J. Aquat. Plant Manage. 53: 44–53

Effect of water lettuce and filamentous algae on phosphorus loads in farm canals in the Everglades Agricultural Area

JEHANGIR H. BHADHA, TIMOTHY A. LANG, SUSANNA M. GOMEZ, SAMIRA H. DAROUB, AND MIHAI C. GIURCANU*

ABSTRACT

Farm canals in the Everglades Agricultural Area (EAA) often contain an abundance of floating aquatic vegetation which assimilates P through thalli, shoots, and leaves and prevents the co-precipitation of P with calcium carbonate within the calcium-saturated canal water column. To test the effects of two prevalent aquatic weed species, water lettuce (*Pistia stratiotes* L.) and filamentous algae (*Lyngbya* Agardh. Ex Gomont. spp.) on water quality, a lysimeter experiment was conducted over a 28 d period to quantify P-uptake and detrital accumulation. The experiment consisted of four treatments, and four water exchanges. The water column P concentration in all treatments was reduced significantly after each water exchange. Treatments without sediments showed highest efficiency for P removal from the water column. Up to 93% reduction in soluble reactive P was observed in treatments containing water lettuce and filamentous algae in the presence of limerock. The removal of P by plant uptake will only serve as a short-term sink because of accumulating P in the plant detritus and its high turn-over rate. Results from the experiment were up-scaled to field conditions, where eight farms were monitored and sampled over a 2-yr period. Percent plant coverage varied with season, and had a direct effect on the P uptake and accumulation of organic biomass and P accumulated in canal sediment. Within the EAA, an estimated 5.5 to 26 mt P is sequestered by water lettuce, and 1.8 to 8.4 mt P is being sequestered by filamentous algae annually. In comparison, 7 to 26 mt of detrital P is being accumulated in organic sediments. The reduction of P in the water column through uptake by water lettuce and filamentous algae is offset by the deposition of detrital plant material that will release P back to the water column. A better approach is likely through the suppressing of growth of floating aquatic vegetation that could potentially increase the co-precipitation P by Ca to form less labile dense sediments. Further reduction in P loads may be achieved by implementing economic and effective management practices to control floating aquatic vegetation.

Key words: agricultural drainage, filamentous algae, floating aquatic vegetation, loads, submerged aquatic vegetation, water lettuce.

*First, second, third, and fourth authors, Assistant Research Scientist, Research Associate, Graduate Student, and Professor, Everglades Research and Education Center (University of Florida), Belle Glade, FL 33430. Fifth author, Research Coordinator, Statistics Department, University of Florida, Gainesville, FL 32611. Corresponding author: jango@ufl.edu. Received for publication August 29, 2012 and in revised form December 19, 2013.

INTRODUCTION

The Florida Everglades is the largest subtropical wetland in the United States covering nearly two million acres. Over the past five decades the ecological integrity of the Everglades has been affected by hydrologic and nutrient imbalances caused by urban and agricultural development. Reducing the phosphorus (P) load from the Everglades Agricultural Area (EAA) basin is one of the prerequisites for restoring the Everglades ecosystem. The canal system of the EAA, which supplies farms with irrigation water from Lake Okeechobee and conveys runoff southward to the Water Conservation Areas, contains an abundance of both filamentous algae (*Lyngbya* Agardh. Ex Gomont. spp.) and water lettuce (*Pistia stratiotes* L.), and other floating and submerged aquatic vegetation (Daroub et al. 2011). The role of aquatic vegetation in the removal of P from agricultural runoff has been investigated in the past (Gu et al. 2001, Dierberg et al. 2002, Knight et al. 2003). In addition to uptake by aquatic vegetation, P removal in the EAA canal waters may result via P co-precipitation with calcium carbonate; Dierberg et al. (2002) observed similar P removal mechanism in the Stormwater Treatment Areas (STAs) of south Florida. The presence of limerock beneath EAA canals provides Ca-saturated water that can precipitate P from the water column during photosynthesis-induced increases in pH (Murphy et al. 1983). This chemical removal of phosphate from water precipitates out as calcium phosphate as observed in the STAs of South Florida.

Two of the most troublesome types of aquatic vegetation in tropical waters are water lettuce and filamentous algae. Both are a nuisance because of their ability to multiply and spread rapidly in open waters (Mehra et al. 1999), but they also have been utilized as sinks for nutrients such as P (Carignan 1982, Gu et al. 2001). Non-rooted submerged aquatic vegetation such as coontail (*Ceratophyllum demersum* L.) and filamentous algae appear to rely exclusively on dissolved nutrients from the water column (Barko and James 1997). The roots of floating aquatic vegetation species, such as water lettuce and water hyacinth [*Eichhornia crassipes* (Mart.) Solms], play an important role in nutrient uptake from the water column. Floating aquatic vegetation has also been shown to reduce suspended solids and turbidity, and improve overall water quality (Lu et al. 2010). Compared to native plants, these invasive species show a higher nutrient removal efficiency because of their high nutrient uptake capacity, fast growth rate, and high biomass production (Reddy and Sutton 1984). Water lettuce has successfully been demonstrated to remove P, although it may not be as effective as a long-term sink because of the high turnover rate which can generate organic labile floc, which accumulates at the sediment-water interface, and is susceptible to transport (Stuck et al. 2001).

Lu et al. (2010) reported a 22 to 31% reduction in total phosphorus (TP) concentration within two detention ponds in the St. Lucie estuary watershed using water lettuce phytoremediation. They found that TP showed a higher reduction than inorganic soluble reactive P (SRP) suggesting that the role aquatic plants play in remediation systems is far more complex than simple plant-uptake. There is extensive information on the use of emergent macrophytes for point and nonpoint nutrient control (Kadlec and Wallace 2008). Mitsch (1992) reported that wetlands typically remove P at rates ranging from 0.4 to 4.0 g m^{-2} yr^{-1} with more eutrophic systems achieving higher removal rates, while Richardson and Craft (1993) found maximum and average P removal rates of 0.6 and 0.4 g m^{-2} yr^{-1}, respectively in the oligotrophic Everglades. Aoi and Hayashi (1992) showed that nutrient removal by water lettuce can vary because of initial nutrient SRP concentration and weather (wet and dry season), but found over 50% reduction in SRP concentrations and over 100% increase in plant biomass. Water lettuce can be considered as a good candidate to reduce P from the water column but requires frequent harvesting to avoid build-up of detritus material. In the EAA, limiting the growth of water lettuce in farm canals has the known benefit of improvement in the conveyance of drainage and irrigation water throughout the farm. Suppressing the growth of water lettuce can impact the plant community in the canal and likely result in increased predominance of algae, phytoplankton, and possibly submerged aquatic vegetation. The change in the canal aquatic plant community should increase the levels of dissolved oxygen in the canal water column, resulting in altered P species of the composition of the EAA farm drainage water. It has been hypothesized that a reduction in the presence of extensive mats of water lettuce will increase sunlight penetration into canal waters favoring P co-precipitation with Ca and Mg carbonates forming cohesive sediments that are less likely to be resuspended and transported off the farm during drainage events (Daroub et al. 2011).

The purpose of this study was to evaluate the role of water lettuce and filamentous algae on P loads in canals in the EAA. These species were chosen because they are the most prevalent species. A lysimeter experiment was conducted to evaluate the effect these two plant species had on the quality of farm canal water. Results from the experiment were compared with field observations from eight farm canals within the EAA. Combining the two approaches helped create a realistic understanding of the role of aquatic vegetation in P cycling within the EAA canals. The main objectives of the lysimeter experiment were to: (i) evaluate the effect water lettuce and filamentous algae on the P concentrations in the water column after multiple water exchanges, (ii) monitor the change in water quality and sediment composition over time, and (iii) estimate P-uptake rates and detrital accumulation for water lettuce and filamentous algae. The objective of the field study was to determine the coverage of water lettuce and filamentous algae within farm canals so that results from the experimental study can be extrapolated to estimate the basin-wide effect of these two prevalent species on P loads.

MATERIALS AND METHODS

Lysimeter experiment

Sixteen lysimeter buckets were set up containing 4 different treatments and 4 replicates each. The four treatments consisted of:

1) limerock + sediment + water lettuce
2) limerock + sediment + filamentous algae
3) limerock + water lettuce
4) limerock + filamentous algae

The buckets were 140 L in volume, 0.6 m tall with top open surface area of 0.24 m^2. Empty containers were first filled with limerock (CaCO) (10 cm), followed by sediments (10 cm) for treatments 1 and 2. The limerock and sediments were collected from local farm canals and added to the buckets. Fine nylon meshes were placed on top of the limerock or sediment to collect any detrital material settled at the end of the experiment. Solid tubing was introduced 5 cm from the top of the bucket to about 20 cm from the bottom of the bucket. This set-up allowed water from the bottom of the buckets to be drained out during each exchange. The buckets were filled with farm canal water using a slow drip technique. Approximately 1 kg of water lettuce or 0.3 kg of filamentous algae was introduced in respective containers. The entire system was let to equilibrate for 7 d prior to starting the first exchange. Four water exchanges using farm canal water were conducted during the 28 d experiment; one exchange was conducted at the end of a 7-d equilibrium period. The P concentration of farm canal water used for the exchanges ranged from 0.11 to 0.18 mg L^{-1}, and water samples were collected from each bucket at time 0, 0.25, 1, 3, and 7 d (over the 28-d experimental duration). The purpose of conducting four exchanges was to provide the plants with sufficient time and nutrients to grow and senesce and form organic floc at the sediment-water interface. The exchanges also provided a scenario similar to drainage events that occur regularly in the field.

The sampled water was analyzed for TP, total dissolved P (TDP), SRP, dissolved organic P (DOP), Ca, and total organic carbon (TOC). The purpose of analyzing the different P fractions is because typically plant P-uptake from soil or water is a function of the dissolved or the reactive fraction, and not necessarily associated with the total P. Water samples were filtered (0.45 μm) and the filtrates were analyzed for TDP and SRP. For TP and TDP analysis water samples were digested with concentrated sulfuric acid, ammonium persulfate using method 365.1 (USEPA 2003). Particulate P (PP) was calculated as the difference between TP and TDP. Dissolved organic P (DOP) was estimated as the difference between TDP and SRP. All samples were analyzed for ortho-P using ascorbic acid method (Murphy and Riley 1962) on an automated air segmented continuous flow analyzer, Auto Analyzer 3 (AA3, Seal). The Ca concentrations were analyzed using method 200.7 (USEPA 2003) on an Inductively Coupled Plasma Mass Spectroscope (ICP-MS). At the end of four exchanges the buckets were drained and any detrital matter collected off the nylon mesh.

Subsamples of limerock, sediment, and plant species were collected pre- and post-experiment and analyzed for physical-chemical properties. The limerock and sediment samples were air-dried and analyzed for P concentration using Mehlich-3 extraction. The plant species and detrital matter were air-dried, ground, and analyzed for P using method 200.7 (USEPA 2003) on an ICP-MS.

Field study

In conjunction with the lysimeter experiment eight farm canals were also surveyed and monitored for aquatic vegetation cover for 2 yr between January 2011 to December 2012. Within the approximately 2,200 km^2 of the EAA, nearly 25 km^2 is covered by farm canals (estimated using Google Earth map coverage tool). An assessment of aquatic vegetation was conducted every 2 mo, with the intention of identifying the species composition, spatial coverage, plant biomass, and TP content within eight farm canals in the EAA. The farms are not treated as replicates because they differ in size, crops grown, and land-management practices, representing two out of the four sub-basins within the EAA. Two representative samples were collected from each farm. Sampling locations were selected at each farm based on spatial coverage of vegetation.

A 1 m^2 floating PVC retainer was placed on the aquatic vegetation biomass to be sampled. All biomass within the square was collected and placed in mesh bags to drain. Filamentous algae was sometimes collected using a long-handle scoop since it does not always float up to the surface, so as to get an accurate mass representation of the algae contained within 1 m^2. Total fresh weight was recorded after draining. The entire sample mass was air dried to constant weight with forced air at 50 C. The weight of the dry sample mass was recorded, and the mass was ground to less than 1 mm in a cyclone mill. The ground material was blended and stored in an airtight container until analysis. Samples were analyzed for water content and TP. Percent moisture content was calculated based on difference between wet mass of vegetation versus oven dry mass, while the dry grounded biomass was analyzed for TP using method 200.7 (USEPA 2003) on an ICP-MS. The mass of TP for individual farm canal biomass was calculated as the product of the dry vegetation biomass TP concentration (mg kg^{-1}) times the mass of vegetation (kg) present in the canals based on the percent coverage. Percent plant coverage for the entire canal was visually estimated by driving along the canal banks and estimating the coverage based on observation. To ensure consistency, the canal length was sectioned into 3 to 4 sections and the percent plant coverage was averaged over the entire length of the canal.

Statistical analyses

Summary statistics, such as sample means and sample standard deviations were calculated for water quality, sediment, and aquatic vegetation variables using SAS statistical program (SAS Institute, 2011). Goodness of fit tests, such as Kolmogorov-Smirnov and Cramer-von Mises tests were carried out to test the normality assumption of the response variables. If the data were not normally distributed, log transformation was used to stabilize the variance and to make the residuals more normally distributed for statistical analysis of linear models. Analysis of variance (ANOVA) methodology was used to compare sediment physicochemical properties pre/post experiment and P species between different treatments and exchanges. Tukey's multiple comparison procedure was carried out to assess significant differences between the means of the treatments, exchanges, and time within the experimental setup. Spearman correlations were calculated for the various P species and associated variables. Nonlinear (exponential) regression analysis was performed to estimate plant P uptake coefficients over time.

RESULTS AND DISCUSSION

Lysimeter experiment: trends in water quality and overall P reduction

At the end of all four exchanges there were significant ($P < 0.05$) decreases in TP, TDP, SRP, and PP concentrations in all four treatments (Figure 1a). A high of 93% SRP reduction was observed in treatments 3 (LR + WL) and 4 (LR + FA) during exchange 1, while the least reduction in SRP of 34% was observed in treatment 2 during exchange 3 (Table 1). Highest PP reduction of 93% was observed in treatments 3 and 4 during exchange 1, while the least reduction in PP was observed in treatment 2 (LR + SED + FA) during exchange 2. Calcium did not show any significant correlation with TP, TDP, and SRP, but was negatively correlated to DOP ($r = -0.18$) and positively correlated with TOC ($r = 0.46$) (Table 2). The presence of Ca in the water is a result of dissolution of underlying limerock within the canals. Generally, treatments 3 and 4 which contained LR + WL and LR + FA did a better job of reducing P concentrations compared to treatments that contained sediments (treatments 1 and 2). Overall, the presence of sediments had a significant effect on TP, TDP, SRP, and TOC concentrations in the water column (Table 3). This corroborates previous studies that showed increased P reduction when water was exposed to limerock and filamentous algae (Knight et al. 2003, Gu et al. 2001). Howard-Williams and Allansson (1981) also showed that algae absorbed twice as much of added P as macrophytes on a per unit area basis, though the macrophyte biomass per unit area was 30 times greater than algal biomass. The application of water lettuce for phytoremediation within the EAA may not be considered desirable because it is difficult to manage in the farm canals. If not

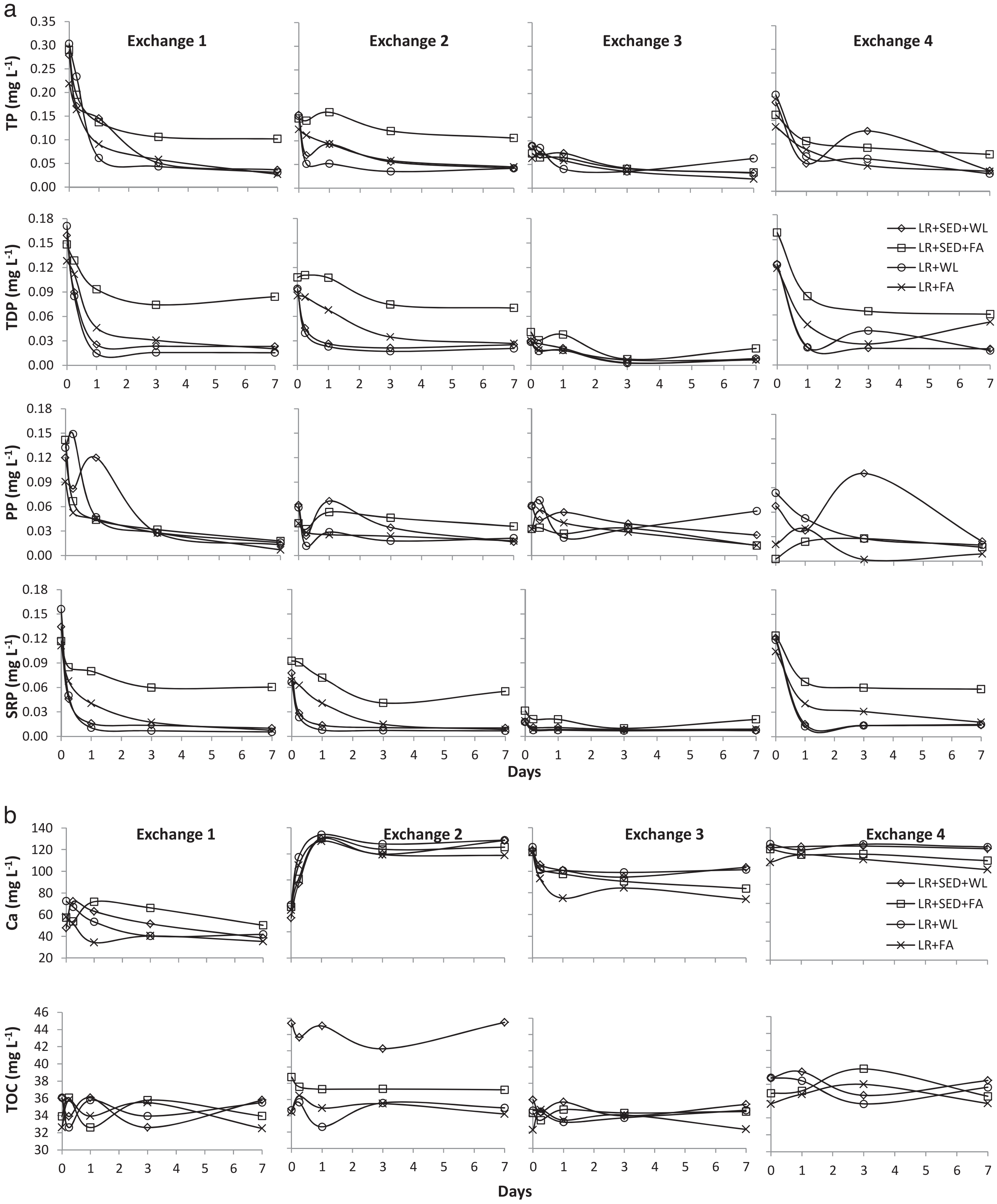

Figure 1. (a) Overall trends in TP, TDP, PP, and SRP concentration for all four treatments and four exchanges. LR (limerock); SED (sediment); WL (water lettuce); FA (filamentous algae). (b) Overall trends in Ca and TOC concentration for all four treatments and four exchanges. LR (limerock), SED (sediment), WL (water lettuce), FA (filamentous algae).

Table 1. Percent P reduction in P species in water column (TP, TDP, SRP, PP) observed in all four treatments during the four exchanges. LR (limerock), SED (sediment), WL (water lettuce), FA (filamentous algae).

	TP	TDP	SRP	PP
% P reduction – LR + SED + WL				
exchange 1	86.9	85.4	92.6	89.0
exchange 2	72.9	72.6	86.7	72.0
exchange 3	64.4	76.1	59.9	58.7
exchange 4	76.9	84.0	88.4	64.2
% P reduction – LR + SED + FA				
exchange 1	64.8	43.2	47.3	87.5
exchange 2	28.0	34.8	40.3	9.5
exchange 3	55.0	49.1	34.0	62.1
exchange 4	51.7	61.7	53.0	37.3
% P reduction – LR + WL				
exchange 1	89.9	84.2	93.3	92.7
exchange 2	72.5	77.9	89.8	64.0
exchange 3	30.0	71.3	57.4	10.3
exchange 4	81.8	85.6	87.4	76.4
% P reduction – LR + FA				
exchange 1	87.5	84.2	93.3	92.7
exchange 2	64.1	68.6	87.7	54.1
exchange 3	69.3	77.9	53.1	61.3
exchange 4	69.0	55.5	83.0	56.3

properly controlled, water lettuce can clog up canals and culverts during drainage pumping. Water lettuce also generates greater biomass than filamentous algae, which ultimately settles at the canal bottom as a form of labile, organic, particulate P. Positive correlation between TP and the various other P fractions would suggest that while the source of P in the water column was primarily from the incoming exchange water, small amounts of it may have been internally cycled from the sediments; this was particularly true in the treatment containing LR + SED + FA where the mean extractable P concentrations were 11% lower in the sediments post-experiment (Figure 3a). The TOC concentrations in exchanges 1 and 4 were similar in lysimeters with water lettuce. The TOC in treatments 1 and 2 were significantly different from treatments 3 and 4, suggesting that the presence of sediment had an effect on the TOC concentrations, and was probably affected by the type of vegetation present (i.e., water lettuce or filamentous algae).

Vegetation type had a significant ($P < 0.05$) effect on all measured constituents in the water column (Table 3). The presence of sediment and vegetation combined had a significant effect on TDP and SRP concentrations. All

Table 2. Spearman correlation coefficients for the variables analyzed in the water column: TP, TDP, SRP, PP, and Ca.

Variable	TP	TDP	SRP	PP	DOP	Ca
TDP	0.84^{***}					
SRP	0.83^{***}	0.93^{***}				
PP	0.74^{***}	0.34^{***}	0.36^{***}			
DOP	0.50^{***}	0.64^{***}	0.40^{***}	0.17^{**}		
Ca	-0.06^{ns}	-0.10^{ns}	-0.04^{ns}	-0.04^{ns}	-0.18^{**}	
TOC	0.37^{***}	0.34^{***}	0.39^{***}	0.18^{**}	0.06^{ns}	0.46^{***}

$^{***}P < 0.0001$
$^{**}P < 0.01$
ns = nonsignificant

Table 3. Analysis of variance f-tests of significance of the main effects, two-way and three-way interactions for sediment, vegetation, and day on TP, TDP, SRP, PP, DOP, Ca, and TOC for the lysimeter water column data.

Source[1]	Df[2]	TP	TDP	SRP	PP	DOP	Ca	TOC
Sed	1	**	***	***	ns	ns	ns	*
Veg	1	**	***	***	**	**	*	***
Sed × Veg	1	ns	***	**	ns	ns	ns	ns
Day	4	***	***	***	***	***	ns	***
Sed × Day	4	ns	ns	ns	ns	ns	ns	ns
Veg × Day	4	***	**	*	ns	ns	ns	ns
Sed × Veg × Day	4	ns	ns	ns	ns	ns	ns	ns

[1]Sed = sediment level, Veg = water lettuce or filamentous algae, Day = day after exchange.
[2]degrees of freedom for numerator.
$^{*}P < 0.05$
$^{**}P < 0.01$
$^{***}P < 0.001$
ns = nonsignificant

parameters except Ca showed a significant $P < 0.001$) change in the water concentration over time. While there was no significant interaction between sediment and day, we observed significant interactions between vegetation and day for TP, TDP, and SRP. The three way interactions between sediment, vegetation, and day were insignificant for all responses (Table 3). Only vegetation (i.e., water lettuce and filamentous algae) had a significant effect on Ca (Table 3), possibly because of precipitation of P with calcium carbonate. The presence of PP organically derived from vegetation can decompose over time (mineralization) forming phosphate ions (PO_4^{3-}) in solution forming DOP or SRP, and both DOP and SRP can ultimately precipitate with limerock ($CaCO_3$) (Stuck et al. 2001).

When data of all four exchanges were combined, there were significant differences in TP concentrations between water lettuce and filamentous algae during 1 and 3 d. Similar significant differences in TDP and SRP concentrations were observed between water lettuce and filamentous algae during 0.25, 1, 3, and 7 d (Figure 2). This would indicate that the type of vegetation growing in the farm canals could have a significant effect on the P concentrations of the canal waters. In this case, water lettuce takes up greater P from the canal water than filamentous algae.

Changes in sediment and vegetation characteristics

The sediments showed variable changes in extractable P (Mehlich-3) at the end of the four exchanges (Figure 3a). There was no significant change in Mehlich-P concentrations of the sediments containing water lettuce or filamentous algae. The pre-study sediment mean Mehlich-P concentration from lysimeters containing water lettuce was 46 ± 10 mg kg^{-1}, while the post-study sediment mean Mehlich P concentration was 58 ± 51 mg kg^{-1} at the end of the four exchanges (28 d). The pre-study sediment mean Mehlich-P concentration of sediments in the buckets containing filamentous algae had an initial P concentration of 47 ± 4 mg kg^{-1}, compared to to 42 ± 18 mg kg^{-1} at the end of the four exchanges. There was no significant differences in the P concentration of the limerock between pre- and post-experimental conditions (range 0–8 mg P kg^{-1}). This suggests that the limerock did not lead to the co-

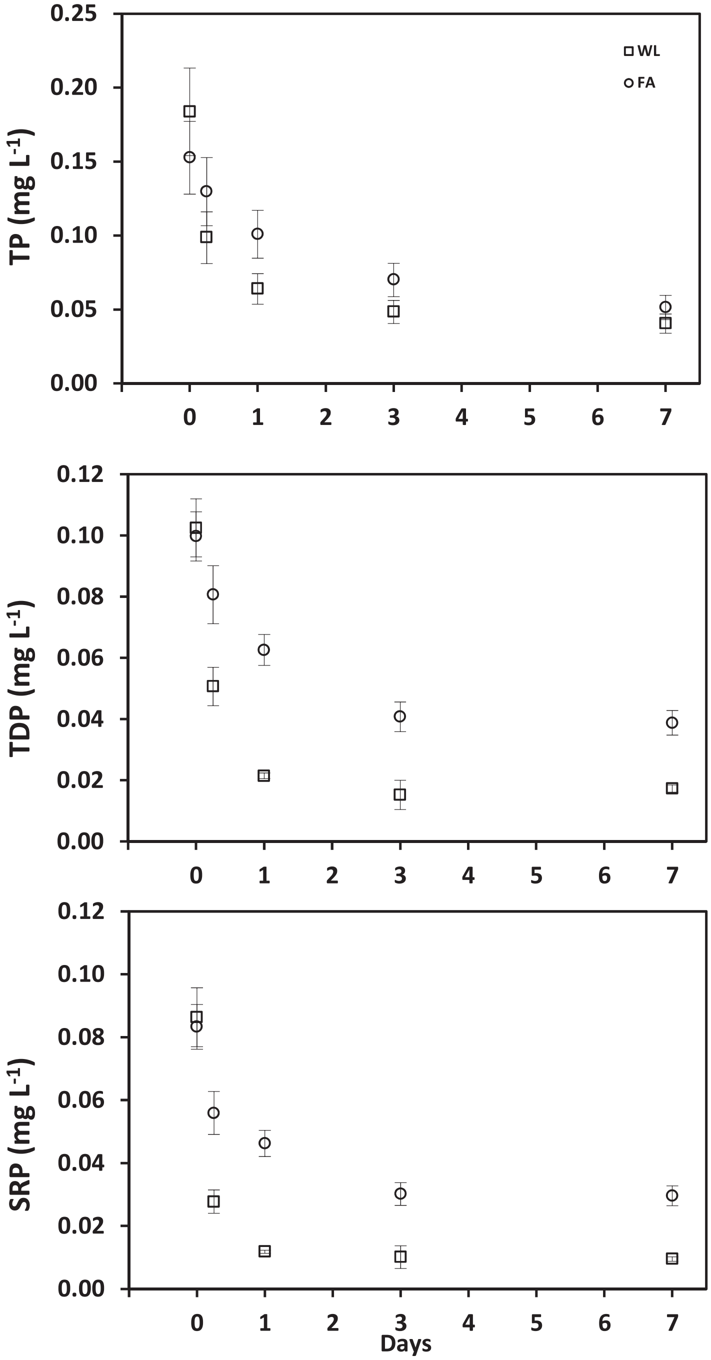

Figure 2. Means and standard deviations of TP, TDP, and SRP concentrations over time across the water lettuce (WL) and filamentous algae (FA) groups for the water column data.

precipitation of calcium phosphate over the 28 d experiment.

There was a significant decrease in P content of the plant biomass pre- and post-study (Figure 3b) and a significant increase in the mass of plant biomass of water lettuce and filamentous algae between pre- and post-experiment (Figure 3c). The lysimeters containing LR + SED + WL showed a significant decrease in TP concentration of the water lettuce biomass from 2,548 ± 62 mg kg^{-1} to 1,609 ± 161 mg kg^{-1} whereas treatments containing LR + SED + FA showed a decrease in the TP concentration of the filamentous algae biomass from 2,864 ± 122 mg kg^{-1} to 2,566 ± 359 mg kg^{-1}. Lysimeters void of sediment also showed a significant reduction in TP concentration of the plant biomass. Lysimeters containing LR + WL showed a significant decrease from 2,505 ± 131 mg kg^{-1} to 1,342 ± 151 mg kg^{-1} + whereas LR + FA treatments showed a significant decrease from 2,914 ± 109 mg kg^{-1} to 2,280 ± 109 mg kg^{-1} between pre- and post-study.

There was an 84% increase in the mass of water lettuce (LR + SED + WL), whereas a 27% increase was observed in the filamentous algae (LR + SED + FA). There was a 63% increase in the mass of water lettuce contained in lysimeters with no sediments (LR + WL) ,whereas a 40% increase in mass was observed in filamentous algae contained in lysimeters with no sediments (LR + FA). These results were similar to findings from Aoi and Hayashi (1992) and indicate that the P content gets "watered down" resulting in a decrease in overall plant biomass P concentrations. This pattern can cause a peak above-ground standing stock of P which is usually reached before above-ground biomass is achieved. Lindsey and Hirt (1999) showed that during an active growth season aquatic vegetation can double in number and size within 6 to 15 d.

At the end of the four exchanges, lysimeters containing LR + WL produced detrital matter which had settled on the mesh at the limerock-water interface. Approximately 0.066 ± 0.02 kg was produced containing 2026 ± 709 mg P kg^{-1}. Based on this observation, we estimated a detritus matter accumulation rate of 0.23 g d^{-1} (dry weight basis) caused by water lettuce senescing in the system.

Field study assessment

Except for one farm canal which had no growth of aquatic vegetation, we observed four types of aquatic vegetation growing in the canals: water lettuce (*Pistia stratiotes*), filamentous algae (*Lyngbya* spp.), duck weed [*Spirodela polyrhiza* (L.) Schleid.], and torpedo grass (*Panicum repens* L.), with water lettuce and filamentous algae being the predominant species consisting over 80% of the total vegetation cover. Overall the vegetation cover in the farm canals ranged from 10 to 48% (Figure 4), corresponding to 1,641 to 8,010 m^2 depending on the canal size. The mass of P (dry mass basis) contained by the vegetation within canals varied between 1.2 to 6.0 kg. This indicates that temporal variability has an effect on the overall vegetation coverage, and ultimately on the amount of P contained by the vegetation. We observed high correlation between percent vegetation cover and mass of P contained by the vegetation in the canals ($r = 0.84$). Past research has indicated that nearly 54 ± 20% of TP leaving the farm during a drainage event is particulate P (PP) derived from plant material (Diaz et al. 2006). Particulate P sources range from soil surface erosion, mobilization of bed-load sediment, to bank rooted aquatic macrophytes (Stuck et al. 2001). Stuck et al. (2001) asserted that PP and TP concentrations in the drainage water was greatly influenced by a "biological control mechanism" (BCM), which was from the detrital aquatic

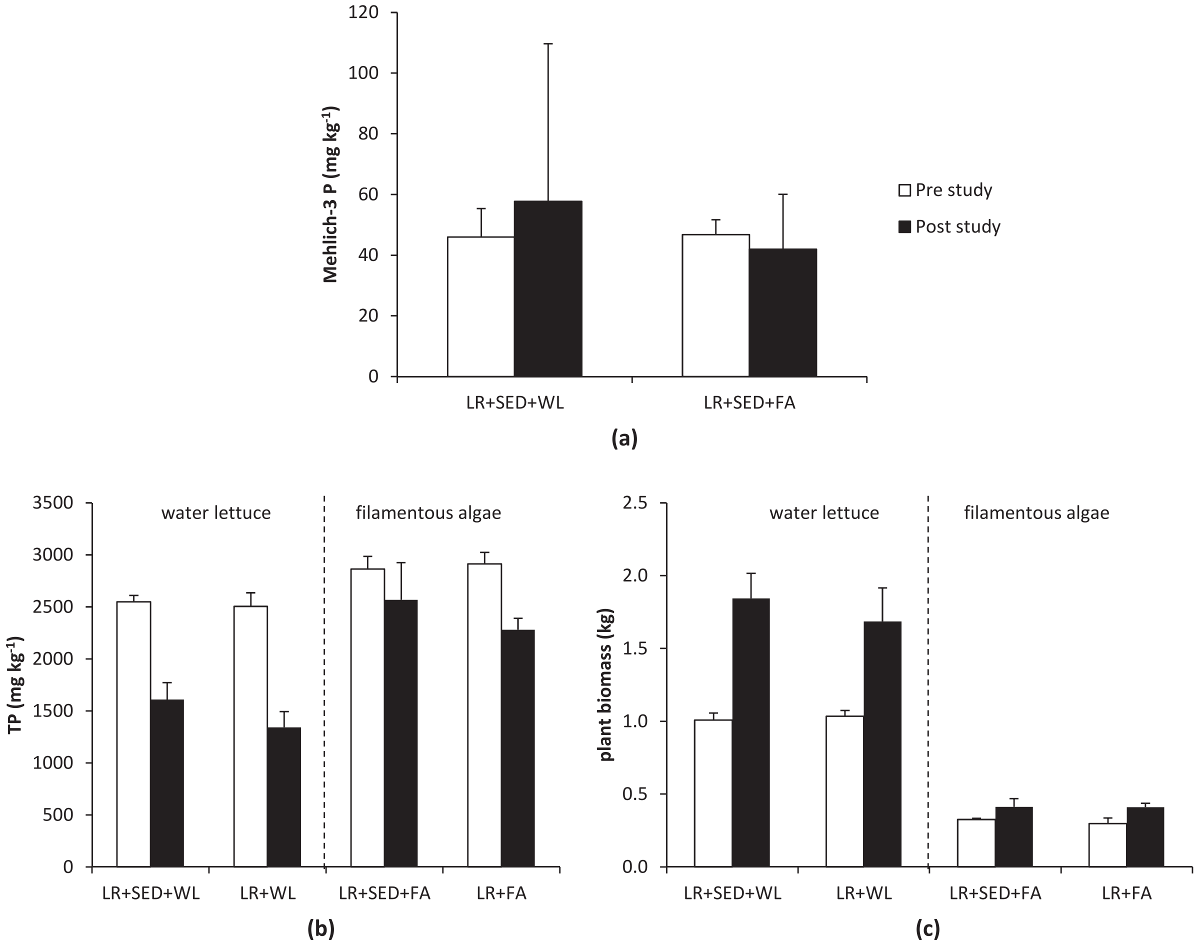

Figure 3. Means and standard deviations of pre- and post-study changes in (a) sediment extractable P, (b) aquatic vegetation P content, and (c) plant biomass. LR (limerock), SED (sediment), WL (water lettuce), FA (filamentous algae).

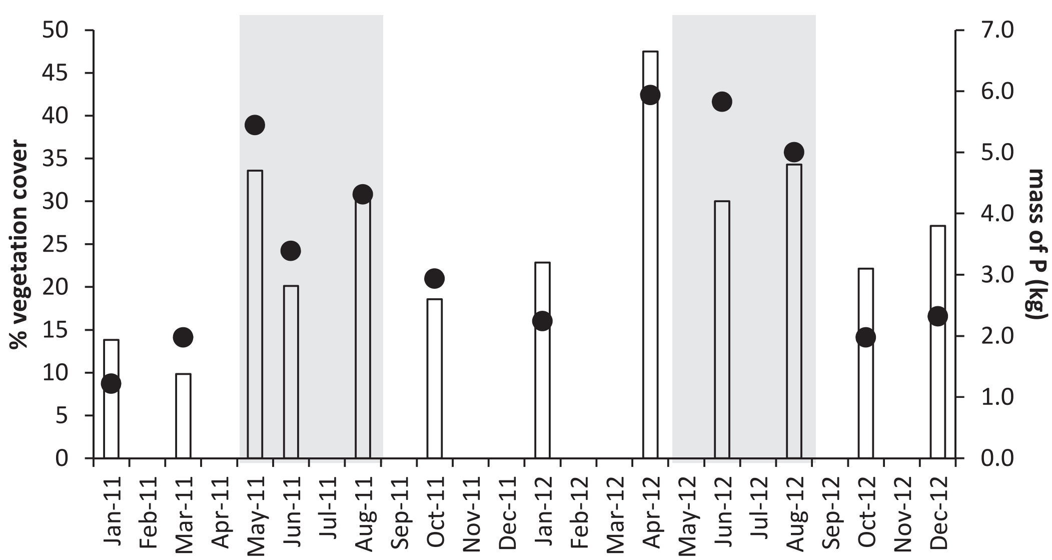

Figure 4. Percent coverage of vegetation and mass (kg) of P sequestered by the vegetation over a 2-yr period. The bars represent % vegetation coverage, black circles represent mass of P, and grey area represents summer season.

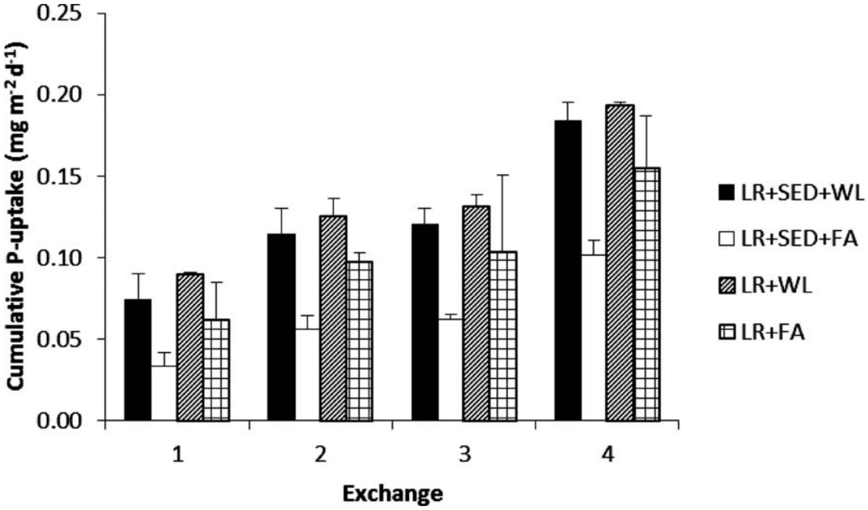

Figure 5. Means and standard deviations of cumulative plant SRP uptake (mg m^{-2} d^{-1}) over the four 7-d exchanges, and four treatments. LR (limerock), SED (sediment), WL (water lettuce), FA (filamentous algae).

vegetation which settled and accumulated at the canal bottom, and is dislodged during flow induced agitation. If this BCM is the source of elevated PP (and TP) concentrations and loads during the 20–30 major pumping events that occur on farms during the course of a year, it is hypothesized that significant reductions in TP loads could be achieved if the aquatic vegetation growth and senescence cycle could be managed or eliminated. This is because under anaerobic conditions sediment P-fluxes to the water column are typically higher than under aerobic condition (Moore et al. 1998). The P associated with Fe would be released upon Fe reduction under anaerobic condition resulting in higher solution P concentrations at the surface (Sah et al. 1989). The presence of dense floating aquatic vegetation for prolonged duration prevents the penetration of sunlight limiting the precipitation of calcium phosphate from the water column forming denser, cohesive sediments that are less likely to get resuspended and transported off the farm during drainage pumping events. It should be pointed out that the aquatic plants are simply part of the P cycling that occurs in the farm canals. These plants work towards removing dissolved P from the water column and concentrate it in their tissues.

Plant P-uptake rate

Plant P-uptake was estimated as the change in mass of SRP per unit area over time in the water column (Figure 5). Floating aquatic vegetation (water lettuce) showed significantly higher SRP uptake than submerged vegetation (filamentous algae) in both sediment and nonsediment conditions. The highest SRP uptake was observed in treatments with no sediments. Treatments containing just LR + WL had the highest mean SRP-uptake during all four exchanges, while the lowest SRP-uptake was seen in LR + SED + FA. Increase in plant P-uptake with time does not necessarily correspond to an increase in the plant biomass P concentration during short-term growing cycles, this is because the C:P ratio also increases as the plant grows resulting in net reduction of P concentration in the plant biomass (Lindsey and Hirt 1999). At the end of all four exchanges, the cumulative SRP-uptake corresponded to 0.18 $\pm$ 0.02 mg m^{-2} d^{-1} in LR + SED + WL; 0.10 $\pm$ 0.01 mg m^{-2} d^{-1} in LR + SED + FA; 0.19 $\pm$ 0.05 mg m^{-2} d^{-1} in LR + WL; and 0.16 $\pm$ 0.03 mg m^{-2} d^{-1} in LW + FA. Overall we observed a 45 $\pm$ 5% higher SRP-uptake in treatments containing LR + SED + WL compared to LR + SED + FA, and a 20 $\pm$ 8% higher P-uptake in treatments containing LR + WL compared to LR + FA. The lysimeter experiment was conducted during May-June when primary productivity is at its highest in tropical areas because of maximum solar radiation, and precipitation. This would suggest that the plant P uptake rates are probably at their highest during this time of the year. During the growth period (summer), the concentration of dissolved P in the water column is generally low compared to the sediment pore water. Phosphorus removal in a water lettuce dominant system occurs through immobilization in the detritus plant tissue and adsorption by the underlying sediments; however, detritus of water lettuce tend to release P back into the water column during decomposition, thus decreasing the overall P removal efficiency of the plant. Haller et al. (1970) reported that greater amounts of P were absorbed by water hyacinth plants from solutions containing higher P concentrations, and that nearly 50% of the absorbed P leached out from the stem and root tissues within 6 d. Plant P-uptake from the water column is also dependent on the hydraulic retention time (HRT). With filamentous algae, Gu et al. (2001) showed that by increasing the HRT from 1.5 to 3.5 d markedly improved the P removal performance; however, doubling the HRT from 3.5 to 7 d had little additional effect. Similar results from this study were observed for both water lettuce and filamentous algae, where $>$ 70% of the plant P uptake occurred within the first 24 h, while the rest continued over the next 6 d.

Based on the P uptake rates from the lysimeter experiment, we estimated that canals predominantly containing water lettuce would take up 148 kg P d^{-1} from the water column compared to 48 kg P d^{-1} if the canals contained only filamentous algae. Extrapolating these values to represent net P uptake from the water column by the plant within the EAA corresponds to 5.5 to 26 mt P yr^{-1} for water lettuce, and 1.8 to 8.4 mt P yr^{-1} for filamentous algae, depending on the time of year and percent plant coverage. However, based on the detrital matter accumulation rate of 0.23 g d^{-1} (dry mass basis) from the lysimeter experiment, nearly 24 mt d^{-1} detrital matter generated from water lettuce would settle at the bottom of the canals in the EAA. This is a high-end estimation during summer, since the coverage of aquatic vegetation in the farms canals is significantly less during the rest of the year. Clearly, there is a P tradeoff with aquatic vegetation being present in the farm canals. They assimilate dissolved P from the water column to facilitate plant growth, but they can generate detrital biomass that ultimately increases the particulate P pool, and potentially clog-up the culverts. Depending on the P concentration of the detrital matter and time of year, we estimate approximately 26 mt P from water lettuce and filamentous algae is being accumulated within the farm canals during summer when primary productivity is at its peak, whereas only about 7 mt P is being accumulated throughout the EAA during the rest of the year. Mechanical harvesting of aquatic vegetation could potentially break the BCM-cycle, thereby reducing P loads exiting the farm canals; however, this is not a feasible practice because of the high cost associated with harvesting and subsequent disposal or processing (e.g., composting and using it as an amendment). Alternatively, long-term management plans to control FAV (water lettuce or hyacinth) in farm canals, and possibly transform them to SAV dominant systems maybe a more effective way of reducing P concentration and loads. Change in canal aquatic plant community from FAV dominated to SAV dominated systems should increase dissolved oxygen resulting in lower P-fluxes from sediments, and altered P species composition of the EAA farm drainage water. Compared to FAV, an SAV dominated system will allow greater light penetration, and subsequent P co-precipitation with Ca and Mg carbonates, producing significantly lesser detrital biomass.

In summary, both water lettuce and filamentous algae displayed high P removal rates from the water column during the 28-d incubation period. Water lettuce showed significantly higher SRP uptake than filamentous algae under both sediment and nonsediment conditions, suggesting that water lettuce requires more P in facilitating plant growth than filamentous algae. The highest TP reduction was also observed in treatments containing no sediment, as sediment can provide an internal source of P. Future field-scale studies should focus on measuring P species as it would help in identifying the source of water in the farm canals, whether it is surface runoff from farmlands, subsurface groundwater flow or irrigation water from District canals. The effectiveness of water lettuce and filamentous algae to reduce P concentrations in farm canals within the EAA is offset by the quantity of labile plant biomass that can negatively impact the farm canals. Although aquatic vegetation may serve as a substantial reservoir for agricultural P, it is still unclear how to manage the weeds so as to reduce the detritus which contributes to the PP load. Herbicide application in the canals can reduce the density of vegetation but not necessarily the potential for contribution of PP to the drainage stream. Long-term Best Management Practices that involve suppressing the growth of FAV and transforming canals to a more SAV dominant aquatic systems has the potential to reduce the generation of organic PP, and P loads in the future.

ACKNOWLEDGEMENTS

This research was funded by the Everglades Agricultural Area – Environmental Protection District. We wish to thank Michael Korbly (Field Technician), Viviana Nadal (Senior Chemist), and Irina Ognevich (Chemist) for their assistance in the field and laboratory.

LITERATURE CITED

Aoi T, Hayashi T. 1996. Nutrient removal by water lettuce. Water Sci. Technol. 34:407–412.

Barko JW, James WF. 1997. Effects of submerged aquatic macrophytes on nutrient dynamics, sedimentation and resuspension. In: Jeppesen, E., Sondergaard, M. Christoffersen, K. (Eds). The structuring role of submerged macrophytes in lakes. Springer-Verlag, New York. pp. 197–216.

Carignan R. 1982. An empirical model to estimate the relative importance of roots in phosphorus uptake by aquatic macrophytes. Can. J. Fish. Aquat. Sci. 39:243–247.

Daroub SH, Lang TA, Josan MS, Bhadha JH. 2011. Implementation and Verification of BMPs for Reducing P Loading from the Everglades Agricultural Area: Floating Aquatic Vegetation Impact on Farm Phosphorus Load. Annual Report submitted to the Everglades Agricultural Area Environmental Protection District and the South Florida Water Management District. pp. 31–34.

Diaz OA, Lang TA, Daroub SH, Chen M. 2006. Best management practices in the Everglades Agricultural Area: Controlling particulate phosphorus and canal sediments. EDIS Publication #SL228. University of Florida, IFAS Extension.

Dierberg FE, DeBusk TA, Jackson SD, Chimney MJ, Pietro KC. 2002. Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. Water Res. 36:1409–1422.

Gu B, DeBusk TA, Dierberg FE, Chimney MJ, Pietro KC, Aziz T. 2001. Phosphorus removal from the Everglades agricultural area runoff by submerged aquatic vegetation/limerock treatment technology: an overview of research. Water Sci. Technol. 44:101–108.

Haller WT, Knipling EB, West SH. 1970. Phosphorus adsorption by and distribution in waterhyacinths. Proc. Soil Sci. Soc. Florida 30:64–68.

Howard-Williams C, Allansson BR. 1981. Phosphorus cycling in a dense *Potamogeton pectinatus*. L. bed. Oecologia 49:56–66.

Kadlec RH, Wallace SD. 2008. Treatment Wetlands. (2nd Ed.). CRC Press, Boca Raton, FL. pp. 59–100.

Knight RL, Gu B, Clarke RA, Newman JM. 2003. Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. Ecol. Eng. 20:45–63.

Lindsey K, Hirt HM. 1999. Use water hyacinth! (A practical handbook of uses for the water hyacinth from across the world). Anamed, Winnenden, Germany. pp. 7–8.

Lu Q, He ZL, Graetz DA, Stofella PJ, Yang X. 2010. Phytoremediation to remove nutrients and improve eutrophic stormwaters using water lettuce (*Pistia stratiotes* L.). Environ. Sci. Poll. Res. 17:84–96.

Mehra A, Farago ME, Banerjee DK, Cordes KB. 1999. The water hyacinth: an environmental friend or pest? A review. Res. Environ. Biotech. 2:255–281.

Mitsch WJ. 1992. Landscape design and the role of created, restored and natural riparian wetlands in controlling nonpoint source pollution. Ecological Engineering 1:27–47.

Moore PA, Reddy KR, Fisher MM. 1998. Phosphorus flux between sediment and overlying water in Lake Okeechobee, Florida: spatial and temporal variations. J. Environ. Qual. 27:1428–1439.

Murphy T, Hall K, Yasaki I. 1983. Co-precipitation of phosphate and calcite in a naturally eutrophic lake. Limnol. Oceanogr 28:28–67.

Reddy KR, Sutton DL. 1984. Waterhyacinths for water quality improvement and biomass production. J. Environ. Qual. 13:1–8.

Richardson CJ, Craft CB. 1993. Effective phosphorus retention in wetlands: fact or fiction? In: Moshiri G. A. (Ed.). Constructed wetlands for water quality improvement. CRC Press. Boca Raton, FL. 271–282 pp.

Sah RN, Mikkelsen DS, Hafez AA. 1989. Phosphorus behavior in flooded-drained soils. II Iron transformations and phosphorus sorption. Soil Sci. Soc. Amer. J. 53:1723–1729.

SAS Institute. (2011). SAS Version 9.3. SAS Inst., Cary, NC.

Stuck JD, Izuno FT, Campbell KL, Bottcher AB, Rice RW. 2001. Farm-level studies of particulate phosphorus transport in the Everglades Agricultural Area. Trans. ASAE 44:1105–1116.

[USEPA] United States Environmental Protection Agency. 2003. Index to EPA Test Methods. April 2003 revised edition.