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Influence of hydropattern and vegetation type on phosphorus dynamics in flow-through wetland treatment systems

M.Z. Moustafa[a,*], J.R. White[b], C.C. Coghlan[a], K.R. Reddy[c]

[a] South Florida Water Management District, Hydrologic & Environmental Systems Modeling 3301 Gun Club Road, MAILSTOP 7512, West Palm Beach, FL 33406, United States
[b] Wetland and Aquatic Biogeochemistry Laboratory, Dept of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, United States
[c] Soil and Water Science Department, University of Florida, Gainesville, FL 32611, United States

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ABSTRACT

Phosphorus (P) flux from wetland soil can be a significant factor affecting overall wetland treatment performance. The purpose of our study was to quantify the effects of water level drawdown on P exchange between surface water and organic soil in a constructed wetland. We used 12 fiberglass mesocosms filled with 30 cm of peat soil to quantify nutrient exchange between surface water and organic soil in a wet–dry–wet cycle. Six mesocosms were planted with emergent macrophytes and six mesocosms were maintained free of emergent vegetation. We evaluated four treatments including continuously and intermittently flooded treatments, both with and without emergent macrophytes. Each treatment was replicated three times and every mesocosm was plumbed to monitor flow volumes and water chemistry. Effluent P concentrations were similar for all four treatments prior to first drawdown period. However, upon re-flooding, all intermittently flooded tanks exhibited a three to fourfold increase in surface water P concentration, which lasted for a period of up to ten weeks. The magnitude of nutrient flux to surface water and the time period over which P release took place were season dependent, with longer duration of high nutrient flux during dry-season drawdowns. Results of repeated measures analysis indicated that hydropattern was the dominant factor affecting P-flux to overlying surface water, while presence or absence of emergent vegetation had no significant influence on effluent concentrations. Organic and particulate phosphorus fluxes were substantially higher in treatments lacking emergent macrophytes, subsequent to the dry-season drawdowns. Intermittently flooded treatments with no emergent vegetation generated the most dissolved and particulate phosphorus. Our results indicate that maintaining saturated soil is sufficient to retain stored P, while plants played no significant role in P retention for a wetland receiving P-loading rate on the order of 0.1 g week^{-1} during a wet–dry–wet cycle.

1. Introduction

The Water Conservation Areas (WCAs) and the Everglades National Park (ENP) encompass what remains of a once larger Everglades ecosystem. For several decades, there has been growing concern in the regulatory, scientific, and environmental communities regarding the biotic integrity of the remaining Everglades. Observed changes in plant and animal populations in portions of the remaining Everglades have been attributed to the disruption of both the system's natural hydroperiod and eutrophication resulting from nutrient-rich stormwater runoff entering the WCAs from the Everglades Agricultural Area (EAA; Fig. 1).

Concerns over degraded water quality in parts of the Everglades have led to legal mandates (the 1994 Everglades Forever Act; Section 373.4592 F.S.) for the restoration and protection of the Everglades ecosystem. The 1994 Everglades Forever Act mandated a series of measures including the construction of Stormwater Treatment Areas (STAs; large constructed wetlands), and setting of STA threshold effluent discharge limits for total phosphorus (TP < 50 μg L^{-1} for Phase 1 and much lower for Phase 2), all of which are intended to restore the remaining Everglades. The first stage of a phosphorus (P) reduction treatment system for the northern Everglades is the installation of Best Management Practices (BMPs; agricultural management techniques that reduces pollutant export from farmland) within the EAA Basin (Izuno and Capone, 1995). Since BMPs were installed, cumulative measured P loads attributable to the EAA have been reduced by more than 50%.

The STAs, with a project area of 180 km^2 (44,937 acres), represent the second stage of a phosphorus reduction treatment system for the northern Everglades. Located south of the EAA, these STAs

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* Corresponding author. Tel.: +1 561 682 6530; fax: +1 561 682 0100.
E-mail addresses: moustafa@sfwmd.gov (M.Z. Moustafa), jrwhite@lsu.edu (J.R. White), krr@ufl.edu (K.R. Reddy).

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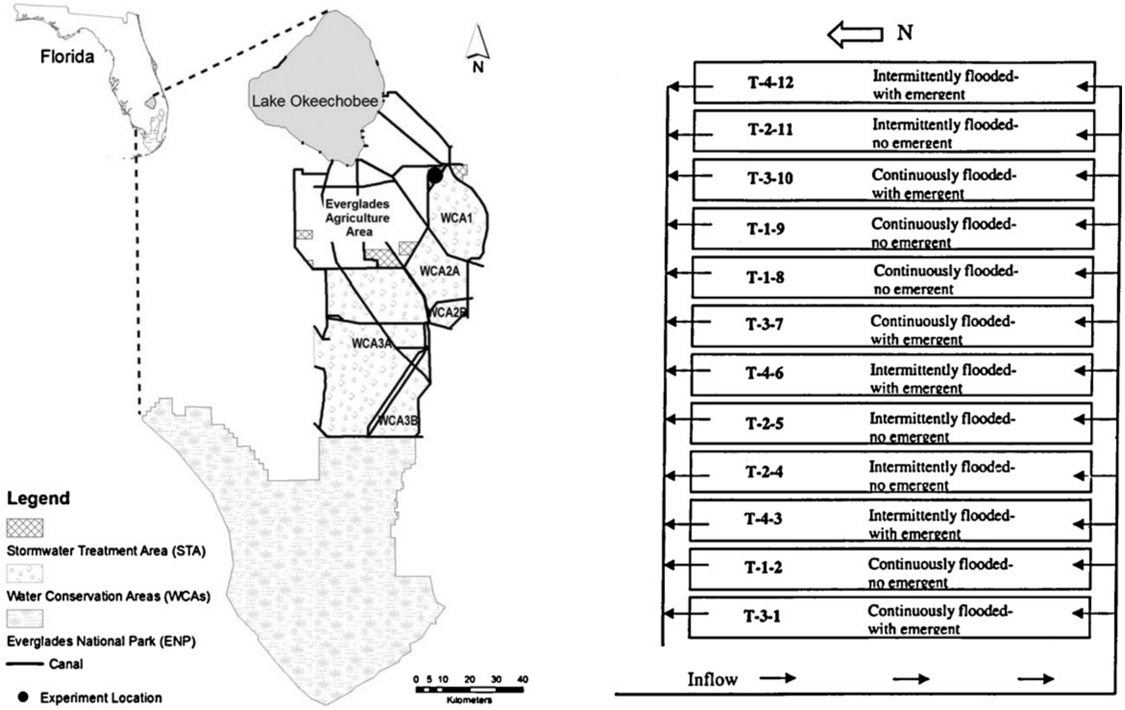

Fig. 1. Location of Everglades Agricultural Areas (EAA), Stormwater Treatment Areas (STA), Water conservation Areas (WCA), Everglades National Park (ENP), experiment location and schematic representing the four treatments set up (e.g., T-4-12 = treatment 4 tank # 12).

are designed as flow-through wetland treatment systems. The STAs will temporarily hold runoff water from the EAA to reduce TP-concentrations to acceptable levels ($<50\,\mu g\,L^{-1}$) before water is released southward into the conservation areas; soils in these systems are peat based.

Considerable research has focused on how to manage these wetlands to minimize P-releases to surface water and meet effluent discharge limits for TP set by the Everglades Forever Act. Of particular concern is the potential for portions of the STAs to go dry during droughts. Previous studies have shown that draining and reflooding of organic soils increases soluble P flux into the water column (Olila et al., 1997). In addition, flooded soils in previously farmed areas may potentially release P to the overlying water column as a result of solubilization of residual fertilizer P stored in the soil (Newman and Pietro, 2001). Exposure of organic peat material to the atmosphere promotes the conversion of organic P into labile inorganic P, which can be released into the water column upon reflooding (Olila et al., 1997; Pant and Reddy, 2001). Conversely, drawdown may consolidate accumulated detritus materials and therefore, increase the stability of inorganic P through precipitation reactions, and increase the potential to accumulate nutrients in the peat soil (Scholz and Trepel, 2004). However, most previous studies involved dry down and reflooding of intact cores under controlled conditions (e.g., no vegetation and no sunlight). Unlike constructed wetlands, these experiments were not designed as flow-through treatment systems (Corstanje and Reddy, 2004; Bostic and White, 2007).

Several management practices can reduce P flux from wetland soils. The use of chemical amendments (primarily alum) for reducing P flux has been investigated recently (Malecki-Brown et al., 2007, 2009) but are generally impractical for large constructed wetland systems (STA sizes range from 2257 to 16,543 acres). However, the influence of hydropattern (wetting and drying of organic soil) and/or the presence or absence of emergent vegetation on nutrient dynamics in wetlands receiving agricultural runoff has rarely been investigated. If organic soil in a large constructed wetland, such as an STA, dries out for any length of time, nutrient flux from the sediment upon reflooding may reduce the overall nutrient reduction efficiency of these systems. Therefore, the main objective of this study was to determine the interactive effects of emergent vegetation (presence or absence) and hydropattern (wetting and drying of organic soil) on nutrient dynamics in surface water flow-through wetland treatment systems. Specifically, our research objectives were to: (1) determine the effects of a wet–dry–wet soil cycle on surface water P-concentrations over a two-year period, (2) determine the effects of presence and absence of emergent macrophyte on P dynamics for a wet–dry–wet soil cycle, and (3) recommend a management plan to minimize the influence of wet–dry–wet soil cycles on P dynamics in a constructed wetland.

2. Methods

2.1. Experiment location and description

Twelve wood and fiberglass mesocosm tanks, measuring 5.9 m long, 1.0 m wide, and 1.0 m deep, were filled with 30-cm of peat soils harvested from Cell 5 of Stormwater Treatment Area 1 West (STA-1W, Fig. 1). Six mesocosms were planted with cattails (*Typha domingensis*) and six were left unplanted. In the planted tanks, there were six transplants per square meter for a total of 36 plants per tank; a three-month period was sufficient for these transplants to establish before starting measurements. Inflows to the mesocosms were pumped from the Everglades Nutrient Removal Project (ENRP) supply canal and were representative of surface water from the EAA. A 5-cm PVC supply line originating from an elevated 200 L barrel supplied each tank with water and another line provided drainage for overflow. Surface water depth was maintained at 40 cm via an outflow stand up PVC pipe. Inflow to each mesocosm was regulated using a 5 ml pipette tip shortened to deliver a known volume of water per unit time. A timer regulated the delivery of water to each of the 12 mesocosms so that the hydraulic loading rate matched the historical rate of 2.6 cm day^{-1} for the ENRP. Pipette tips were replaced every 10–14 days or when blocked by algal growth and water was pumped on a time-based flow system, with flow running for 2.5 min and off for 12.5 min to deliver the required 2.6 cm day^{-1}. The experimental design consisted of four treatment types with three replicate mesocosms randomly assigned to each treatment and are defined as follows:

1. Treatment 1: Continuously flooded sediment with no emergent macrophytes (CWO),
2. Treatment 2: Intermittently flooded sediment with no emergent macrophytes (IWO),
3. Treatment 3: Continuously flooded sediment with emergent macrophytes (CW),
4. Treatment 4: Intermittently flooded sediment with emergent macrophytes (IW).

Small plant such as *Chara* spp., filamentous green algae, Lemna, and *Salvinia rotundifolia* were present in all tanks, however, the emergent tanks were dominated by cattail at over >98% of the total biomass. The SAV tanks were maintained free of emergent macrophytes and were dominated by two submerged aquatic plants (*hydrilla verticillata* and *ceratophyllum demersum* at >98% of the total biomass during sampling (White et al., 2006) with unidentified floating algae comprising the remaining biomass.

2.2. Analytical methods

A total of 13 water quality samples were collected weekly following standard methods (APHA, 1998); one at the inflow and 12 at the outflows. The inflow sample was composed of 12 sub-samples collected near the header of each individual tank. Weekly water quality samples were analyzed for total phosphorus (TP), total dissolved phosphorus (TDP), and soluble reactive phosphorus (SRP). Samples were digested in an autoclave using persulfate–sulfuric acid reagent, and then analyzed using single ascorbic acid reagent on a Rapid Flow Analyzer (APHA SM #4500PF). Values of monitored parameters that fell below detection limits were set to detection value. Additional nutrient concentrations used in our analyses were calculated as follows:

- Organic phosphorus (ORG-P) = TP – SRP
- Dissolved organic phosphorus (DOP) = TDP – SRP
- Particulate phosphorus (PP) = TP – TDP

2.3. Experimental procedures

The mesocosms were operated under steady flow conditions (hydraulic loading rate = 2.6 cm day^{-1}, hydraulic residence time = 15 days, and water depth = 40 cm). Four soil-drawdown events were performed during dry- and wet-season conditions and each event lasted five weeks. Dry out within the six intermittently flooded mesocosms was achieved by shutting off the inflow and reducing the outflow pipe height to just below the soil layer. After every dry out period, the six mesocosms were re-flooded simultaneously to a depth of 40 cm and water was held for one week, after which flow through conditions were restored. For continuously flooded mesocosms, pre-selected hydraulic loading rate and water depth were maintained at all times. All four treatments were unprotected from rainfall to mimic actual field conditions.

2.4. Statistical analysis

Data were examined using SAS® (SAS Institute Inc, 1999) to quantify the effects of emergent macrophytes and hydropattern on nutrient concentration including TP, SRP, DOP, and PP (Standard Error (SE) is reported). A repeated measures ANOVA was run for each of these experiments (significance level of $P \leq 0.05$) using PROC GLM (von Ende, 1993). Vegetation and hydrology were the main effects and inflow concentration was the within-subject effect in the analyses. The experiment was run for 119 weeks. Any week that had missing data for at least one tank was removed from the analysis. As a result, DOP and TP experiments retained 77 weeks, PP experiments retained 75 weeks, and SRP experiments retained 78 weeks in the analyses. The Greenhouse–Geisser adjusted *P* value was reported for all within-subjects effects because this *P* value adjusts for a violation of the sphericity assumption (von Ende, 1993).

3. Results

3.1. Assessment of hydropattern and vegetation on phosphorus dynamics

Total phosphorus (TP). Inflow TP concentrations varied seasonally and ranged from 26 to 365 μg TP L^{-1} with a mean of 98 μg TP L^{-1} (±5.2 SE) for the two-year period of record (Table 1). Outflow TP concentration means for the continuously flooded treatments were much lower and less variable, ranging from 13 to 78 μg TP L^{-1} for CW and from 12 to 56 μg TP L^{-1} for CWO. While mean outflow TP concentration for intermittently flooded treatments were similar, these means were almost twice those for continuously flooded treatments. Minimum effluent TP concentrations for all treatment were similar, but the maximum effluent values for intermittently flooded treatments (180 and 176 μg TP L^{-1}) were triple those for continuously flooded treatments (Table 1).

Effluent TP concentrations from all four treatments were similar prior to all drawdown periods (Fig. 2). However, intermittently flooded treatments exhibited two to sixfold increases in surface water TP concentration upon re-flooding (Fig. 2). Initial spikes in effluent TP concentrations for intermittently flooded treatments were much higher than inflow concentration and remained elevated above pre-drawdown concentrations for approximately seven and nine weeks during wet- and dry-season drawdowns, respectively (Fig. 2).

Continuously flooded treatment TP-reduction means were significantly different, while intermittently flooded treatment means were not significantly different (Table 2). Weekly P-reduction rates ranged between 1 and 95 for CWO and between 27 and 95 for CW, while intermittently flooded treatments P-reduction rates ranged between −222 and 91 for IWO and between −147 and 90 for IW. In general, all treatments performed similarly during non-drawdown events (Fig. 2). However, continuously flooded treatments achieved 100% net P-reduction (no TP export for the entire period of record), whereas intermittently flooded treatments both only achieved 82% of the time.

Soluble reactive phosphorus (SRP). Inflow SRP concentrations ranged from 9 to 241 μg SRP L^{-1} with a mean of 60 μg SRP L^{-1} (±4.0) (Table 1). Effluent SRP concentrations for continuously flooded treatments were substantially lower and less variable compared to inflow values, ranging between 4 and 18 μg SRP L^{-1} for CWO and between 4 and 29 μg SRP L^{-1} for CW (Table 1). Mean

Table 1
Summary statistics for influent and effluent concentrations for total phosphorus (TP), soluble reactive phosphorus (SRP), dissolved organic phosphorus (DOP), and particulate phosphorus (PP), for all four treatments.

Variable ($\mu g\,L^{-1}$) treatment	Mean	Standard error	Median	Minimum	Maximum	Number of observations
Inflow TP	98	5.2	75	26	365	118
CWO[a]	25[f]	0.8	24	12	56	119
IWO[b]	46[h]	4.5	24	11	180	99
CW[c]	23	1.0	21	13	78	119
IW[d]	47	3.6	34	16	176	99
Inflow SRP	60	4.0	44	9	241	119
CWO	6[e]	0.2	6	4	18	119
IWO	16[g]	2.3	7	4	103	99
CW	8	0.4	7	4	29	119
IW	24	2.8	12	5	142	99
Inflow DOP	7	0.2	7	1	15	119
CWO	10[e]	0.8	7	1	39	99
IWO	6[g]	0.2	6	1	12	119
CW	12	0.4	11	3	25	99
IW	7	0.5	7	1	44	118
Inflow PP	31	2.8	21	3	174	115
CWO	11[f]	0.6	10	1	40	119
IWO	20[g]	2.2	9	2	74	99
CW	9	0.7	8	2	60	119
IW	12	1.0	8	1	50	99

[a] Continuously flooded sediment with no emergent macrophytes (CWO).
[b] Intermittently flooded sediment with no emergent macrophytes (IWO).
[c] Continuously flooded sediment with emergent macrophytes (CW).
[d] Intermittently flooded sediment with emergent macrophytes (IW).
[e] Significantly different (CWO vs. CW).
[f] Not significantly different (CWO vs. CW).
[g] Significantly different (IWO vs. IW).
[h] Not significantly different (IWO vs. IW).

effluent SRP concentrations for intermittently flooded treatments, ranged between 4 and 103 μg SRP L^{-1} for IWO and between 5 and 142 μg SRP L^{-1} for IW. Effluent SRP concentration means of continuously flooded treatments were similar and less than half the mean value of both intermittently flooded treatments (Table 1). Effluent SRP for both continuously flooded treatments were much lower during all drawdown period and distinctly lower during dry- compared to wet-season drawdowns (Fig. 3). Excluding all drawdown periods, effluent concentrations from both continuously flooded and intermittently flooded treatments were significantly differ-

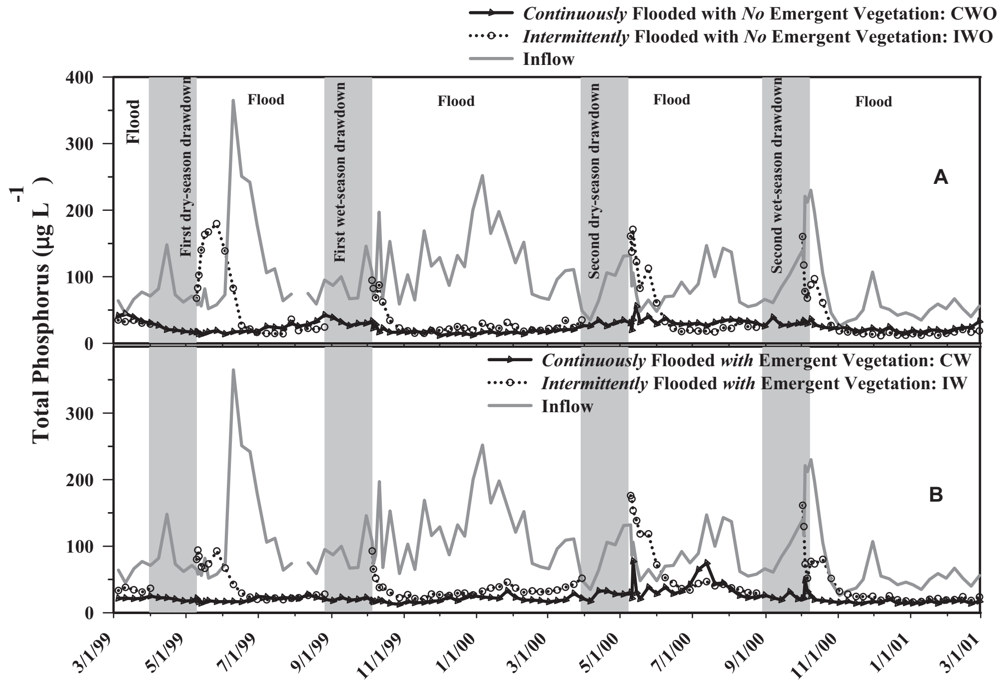

Fig. 2. Inflow and outflow total phosphorus concentrations (TP) for all four treatments from March 1999 through March 2001. Panel A = effluent time series for treatment with no emergent vegetation (CWO and IWO). Panel B = effluent time series for treatment with emergent vegetation (CW and IW). Inflow to all treatment (solid gray line), intermittently flooded treatment (dotted line with open circle), and continuously flooded treatment (solid black line with open triangle).

Table 2
Summary statistics for percent reductions for total phosphorus (TP), soluble reactive phosphorus (SRP), dissolved organic phosphorus (DOP), and particulate phosphorus (PP), for all four treatments.

Treatment	Variable	Mean	Standard error	Median	Minimum	Maximum	Number of observations
CWO[a]	*TP*	67[e]	2	69	1	95	118
IWO[b]		42[f]	6	67	−222	91	98
CW[c]		71	1	73	27	95	118
IW[d]		40	5	59	−147	90	98
CWO	*SRP*	85[e]	1	86	30	98	118
IWO		65[g]	5	85	−181	97	98
CW		82	1	85	−11	98	118
IW		46	6	68	−229	94	98
CWO	*DOP*	−43[e]	14	8	−767	133	119
IWO		−46[g]	36	6	−1583	1667	107
CW		12	16	25	−567	767	119
IW		−97	33	−52	−1533	1133	107
CWO	*PP*	28[e]	3	37	−150	82	117
IWO		7[g]	10	53	−303	95	95
CW		54	4	68	−174	97	116
IW		35	3	47	−57	77	98

[h] Not significantly different at $\alpha = 0.01$ between IWO and IW.
[a] Continuously flooded sediment with no emergent macrophytes (CWO).
[b] Intermittently flooded sediment with no emergent macrophytes (IWO).
[c] Continuously flooded sediment with emergent macrophytes (CW).
[d] Intermittently flooded sediment with emergent macrophytes (IW).
[e] Significantly different at $\alpha = 0.01$ between CWO and CW.
[f] Not significantly different at $\alpha = 0.01$ between CWO and CW.
[g] Significantly different at $\alpha = 0.01$ between IWO and IW.

ent (Table 1). Both intermittently flooded treatments exhibited three- to fifteenfold increases in surface water SRP concentration upon re-flooding and were much higher than inflow values for approximately 3–5 weeks, particularly after dry-season drawdowns (Fig. 3). On average, this high SRP flux lasted six and ten weeks during dry- and wet-season drawdowns, respectively.

Soluble reactive phosphorus percent reduction means for continuously flooded (CW and CWO) and intermittently flooded treatments (IWO and IW) were significantly different (Table 2). Excluding all drawdown periods, SRP percent reductions for the two continuously flooded treatments were almost identical, while intermittently flooded treatment with no emergent vegetation

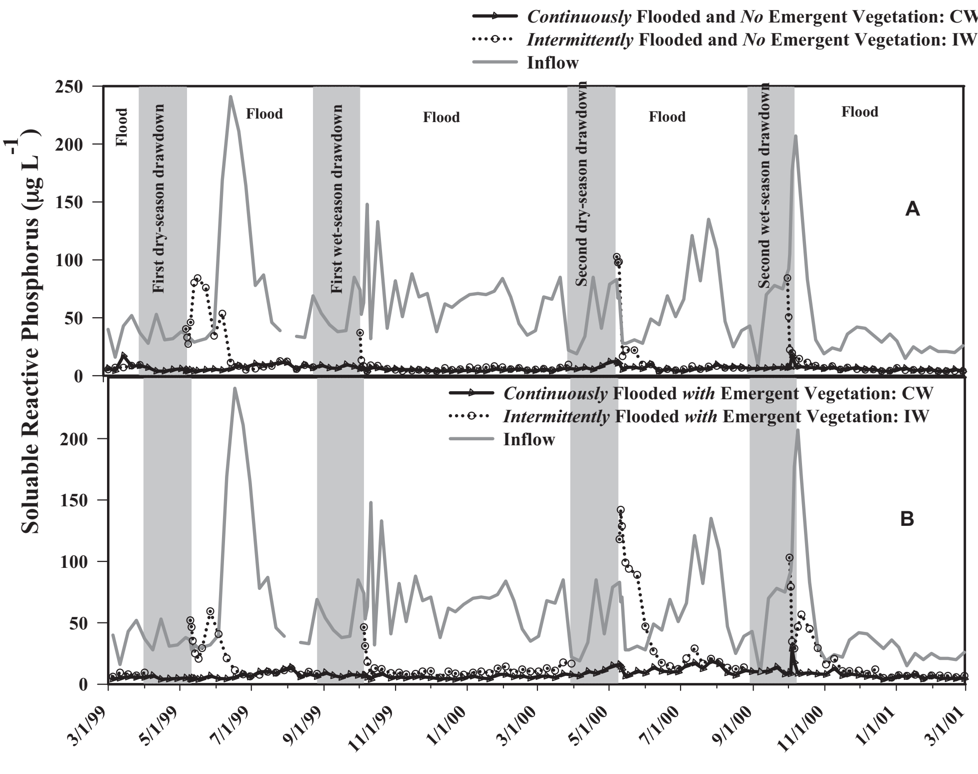

Fig. 3. Inflow and outflow soluble reactive phosphorus (SRP) concentrations for all four treatments from March 1999 through March 2001. Panel A = effluent time series for treatment with no emergent vegetation (CWO and IWO). Panel B = effluent time series for treatment with emergent vegetation (CW and IW). Inflow to all treatment (solid gray line), intermittently flooded treatment (dotted line with open circle), and continuously flooded treatment (solid black line with open triangle).

(IWO) consistently outperformed intermittently flooded treatment with emergent vegetation (IW). Intermittently flooded treatments (IWO and IW) exported SRP 11 and 13 times, respectively, and all export events occurred immediately after drawdown periods (Fig. 3).

Dissolved Organic Phosphorus (DOP). With the exception of dry-season drawdown for IWO, both influent and effluent DOP concentrations for all remaining treatments were similar and no substantial decrease in DOP was observed after passing through the mesocosms (Fig. 4). Inflow DOP concentrations fluctuated between a minimum of almost 1 and a maximum of 15 μg DOP L^{-1} (Table 1). However, DOP outflow concentration means for continuously flooded treatments were slightly less variable than intermittently flooded treatments (Table 1). Effluent DOP concentrations ranged between 1 and 39 μg DOP L^{-1} for CWO and between 3 and 25 μg DOP L^{-1} for CW and their means were significantly different (Table 1). Effluent DOP for intermittently flooded treatments were similar, ranging between 1 and 12 for IWO and between 1 and 44 μg DOP L^{-1} for IW, and their means were also significantly different (Table 1).

Periodically, all treatments exported DOP (Fig. 4). The intermittently flooded treatment with no emergent vegetation (IWO) maintained the highest DOP assimilation and only exported DOP 20% of the time. Poor DOP performance was also evident from all treatment means over the two-year study (Table 2).

Particulate phosphorus (PP). Inflow PP concentrations fluctuated widely ranging between 3 and 174 μg PP L^{-1} (Table 1). Outflow PP concentrations for continuously flooded treatments were much lower and less variable, ranging between 1 and 40 μg PP L^{-1} for CWO and between 2 and 60 μg PP L^{-1} for CW and their means were not significantly different (Table 1). Intermittently flooded treatments effluent PP ranged between 2 and 74 μg PP L^{-1} and between 1 and 50 μg PP L^{-1} for IWO and IW, and their means were significantly different (Table 1). Although effluent PP concentrations for intermittently flooded treatments were, in general, slightly higher than continuously flooded treatments, PP concentrations in CW were the lowest among all treatments. Effluent concentrations for the intermittently flooded treatment IWO were much higher than the IW for all drawdown periods (Fig. 5).

Water levels during flood periods were similar among all treatments. However, effluent PP concentrations in IWO exhibited a fivefold increase immediately after re-flooding and were higher than inflow concentration during both dry- and wet-season drawdowns (Fig. 5). Unlike previous trends for other P forms, the high PP flux for IWO lasted for four weeks and was of similar magnitude during both dry- and wet-season drawdown (Fig. 5). After the high PP flux period, surface water concentrations at the outlet of all treatments returned to pre-flooding conditions.

On average, 30% of influent TP was in PP forms. Although effluent TP means for intermittently flooded treatments (IWO and IW) were not significantly different (Table 1), the mean ratio of PP to TP was higher for IWO (44%) than IW (24%). Similarly, effluent means for TP for continuously flooded treatments (CWO and CW) were almost equal (Table 1), although the CWO mean ratio of PP to TP (46%) was modestly higher than the CW ratio (41%).

Average PP percent reduction for the continuously flooded treatment with emergent vegetation (CW) outperformed the continuously flooded treatment with no emergent vegetation (CWO), with reductions ranging between 174 and 97% and −150 and 82% for CW and CWO, respectively (Table 2). Similarly, the intermittently flooded treatment with emergent vegetation (IW) outperformed IWO, with reductions ranging between −57 and 77% and −303 and 95%, respectively.

3.2. Phosphorus analytical results using the ANOVA model

The analytical results of running the ANOVA model for effluent P concentrations and P-reduction efficiency of the various P forms are summarized in Tables 3 and 4. We found that DOP, TDP, TP, PP, and SRP effluent concentrations were significantly influenced by hydropattern or inflow concentration, and the interaction between the two factors (Table 3). Similarly, all P-reduction efficiencies, with the exception of PP%, were significantly impacted by inflow concentration or hydrology and their interaction, but not by vegetation (presence or absence of emergent macrophytes, Table 4). Vegetation, as a single factor, or in interaction with other factors, had no significant impact on P-reduction efficiency (Table 4).

4. Discussion

Our results indicated that hydropattern, not vegetation-type, was the dominant factor affecting P-dynamics followed by influent concentration after a drawdown event. Interaction effects between hydropattern and influent concentration always had a significant impact on effluent concentrations and P-reductions (Tables 3 and 4).

The large difference between TP weekly values entering and leaving the continuously flooded treatments indicated that the mesocosms were effective in removing TP from stormwater runoff (Fig. 2). All effluent TP concentrations for intermittently flooded treatments were much higher than inflow concentration and remained high on average for approximately seven and nine weeks during wet- and dry-season drawdowns, respectively (Fig. 2). This suggests internal loading of P from the soil to the water column (Malecki et al., 2004). In addition, intermittently flooded treatments net TP-releases were more evident and lasted longer during dry- compared to wet-season drawdown (e.g., there was no net TP-release during wet-season drawdown for intermittently flooded) and this seasonal effect was due to higher rainfall during wet periods which significantly reduced soil oxidation and concomitant P release (Bostic and White, 2007).

Hydropattern significantly impacted TP reduction (Fig. 2). Net TP release upon re-flooding from intermittently flooded treatments clearly demonstrated that hydropattern had a measurable impact on TP reduction in a constructed wetland (Fig. 2). Total P flux, upon re-flooding from (IWO and IW), and the time period, over which TP export took place, were treatment dependent (continuous vs. intermittently flooded treatments). More positive net TP-reduction was evident for continuously flooded (CWO and IWO) compared to intermittently flooded treatments with emergent vegetation (CW and IW).

The observed indifference in SRP effluent concentrations for all four treatments, excluding drawdown periods, suggests that hydropattern was controlling SRP treatment (Fig. 3). Dry season drawdowns SRP net export was evident and there were no net export of SRP during wet season drawdowns. Clearly, for SRP, maintaining a wet soil is important to prevent release regardless of vegetation type.

With the exception of dry-season drawdowns for intermittently flooded treatment with no emergent vegetation (IWO), there were no substantial decreases in observed DOP values after passing through the mesocosms for all treatments, underscoring the difficulty in removing DOP in treatment wetlands (Fig. 4). Effluent DOP concentrations for intermittently flooded treatments, during dry-season drawdown events, were substantially higher than continuously flooded treatments, and also inflow values demonstrating that plants and peat soil were a source of DOP.

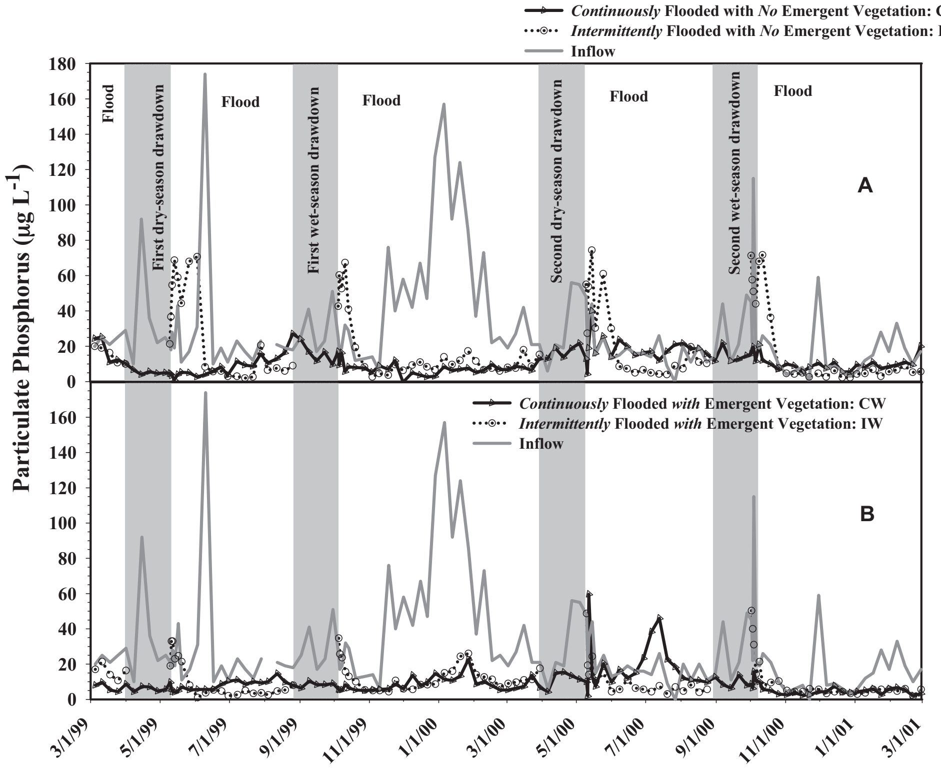

Fig. 4. Inflow and outflow dissolved organic phosphorus (DOP) concentrations for all four treatments from March 1999 through March 2001. Panel A = effluent time series for treatment with no emergent vegetation (CWO and IWO). Panel B = effluent time series for treatment with emergent vegetation (CW and IW). Inflow to all treatment (solid gray line), intermittently flooded treatment (dotted line with open circle), and continuously flooded treatment (solid black line with open triangle).

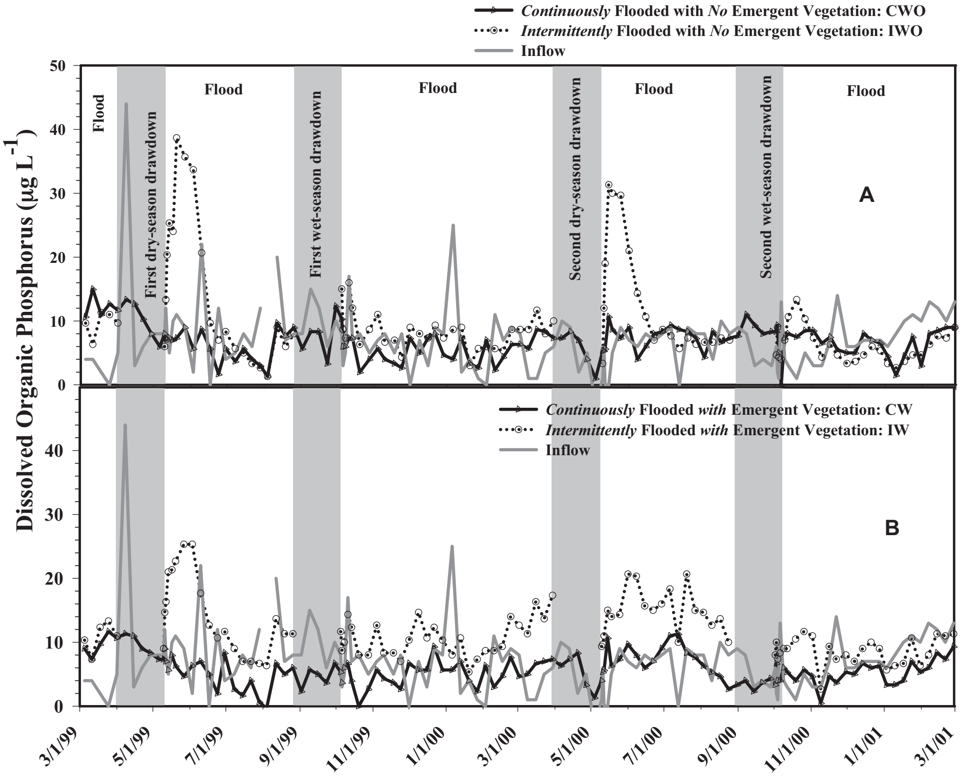

Fig. 5. Inflow and outflow particulate phosphorus (PP) concentrations for all four treatments from March 1999 through March 2001. Panel A = effluent time series for treatment with no emergent vegetation (CWO and IWO). Panel B = effluent time series for treatment with emergent vegetation (CW and IW). Inflow to all treatment (solid gray line), intermittently flooded treatment (dotted line with open circle), and continuously flooded treatment (solid black line with open triangle).

Table 3
Repeated measures ANOVA comparing the effects of vegetation (presence or absence of emergent macrophytes) and hydropattern (continuous or intermittent water flow) on effluent P-concentration for 12 tanks surveyed weekly (*P* values are shown).

Sources of variation	TP *P* value	*df*	SRP *P* value	*df*	DOP *P* value	*df*	TDP *P* value	*df*	PP *P* value	*df*
Vegetation	0.97	1	0.24	1	0.74	1	0.32	1	0.04[a]	1
Hydrology	<0.01[a]	1	<0.01[a]	1	<0.01[a]	1	<0.01[a]	1	0.02[a]	1
Inflow concentrations	<0.01[a]	76	<0.01[a]	77	<0.01[a]	76	<0.01[a]	76	0.06	77
Vegetation × hydrology	0.95	1	0.43	1	0.35	1	0.41	1	0.05[a]	1
Inflow concentrations × vegetation	0.36	76	0.26	77	0.14	76	0.32	76	0.17	77
Inflow concentrations × hydrology	0.01[a]	76	<0.01[a]	77	<0.01[a]	76	<0.01[a]	76	0.04	77
Inflow concentrations × Vegetation × hydrology	0.63	76	0.31	77	0.19	76	0.39	76	0.25	77

[a] Significantly different.

The amount of PP removed by intermittently flooded treatment with emergent vegetation (IW 40% ±5.59) was five times more than intermittently flooded treatment with no emergent vegetation (IWO; 8% ±9.93), which may indicate that presence of emergent vegetation has a deterministic impact on PP reduction in a constructed wetland (Fig. 5). However, improved treatment for PP% by emergent vs. submerged vegetation may be due to the recalcitrance nature of the emergent compared to submerged aquatic vegetation. For example, treatment with no emergent vegetation (CWO) mean ratio of PP to TP (46%) was higher than treatment with emergent vegetation (CW) mean (41%). The highest PP to TP ratios are evident for CWO and IWO suggesting that no emergent vegetation treatments (CWO and IWO) significantly generated more PP compared to treatments with emergent vegetation.

Effluent TP concentration data could be grouped into three major phases: (1) wet-season drawdown, (2) dry-season drawdown, and (3) flooded periods to determine the influence of hydropattern, inflow concentration, and vegetation on effluent concentrations. ANOVA results indicated that inflow concentration was the dominant factor (Table 5). Hydropattern, as a single factor, had an impact during wet- and dry-season drawdown periods. However, vegetation had no significant impacts during any of the three phases. The interaction between inflow concentration and vegetation had a significant impact only during the flooded periods, while interaction between inflow concentration and hydrology was evident during both wet-season drawdown and flooded periods (Table 5).

Several batch experiments involving wetland soils have documented increased rate of P release under aerobic conditions (McLatchey and Reddy, 1998; Bostic and White, 2007). Our results showed a greater flux of P into the overlying water column immediately after the first drawdown and a continued flux for several weeks after reflooding. Pant and Reddy (2001) also detected higher measured P flux with decreasing moisture content of organic soils.

Differences between inflow and outflow were greatest for SRP and TDP, moderate for PP, and minimal for DOP. Therefore, we attribute the observed decrease in effluent TP concentration to be due to uptake in SRP and TDP with little treatment of PP and DOP.

Our results suggested that PP reduction is related to vegetation type. For example, cattails (*T. domingensis*) are characterized with high turnover rate compared to sawgrass (*Cladium Jamaicense*), and turnover rates, in general, are much higher in a subtropical climate because growth continues over a longer growing season (Kadlec and Knight, 1996). Similarly, periphyton and algae are characterized by very high turnover rates; the most rapid uptake is by microbiota (bacteria, fungi, algae, micro-intervtebrates, etc.) because these organisms grow and multiply at high rates (Kadlec and Knight, 1996). Therefore, PP would accumulate at a much higher rate in a wetland dominated by either cattail or periphyton compared to sawgrass. In this case, the turnover rate may exceed, or equal, the amount of detritus material being generated and deposited from existing vegetation.

Decomposition of submerged aquatic vegetation (SAV), particularly during drawdown periods may be responsible for the high flux of PP and SRP. However, this observation was not strongly demonstrated for effluent DOP. Intermittently flooded treatment with emergent vegetation (IW) had the lowest effluent PP concentrations among all treatments. This observation indicated that IW not only exported less PP than any other treatment but also effluent PP was consistently less than influent values. The presence of emergent vegetation in wetland environment tends to slow water flow, thus reducing its ability to transport sediment, which would lead to lower effluent PP values as observed in our experiment results (Fig. 5). Even with continuously flooded conditions, the decrease in DOP concentrations in our experiment was non-existent (0%), and therefore additional research is required to investigate mechanisms and management strategies to transform this DOP fraction to SRP, which is more efficiently attenuated in these wetland systems (White et al., 2006).

It is more likely that a large wetland would undergo drawdown during a dry-season as opposed to the wet season. Therefore, it is critical to properly manage these wetlands/STAs during dry-season to minimize P-releases to surface water and meet legal requirements. Impacts during wet-season drawdown were minimal and totally disappeared during the second wet season drawdown (Fig. 5), suggesting that saturated soil is sufficient to retain stored

Table 4
Repeated measures ANOVA comparing the effects of vegetation (presence or absence of emergent macrophytes) and hydropattern (continuous or intermittent water flow) on P constituents' percent removal for 12 tanks surveyed weekly (*P* values are shown).

Sources of variation	TP *P* value	*df*	SRP *P* value	*df*	DOP *P* value		TDP *P* value	*df*	PP *P* value	*df*
Vegetation	0.84	1	0.38	1	0.61	1	0.43	1	0.07	1
Hydrology	<0.01[a]	1	<0.01[a]	1	<0.01[a]	1	<0.01[a]	1	0.10	1
Vegetation × hydrology	0.99	1	0.50	1	0.18	1	0.46	1	0.54	1
Inflow concentration	<0.01[a]	75	0.03[a]	75	<0.01[a]	68	<0.01[a]	76	0.03[a]	73
Inflow concentration × vegetation	0.41	75	0.26	75	0.52	68	0.30	76	0.18	73
Inflow concentration × hydrology	0.03[a]	75	0.04[a]	75	0.01[a]	68	0.02	76	0.03[a]	73
Inflow concentration × Vegetation × hydrology	0.39	75	0.28	75	0.33	68	0.34	76	0.27	73

[a] Significantly different.

Table 5
Repeated measures ANOVA comparing the effects of vegetation (presence or absence of emergent macrophyte) and hydropattern (continuously or intermittently flooded) on effluent TP concentration for 12 tanks surveyed weekly (*P* values are shown). Data are analyzed separately for wet (12 weeks), dry (18 weeks), and flooded (47 weeks) periods (degrees of freedom are listed in parentheses).

	Wet		Dry		Flooded	
Sources of variation	*P* value	*df*	*P* value	*df*	*P* value	*df*
Inflow concentration	<0.01[a]	11	<0.05	17	<0.01[a]	46
Hydrology	<0.01[a]	1	0.01[a]	1	0.30	1
Vegetation	0.13	1	0.72	1	0.06	1
Vegetation × hydrology	0.52	1	0.69	1	0.13	1
Inflow concentration × vegetation	0.22	11	0.34	17	0.01[a]	46
Inflow concentration × hydrology	<0.01[a]	11	0.09	17	0.05	46
Inflow concentration × vegetation \ hydrology	0.11	11	0.29	17	0.53	46

[a] Significantly different.

P. Therefore, we recommend the maintenance of wet soils during dry-season months to prevent the associated release of SRP to the water column in a treatment wetland. Another management alternative, which can be implemented during dry-season dry out, is controlling hydraulic loading rate in and out of the wetland, and hence water residence time. Controlling hydraulic loading rates in these STAs can be easily accomplished because all STAs inflows and outflows discharge pumps are remotely controlled. This would allow holding of flood-water inside the STAs for approximately 4-5 weeks or until TP concentrations in surface water near the outflow site, are low enough to allow for discharge to the receiving water. Alternatively, a dry wetland may be flooded over a long period of time (i.e., low hydraulic loading rate), which would allow P concentrations to equilibrate before outflow commences. And finally, maintaining wet soils inside the wetland, not necessarily an inundated or flooded one, would minimize P-releases to surface water particularly during dry season.

Constructed wetlands in subtropical areas are likely to be colonized by both emergent and non-emergent macrophytes. This mixture of emergent and non-emergent plant-type colonization create optimum environment for nutrient reduction, in general, and provide a good acceptable explanation as to the popular increase in using constructed wetlands in last two decades for water quality improvement. The mixture of both emergent and non-emergent plant-type in a constructed wetland result in water quality improvement for different P forms, and our experiment results support this conclusion. For example, while emergent macrophyte treatments (CW and IW) performed best to retain TP and PP, the non-emergent vegetation-type treatment (CWO and IWO) provided best performance for SRP; all four treatments removed equal amounts of TDP. By combining both plant-types in a constructed wetland, we are increasing the likelihood for better P-reduction in contrast to single-mono-type vegetation as long as the soil is kept moist and not allowed to dry out.

5. Conclusions

The objective of this study was to determine if water treatment by large constructed freshwater wetlands, receiving TP concentrations on the order of 0.1 g (100 μg) week^{-1}, could be improved by managing hydropattern and vegetation communities, and meet legal mandates for effluent TP concentrations. The most significant finding of this study was the high nutrient flux, compared to inflow values, to surface water promptly after re-flooding for a period of time, particularly during dry season as well as the poor reduction of DOP by all treatments. Under the optimum conditions of a well-maintained water column, the reductions of DOP averaged zero. However, the effect of soil drawdown lead to a net export of DOP from the mesocosms, suggesting that periodic drawdown, particularly during dry seasons, is not a good option to manage a constructed wetland for low P effluent concentrations and would lead to failure in improving effluent water quality (Bostic et al., 2010). This conclusion is applicable to both continuously and intermittently flooded treatments irrespective of vegetation type.

Care must be taken to prevent large constructed wetlands/STAs with peat soils from becoming dry. If this situation cannot be prevented, water must be held within the re-flooded wetland, for at least four to six weeks (wet vs. dry season dryout), until P concentrations in surface water decrease to meet concentration goals. Another option would be to reflood the wetland over a longer period of time. Moist soil, not necessary flooded or inundated, is a good management alternative, particularly during dry season, to minimize soil-P oxidation and P flux to surface water after re-flooding.

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