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Influence of hydropattern and vegetation on phosphorus reduction in a constructed wetland under high and low mass loading rates

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ABSTRACT

Large constructed wetlands are extensively used in south Florida for surface water quality improvement as well as for flood control. Due to the periodic wet–dry climate of this region, it is likely that soils in these large constructed wetlands may become dry or partially dry (experiencing drawdown), which represent a challenge to managing and optimizing phosphorus (P) reductions in these systems. Therefore, we designed an experiment to study the interactive effect of hydropattern (batch vs. continuous flow) and the presence or absence of emergent vegetation on P exchange between surface water and organic soil in two sets of 12 mesocosms. These 24 mesocosms were filled with 30-cm deep peat soil, and each set were subjected to either high (12.5 $g\,m^{-2}\,year^{-1}$) or low (3.4 $g\,m^{-2}\,year^{-1}$) P loading from surface water. All treatments performed similarly prior to surface water drawdown with P reductions being relatively high for high P loading rates and being low for low P loading rates. Mesocosms subject to wet–dry–wet cycles exhibited a three- to four-fold increase in surface water effluent P concentrations immediately following soil re-flooding, which lasted 1–3 and 3–10 weeks for low and high P loading rates, respectively. The magnitude of P flux from sediment to surface water and the time period over which P release took place were P loading-dependent (higher loading led to higher P flux compared to lower P loading rates), and season-dependent (a longer duration of higher P flux experienced during dry- compared to wet-season drawdowns). Results indicated that hydropattern was the dominant factor affecting P flux to overlying surface water for the high P loading rate, while the presence or absence of emergent vegetation was the dominant factor influencing P release for the low P loading rate. Treatments lacking emergent vegetation generated the most particulate P (PP) for both high and low P loading rates. All P fractions were correlated to either hydropattern or inflow concentrations, for both low and high P loading rates, and, with the exception of PP, correlated to vegetation at low-P loading rate. Our results indicated that the presence or absence of emergent vegetation is a critical factor in the management of large constructed wetlands receiving low P loadings while hydropattern should be the focus in managing treatment systems receiving high loads of P. Regardless of the P loading rates, maintaining moist soils in large constructed wetlands is a good management strategy, particularly during dry climatic periods, to minimize soil P oxidation and P flux to surface water after soil re-flooding.

1. Introduction

The Everglades is a subtropical wetland that once encompassed 1.2×10^4 km^2 of southern Florida and extended 160 km from south of Lake Okeechobee to the mangrove estuaries of Florida Bay and the Gulf of Mexico. At approximately 1/2 of its original extent, the remaining system is contained mainly within the boundaries of the Water Conservation Areas (WCAs) and the Everglades National Park (ENP). Historically, the Everglades was an oligotrophic peatland system that received most of its water and nutrients via rainfall (Davis, 1994). Much of the Everglades north and west of the WCAs has been converted to farmland, locally known as the Everglades Agricultural Area (EAA) which is a major source of water that flows into the WCAs and ultimately the ENP. Both the introduction of phosphorus (P)-rich water and alterations to surface hydrology have caused shifts in the floral and faunal communities of the Florida Everglades (Rutchey and Vilchek, 1994; McCormick and O'Dell, 1996). The Everglades Forever Act (EFA; Section 373.4592, Florida Statutes) was enacted by the Florida Legislature in 1994

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and authorized a series of measures including the construction of Stormwater Treatment Areas (STAs), the utilization of Best Management Practices (BMPs), and the setting of a threshold discharge limit for phosphorus, to ensure the protection and restoration of the remaining Everglades. The STAs, with a total area of 180 km^2, are designed to treat runoff from the EAA and reduce total phosphorus (TP) concentrations to <50 $\mu g L^{-1}$ before the water is released southward into the Everglades (EFA; Section 373.4592, Florida Statutes).

Management of large constructed wetlands is an emerging science. Options currently recommended to increase P reduction in smaller scale systems include the harvesting of vegetation, the addition of chemical amendments (Malecki-Brown et al., 2007, 2009), soil removal (Wang et al., 2006), and fire (White et al., 2008). However, these options are generally not feasible for such large systems (STA sizes range from 2257 to 16,543 acres). Hydroperiod management of these large constructed wetlands is critical because of the periodic wet–dry climate of the region, alternating between wet and dry conditions following the rainfall patterns. During dry seasons, soils of the STAs are likely to dry out (due to less rain or spatially due to changes in topography), which can triggers P release (upon re-flooding) from organic soils (Corstanje and Reddy, 2004; White et al., 2006). Optimizing phosphorus reductions through the use of STAs is a major focus of Everglades Restoration, and therefore, the overall objective of this study was to determine if P reduction by large constructed freshwater wetlands could be improved by managing hydropattern (e.g., minimizing soil dry out or soil exposure to the atmosphere, by controlling the hydraulic loading rates of an STA). We also sought to determine the relative importance of presence or absence of emergent vs. submerged vegetation as an alternative strategy to optimize P reduction in these STAs. Specifically, our objectives were to: (1) determine the impacts of a wet–dry–wet soil cycle on P-dynamics in a wetland receiving a low loading rate (3.4 g P m^{-2} $year^{-1}$), (2) determine the impacts of the presence or absence of emergent macrophytes on P dynamics for a wet–dry–wet soil cycle, (3) compare P-dynamics for a wet–dry–wet soil cycle in wetlands receiving high and low P loading rates, and (4) develop a management plan to minimize the impacts of wet–dry–wet soil cycles on P dynamics in a constructed wetland.

Experiment I, ran from January 1999 through March 2001, while Experiment II, started on January 2000 and ended in March 2001. Data presented in this manuscript cover Experiments I and II from January 2000 through March 2001. Water and nutrient balance were documented for the high and low P-loading experiment, respectively, only using first year data (White et al., 2004, 2006), while phosphorus reduction were documented from the first two years from the high P-loading experiment (Moustafa et al., 2011). This paper discusses and reviews management options to minimize the impacts of wet–dry–wet cycle in large constructed wetlands and compares P dynamics and treatment efficiency for wetlands under high and low mass loading rates, using available data from the second year of high P-loading experiment and the first year data from low P-loading experiment.

2. Methods

This mesocosm study consisted of one experiment design with differing P loads: the first with high loading rates, designated Experiment I (north site); and the second with low loading rates, designated as Experiment II (south site). Within each setup there were four treatment scenarios: (1) two plant treatments – one emergent, with planted *Typha domingensis* and other emergents, and a second, non-emergent treatment that was not planted and

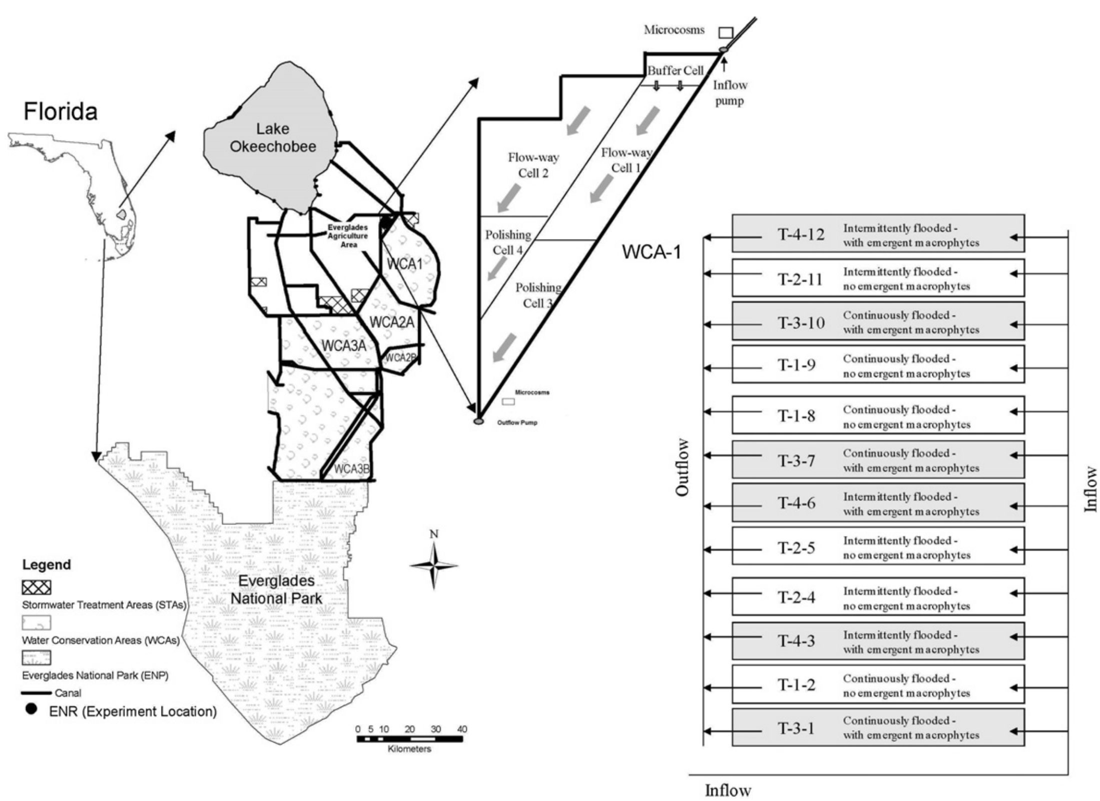

Fig. 1. Location of Everglades Agricultural Area (EAA), Stormwater Treatment Areas (STAs), Water Conservation Areas (WCAs), and Everglades National Park (ENP). Mesocosms setup for both Experiments I and II were located near the inflow and the outflow of STA-1W, respectively. Twelve mesocosms representing four treatments, three mesocosms per treatment. T-3-1, Treatment three mesocosm 1: continuously flooded mesocosms with emergent macrophytes.

Table 1
Summary statistics of weekly flow values at high (Experiment I) and low (Experiment II) phosphorus loading rates. Flow values (L day^{-1}) were not statistically different at α = 0.01 considering only one treatment pair at a time (e.g., CWOH vs. CWOL).

Variable	CWOH[a]	CWOL[a]	IWOH[b]	IWOL[b]	CWH[c]	CWL[c]	IWH[d]	IWL[d]
Mean (±std. dev.)	152 (0.72)	154 (0.64)	150 (0.75)	154 (0.95)	152 (0.62)	153 (0.75)	150 (0.73)	155 (0.73)
Minimum	138	145	142	123	142	142	141	141
Maximum	162	165	161	163	162	167	158	167
Count (*n*)	53	53	44	45	53	53	44	45

[a] Continuously flooded mesocosms without emergent macrophytes for low and high P loading rate (CWOL and CWOH).
[b] Intermittently flooded mesocosms without emergent macrophytes (IWOL and IWOH).
[c] Continuously flooded mesocosms with emergent macrophytes (CWL and CWH).
[d] Intermittently flooded mesocosms with emergent macrophytes (IWL and IWH).

maintained free of all emergents; and (2) two hydropattern treatments – one that was continuously flooded, and a second that was intermittently flooded. Each treatment consisted of three replicate mesocosms.

Twenty-four mesocosms (Fig. 1) were utilized to implement this design – 12 received the same inflow as Stormwater Treatment Area 1 West (STA-1W) for Experiment I, and 12 received the outflow of STA-1W for Experiment II. The location of Experiment I mesocosms resulted in high P loading rates (~0.1 mg TP week^{-1}), and the location of Experiment II mesocosms resulted in low P loading rates (~0.03 mg TP week^{-1}). Each mesocosm measured 1 m wide by 5.9 m long and 1 m deep, and all were filled with 30 cm of organic soils harvested from STA-1W.

For each experiment, six mesocosms were planted with cattails (*Typha domingensis* – emergent treatment) and six were unplanted (non-emergent treatment). The Typha mesocosms contained six plants per square meter, for a total of 36 plants per mesocosm. Other emergent plants, including *Brachiaria mutica*, *Cyperus spp*., *Amaranthus spp*., colonized all mesocosms subsequent to planting of Typha. However, the emergent tanks were dominated by cattail at over 98% of the total biomass. The non-emergent mesocosms were kept and maintained free of emergent plants and were dominated by two submerged aquatic plants (*hydrilla verticillata* and *ceratllum demersum*) at over 98% of the total biomass with unidentified floating algae comprising the remaining biomass (White et al., 2006).

Two five-week drawdown periods were selected to represent dry and wet periods during the wet and dry climatic seasons (intermittently flooded treatments). Drawdown and reflood cycles were synchronized between Experiments I and II, which allowed us to compare the results of all treatments. The primary advantage of this controlled study is that it provided an accurate water and nutrient mass balance, in which the roles of soil, emergent macrophyte and floating periphyton on P reduction and release can be accurately quantified.

We evaluated four treatments, including continuously and intermittently flooded mesocosms (two five-week drawdown periods), both with and without emergent macrophytes. The four treatments, with triplicate mesocosms randomly assigned to each treatment for low and high P loading rate experiments, are defined as follow:

(1) Continuously flooded mesocosms without emergent macrophytes (CWOL and CWOH).
(2) Intermittently flooded mesocosms without emergent macrophytes (IWOL and IWOH).
(3) Continuously flooded mesocosms with emergent macrophytes (CWL and CWH).
(4) Intermittently flooded mesocosms with emergent macrophytes (IWL and IWH).

Both experiments were operated under steady flow conditions (hydraulic loading rate = 2.6 cm day^{-1}, hydraulic residence time = 15 days, and water depth = 40 cm). Therefore, any changes in mass loads over time were a direct result of changing P concentrations in the inflow water. For the intermittently flooded treatments, a dry out period of five weeks was selected to represent dry (winter) and wet (summer) season conditions. Outflow concentrations from each treatment were averaged, three per treatment and we used these means for comparisons among treatments and between Experiments I and II. Rainfall contributions were not considered in this experiment and further details pertaining to experimental procedure are documented in Moustafa et al. (2011).

2.1. Water samples

Weekly surface water samples were analyzed for TP, total dissolved phosphorus (TDP), and soluble reactive phosphorus (SRP). The inflow sample was collected at the head tank feeding all mesocosms, while outflow samples were collected at the outflow pipe for each mesocosm; a total of 13 samples per week were analyzed for each experiment (Fig. 1). Filtered samples were collected for SRP and TDP determinations, and unfiltered samples were collected for TP analysis. SRP levels were determined colorimetrically (Method 365.1; USEPA, 1993), after autoclave digestion. Particulate P (PP) was determined by subtracting TDP from TP. Values of monitored parameters that fell below detection limits were set to the detection limit value (TP = 2 μg L^{-1} and SRP = 2 μg L^{-1}). Particulate P and SRP presented the majority of TP. Ratios of SRP/TP = 63 (H) and 45 (L); PP/TP = 28 (H) and 36 (L); on average SRP and PP contributes 91% (H) and 81% (L) of the total observed TP; these ratios are based on mean observed constituent concentrations.

2.2. Statistical analyses

All statistical analyses were performed using SAS® (SAS Institute Inc, 1999). Repeated measures ANOVA was run for each of these experiments (significance level of $P \le 0.05$). We applied ANOVA to the response variables (e.g., TP, SRP, and PP) and estimated the main effects of each factor as well as their interactions. Through a stepwise selection procedures, and by following the effect heredity principle (Wu and Hamada, 2000), which is, in order for an interaction to be significant at least one of its parent factors should be significant. The results of the ANOVA and the corresponding standard errors are then measured. Two factors from our treatment systems were selected for the ANOVA model, presence or absence of macrophyte (F1) and hydropattern (wet or dry, F2). Influent water quality to all treatments was variable at different times. Hence, an "inflow concentration" factor (F3) was added to represent the influence of time. Any week that had missing data for at least one tank was removed from the analysis.

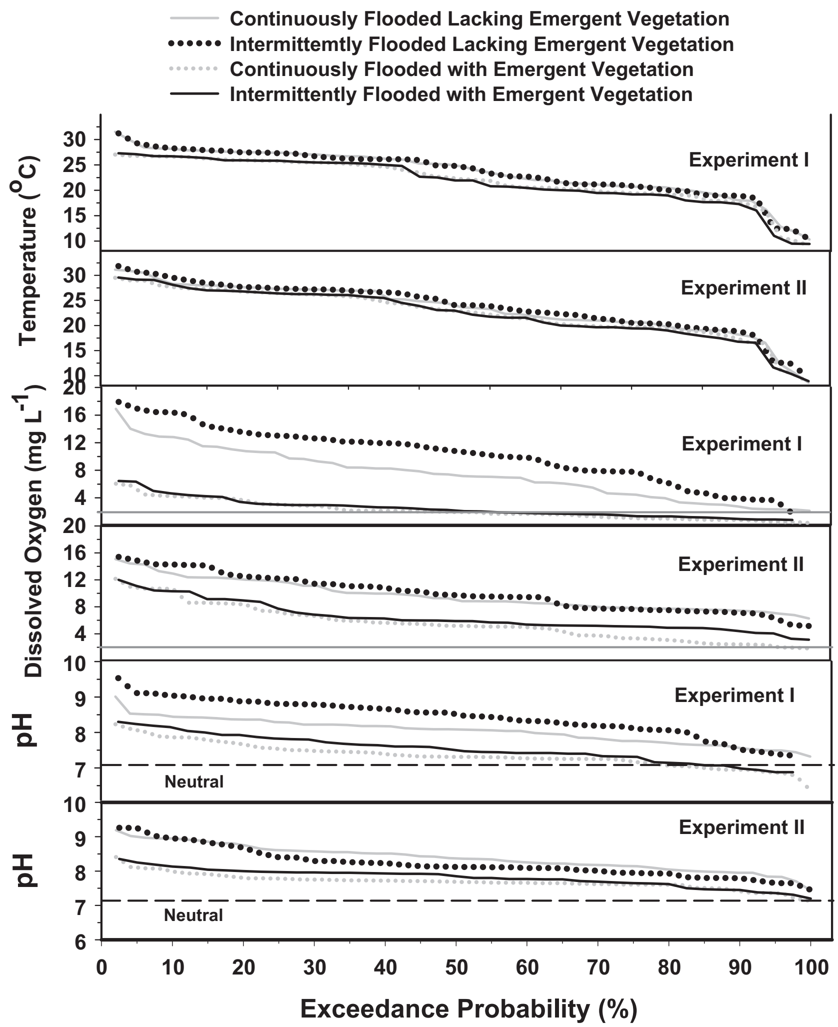

Fig. 2. Exceedence probability curves for environmental parameters measured at four treatments representing high and low mass loading rate (Experiments I and II): continuously flooded with no emergent vegetation (solid black line), intermittently flooded with no emergent vegetation (dotted black line), continuously flooded with emergent vegetation (solid grey line), and intermittently flooded with emergent vegetation (dotted grey line).

3. Results

3.1. Environmental factors

3.1.1. Hydrology

The hydrology of this experiment remained at the targeted hydraulic loading rate of 2.6 cm day^{-1} and maintained a surface water depth of 40 cm. Mean hydraulic loading rates ranged between 2.56 and 2.63 cm day^{-1} in both experiments and were not significantly different between Experiments I and II and among all four treatments at $\alpha = 0.01$ (Table 1).

3.1.2. Temperature

Observed water temperatures were similar across all treatments. However, shading due to the presence of emergent vegetation is evident when one compares water temperatures in treatments lacking emergent vegetation to treatment with emergent vegetation. Treatments lacking emergent vegetation consistently exhibited higher temperature compared to treatments with emergent vegetation (Fig. 2).

3.1.3. Dissolved oxygen

Dissolved oxygen concentrations for treatments lacking emergent vegetation were consistently higher, and these high concentrations lasted longer than treatments with emergent vegetation (Fig. 2). Dissolved oxygen concentrations for continuously flooded treatments lacking emergent vegetation were less than intermittently flooded treatments by about 2 mg L^{-1} in Experiment I and were almost absent or reversed in Experiment II.

3.1.4. pH

Presence or absence of emergent vegetation had a noticeable impact in treatments lacking emergent vegetation and resulted in higher pH values compared to treatments with emergent vegetation (Fig. 2). The hydrology regime had a smaller yet more noticeable impact on pH values compared to presence or absence of emergent vegetation. For example, pH in Experiment II never fell below 7, while pH values in Experiment I were less than 7 approximately 10% of the time (Fig. 2).

3.1.5. Soil/sediment/redox potential

Redox values for continuously flooded-soil treatments were stable at 5 and 10 cm depths for Experiments I and II (Table 2). Experiment II redox was consistently higher than Experiment I for both 5 and 10 cm depths (except IWH at 10 cm). Mean redox for continuously flooded treatments (CWOH and CWH) during dry season drawdown was higher than its counterpart in Experiment II at

Table 2
Summary statistics of weekly redox values (at 5 and 10 cm) at Experiments I and II after one year. Listed values are mean and ±one standard deviation.

Treatment	CWOH[a]		IWOH[a]		CWH[b]		IWH[b]		CWOL[c]		IWOL[c]		CWL[d]		IWL[d]	
Soil depth (cm)	5	10	5	10	5	10	5	10	5	10	5	10	5	10	5	10
Mean	−402.0	−385.3	−249.2	−10.5	−367.5	−130.0	−175.5	116.3	−94.6	−113.5	137.9	176.0	−117.2	−127.8	103.4	92.4
Std. dev.	41.0	43.6	229.5	232.9	33.6	48.0	262.2	212.5	66.6	41.2	254.4	269.3	35.3	62.3	253.8	239.5
Min	−442.5	−479.7	−499.7	−275.0	−458.0	−196.3	−457.3	−169.3	−163.7	−198.0	−176.3	−194.0	−195.3	−258.0	−174.3	−157.0
Max	−128.0	−128.0	343.5	611.5	−224.3	92.7	317.3	518.0	148.0	12.7	609.0	683.0	33.0	137.3	636.3	603.0
Count (*n*)	62	62	62	62	62	62	62	62	60	60	60	60	60	60	60	60

[a] Continuously and intermittently flooded mesocosms without emergent macrophytes under high P loading rate (CWOH and IWOH).
[b] Continuously and intermittently flooded mesocosms with emergent macrophytes under high P loading rate (CWH and IWH).
[c] Continuously and intermittently flooded mesocosms without emergent macrophytes under low P loading rate (CWOL and IWOL).
[d] Continuously and intermittently flooded mesocosms with emergent macrophytes under low P loading rate (CWL and IWL).

both soil depths. This trend was reversed for intermittently flooded treatments, in which redox means in Experiment I were lower than its counterpart in Experiment II. Sediment redox potential increased significantly for intermittently flooded treatments during drawdown periods and these values were significantly higher during dry, compared to wet, period drawdown in both experiments.

Soils were characterized by low dry weight bulk densities and high dry weight percent moisture contents in both Experiments (Table 3). No statistically significant differences were detected in bulk density or moisture content across treatments and experiments. All soil bulk density means in Experiment I were lower than Experiment II. Mean total soil P, C, and N values in Experiment II were less than values observed at Experiment I (Table 3).

3.2. Phosphorus dynamics

3.2.1. Total phosphorus (TP)

Effluent TP concentration means for high and low P inflow treatments were significantly different at $\alpha = 0.05$ and there were no seasonal trends observed in Experiment I or II (Table 4). In general all effluent TP concentrations for continuously and intermittently flooded treatments in Experiment II were similar to one another regardless of the hydrology and presence or absence of emergent vegetation (Fig. 3). However, immediately after soil re-flooding, high rate of TP flux to surface water was evident for all intermittently flooded treatments (Fig. 3). The high flux period lasted 1–2 and 4–6 weeks for low and high P loading rate, respectively. This high TP flux to surface water lasted a shorter time for wet-season, compared to dry-season drawdowns and the magnitudes of this high flux were also season-dependent (i.e., higher TP flux to surface water upon reflooding during dry- compared to wet-season drawdowns; Fig. 3). All effluent treatment mean, minimum, and maximum concentrations for Experiment II were consistently lower, by as much as 40–60%, than Experiment I results. Also, all effluent TP mean concentrations were significantly different comparing results from Experiments I and II (Table 4). Percent TP reduction means were high and low for high- and low-TP inflow loading rate, respectively (CWOH > CWOL, IWOH > IWOL, etc.). Continuously flooded TP percent reductions remained positive throughout in Experiment I. However, intermittently flooded treatments in Experiment I (IWOH and IWH) and all four treatments in Experiment II exported TP (Table 4). Intermittently flooded treatments lacking emergent vegetation (IWOL and IWOH) performed better, in terms of TP percent reduction, compared to treatments with emergent vegetation (IWH and IWL).

3.2.2. Soluble reactive phosphorus (SRP)

Effluent SRP concentrations for all treatments in Experiment II (Fig. 4) were low compared to inflow values and their means were almost identical regardless of treatments (Table 5). We observed brief periods where effluent SRP concentrations were comparable to inflow values, immediately after drawdown periods and the magnitudes of those peaks were higher after dry compared to wet-climate season drawdown (Fig. 4).

Little variability was evident in SRP influent concentrations in Experiment II compared to Experiment I, as indicated by the observed range, yet their means were significantly different (Table 5). All effluent SRP concentration means for Experiment I were significantly higher than their counterparts in Experiment II (Table 5).

Higher percent SRP reductions were observed for Experiment I compared to Experiment II for all four treatments (Table 5). With the exception of the continuously flooded treatments with no emergent vegetation (IWH) in Experiment I, SRP reductions were

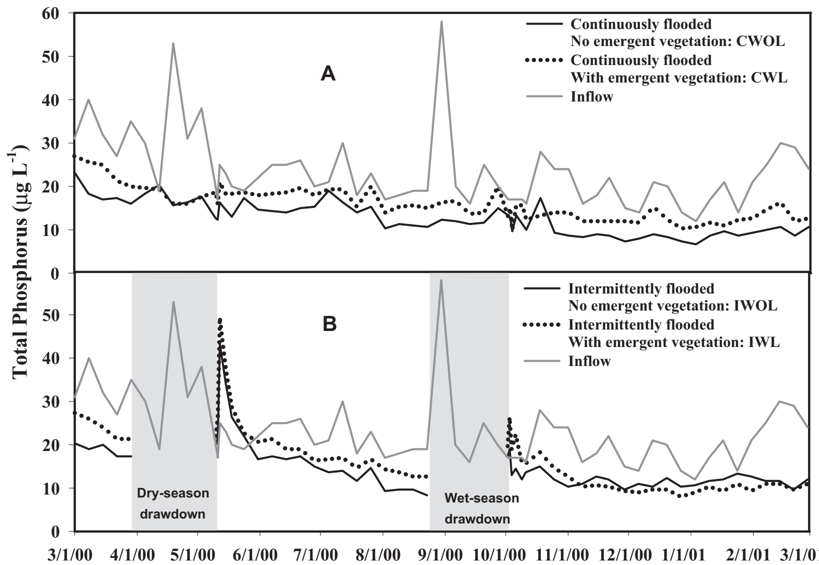

Fig. 3. Inflow and outflow total phosphorus concentrations (TP) for all four treatments. Panel A = Effluent time series for continuously flooded treatments (CWOL and CWL); Panel B = Effluent time series for wet–dry–wet cycle treatments (IWOL and IWL).

significantly different and almost twice that of their counterparts in Experiment II (Table 5). Percent SRP reductions for all continuously flooded treatments remained positive except for CWH (Table 5).

3.2.3. *Particulate phosphorus (PP)*

The maximum influent PP concentrations for Experiment I reached 115 μg L^{-1}, while the maximum PP concentrations in Experiment II reached only 39 μg L^{-1} (Table 6). The overall means for Experiment I and Experiment II were significantly different and effluent PP did not seem to respond to spikes of high inflow values (Fig. 5). Aside from the time periods immediately after the re-wetting of IWL, effluent PP concentrations remained below 10 μg L^{-1} for all treatments regardless of inflow values (Fig. 5). Periods of high effluent PP concentrations were evident, occurring immediately after soil drawdown periods (Fig. 5).

Effluent concentrations for continuously flooded treatments in Experiments I and II were as expected (effluent concentrations were reduced after passing through the mesocosm) and PP means within an experiment were also similar. However, all effluent PP mean concentrations were significantly different between Experiment I and Experiment II, and effluent PP mean concentrations for IWOH and IWH were twice that of IWOL and IWL (Table 6).

Percent PP reduction varied considerably among treatments (Table 6). Mean percent reductions for continuously flooded treatments lacking emergent vegetation (CWOH and CWOL) were similar (9% vs. 9%), while different for CWH (37% reduction in Experiment I vs. 9% export in Experiment II). The observed fluctuations in PP reduction efficiencies were also reflected in the calculated performance range. Performances for intermittently flooded treatments (IWOH and IWH) in Experiment I were

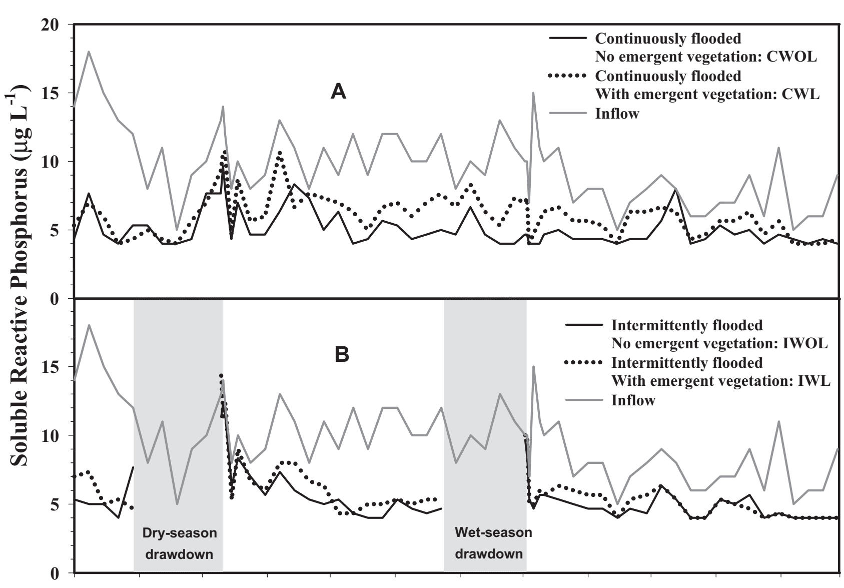

Fig. 4. Experiment I inflow and outflow soluble reactive phosphorus concentrations (SRP) for all four treatments. Panel A = Effluent time series for continuously flooded treatments (CWOL and CWL); Panel B = Effluent time series for intermittently flooded treatments (IWOL and IWL).

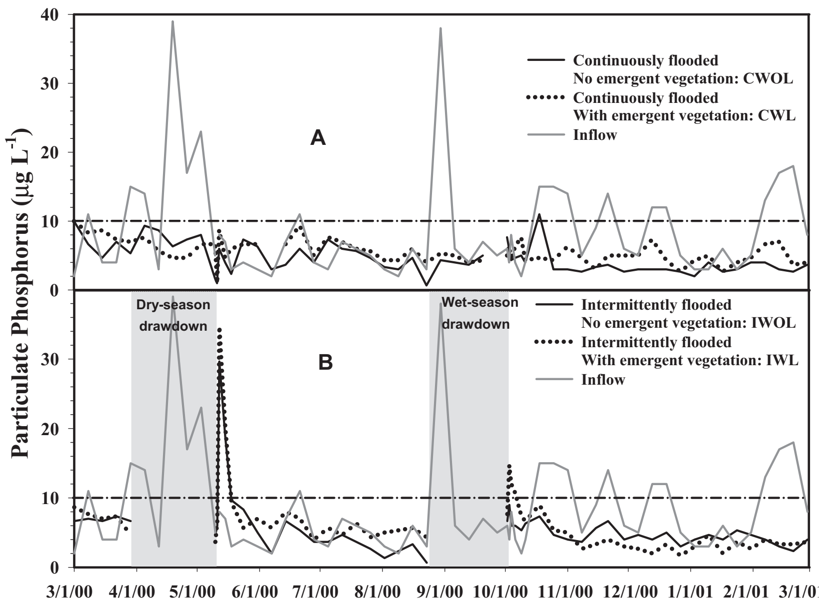

Fig. 5. Experiment I inflow and outflow particulate phosphorus concentrations (PP) for all four treatments. Panel A = Effluent time series for continuously flooded treatments (CWOL and CWL); Panel B = Effluent time series for intermittently flooded treatments (IWOL and IWL).

positive, while negative for their counterparts in Experiment II (Table 6).

3.3. ANOVA model results

Our results indicated that effluent TP concentrations in Experiment I were correlated to a single factor: hydropattern (main effect) or inflow concentrations (within subject effect representing time influence), and the combined effects of two factors: hydrology and inflow concentration, which indicate that hydrology and influent concentrations had the greatest influence on effluent TP at high P loading rates (Table 7). However, effluent TP concentrations in Experiment II were correlated to a single factor: either vegetation or inflow concentration, and their interactions, which indicate that vegetation and inflow concentrations had the greatest influence on effluent TP in Experiment II (Table 7).

Effluent concentrations for all P fractions were significantly influenced by hydrology or inflow concentration, and the interaction between the two factors in both experiments (Table 7). Effluent PP concentrations were significantly impacted by a single factor, either vegetation or hydrology and the interaction between the two factors, which meant that vegetation and hydrology had the greatest influence on PP effluent concentrations for Experiment I. This trend was opposite for Experiment II (i.e., PP results has no correlation to vegetation or hydrology), where only inflow concentrations, a single factor, had the greatest impact on effluent PP (Table 7).

Percent reductions for all P-fractions in both experiments were influenced by a single factor: inflow concentration and the interaction of two factors: inflow concentrations and hydrology. Percent reductions for SRP, TP, and PP were highly correlated to vegetation as a single source of variation in Experiment II, which was exactly the opposite of Experiment I results (Table 8). With the exception of PP, the percent reductions for SRP and TP were highly influenced by hydrology in Experiment I.

4. Discussion

Several studies have documented increased nutrient release rates for carbon (DeBusk and Reddy, 1998), nitrogen (White and Reddy, 2001), and phosphorus (McLatchey and Reddy, 1998; White and Reddy, 2001) in batch experiments with increased oxygen penetration in wetland soils. The aerobic and facultative microbial communities utilized oxygen, not readily available during flood conditions, as the terminal respiratory electron acceptor; and consequently the mineralization rate of the organic matter increased (White and Reddy, 2003). Therefore, the first drawdown during the dry period led to a greater flux of P into the overlying water column, which continued for two weeks after reflooding. This result corroborated with other research which found an increased flux of P under aerobic conditions compared to an anaerobic water column (Grace et al., 2008) as well as correlations of higher measured P flux related to decreases in moisture content from organic soils (Pant and Reddy, 2001). This relationship is generally due to the oxidation of these highly organic soils. For those systems with significant Fe, there can be higher P release under anaerobic conditions due to the reduction of ferric iron to soluble ferrous iron and concomitant release of P (White et al., 2004; Reddy et al., 2011).

The selected hydraulic loading rate in both experiments produced a hydraulic retention time of 15 days. This residence time was equal to the high end of the optimum recommended values of 1–15 days for wastewater treatment wetlands (USEPA, 1985) and twice the reported values for small constructed wetlands treating agricultural drainage water (Reinhardt et al., 2005). This hydrologic regime significantly affected TP reduction in both experiments, as indicated by our ANOVA model results, and particularly for Experiment I. Inflow loading rates for all P fractions were significantly different between the two experiments at $\alpha = 0.01$. Mean TP loading rates for Experiments I and II (12.49 and 3.40 g P m^{-2} year^{-1}, respectively) were two orders of magnitude less than the USEPA recommended values (USEPA, 1985). However, EPA's recommended values are intended for small-size wetlands compared to the size of these STAs.

The relationship between P percent reductions, or effluent concentrations, as a function of mass loading rates with varying plant communities has been recently investigated (Gu and Dreschel, 2008). The major objectives of that study were to assess treatment performance by varying plant communities under constant hydraulic loading rate and various inflow TP concentrations.

Table 3
Soil total carbon, nitrogen, and phosphorus, bulk density, and moisture content collected from the four treatments at Experiment I (high mass loading rate) and II (Low mass loading rate) sites after one year. Listed values are mean and ±one standard deviation.

Treatment		Total carbon (mg kg^{-1})		Total nitrogen (mg kg^{-1})		Total phosphorus (mg kg^{-1})		Bulk density		Moisture content	
Hydrology	Vegetation	High	Low	High	Low	High	Low	High	Low	High	Low
Continuously flooded	No emergent	343 (±11.0)	219 (±40.4)	18.4 (±0.83)	8.3 (±3.5)	404.3 (±39.6)	214 (±59.3)	0.17 (±0.03)	0.39 (±0.03)	75.6 (±0.5)	66.8 (±2.3)
Intermittently flooded[a]	No emergent	345 (±16.0)	260 (±25.4)	18.6 (±1.32)	11.7 (±1.7)	375.7 (±44.88)	219.8 (±8.1)	0.24 (±0.02)	0.34 (±0.03)	75.7 (±3.6)	69.7 (±2.6)
Continuously flooded	Emergent	351 (±10.8)	255 (±59.5)	19.2 (±0.87)	13.6 (±7.8)	365.7 (±55.2)	217.1 (±24.2)	0.22 (±0.03)	0.38 (±0.07)	75.2 (±1.7)	68.2 (±6.2)
Intermittently flooded[a]	Emergent	368 (±15.1)	279 (±20.9)	20.1 (±1.1)	13.6 (±2.3)	367 (±108.8)	253 (±16.6)	0.22 (±0.05)	0.34 (±0.04)	71.8 (±0.6)	71.0 (±2.4)
CWOL and CWL	No emergent	344 (±12.3)	240 (±37.6)	18.5 (±1.0)	10 (±3.1)	390 (±41.0)	217 (±38.0)	0.20 (±0.04)	0.36 (±0.04)	75.6 (±2.3)	68.3 (±2.7)
IWO and IW	Emergent	359 (±14.9)	267 (±41.9)	19.6 (±1.0)	13.6 (±5.1)	366.3 (±77.1)	235.0 (±27.0)	0.22 (±0.04)	0.36 (±0.1)	73.5 (±2.2)	69.6 (±4.5)
All treatments		351 (±15.4)	267 (±41.9)	19.1 (±1.1)	13.6 (±5.1)	378.2 (±60.2)	235.0 (±27.0)	0.21 (±0.04)	0.36 (±0.1)	74.6 (±2.4)	69.6 (±4.5)

[a] Two one-month long drawdown periods during wet and dry season.

Table 4
Summary statistics of Experiment I (H) and II (L) for total phosphorus (TP). Different letter superscripts indicate that the means are significantly different at $\alpha = 0.01$ or 0.05 considering only one treatment pair at a time (e.g., CWOL vs. CWOL).

Treatment Total phosphorus concentration (μg L^{-1})	Inflow (high)	Inflow (low)	CWOH[c]	CWOL[d]	CWH	CWL	IWOH	IWOL	IWH	IWL
Mean	86[a]	23	27[a]	13	26[a]	16	45[a]	15	54[a]	17
Standard error	6.1	1.1	0.9	0.5	1.8	0.5	6.4	0. 9	6.3	1.1
Median	69	21	28	12	22	16	22	13	37	16
Minimum	26	12	16	7	14	10	11	8	16	8
Maximum	230	58	56	23	78	27	171	43	176	49
# of observations	60	60	60	60	60	60	50	50	50	50

Treatment Total phosphorus percent reduction	CWOH	CWOL	CWH	CWL	IWOH	IWOL	IWH	IWL
Mean	61[a]	44	65[a]	27	46[a]	28	30[b]	19
Standard error	2.3	2.2	1.9	2.2	6.5	4.0	7.4	5.0
Median	66	43	66	23	66	35	53	26
Minimum	6	−7	27	−2	−73	−73	−147	−97
Maximum	86	100	90	72	88	67	77	67
# of observations	60	60	60	60	50	50	50	50

Different superscripts (a, b) signify that inflow and effluent concentration means for high P loading (H) are significantly from their counterparts (L) at $\alpha = 0.01$ and 0.05, respectively and (c, d) signify continuously flooded mesocosms without emergent macrophytes in high and low P-loading rates (CWOH and CWOL), respectively.

Table 5
Summary statistics of Experiment I (H) and II (L) for soluble reactive phosphorus (SRP). Different letter superscripts indicate that the means are significantly different at $\alpha = 0.01$ or 0.05 considering only one Treatment pair at a time (e.g., CWOL vs. CWOL).

Treatment Soluble reactive phosphorus (SRP) concentration ($\mu g\,L^{-1}$)	Inflow SRP (high)	Inflow SRP (low)	CWOH[c]	CWOL[d]	CWH	CWL	IWOH	IWOL	IWH	IWL
Mean	57[a]	10	7[a]	5	10[a]	6	16[a]	6	32[a]	6
Standard error	5.4	0.4	0.3	0.2	0.6	0.2	3.5	0.3	5.1	0.3
Median	42	10	6	5	9	6	7	5	16	5
Minimum	9	5	4	4	4	4	4	4	5	4
Maximum	207	18	18	10	29	11	103	12	142	14
# of observations	60	60	60	60	60	60	50	50	50	50

Treatment Soluble reactive phosphorus percent reduction	CWOH	CWOL	CWH	CWL	IWOH	IWOL	IWH	IWL
Mean	83[a]	44	77[a]	34	70[a]	40	34	36
Standard error	1.42	2.1	1.9	2.0	4.7	2.6	11.3	2.7
Median	85	46	79	32	81	37	68	33
Minimum	30	0	−11	4	−46	3	−254	−10
Maximum	96	73	96	69	94	72	85	67
# of observations	60	60	60	60	50	50	50	50

Different superscripts (a, b) signify that inflow and effluent concentration means for high P loading (H) are significantly different from their counterparts (L) at $\alpha = 0.01$ and 0.05, respectively and (c, d) signify continuously flooded mesocosms without emergent macrophytes in high and low P-loading rates (CWOH and CWOL), respectively.

Table 6
Summary statistics of Experiment I (H) and II (L) for particulate phosphorus (PP). Different letter superscripts indicate that the means are significantly different at $\alpha = 0.01$ or 0.05 considering only one treatment pair at a time (e.g., CWOL vs. CWOL).

Treatment Particulate phosphorus concentration (PP) ($\mu g\,L^{-1}$)	Inflow PP (high)	Inflow PP (low)	CWOH[c]	CWOL[d]	CWH	CWL	IWOH	IWOL	IWH	IWL
Mean	22[a]	8	14[a]	5	11[a]	6	20[a]	6	11[a]	6
Standard error	2.4	1.0	0.8	0.3	1.3	0.24	3.2	0.6	1.5	0.8
Median	19	6	13	4	8	5	8	5	6	5
Minimum	2	0	4	1	2	2	2	1	2	2
Maximum	115	39	40	11	60	10	74	30	50	35
# of observations	60	60	59	59	59	59	50	50	50	50

Treatment Particulate phosphorus percent reduction	CWOH	CWOL	CWH	CWL	IWOH	IWOL	IWH	IWL
Mean	9	9	37[a]	−9	7	−12	34	−35[a]
Standard error	5.8	10.8	7.1	11.5	11.7	12.6	3.8	16.4
Median	10	31	47	6	44	17	45	0
Minimum	−150	−400	−174	−400	−258	−271	−55	−333
Maximum	82	89	93	100	92	87	73	83
# of observations	58	58	58	58	48	48	48	48

Different superscripts (a, b) signify that inflow and effluent concentration means for high P loading (H) are significantly different from their counterparts (L) at $\alpha = 0.01$ and 0.05, respectively and (c, d) signify continuously flooded mesocosms without emergent macrophytes in high and low P-loading rates (CWOH and CWOL), respectively.

Table 7
Repeated measures ANOVA comparing the effects of presence or absence of emergent macrophytes and hydropattern (continuous or intermittently flooded soils) on effluent P-concentration for 12 mesocosms surveyed weekly (*P*-values are listed) for Experiments I and II, receiving high (H) and low (L) P loading rates, respectively.

Source of variation	Total phosphorus			Particulate phosphorus			Soluble Reactive Phosphorus		
	df	*F*	*P*-values	*df*	*F*	*P* values	*df*	*F*	*P* values
Vegetation H[a]	1	2.0	0.2	1	5.7	0.1	1	6.7	0.04
(L[b])	1	14.3	0.02	1	4.9	0.09	1	25.2	<0.01
Hydrology H	1	17.2	<0.01	1	0.4	0.6	1	19.7	<0.01
(L)	1	6.9	0.06	1	7.1	0.06	1	1.5	0.26
Vegetation × hydrology H	1	1.3	0.3	1	1.9	0.2	1	2.9	0.14
(L)	1	1.3	0.31	1	0.3	0.6	1	4.9	0.06
Inflow concentrations H	46	14.8	<0.01	46	4.6	<0.01	45	15.0	<0.01
(L)	47	33.4	<0.01	47	11.6	<0.01	47	29.1	<0.01
Inflow concentrations × vegetation H	46	0.74	0.9	46	1.5	0.02	45	1.4	0.05
(L)	47	1.6	<0.02	47	0.9	0.60	47	1.8	<0.01
Inflow concentrations × hydrology H	46	9.8	<0.01	46	2.8	<0.01	45	12.9	<0.01
(L)	47	11.6	<0.01	47	7.2	<0.01	47	4.7	<0.01
Inflow concentrations × vegetation × hydrology H	46	0.6	1.0	46	1.1	0.4	45	1.4	0.04
(L)	47	1.7	<0.01	47	1.5	0.04	47	0.2	0.3

[a] High phosphorus loading rate (Experiment I).
[b] Low phosphorus loading rate (Experiment II).

Table 8
Repeated measures ANOVA comparing the effects of presence or absence of emergent macrophytes and hydropattern (continuous or intermittently flooded soils) on P-percent reduction for 12 mesocosms surveyed weekly (*P*-values are listed) for Experiment I and II, receiving high (H) and low (L) P loading rates, respectively.

Source of variation	Total phosphorus			Particulate phosphorus			Soluble reactive phosphorus		
	df	*F*	Percent reduction	Percent reduction	Percent reduction	*P* values	*df*	*F*	*P* values
Vegetation H[a]	1	1.2	0.32	1	5.7	0.05	1	6.0	0.05
(L[b])	1	11.0	0.03[a]	1	16.6	<0.01[a]	1	19.3	<0.01[a]
Hydrology H	1	8.2	<0.04[a]	1	0.01	0.94	1	12.0	<0.01
(L)	1	6.2	0.07	1	3.7	0.09	1	0.6	0.45
Vegetation × hydrology H	1	1.5	0.27	1	0.08	0.79	1	3.0	0.13
(L)	1	1.5	0.29	1	0.0	0.98	1	4.4	0.07
Inflow concentration H	46	8.2	<0.01	45	4.1	0.01	45	7.3	<0.01[a]
(L)	47	26.8	<0.01	45	34.2	<0.01	47	24.7	<0.01[a]
Inflow concentration × vegetation H	46	0.4	0.99	45	2.1	<0.01	45	2.2	<0.01[a]
(L)	47	1.4	0.06	45	1.6	0.01	47	1.7	<0.01[a]
Inflow concentration × hydrology H	46	5.0	<0.01	45	2.5	<0.01	45	6.3	<0.01
(L)	47	10.9	<0.01	45	4.0	<0.01	47	4.4	<0.01
Inflow concentration × vegetation × hydrology H	46	0.4	0.99	45	0.5	0.89	45	2.1	<0.01
(L)	47	2.3	<0.01	45	2.0	<0.01	47	1.0	0.54

[a] High phosphorus loading rate (Experiment I).
[b] Low phosphorus loading rate (Experiment II).

They reported that average effluent P concentrations were 25 and 30 μg L^{-1}, or TP percent reductions of 64 and 55, yielding mass reduction rates of 0.63 and 0.57 g m^{-2} $year^{-1}$ for cattail and submerged aquatic vegetation (SAV) cells, respectively. Results (Table 4) for continuously flooded treatments (CWOH and CWH) from Experiment I, compared to the results of Gu and Dreschel (2008), for TP percent reductions (61 and 65% vs. 64 and 55% for cattail and SAV, respectively), and outflow TP concentrations (27 and 26 vs. 25 and 30 for cattail and SAV, respectively), are in strong agreement. Influent TP concentration means were 86 and 23 μg L^{-1}, for Experiment I and II compared to the previous study which were 72 and 43 μg L^{-1} for cattail and SAV, respectively. The difference in TP inflow concentrations between our study and theirs is attributed to the location of the inflow pipe for both experiments. Our experiment site was located near the inflow and the outflow sites of STA-1W, which resulted a direct receiving of EAA runoff at Experiment I and of reduced EAA runoff concentrations after passing through the entire length of STA-1W. On the other hand, the Gu and Dreschel (2008) study utilized sites that were located mid-way between inflow and outflow sites in STA-1W. Both experiment hydrologic regimes were very similar (water depth = 30 vs. 40 cm), and the hydraulic loading rates were almost identical (9.3 vs. 9.5 m $year^{-1}$). Hydraulic residence times for both of our experiments were almost twice as long (15 vs. 8 days) as those reported by Gu and Dreschel (2008).

The major difference between Experiment I and Experiment II is the P loading rate. All other environmental factors were equal (hydrology, sediments, number of emergent macrophyte plants per square meter, etc.) or controlled to maintain equality (keeping SAV mesocosms free of emergent macrophytes). Soil used in these experiments was obtained from the same source and all drawdown periods lasted for five weeks to ensure an equal time of soil exposure to the atmosphere, which resulted in almost identical surface water temperatures in all the mesocosms (temperature and dissolved oxygen data not shown). Soil bulk densities in these experiments are typical for organic soils found in the northern Everglades (White and Reddy, 2001) and the total C and N contents from these experiments are typical of south Florida peat soils and those found in un-impacted areas of the northern Everglades (Reddy et al., 1993; White and Reddy, 2000, 2003). Other environmental variables that were not controlled were similar in value and we assume that their impacts on observed effluent concentrations and calculated percent reductions were negligible. For example, water temperature remained above 10 °C for the entire period of record, while pH and O_2 values were slightly different for Experiment I and Experiment II. However, the slight differences in temperature, pH, or dissolved oxygen did not lead to higher TP reduction in Experiment II. On the contrary, TP reduction was significantly higher in Experiment I when compared to Experiment II. Even though the solubility of oxygen in surface water decreases as temperature increases (USGS, 1981), we do not believe that the small increase in temperature (CWO and IWO treatments in both Experiments) is responsible for the observed low O_2 concentration in treatments with emergent vegetation (CW and IW). Rather, the dominance of submerged aquatic vegetation is responsible for higher O_2 observed in these treatments (Gu et al., 2006; Chimney et al., 2006).

The greatest observed change between inflow and outflow in all P fractions was noted in effluent SRP concentrations in both experiments with only slight differences for PP. Therefore, we attribute the observed decrease in effluent TP concentration to be driven primarily by removal of SRP and to a far lesser extent, PP. Our results also suggest that PP reduction is related to the presence or absence of emergent vegetation. Emergent vegetation tends to slow down water flow, thus reducing the transport of particulates in the water column (Kadlec and Knight, 1996), which would lead to lower effluent PP values as observed in our study (Fig. 5).

It is likely that a large constructed wetland would go dry, or partially dry, during a dry season or during drought periods in regions dominated by wet–dry weather cycles such as in south Florida. Thus, it is critical to manage these wetlands during dry climatic periods to minimize P releases to surface water and the subsequent discharges of high nutrient-laden water downstream. A minimal P release was related to the wet season drawdown when compared to dry period drawdown. This suggests that maintaining a wet soil, not necessarily flooded, could minimize soil dry out, and consequently reduce the P flux to the overlying surface water upon reflooding. Therefore, we recommend the maintenance of wet soils during dry months to prevent the associated release of P to the water column.

Constructed wetlands in subtropical areas are likely to be colonized by both emergent and non-emergent macrophytes (Kadlec and Knight, 1996). This mixture of emergent and non-emergent plants creates an optimum environment for nutrient reduction in general, as evidenced by the increase in constructed wetland use during the last two decades. The mixture of both emergent and non-emergent plants in a constructed wetland results in water quality improvements for different P fractions. For example, continuously and intermittently flooded treatments with emergent macrophyte treatments (CW and IW) performed best in retaining PP, while treatments with non-emergent plants (CWO and IWO) performed best for SRP reductions (Tables 5 and 6); SRP and PP make up, on average, 91% and 81% of the high and low TP inflow concentrations. Combining emergent and non-emergent vegetation in constructed wetlands would lead to a greater TP reduction compared to a monoculture. It is also evident from the results of our ANOVA model, that vegetation was the dominant factor for the removal of TP and PP, in Experiment II (Tables 7 and 8). This result is opposite to our ANOVA model results for Experiment I, and further suggests that emergent vegetation is not only necessary for water quality improvement, but a critical factor for wetlands receiving low phosphorus loading rates.

5. Conclusions

In summary, there were no substantial differences in P assimilation among hydrologic treatments for mesocosms receiving low P loadings as observed among all outflows. However, treatments with emergent macrophytes outperformed treatments lacking emergent vegetation at low P loadings (Experiment II). Both the magnitude and duration of the high TP concentrations in the surface water after rewetting were season-dependent for both experiments. However, the impacts of the P flux to the surface water are not as important in magnitude or as long lasting for the low P- compared to high P-loading experiment. The percentages of TP reduction rates were higher at high P loading rates and low at low P loading rates. Our results indicate that the presence of emergent vegetation is the most critical for managing large wetland treatment systems receiving low P loadings, while hydrology should be the focus in managing treatment systems receiving high P loadings. Therefore, for these large treatment systems, the upstream section of the wetland, receiving the higher P load may need to be managed differently with respect to the downstream end of the treatment wetland.

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