

# Phosphorus in periphyton mats provides the best metric for detecting low-level P enrichment in an oligotrophic wetland

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## Abstract

Growing concern over the ecological consequence of phosphorus (P) enrichment in freshwater wetlands has elicited considerable debate over the concentration of water column P associated with eutrophication. In the oligotrophic Everglades, the displacement of native communities by enriched ones is widespread and has occurred at sites experiencing only minimal elevations in P input. To help define regulatory criteria for P inputs to the Everglades, we constructed an experiment that mimics P input to the natural system by continuously delivering P at concentrations elevated 5, 15 and 30  $\mu\text{g l}^{-1}$  above ambient to 100-m long flow-through channels. We compared patterns of P accumulation in the water, periphyton, detritus and soils among the channel treatments and also along a 16 km transect from an enriched canal that inflows to the interior of the same marsh. Water column TP and SRP were unrelated to input TP concentration in both the experiment and the marsh transect. However, concentrations of TP in periphyton mats were significantly elevated at all levels of experimental enrichment and as far as 2 km downstream from water inputs into the marsh. Elevated periphyton TP was associated with significant loss of periphyton biomass. In oligotrophic wetlands, traditional measures of water column SRP and TP will substantially underestimate P loading because biotically incorporated P is displaced from the water column to benthic surfaces. Using periphyton TP as a metric of P enrichment is uncomplicated and analogous to pelagic TP assessments in lakes where most P is sequestered in phytoplankton.

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## 1. Introduction

In wetlands, microbial activity is typically confined to benthic surfaces and, therefore dissociated from (and not included in measurements of) water column nutrients [1]. Yet recent efforts to establish water quality

criteria for wetlands employ lake assessment methods (i.e., measures of water column P; [2,3]) that would exclude the majority of microbially sequestered nutrients, and result in an underestimation of nutrient availability when compared to lakes in a similar enrichment setting.

Few systems provide a better example of the need for appropriate water quality measures than the Florida Everglades, a large and fragile wetland where the extent of loss and ecological damage resulting from water quality degradation is severe [4]. There is now a

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multi-billion dollar effort underway to restore water quantity and quality in this system, which in order to be effective must be based on standards that will not further threaten native biota and ecological function [5]. This task is has been federally mandated through the Everglades Forever Act (Florida Legislature, 1994), which requires establishment of a water quality criterion for Everglades wetlands. Research has been focused on delimiting a water quality standard that will effectively deter further ecological damage and reverse deleterious changes.

Many of the biotic changes observed in this system over the past several decades have been attributed to excessive loads of phosphorus (P) coming into this naturally oligotrophic, P-limited wetland from canals draining the surrounding, rapidly growing agricultural and urban landscape (reviewed by [4,6]). These changes are most evident in marshes in proximity to the Everglades Agricultural Area and urban areas, where decades of P enrichment have elevated soil P content [7,8] and caused transformations in productivity and composition of macrophytes [4,9,10–14], periphyton [15–20], and consumers [21,22]. Several studies have added P to experimental enclosures to elevate concentrations above ambient levels in order to determine thresholds that elicit ecological change [19,23–28,29,30]. These studies have demonstrated correlations between water column P and a variety of biotic changes, especially in periphyton communities, and provide the primary basis for the water column P standard that will be established for the Everglades. However, with the exception of the study presented in Pan et al. [19] and Qualls and Richardson [29], experimental enrichment studies have aimed at raising water column TP to specified levels based on periodic batch dosing of mesocosms, which is unlike the continuous delivery of nutrients experienced in the flowing waters of the Everglades. In addition, most of the enrichment experiments and gradient analyses have been confined to regions in the Northern Everglades that have had a long history of exposure to elevated P, and therefore contain communities that may behave differently than in more pristine portions of the marsh.

In order to mimic the way that P enters the Everglades system, and evaluate the levels of P enrichment that cause ecological change in a previously unenriched marsh, we conducted an experiment that delivers P in known quantities at rates dependent on natural, measured flows. We measured the fate of P in the water column and in biotic components of the system in order to assess effects of excess delivery, and determine early warning signals of impending ecosystem change. Early indications of ecological change are important in ecosystem monitoring and restoration, in part because the magnitude of reduction and time necessary to reverse eutrophication (once observed throughout the

system) can be substantially greater than that which caused it [31]. While the experiment is of sufficiently large spatial and temporal scale (100 m, 4 yr) to detect long-term cumulative effects at the ecosystem level, the present work reports on responses in the periphyton community, whose initial responses occurred over a much shorter (days to months) time scale. In addition, to determine the applicability of experimental results to the larger system, we examined patterns of P accumulation in water and periphyton along a transect from canal input structures to the interior of the same marsh.

## 2. Methods

Three replicate flow-through experimental flumes were constructed in pristine areas of Shark River Slough in Everglades National Park (Fig. 1). The flumes are located in peat-based wet prairie marshes, which are characterized by thick, floating periphyton mats and a macrophyte community dominated by *Utricularia purpurea*, *Eleocharis cellulosa*, *Panicum hemitomon* and *Sagittaria lancifolia*. Each flume contains four, 100-m long  $\times$  3-m wide channels that enclose areas of natural marsh and are open at both ends and to the sediments (see Fig. 2). Channels are positioned parallel to water flow and an automated system delivers  $\text{NaH}_2\text{PO}_4 + \text{Na}_2\text{HPO}_4$  (pH=7) at concentrations of 0, 5, 15 and  $30 \mu\text{g l}^{-1}$  ( $\sim 0.00, 0.16, 0.48, \text{ and } 0.97 \mu\text{M}$ , respectively) to a 10-m long mixing box at the head of each channel. Concentrations are kept constant by continuously adjusting P delivery according to velocity and stage measured by a pressure transducer and acoustic Doppler flow sensor capable of measuring very low velocity flow ( $< 5 \text{ mm s}^{-1}$ ) at the head of each channel. For further details on the experimental setup, see Childers et al. [32].

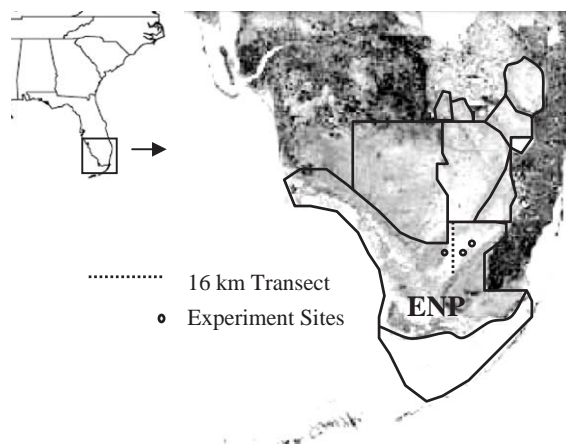


Fig. 1. Location of experimental flumes and transect in Everglades National Park (ENP), Florida.

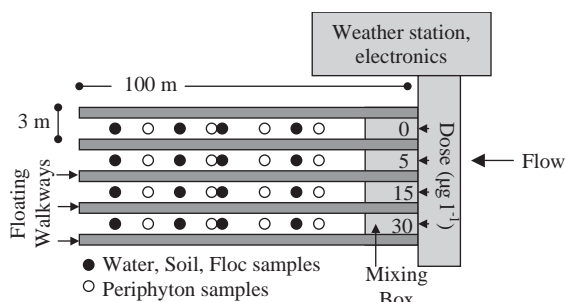


Fig. 2. Schematic showing the design of the experimental flumes. Each of the 3 flumes has 4 treatments that were randomly assigned to the 4 channels. A 10 m mixing box with a plastic floor receives soluble P at rates based on the volume of water at the head of the channel. Biologically incorporated P (TP) then flows into the 100-m long  $\times$  3-m wide channels of natural marsh that are contained by plastic curtains anchored at the base into the marsh soil and at the surface to the floating walkways. Samples are taken at designated downstream locations.

Total P concentration was measured in the water, flocculent detritus (floc), soil and periphyton at 4 downstream locations in each channel. Sampling stations were deliberately staggered by parameter at selected distances downstream, in order to minimize disturbance to the many parameters that will be measured during the extended 5 years of study (8, 33, 58 and 83 m for water, floc and soil; 5, 19, 37 and 67 m for periphyton). Water column SRP and TP were measured in triplicate 500 ml water samples that were first filtered through 100  $\mu\text{m}$  Nyltex<sup>®</sup> screening to exclude floating debris. Sediments were sampled using a coring device that effectively separated the floc from soil (see [33]). Triplicate floc and soil samples were combined into one composite sample for each component. Anomalous materials (live roots, snail shells, etc.) were removed from the soil and floc samples in the lab. The floating periphyton mat was sampled with a 4.2-cm<sup>2</sup> diameter metal coring device. Fifteen cores were extracted from the periphyton at each location and were then combined into one sample. In the lab, fragments of the submerged macrophyte, *U. purpurea*, and other dead plant material and animals were removed from the mat. Two subsamples of homogenized periphyton were dried to constant weight at 100°C ( $\sim$ 2 days), weighed and then analyzed for TP. Because periphyton often contains a large proportion of inorganic calcite, the second subsample was subsequently combusted in a muffle furnace at 500°C for 4 h and re-weighed for estimation of AFDM. All measures of periphyton biomass determined from the core samples ( $\mu\text{g cm}^{-2}$ ) were multiplied by aerial cover, determined from digital photographs of sampling quadrats, to expand estimates to a  $\text{m}^{-2}$  basis. Floc, soil and

periphyton samples were dry-combusted [34] prior to P analysis. SRP (water) and TP (water and tissue) were analyzed colorimetrically [35].

This study summarizes data from samples taken after 0 (pre-dose), 60, 120 and 180 days of continuous dose application, from the start of dosing in October 1998 until April 1999. We tested for treatment effects on concentrations of SRP and TP in the water column and TP in the periphyton, floc and soils using a repeated-measures (M)ANOVA (3 sites, 4 treatments, 4 locations nested within sites and 4 repeated measures). To determine explicit spatial and temporal patterns of P accumulation in these components we calculated the difference between dose day *n* and day 0 values for each site, treatment and distance, and were compared treatment to control means using a one-sided post hoc Dunnett test with adjustments for multiple contrasts ( $p < 0.01$ ). We used multiple, linear least-squares regression to determine effects of cumulative load (received at the head of the channel) and distance from load on P concentrations in each compartment. Cumulative P load (g), controlled by the pumping rate of P into the channels based on depth and velocity-calibrations of the Campbell Scientific Datalogger (CR10X) in each channel, is the product of input concentration ( $\text{g m}^{-3}$ ), velocity ( $\text{m d}^{-1}$ ), depth (m), area (constant, 3 m) and duration of loading (d). Correlations among response parameters were examined by Pearson correlation with Bonferroni probabilities. P concentrations, load and distance were log transformed prior to analysis to fit a normal distribution.

To extend our results to the natural system, we sampled TP and SRP in water and periphyton at 12 sites in the same slough, distributed along a transect that began near the S-12C gate structure on the C-4 canal (which separates Everglades National Park from the water conservation areas to the North), and extended 16 km south (about 4 km south of the southernmost experimental flume; Fig. 1). Triplicate samples of periphyton and water were collected in during a relatively low-water period in June 1999 and a relatively high-water period in January 2000. Samples were processed following the same methods explained for the experiment, and trends in SRP and TP for water and periphyton relative to distance from canal water inputs were analyzed using linear regression following log transformation of P data.

### 3. Results and discussion

During 180 days of continuous dose application we detected no treatment effect on water column SRP, TP or soil TP concentration (MANOVA, Table 1, Fig. 3). Post hoc paired contrasts for these variables also revealed no significant elevations in treatment plots

Table 1

Effects of dose treatment, time and distance from dose on periphyton (peri), flocculent detritus (floc), soil and water TP content and water SRP detected by repeated measures (M)ANOVA

Source	df	Peri TP	Floc TP	Soil TP	H <sub>2</sub> O TP	H <sub>2</sub> O SRP
Site	2	0.08	1.07	6.90*	0.07	0.04
Trt	3	2.13	1.22	0.55	1.21	0.72
Dist(Site)	9	0.42	0.01	2.29	0.27	0.37
Trt*Dist(Site)	27	0.32	0.01	1.01	0.31	0.38
Error	6					
Within time						
Time	3	3.92*	1.02	26.31*	1.63	1.13
Time*Site	6	1.65	0.95	2.94	6.96*	0.35
Time*Trt	9	2.29*	1.10	1.95	1.07	0.68
Time*Dist(Site)	27	0.52	0.00	0.98	0.29	0.40
Time*Trt*Dist(Site)	81	0.39	0.01	1.12	0.50	0.39
Error	18					

Degrees of freedom and F-values are given.

\*Significant at the  $p < 0.05$  level.

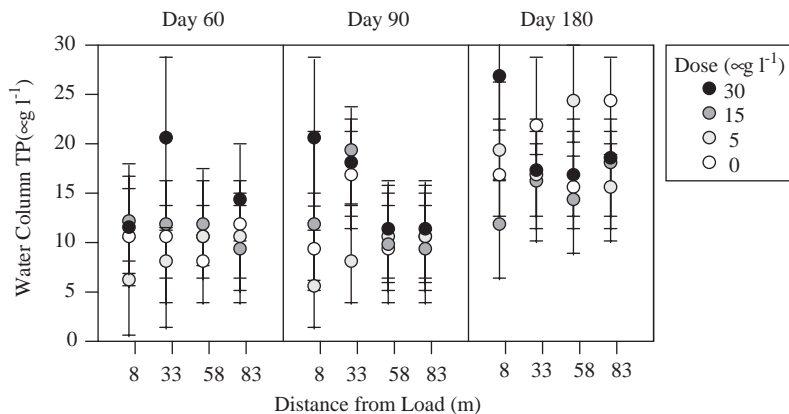


Fig. 3. Patterns of TP in the water column in plots 8, 33, 58 and 83 m from P inputs of 0, 5, 15 and  $30 \mu\text{g l}^{-1}$  above ambient. Bars represent the standard deviation of the mean of the three experimental flumes in Everglades National Park.

relative to controls at any time or date. However, we did find a significant treatment effect on periphyton P concentrations over time (Table 1, Fig. 4). After 60 d elevated concentrations were detected at the upstream sampling sites (5 and 19 m from source) in the 15 and  $30 \mu\text{g l}^{-1}$  treatments (paired-contrasts, Fig. 4). After 120 days of dosing at these concentrations all downstream plots were significantly elevated from controls. By 180 d concentrations 19 m downstream from the low dose treatment ( $5 \mu\text{g l}^{-1}$ ) were significantly elevated ( $160\text{--}400 \mu\text{g g}^{-1}$ ) compared to ambient levels in pre-dose and control samples ( $75\text{--}150 \mu\text{g g}^{-1}$ , Table 2). Although our nested (M)ANOVA did not detect significant treatment effects on floc TP (Table 1), paired means contrasts revealed significant elevations after 180 d of treatment at the  $30 \mu\text{g l}^{-1}$  level (all downstream distances,  $p < 0.01$ ).

While we detected several treatment effects on periphyton TP, variation in response parameters was increased by natural differences among our 3 replicate flumes in water volume and velocity. During the 180 d period, water depth ranged from 0.5 to 1.2 m ( $w = 0.79 \text{ m}$ ) and velocity from 3 to  $13 \text{ mm s}^{-1}$  ( $w = 5.4 \text{ mm s}^{-1}$ ), resulting in cumulative loads of P to the mixing box ( $3 \text{ m} \times 10 \text{ m}$ ) at the head of each channel of 0.2, 0.7 and  $1.4 \text{ g m}^{-3} \text{ d}^{-1}$  to the 5, 15 and  $30 \mu\text{g l}^{-1}$  treatments, respectively. We therefore also used regression models with load and distance as independent variables to understand the treatment effects. We found a significant effect of P load and distance from input on all parameters except soil TP (Table 2; Fig. 5). Water column SRP and TP showed weak but significant responses to load and distance (Table 2, Fig. 5). While

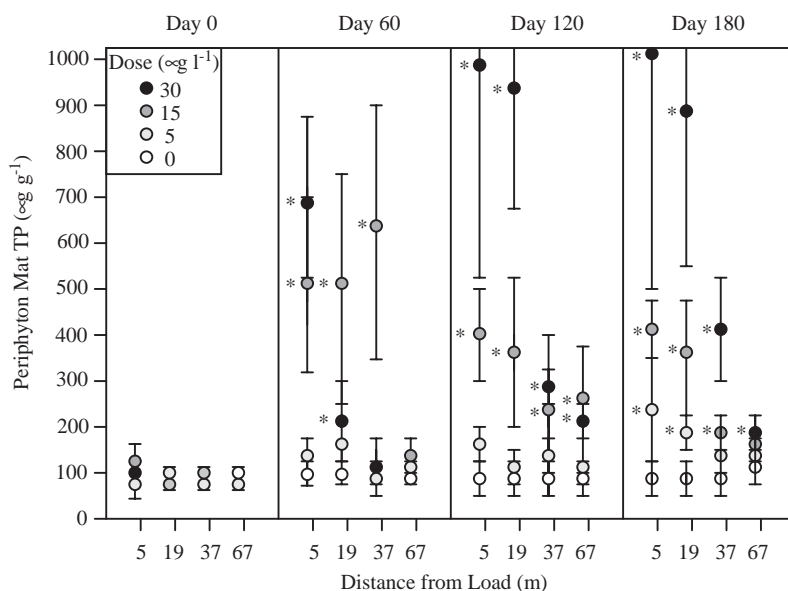


Fig. 4. Patterns of P accumulation in the floating periphyton mat in plots 5, 17, 37 and 67 m from P inputs of 0, 5, 15 and 30  $\mu\text{g l}^{-1}$  above ambient. Bars represent the standard deviation of the mean of the three experimental flumes in Everglades National Park. Significant departures from control values are denoted with \* ( $p < 0.0001$ ).

Table 2

Regression parameters and diagnostics for the relationship of periphyton, flocculent detritus (floc), soil and water TP content and water SRP to load and distance (dist) from load source using the multiple, linear least-squares model:  $\text{Log}(\text{Phosphorus content} + 1) = \text{slope}(\text{Log}(\text{Load} + 1)) + \text{slope}(\text{Log}(\text{Distance} + 1)) + \text{intercept}$ ; where  $\text{Load} = \text{input concentration} \times \text{velocity} \times \text{depth} \times \text{area} \times \text{duration of loading}$

	Slope (load)	Slope (distance)	Intercept	Multiple R <sup>2</sup>
Periphyton	0.52***	-0.36***	1.25	0.38***
Floc	0.13***	-0.14***	2.50	0.28***
Soil	-0.02	-0.01	2.50	0.01
H <sub>2</sub> O TP	0.19*	-0.08	0.64	0.08*
H <sub>2</sub> O SRP	0.29***	-0.11	0.29	0.13***

\*Significant for  $p < 0.01$ .

\*\*\*Significant for  $P < 0.0001$ .

correlated with water column SRP and TP (Table 3), the TP content of periphyton and floc showed much stronger relationships to load and distance (Table 2, Fig. 5).

Periphyton TP content declined with distance across the larger spatial scale (16 km) represented in the transect study ( $r^2 = 0.65$ ;  $p < 0.001$ ; Fig. 6). Enriched mats (significantly  $> 150 \mu\text{g g}^{-1}$ , defined by the experiment) were found 0–2 km downstream of the S-12 gate that controls the primary hydrologic input to this marsh [36]. However, as in the experiment, there was no significant relationship of water column TP or SRP to distance from this input.

The absence of a strong relationship between load and water column TP has been observed in other areas of the Everglades, and in other wetland basins outside the Everglades. Smith and McCormick [37] compiled 20 years of inflow and water column P data from Water Conservation Area 2A and found only a weak relationship between canal P inputs and marsh water P, except at locations adjacent to the canal. They attribute the lack of a strong relationship in part to retention and assimilation in the marsh, although P bound in biological components was not measured at the same frequency and therefore not included in their analyses. Our results, together with these data from WCA-2A,

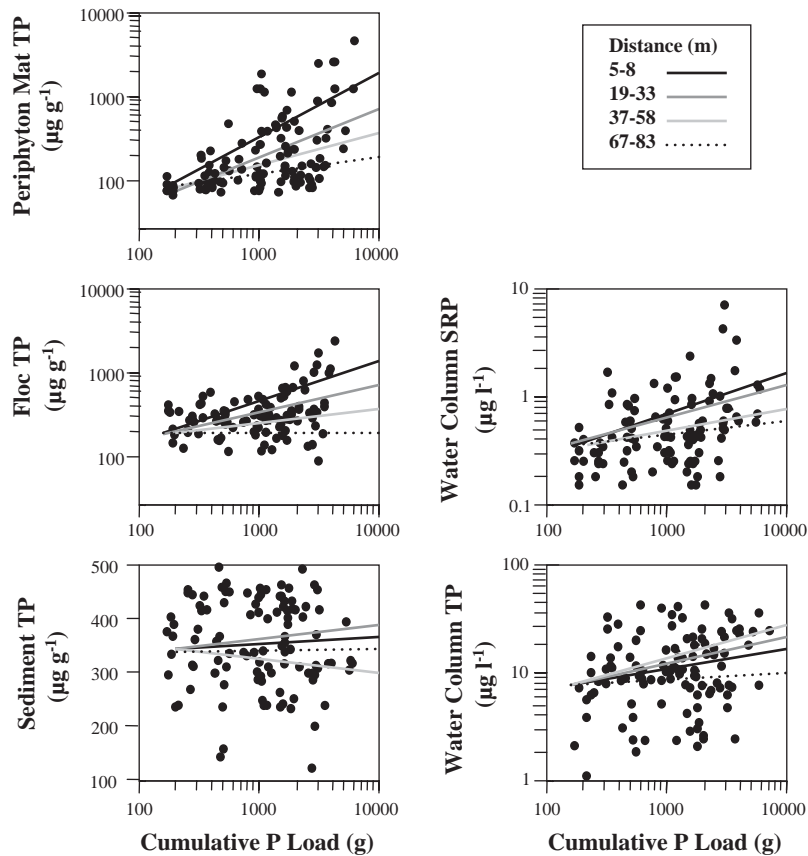


Fig. 5. Response of periphyton, floc, soil and water column TP and water column SRP concentration to cumulative P loaded to 3 experimental flumes in Everglades National Park. Cumulative P load (g) is the velocity and depth-calibrated amount of P delivered to the head of each channel after 60, 120 and 180 days of dosing. Linear least-squares regression lines are provided for each downstream sampling distance. Regression parameters and diagnostics for these relationships are provided in Table 2.

Table 3

Pearson correlation matrix of periphyton (peri), flocculent detritus (floc), soil and water TP content, water SRP and P load to the head of the channel

	Peri TP	Floc TP	Soil TP	H <sub>2</sub> O TP	H <sub>2</sub> O SRP	P Load
Peri TP	1.000					
Floc TP	0.500***	1.000				
Soil TP	0.090	0.177	1.000			
H <sub>2</sub> O TP	0.485***	0.227	0.017	1.000		
H <sub>2</sub> O SRP	0.417***	0.303*	0.072	0.364**	1.000	
P Load	0.505***	0.457***	0.002	0.248	0.297	1.000

\*Significant Bonferroni probabilities of  $p < 0.01$ .

\*\*Significant Bonferroni probabilities of  $p < 0.001$ .

\*\*\*Significant Bonferroni probabilities of  $p < 0.0001$ .

support the model predictions of Howard-Williams [38] that elevated P concentrations will not appear in downstream areas until the assimilative capacity of the biota has been saturated. Benthic periphyton communities have a high affinity for P and can be an

increasingly important sink for P as water column SRP decreases [39,40]. In our experiment the biotic demand of the periphyton was great enough to reduce the residence time of excess water column P such that the instantaneous water column TP concentration

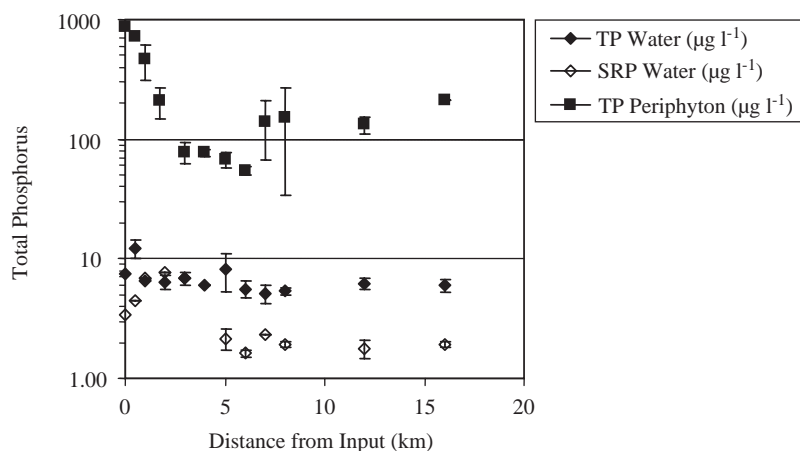


Fig. 6. Patterns of water column SRP and TP and periphyton TP along transect from a canal inflow (S-12C gate) to Shark River Slough, Everglades National Park to a station 16 km south in the interior of the marsh. Bars represent the standard deviation of the mean of 3 replicates taken in June 1999 and again in January 2000.

fluctuated near ambient levels ( $\sim 10 \mu\text{g l}^{-1}$ ) regardless of dosing treatment. Even after 180 days of dosing at our highest levels ( $30 \mu\text{g l}^{-1}$ ) SRP remained near or below colorimetric detection limits of  $1 \mu\text{g l}^{-1}$ . Enhancements in the water column, soils or plants should only be observed over a longer time course, when the periphyton community becomes saturated and enriched tissues accumulate in the sediments. These lags have been noted in enriched lakes [25,41] and recently in enriched wetlands (G. Goldsborough, personal communication) and can lead to difficulties in assessing short-term response to changes in P load, and obfuscate understanding of management impacts on water quality.

These data suggest that measurements of P in the periphyton mat could be used as an early signal of enhanced P load. To be used as a criterion to measure ecosystem degradation, however, state law requires that the change constitutes an ecosystem “imbalance.” What are the ecosystem consequences of elevated P content in Everglades periphyton mats? In our study, dosing produced a conspicuous loss of the floating periphyton mat (Fig. 7). Dry weight biomass declined significantly with increasing tissue P concentration (measured in dried material,  $r^2 = 0.16$ ,  $p < 0.0001$ ), which was a result of a loss of both inorganic (mostly calcite) and organic components of the periphyton. Because adsorption to calcite accounts for only a small fraction ( $< 5\%$ ) of the TP content [42], and is incompletely removed by acidification, the correlation of the loss of organic biomass with increased tissue P content ( $r^2 = 0.16$ ,  $p < 0.0001$ ) can be primarily attributed to P sequestration in a reduced mat community rather than a loss of the inorganic contribution to the TP estimate. At ambient (pre-dose) tissue P concentrations (75–150  $\mu\text{g P g}^{-1}$  dry mass), mean periphyton AFDM was

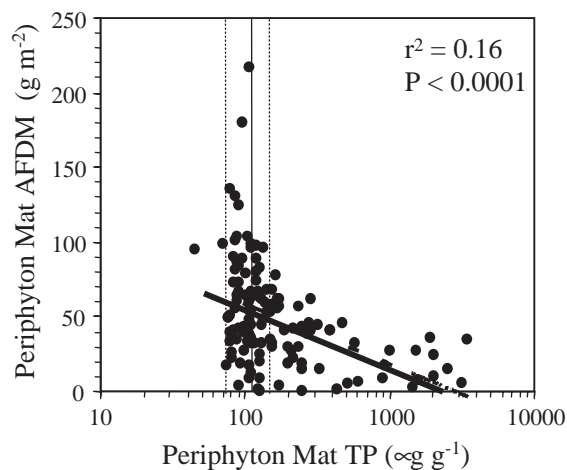


Fig. 7. Plots shows the decrease in the ash-free dry weight (AFDM) of periphyton with increasing mat P content during 180 days of dosing in the experimental flumes. The solid line indicates the mean mat TP content in pre-dose samples, and the dotted lines represent the standard deviation of that mean.

$62 \text{ g m}^{-2}$  (standard error = 37) while the mean AFDM of enriched mats ( $> 150 \mu\text{g P g}^{-1}$  dry mass) was significantly lower ( $31 \text{ g m}^{-2}$ , standard error = 21;  $p < 0.0001$ ). Previous studies in the Water Conservation Areas north of our study area have documented greater than 50% loss of periphyton mat biomass and altered species composition and metabolism when mat concentrations were elevated above  $500 \mu\text{g P g}^{-1}$  dry mass [19,26,43]. Compositional shifts from a floating, calcareous, cyanobacterial mat, dominated by *Schizothrix calcicola* and *Scytonema hofmannii*, to a less-diverse filamentous green algae and diatom-dominated community with P

enrichment, noted in this study and shown elsewhere [26] also contributes to the decline in AFDM with increased tissue concentration of P. Stoichiometric data from eutrophied pelagic waters have shown that diatoms and other eukaryotic algae contain more P than relatively N-rich cyanobacteria [44,45]. In addition, it is likely that heterotrophic bacteria residing in the periphyton, which are low in C but P-rich in comparison to other organisms, are stimulated with elevated P and contribute to the increase in P content per unit periphyton biomass [46–49]. Finally, disintegration of the floating periphyton mat and contribution to the floc may stimulate heterotrophic activity in the benthos, explaining why a portion of variation in floc TP was related to P load (Fig. 1). Increased periphyton TP is the first easily measured symptom of a cascade of biological responses and can be used to indicate that a change in ecosystem state has begun.

The detection of biotic imbalances downstream of inputs only  $5\mu\text{g l}^{-1}$  above ambient has important regulatory implications for the Everglades and other oligotrophic wetlands. This concentration is considerably lower than water column concentrations shown in previous studies to cause significant alterations (estimates range between 13 and  $50\mu\text{g TP l}^{-1}$ ; [19,20,25,26,50]) and 10% the current input concentration ( $50\mu\text{g TP l}^{-1}$ ) allowed by government standards. During the past 20 years, concentrations of TP entering Everglades National Park from input structures have increased from an average of  $8\text{--}18\mu\text{g TP l}^{-1}$  [36]. Differences in periphyton community composition have been detected as much as 6 km from these inputs [51]. Removal and recycling of P within the periphyton would elicit compositional change without a concomitant elevation in water column or soil TP. Cumulative ecological effects of small increases in P input have now been documented both descriptively and experimentally, suggesting that protection of Everglades marshes will require that water inputs are regulated to have TP concentrations at ambient marsh concentrations (approximately  $8\text{--}13\mu\text{g l}^{-1}$ , R. D. Jones, unpubl. data). Furthermore, periphyton tissue concentrations reflect nutrient load, the combination of water quality and water movement, suggesting input water quality measurements must be accompanied by hydrologic monitoring. Effective conservation and restoration of the Everglades and other nutrient-deprived marshes will depend on measuring enhanced concentrations in biota and regulating nutrient loads to maintain ambient conditions.

Using standard trophic metrics [52], we found water column TP concentrations indicating oligotrophy ( $<10\mu\text{g l}^{-1}$ ) existing concurrently with algal communities indicating hypereutrophy ( $\text{TP} > 500\mu\text{g m}^{-3}$ ). Periphyton indicators of water quality degradation in wetlands have been strongly advocated [53–55] but

compositional and metabolic indicators will reflect P availability in their immediate surroundings (within the periphyton matrix) rather than the water column. Methodology for incorporating a measurement of periphyton TP into standard water quality monitoring practices is uncomplicated. Spatial and temporal variability in P concentration in periphyton tissue is typically much lower than in the water column, so fewer samples are required to derive estimates. Since the desired metric is concentration (mass P per dry mass) rather than aerial quantity (mass P per area), periphyton sampling can be non-quantitative, consisting of removal of enough material (typically 1 dry g) from the attachment substrate which can be dried and analyzed using standard protocols for solids [56].

#### 4. Conclusions

Pelagic ecologists have acknowledged that most P is retained and rapidly recycled in biological tissues when availability is low relative to the needs of the biota, such that instantaneous measures of SRP in the water column are below detection limits [57]. This concept is applied in enrichment assessments in lakes through analysis of TP, which includes the dominant plankton-bound component. In shallow-water habitats, substrate-associated, rather than free-living, microbial communities regulate water column nutrient concentration [24], but the detection and control of wetland nutrient enrichment continues to be based on water column samples. This misapplication is particularly critical in the Everglades where water quality standards established in the near future will guide the long-term restoration of this critically threatened ecosystem. This study shows significant alterations in periphyton nutrient content and biomass, widely recognized as indicative of enrichment in this system [54], downstream of marginally detectable P elevations (5 ppb above ambient). Eutrophication will be undetected by standard measures of water column P concentration until biological systems are saturated in P, by which time the structure and function of the ecosystem may be irreparably altered. Measuring TP in periphyton, which is ubiquitous in the Everglades and most shallow-water systems, is as uncomplicated as water column assessments, and provides a reliable estimate of P input that can be used to prevent eutrophication and assess the progress of restoration.

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