture contents, as the tanks remained uncovered during the year-long study to best mimic field conditions (Figure 6). The higher redox values indicate a greater penetration of oxygen into the soil profile. The aerobic and facultative microbial communities utilized this previously unavailable oxygen as the terminal respiratory electron acceptor, increasing the mineralization rates of the organic matter. Several studies have documented increased rates of release of nutrients, including C (DeBusk and Reddy, 1998), N (White and Reddy, 2001), and P (McLatchey and Reddy, 1998) in batch experiments involving organic wetland soils. Consequently, the first drawdown, during the dry season, led to a greater flux of P into the overlying water column, which continued for several weeks after reflooding. This result accords with the findings of Pant and Reddy (2001), who found correlations between increases in P flux and decreases in moisture content in organic soils.

A mass balance was conducted taking into account P (1) removed from the water column, (2) in the soil, and (3) stored in the vegetation. The overwhelming majority of the P was located in the soil, at 24·05 g m^{-2}. The amount of P removed from the water column was low when compared with both the P stored in the soil and the above-ground biomass (Table VI). The vegetation pool comprised approximately 10% of the soil P, whereas the water column was stripped of <0·5% of the mass of P stored in the 0–30 cm soil interval, which was the likely reason there was no significant difference detected in the available P fractions of the soil over time. The vegetation incorporated a greater mass of P than was removed from the water column during the year. The water column was not completely stripped of soluble inorganic P, despite the vegetation requiring P for establishment and growth during the year. This result suggests that there is a limit on the absolute level of P removal from the water column by both algae and macrophytes. Thus, there is also likely to be a limit on how much the water quality can be improved through such removal. In addition, the macrophytes took up

Table VI. P mass balance for the mesocosm study at the ENR Project after 1 year. Depicted are mean ($n = 3$) values ±1 standard deviation (vegetation and soil P pools represent total storage)

Treatment		Phosphorus (gP m^{-2})			
Hydrology	Vegetation	P-in	Vegetation P	Soil P	P-out
Continuously flooded	No emergents	0·788 ± 0·014	1·81 ± 0·62	21·5 ± 6·08	0·157 ± 0·016
Intermittently flooded[a]	No emergents	0·678 ± 0·001	1·21 ± 0·11	24·7 ± 6·49	0·221 ± 0·111
Continuously flooded	Emergents	0·785 ± 0·008	2·49 ± 0·83	26·4 ± 3·09	0·142 ± 0·008
Intermittently flooded[a]	Emergents	0·674 ± 0·004	3·14 ± 1·46	23·6 ± 5·34	0·197 ± 0·039

[a] Two 1 month long drawdown periods.

P stored in the relatively stable peat soil for growth, and this has the potential to be released into the water column upon senescence of these plants.

The mesocosms provided significant annual net reductions in the water column concentrations of SRP (91% for the flooded treatment and 80% for the intermittently flooded treatment). However, the net reduction of DOP for the continuously flooded treatments, with or without emergents, was just 17% (Table I). There was a net *increase* of 16% over the inflow concentration of DOP for the emergent and no-emergent treatments that underwent drawdown over the year. This result suggests that the drawdown events led to a net export of DOP, which was transported out of the mesocosms in the outflow surface water.

In summary, the single most important finding of this study was the generally poor reduction of DOP by the treatments. Under the optimum conditions of a well-maintained water column, the reductions of DOP averaged 17%. However, the effects of drawdown were much worse, leading to a net annual export of DOP from the mesocosms, suggesting that periodic drawdown would lead to failure to meet the proposed surface water quality standard of 10 μg l^{-1} of TP entering the Everglades.

CONCLUSIONS

The first year's data on soils, vegetation, and water quality from the mesocosm study at the inflow of the ENR Project have yielded several important insights into the function of these wetland systems for sequestering P and improving surface water quality. The soil P fractionation data demonstrated that the majority (>75%) of soil P is stored in the HCl-P and Residual-P_o fractions. The HCl-P fraction, which represents the calcium- and magnesium-bound P, is generally stable providing that the pH remains circum-neutral to basic. The Residual-P_o, which is generally composed of highly refractory organic P, is also considered relatively stable.

In addition, approximately half of all P is bound in the organic pool, and the other half is found in the inorganic P pool in these peat soils. Although both vegetative treatments were comparable in SRP removal from the water column, the emergent (*Typha*) treatment had a significantly greater biomass produced. The relative susceptibility of the resultant biomass to subsequent remineralization over time might also be an important factor in regulating water column concentrations over the long term.

The effect of drawdown on surface water quality was clear, in that it caused the net release of DOP from the mesocosms. Upon reflooding after the first drawdown event, the drawdown treatments released a significant amount of P (both SRP and TDP) compared with the continuously flooded treatments. Analysis of the water-quality data shows that there was a net production of DOP from the drawdown treatments. The presences of macrophytes and algae in these systems appears to affect the overall P retention. In addition, the macrophytes took up more P than was removed from the water column and, in effect, transformed the relatively stable soil P forms into detrital components, which appear to be susceptible to remineralization during periods of drawdown.

The greatest challenge in managing these large, stormwater treatment wetlands will be to maintain soils in a flooded condition during the dry months to prevent the associated release of SRP and DOP from these organic sediments. Even with continuously flooded conditions, the decrease in DOP concentrations is small (17%). Therefore, additional research will be required to investigate mechanisms and management strategies to transform this DOP fraction to SRP (which is more efficiently attenuated in these wetland systems) in order to reach the proposed surface water-quality standard of 10 $\mu g\ l^{-1}$ total P for the Everglades, which is representative of the pristine Everglades ecosystem.

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