Wetlands Ecol Manage (2009) 17:291–302
DOI 10.1007/s11273-008-9107-5

ORIGINAL PAPER

Sawgrass (*Cladium jamaicense*) responses as early indicators of low-level phosphorus enrichment in the Florida Everglades

**Stephen M. Smith · Jennifer A. Leeds ·
Paul V. McCormick · P. Brian Garrett ·
Malak Darwish**

Received: 29 October 2007 / Accepted: 23 June 2008 / Published online: 19 October 2008

Abstract Anthropogenic phosphorus (P) inputs to the Florida Everglades have produced dramatic changes in the wetland vegetation of this otherwise oligotrophic system. While the proliferation of undesirable plant species in response to enrichment has been well documented, nutrient-related changes in the physiological and morphological attributes of existing vegetation, prior to any shifts in species composition or changes in the spatial extent of certain taxa, have yet to be adequately characterized. In this experiment, three sawgrass-dominated areas were enriched with P for 3 years at rates of 0.4 g P/m^2/year (HP), 0.1 g P/m^2/year (LP), or 0 g P/m^2/year (controls) to assess potential impacts of P-enriched discharges from stormwater treatment areas into the Everglades. Elevated concentrations of TP in rhizomes and leaves and reduced ratios of leaf N:P were detected in HP plants within $\sim$1 year at most sites. Live leaf densities, plant heights, and plant densities of the HP groups were generally higher than LP and control groups after 2 years, a pattern that was evident even after major fire events**.** Total aboveground biomass was significantly elevated in both HP and LP treatments at two of the three sites after 3 years. No change in species composition was detected during the study. Planned hydrologic restoration measures will increase P loads into parts of the Everglades that have not previously experienced anthropogenic P enrichment. Monitoring native vegetation such as sawgrass can be a sensitive and relatively robust means of detecting unintended P enrichment in these areas prior to shifts in vegetation community composition or changes in area cover of key species.

Keywords Ecological indicators · Everglades · Phosphorus · Plant morphology · Sawgrass · Vegetation community · Wetlands

Introduction

For more than a century, the Florida Everglades has experienced a variety of human-related impacts that

---

S. M. Smith (✉)
United States Department of the Interior, National Park Service, Cape Cod National Seashore, 99 Marconi Site Road, Wellfleet, MA 02667, USA
e-mail: stephen_smith@nps.gov

J. A. Leeds
Everglades Restoration Resource Department, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, USA

P. V. McCormick
Lake Okeechobee Division, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, USA

P. B. Garrett · M. Darwish
Everglades Division, Watershed Management Department, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, USA

have disrupted the delicate balance of this ecosystem. Over half of the historic Everglades has been lost to agricultural and urban use. Much of the remaining system has been hydrologically altered (Sklar et al. 2002), and areas receiving drainage from surrounding development have been enriched with phosphorus (P) and other nutrients (McCormick et al. 2002). Vegetation responses to these impacts have diminished landscape complexity and species diversity.

The replacement of existing vegetation communities by dense monocultures of cattail (*Typha domingensis*, Pers.) in response to long term P enrichment (Davis 1994) has had numerous ecological consequences including reduced productivity of submerged plants and benthic periphyton, depletion of dissolved oxygen in the water, and changes in invertebrate and vertebrate community structure (Crozier and Gawlik 2001; McCormick et al. 2002). Subtler changes in individual plant populations in response to enrichment have not been so widely studied but also may result in ecosystem-level changes. For example, sawgrass (*Cladium jamaicense,* Crantz.) stands in areas with elevated water column and soil TP concentrations, which reflect many decades of low-level P input, have plant densities, stand heights, and biomass that are higher than those in unenriched areas (Urban et al. 1993; Miao and Sklar 1998). Such changes are important in that the physical and physiological characteristics of sawgrass stands, which are a dominant landscape feature across much of the Everglades, can affect the functioning of the larger system. For example, changes in individual plant and stand morphology can affect hydrology, both directly by impeding surface water flow and indirectly by increasing evapotranspiration. Higher levels of combustible plant material can fuel larger, hotter fires which, if these events occur when water levels are below ground, can result in ecologically damaging peat fires (Smith and Newman 2001; Smith et al. 2001).

A series of treatment wetlands or stormwater treatment areas (STAs) have been constructed to reduce anthropogenic P inputs and restore hydrologic conditions across portions of the Everglades (Chimney and Goforth 2001). Through natural biogeochemical processes, the STAs are able to achieve substantial reductions in total P (TP) concentrations in agricultural runoff before being discharged into the system. Despite the fact that reductions of ~80% in TP have been attained (Pietro et al. 2006), STA outflow concentrations are high relative to those routinely measured in pristine marsh areas. For example, mean concentrations of TP in STA discharges to the Everglades commonly fall within the 20–80 μg/l range (Pietro et al. 2006), which is considerably higher than the 5–10 μg/l range documented in the Everglades interior (McCormick et al. 2002). Accordingly, there is concern about how STA discharges may impact existing vegetation, which is mostly dominated by sawgrass, in adjacent receiving areas that have heretofore been relatively unaffected by P enrichment.

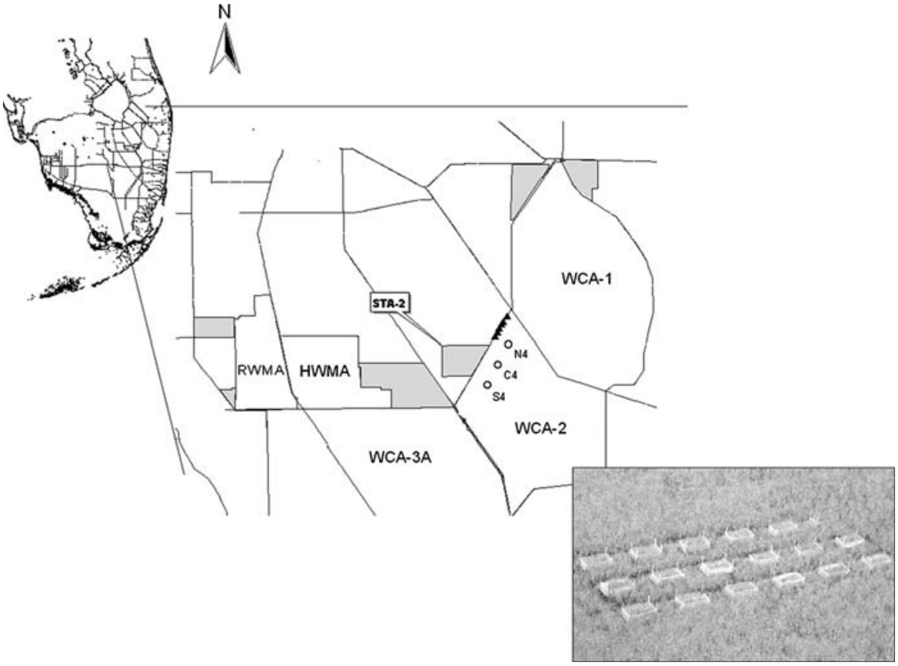
While considerable attention has focused on the P levels required to cause shifts in Everglades plant communities towards dominance by undesirable species such as cattail, the capacity of native vegetation to assimilate excess P without showing a measurable change in morphology or physiology is not well understood. Furthermore, the utility of such measures as early indicators of P enrichment has not been assessed. We conducted a 3-year field study to evaluate the short-term effects of P enrichment on sawgrass—the most widespread native species in the Everglades. Our objectives were to document the effect of different P loads on various plant and soil characteristics and to identify those most sensitive to P enrichment. This information provides a basis for predicting wetland responses to STA-based restoration and selecting sensitive indicators of P enrichment in this oligotrophic wetland.

Methods

Study area

The experiment was conducted in western Water Conservation Area 2A (WCA-2A), which is the receiving area for STA-2 discharges (Fig. 1). In April 1998, three sites were selected for the study, each located approximately 4 km away (designated N_4, C_4, S_4) from the northwest levee (L-6) across which STA-2 discharges occur. Sawgrass stands are the dominant vegetation throughout this region and are broken only occasionally by wet prairies or sloughs. Nutrient conditions at all sites were typical for the oligotrophic Everglades, with water and soil TP concentrations of <10 μg/l and 300–500 mg/kg, respectively. From a hydrologic perspective, the N_4

Fig. 1 Map of South Florida and the northern Everglades (enlarged) showing stormwater treatment area locations (shaded regions), Water Conservation Areas (WCAs), Rotenberger Wildlife Management Area (RWMA), and Holeyland Wildlife Management Area (HWMA). Small black triangles along the NW border of WCA-2A represent STA-2 discharge locations



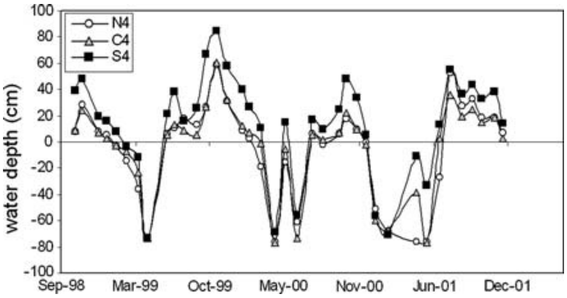


Fig. 2 Hydrographs of N_4, C_4, and S_4 sites during the study period of October 1998 to December 2001

and C_4 sites were similar to each other compared to the wetter S_4 site as indicated by monthly water level measurements taken manually at each site during the experiment (Fig. 2). At each site, the experimental area was chosen to encompass an area of relatively homogeneous sawgrass cover and height.

Experimental design

At each site, eighteen 1.25 × 2.4 m (~3 m^2) plots were established by enclosing an area of the marsh with transparent 0.6-m high Palruff® walls. The plots were set up as three rows of six plots each, spaced 2.4 m apart to minimize the possibility of P exchange between plots (Fig. 1). The walls were pushed a little way into the ground (~3–5 cm) in a way that would not sever any large plant roots. The walls were then held in place by tying them to aluminum poles at the corners of each plot. The plots were rectangular rather than square, so we were able to lean over the side and effectively sample away from the edges. Because the walls did not fit together perfectly, there was some water exchange with the surrounding marsh through corner openings ~3–4 cm wide. In this way, the plots were not completely sealed off from the outside environment.

Plots were randomly assigned to three different treatment groups (n = 6), which included high P (0.4 g/m^2/year) and low P (0.1 g/m^2/year) additions and controls, which received no P additions. Dosing was done 6 times (October 1998, June and October of 1999 and 2000, and June 2001). Phosphorus was added as slow-release, granular Triple Super Phosphate (P_2O_5; TSP) coated with a Polyon® polymer (Pursell Industries, Inc., Sylacauga, AL, USA). The thickness of the polymer coating allowed for gradual and complete release over a ~3 mo. period.

Soil and plant tissue nutrient analysis

All plant and soil data were collected from the inner portion (at least 30-cm away from the walls) of the plots at random locations. Soil and plant tissue nutrients were sampled at the beginning of the experiment in October 1998 and then semi-annually until December 2001, although some plant data were not collected due to fires. Soils were sampled by extracting cores from randomly selected locations in each plot using a 3-cm diameter T-handle corer inserted to a depth of 10 cm. Three samples of living leaves and rhizomes were collected from three randomly selected plants within each plot and combined into a single sample. All soil and plant nutrient samples were stored at approximately 4°C before being processed for total nitrogen (TN) using a Carlo-Erba (Milan, Italy) Model NA 1500 Series 2 elemental analyzer and for TP using standard methods (EPA Method no. 365.4).

Plant measurements

Sawgrass measurements were taken initially on October 1998 and then semi-annually until December 2001. Numbers of live and dead leaves per plant, maximum leaf heights (cm), and leaf diameters at mid-leaf height (mm) were recorded on three randomly chosen plants from the west, central, and east portions of each plot. Live and dead leaf densities were recorded less frequently (annually) due to the amount of time and labor required to collect those data. To estimate plant densities, a 1-m^2 quadrat was placed in the middle of each plot and the number of individual ramets counted. In addition, general vegetation surveys were conducted annually to document species composition. In January 2002, aboveground biomass (live and dead leaves) was estimated by digital photography where the vegetation is photographed against a black background. The images are reduced to three colors representing live (green), dead (red) and no (black) vegetation and the number of pixels of each are counted and converted to biomass units based on regression formulae developed by Smith et al. (2000).

Data analysis

Data from individual sites were subjected to normality and homogeneity of variance tests and subsequently analyzed by repeated-measures ANOVA. Plant biomass, a parameter that was only measured at the end of the study, was log-transformed and tested by one-way ANOVA. When a significant treatment effect was detected ($\alpha = 0.05$), comparisons among specific groups for each sample date were then conducted using Tukey's Honest Significant Difference tests (Statistica ver. 4.5).

Preliminary statistical analyses

Initial statistical tests showed that virtually all data, with the exception of a few parameters on just a handful of sampling dates, were found to be normally distributed and have statistically equal variances. As such, the data were not subjected to any transformations given that the F test is remarkably robust to both deviations from normality and heterogeneity of variances (Hsu 1938; Box 1954a, b; Box and Anderson 1955; Lindman 1974). ANOVA *F* and *P* values are listed in Table 1.

Results

Considerable variation in environmental conditions occurred during the course of the experiment. A fire passed through the N_4 and C_4 plots in June 1999 while the S_4 plots burned in June 2001. As a result, no dead leaves were present to enumerate in the fall of 1999 for the N_4 and C_4 sites and although short live leaves were present (the plants had grown new shoots by the sampling date), they were not counted at this time. Both live and dead leaves were absent in June 2001 at the S_4 site. Plant tissue and soil nutrient samples were collected, and leaf diameter and plant densities recorded, at S_4 just prior to the fire. However, we missed collecting data on plant heights and leaf densities at this time since the site burned before the next sampling trip that was to occur a few days later. Following the 1999 fire, the plot walls were immediately replaced. In 2001, they were not since the experiment ended shortly thereafter. In addition to these fires, two tropical storms occurred in October of 1999 and 2000 and a severe drought occurred during the winter–spring of 2001.

Soil nutrients

Baseline (October 1998) soil TP concentrations averaged 365 ± 13, 281 ± 13, and 305 ± 10 mg/kg (0–10 cm layer, average of all 18 plots) at N_4, C_4, and S_4, respectively. During the dosing period,

Table 1

Parameter	Site	*F*	*P*	Parameter	Site	*F*	*P*
Soil TP	N_4	1.28	0.29	Plant heights	N_4	1.33	0.22
	C_4	2.31	0.05		C_4	10.37	0.00
	S_4	1.69	0.17		S_4	4.60	0.00
Rhizome TP	N_4	3.41	0.01	Leaf diameters	N_4	2.73	0.00
	C_4	2.96	0.02		C_4	5.04	0.00
	S_4	5.54	0.00		S_4	2.50	0.01
Live leaf TP	N_4	5.60	0.00	Live leaf densities	N_4	2.38	0.04
	C_4	2.37	0.04		C_4	5.09	0.00
	S_4	2.42	0.04		S_4	1.44	0.24
Rhizome N:P	N_4	3.07	0.01	Plant densities	N_4	2.42	0.04
	C_4	3.47	0.01		C_4	11.11	0.00
	S_4	3.78	0.01		S_4	10.13	0.00
Live leaf N:P	N_4	3.24	0.01	Dead biomass	N_4	1.53	0.29
	C_4	3.47	0.01		C_4	5.90	0.04
	S_4	3.78	0.01		S_4	3.70	0.09
				Live biomass	N_4	16.24	0.00
					C_4	0.00	0.96
					S_4	5.11	0.05
				Total biomass	N_4	5.32	0.04
					C_4	7.35	0.02
					S_4	10.04	0.01

concentrations were consistently highest in the HP plots and lowest in control plots (Fig. 3a), but exhibited considerable temporal variation among sites. As a result, significant differences only occurred between the HP and C plots in December 2001 at C_4. Treatments did not differ with respect to soil TN and TC throughout the study (data not shown).

Tissue nutrient concentrations

Baseline rhizome TP concentrations at all three sites were initially similar among all treatment groups and < 250 mg/kg at all sites. After 7 months, TP concentrations in the rhizomes of HP plants at C_4 and S_4 were significantly higher than in those of the LP or control plants (Fig. 3b). This trend generally was maintained throughout the study period although variability within the treatment groups grew larger after fire and drought events. At N_4 the HP treatments were significantly different from the controls but not the LP treatment on most dates, except the last. Similar patterns were observed for live leaf TP concentrations, although the response was slower. The HP treatments had significantly higher TP concentrations than the LP or control groups, which were similar to each other, on most dates after 5-99 (Fig. 3c). In contrast, no treatment effects on leaf or root TN concentrations were detected (data not shown).

Leaf TN:TP ratios were significantly lower in HP compared to LP or control plants by 11-99 at N_4, 11-01 at C_4, and 6-00 at S_4. The magnitude of difference between these two groups generally increased throughout the study period at N_4 and C_4 (Fig. 3d). The LP and control groups were more often similar than not and there was only one significant difference between the two (S_4, 6-01). Rhizome TN:TP concentrations also reflected the increasing concentrations of TP. TN:TP was significantly lower for HP plants compared to the controls between 1 and 2 years into dosing (Fig. 3e). However, because of increased variability in rhizome TP (discussed above), differences in TN:TP ratios, although generally maintaining a similar pattern among the treatment groups, lost statistical significance toward the end of the study period.

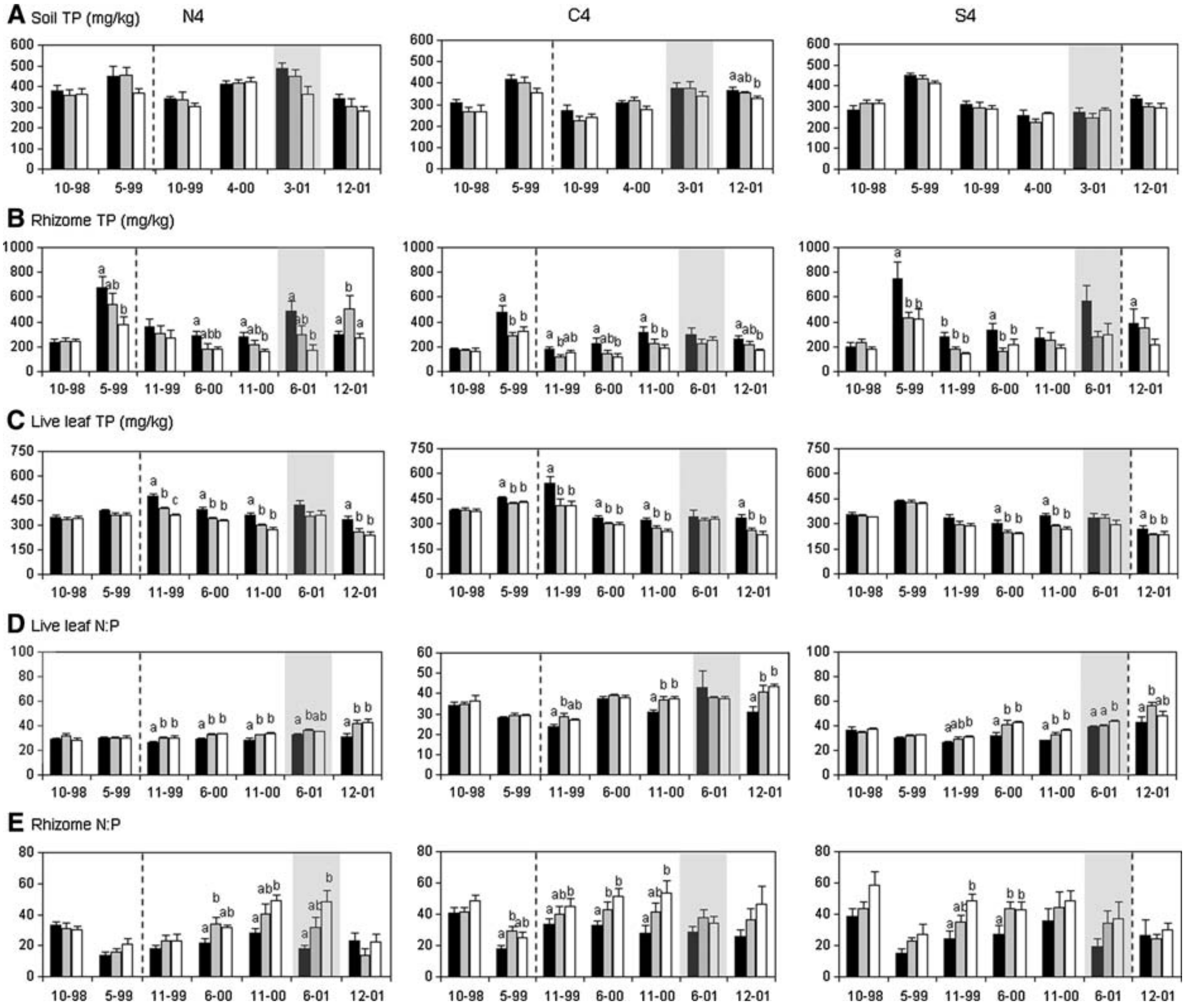


Fig. 3 Soil and plant tissue TP concentrations over time (dark-shaded bars = HP treatment, light-shaded bars = LP treatment, open bars = control; means with the same or a shared letter are statistically equal; error bars represent standard error of the mean; dashed vertical line separates pre- versus post-fire sampling, gray block represents sampling during drought period; n.s. = not sampled)

Plant height

At the N_4 site, plant heights were statistically similar among treatments throughout the study, even though values for the HP group were higher than both the LP and control groups after 6-00 (Fig. 4a). At the C_4 and S_4 sites, heights of HP plants were significantly greater than those of LP or control plants after 20 mo. (6-00) and 25 mo. (11-00), respectively. This treatment effect was lost at the S_4 site on the last sampling date (12-01), presumably because S_4 plants were still recovering from the June 2001 fire.

Leaf diameter

Enrichment effects on mid-height leaf diameter were not observed at the N_4 site until 12-01 (Fig. 4b) when HP plants had larger values than both LP or control plants. At the C_4 site, significant differences among all three treatments emerged in 11-00, with HP plants having the largest leaf diameters and control plants having the lowest. Treatment effects at S_4 also appeared in 11-00, at which point HP plants were taller than those of the other two groups. Similar to the trend in plant height, his difference was lost at S_4

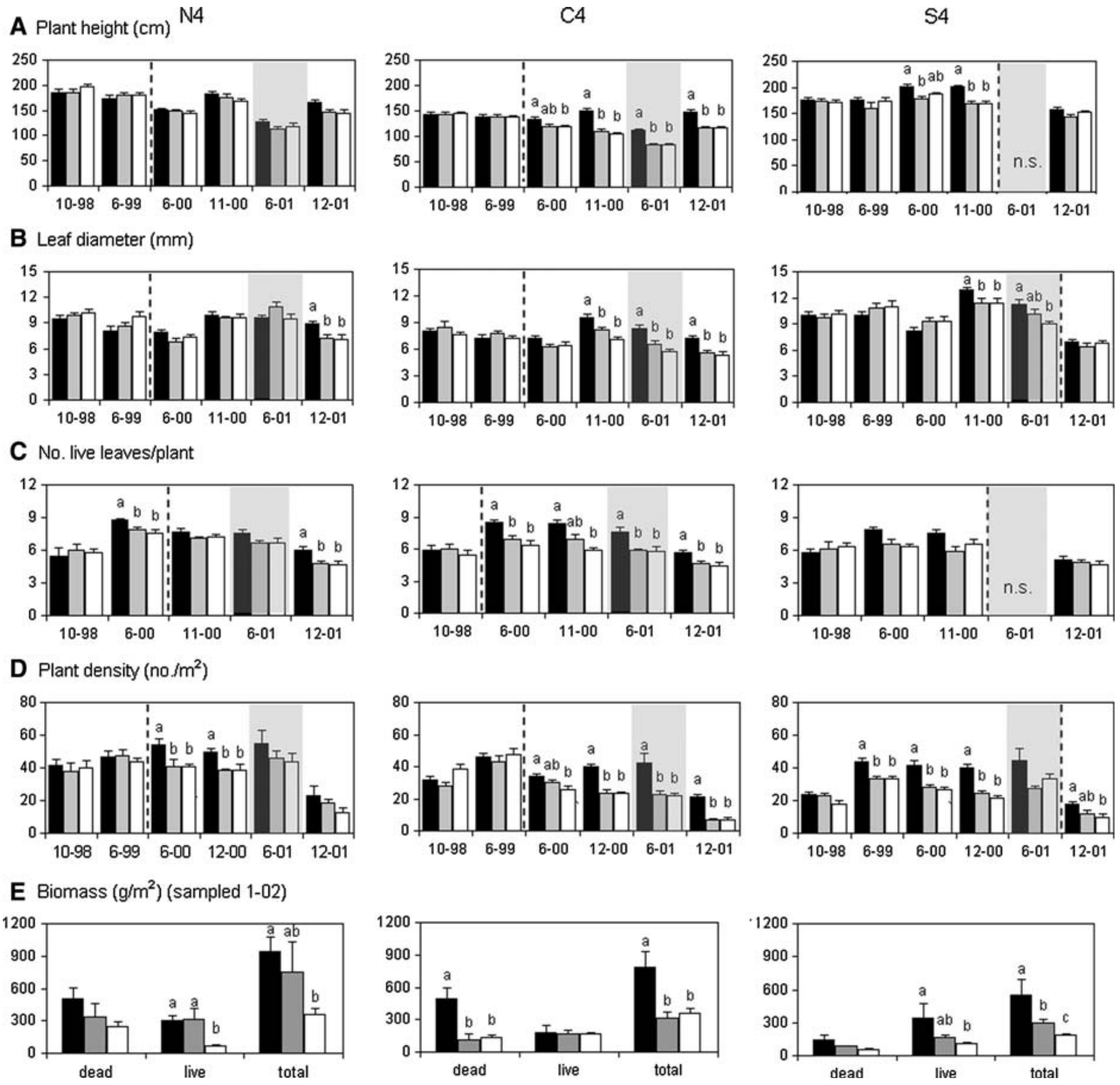


Fig. 4 Plant and stand attributes over time (dark-shaded bars = HP treatment, light-shaded bars = LP treatment, open bars = control; means with the same or a shared letter are statistically equal; error bars represent standard error of the mean; dashed vertical line separates pre- versus post-fire sampling, gray block represents sampling during drought period)

by 12-01—a time when the plants were still recovering from fire.

Live and dead leaf numbers

By June 2000, HP plants at N_4 and C_4 had greater numbers of live leaves than either LP or control plants, which were similar to each other (Fig. 4c). This trend continued throughout the study period, although statistical significance was lost on two dates at N_4 (11-00, 6-01). At S_4, the treatment groups showed a similar pattern, but the differences were not statistically significant. Dead leaf densities did not exhibit any consistent or significant patterns among the different treatment groups at any site (data not shown).

Plant density

Although initially similar at all three sites, plant densities showed obvious and consistent treatment effects over time with HP plots quickly attaining higher plant densities than either LP or control plots, which were similar to each other (Fig. 4e). The effect was significant at the S_4 site after 8 months (6-99) and at N_4 and C_4 after 20 months (6-00). Because of increased within-group variability, these differences were not statistically significant on 6-01 or 12-01 at N_4 and on 6-01 at S_4. At C_4, the trend was significant throughout the study period.

Biomass

At the N_4 site, dead biomass was highest in the HP plots, lower in the LP plots, and lowest in the control plots; however, these differences were not statistically significant (Fig. 4e). At C_4, the HP plots were statistically higher than the LP or control groups and no significant treatment effects were observed at S_4. Live biomass was significantly higher in the HP and LP treatments compared to the control at N_4. At C_4 no significant effects were observed. At S_4, the HP treatment yielded significantly higher live biomass than the control. The LP group fell midway between the HP and control groups and was statistically similar to both. Total biomass showed the strongest response to P dosing. Total biomass was significantly greater in HP plots than in LP and control plots at all three sites. At C_4, the LP group was significantly higher than the control group.

Species composition

Species survey data (not shown) showed that all plots remained virtually 100% sawgrass throughout the study, with only occasional occurrences of other species such as *Sagittaria lancifolia* L., *Nymphaea odorata* Soland, *Peltandra virginica* (L.) Kunth, *Cephalanthus occidentalis* L., *Psylocaria nitens* (Vahl.) A. Wood, and *Polygonum hydropiperoides* Michx. in very small numbers.

Although data were not collected from outside the enclosures (i.e., unwalled control areas), there was no noticeable effect of the walls on plants growth. In other words, plant heights, densities, etc. inside the control treatments were visually indistinguishable from those outside. Other experiments in the Everglades have quantitatively demonstrated no significant effects of enclosing marsh vegetation (Newman et al. 2001, 2004).

Discussion

The spatial distribution of key species and changes in community composition are perhaps the most widely used vegetation indicators of anthropogenic impacts in wetlands and the basis for adaptive management (Galatowitsch and van der Valk 1996; Weieher et al. 1996; Posey et al. 1997; Weinstein et al. 1997; Stein and Ambrose 1998; Detenbeck et al. 1999; Visser et al. 1999; Mushet et al. 2002; Hinkle and Mitsch 2005; Teal and Weishar 2005). Research on the effects of eutrophication on Everglades vegetation also has focused on community change, in particular the conversion of sawgrass and slough communities to monotypic cattail stands (e.g., Davis 1994; Craft et al. 1995; Rutchey and Vilchek 1999). These community shifts typically occur over many years in locations where soil P concentrations already have been elevated. We found that changes in the stand characteristics of sawgrass, a species adapted to extremely low P levels, can occur before soil enrichment and long before any shift towards more aggressive, nutrient-loving species is observed.

Our findings support the idea that monitoring specific characteristics of native vegetation can provide an early warning of enrichment and allow for action before additional P accumulation and the onset of more pronounced community-level impacts. While vegetation monitoring is commonly used within the context of adaptive management, species area cover and community composition may not be as useful in systems where plant phenology or tissue nutrient status of extant monotypic stands are the first variables to exhibit change. This “within-species” approach has, in fact, been used with other freshwater taxa (Craft et al. 2007), as well as salt marsh macrophytes (Wigand et al. 2007), macroalgae (Fong et al. 1998), and seagrasses (KunSeop et al. 2004).

Sawgrass stands in our experimental plots exhibited several responses that might serve as rapid and sensitive indicators of low-level P enrichment. Elevated concentrations of TP in the rhizomes of sawgrass receiving doses of 0.4 g/m^2/year were detected within a year or less at all three sites. Thus, sawgrass tissue TP content and TN:TP ratios appear to be good indicators of enrichment and precursors to visible, structural change. Plant heights, densities, and leaf thickness also showed enrichment effects, but took longer to respond (~1.5–2 year). We cannot speculate on when enrichment effects on aboveground biomass may have appeared because we estimated this parameter only once at the end of the treatment period. However, it is noteworthy that total biomass was the only measure to show a significant effect of the 0.1 g/m^2/year dosing rate.

Treatment differences for some of the above variables were lost at certain sites on two different sampling dates—June 2001 and Dec 2001. In some of these cases, the general patterns among treatments (i.e., HP > LP or C) were maintained but statistical significance was lost. To a certain extent, this finding depends upon the statistical methods used. In our analysis, Tukey's test was used to compare specific means, which yields conservative results. More sample replication may have reduced the within-group variance that led to this outcome. In other cases, the patterns themselves were lost. While the reasons for this are unclear, the June 2001 sampling date followed a fairly severe drought period that may have altered the expression of enrichment effects. Results of the December 2001 sampling may be related to the P-dosing having ended well before (6 months) to this last sampling date. In addition, December may be a less desirable time to sample since plant growth and vigor are diminished at this time of year. Finally, it is not known to what extent the fires affected these variables. Certainly, the translocation of carbohydrates and nutrients from roots and rhizomes to re-growing shoots could influence variables like rhizome P and N:P. Despite these confounding factors, however, live leaf TP, plant density, leaf diameter, and total biomass still exhibited significant differences at the end of the study.

Similar responses of sawgrass to P enrichment were observed in another northern Everglades location within a comparable time-frame but at much higher loading rates (4.8 g/m^2) by Chiang et al. (2000) and in the southern Everglades at loading rates as low as 0.04 g/m^2 by Daoust and Childers (2004). As in our study, these other investigators documented no detectable change in the species composition of sawgrass-dominated plots during their enrichment experiments. Inter-study differences in the loading rate at which responses were detected could be related to the particular dosing and measurement methods used by different investigators or to background differences in P levels among experimental locations. For example, among our 3 studies, the lowest background soil P occurred at the site used by Daoust (1998) and the highest at the site used by Chiang et al. (2000). Similarly, plant variables at our S_4 and C_4 sites appeared more sensitive than those at the N_4 site where soil P was higher. These patterns suggest that sawgrass in different areas receiving STA discharges may vary in their sensitivity to P loading rates based on antecedent soil P levels. Despite such differences, all variables in the different treatment groups within each site were statistically equal at the beginning of the study but exhibited significant separation thereafter. Thus, the results collectively show that predictable and measurable changes in sawgrass occur relatively quickly in response to P enrichment and prior to any shifts in species composition.

In contrast to these vegetation changes, evidence of soil enrichment was weak or absent based on the soil nutrient data that we collected. These findings are consistent with those of Newman et al. (2004), who found that tissue P concentrations in Everglades slough vegetation responded more quickly to P enrichment than either soil or porewater P levels. In addition to removing P from the porewater, plants may have assimilated P directly from the surface water via adventitious roots as it was slowly released from the pellets at the soil surface. The responsiveness of soil measures to P enrichment might be improved by sampling only the surface layer (e.g., Noe et al. 2002) instead of the larger (0–10 cm) depth fraction we analyzed. However, because of their unconsolidated and heterogeneous nature, surface soils in the Everglades are difficult to sample in a consistent manner, yield more variable estimates of soil properties (Corstanje et al. 2006) and, therefore, still may not be as sensitive as biological measures of P enrichment from a statistical standpoint.

The lack of changes in species composition during this 3-year experiment is noteworthy given that fire created opportunities for plant establishment by eliminating light attenuation as a factor inhibiting germination. Only a very small number of species other than sawgrass were present at various times throughout the study and cattail was never documented in any of the plots. While cattail has been shown to respond aggressively to P enrichment and to be competitively superior to sawgrass under P-enriched conditions (Newman et al. 1996; Miao and Sklar 1998), the probability and timing of a species shift likely is dependent on numerous factors. The low levels and relatively short duration of P enrichment may have been insufficient to promote cattail germination and seedling survival. The study location was far from any large areas of cattail, and, while cattail has wind-dispersed seeds, this species does not appear to have persistent seed banks in the Everglades (van der Valk and Rosburg 1997, Leeds et al. 2002). Finally, the surface fires that occurred during the experiment temporarily removed most of the above-ground biomass from the plots, but may not have been severe enough to create gaps in the sawgrass canopy for a sufficient period of time to allow other species to establish. Even at sites where nutrient conditions are suitable for cattail expansion, this dependence on the timing of seed dispersal, disturbance, and the convergence of other environmental conditions may result in a lag time between P enrichment and cattail establishment as predicted by Wu et al. (1997). Thus, a reliance on species shifts alone to detect P impacts may not be suited to the adaptive management framework currently being developed for Everglades restoration, which emphasizes the need for early detection of ecosystem responses to allow for proactive management actions.

Current restoration efforts require “population-level measures” whereby scientists and managers can gauge the success and any unintended consequences of restoration actions. While changes in vegetation community and landscape patterns provide the ultimate measures of restoration success (RECOVER 2004) as well as downstream nutrient impacts from STA operation (USACOE 1994), population measures such as nutrient content and stand characteristics may provide sensitive and relatively rapid indications of the effects of changes in nutrient loading caused by hydrologic restoration measures.

The Everglades is a dynamic, disturbance-prone ecosystem; therefore, indicators also need to be sufficiently robust to reliably detect changes in wetland nutrient status. In this study, we documented that sawgrass responded predictably to low-level P loading despite natural fluctuations in hydrology (flooding, drought), fire, and the natural seasonality of plant vigor. The metrics we used are fairly easily measured without specialized equipment and, therefore, are suitable for routine, rapid assessment. Live leaf TP, live leaf densities, plant densities, and total biomass showed significant treatment effects that were largely maintained through the kinds of disturbances mentioned above. And, while it is not clear that significant changes in sawgrass stand characteristics portend future undesirable community-level shifts (e.g., conversion of sawgrass to cattail), these changes have their own ecological consequences. As described in the introduction, increased sawgrass stature, density, and production can alter habitat quality for other native species, fire intensity, and possibly landscape patterns related to the maintenance and recovery of the historic ridge and slough landscape.

Conclusion

Restoration of the Everglades includes the construction and operation of STAs that in the process of improving hydrology and water quality will still deliver a certain amount of excess P to this wetland. Many of the areas receiving STA discharges have not been previously exposed to excess P loading and contain various mixtures of native vegetation including sawgrass as a dominant species. Monitoring a suite of simple sawgrass metrics including tissue P, plant density and height, leaf diameter, and stand biomass should provide a sensitive and robust means of detecting unintended P enrichment as a consequence of hydrologic restoration measures.

Acknowledgement This work was funded by the South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406.

References

Box GEP (1954a) Some theorems on quadratic forms applied in the study of analysis of variance problems: I. Effect of inequality of variances in the one-way classification. Ann Math Stat 25:290–302

Box GEP (1954b) Some theorems on quadratic forms applied in the study of analysis of variance problems: II. Effect of inequality of variances and of correlation of errors in the two-way classification. Ann Math Stat 25:484–498

Box GEP, Anderson SL (1955) Permutation theory in the derivation of robust criteria and the study of departures from assumptions. J Royal Stat Soc 17:1–34

Chiang C, Craft CB, Rogers DW, Richardson CJ (2000) Effects of 4 years of nitrogen and phosphorus additions on Everglades plant communities. Aquat Bot 68:61–78

Chimney MJ, Goforth G (2001) Environmental impacts to the Everglades ecosystem: a historical perspective and restoration strategies. Water Sci Tech 44:93–100

Corstanje R, Grunwald S, Reddy KR, Osborne TZ, Newman S (2006) Assessment of the spatial distribution of soil properties in a Northern Everglades marsh. J Environ Qual 35:938–949

Craft C, Vymazal J, Richardson C (1995) Response of Everglades plant communities to nitrogen and phosphorus additions. Wetlands 15:258–271

Craft C, Krull K, Graham S (2007) Ecological indicators of nutrient enrichment, freshwater wetlands, Midwestern United States (U.S.). Ecological Indicators 7:733–750

Crozier GE, Gawlik DE (2001) Avian response to nutrient enrichment in an oligotrophic wetland, the Florida Everglades. Condor 104:631–642

Daoust R, Childers D (2004) Effects of low-level phosphorus additions on two freshwater Everglades wetland communities. In: Determination of the effects of phosphorus addition on several Everglades marsh communities, M.S. Thesis, Florida International University, Miami, FL, pp 82–159

Davis SM (1994) Phosphorus inputs and vegetation sensitivity in the Everglades. In: Davis SM, Ogden JC (eds) Everglades: the ecosystem and its restoration. St. Lucie Press, Delray Beach, FL, pp 357–378

Detenbeck NE, Galatowitsch SM, Atkinson J, Ball H (1999) Evaluating perturbations and developing restoration strategies for inland wetlands in the Great Lakes Basin. Wetlands 19:789–820

Fong P, Boyer KE, Zedler JB (1998) Developing an indicator of nutrient enrichment in coastal estuaries and lagoons using tissue nitrogen content of the opportunistic alga, *Enteromorpha intestinalis* (L. Link). J Exp Mar Biol Ecol 231:63–80

Galatowitsch SM, van der Valk AG (1996) Characteristics of recently restored wetlands in the prairie pothole region. Wetlands 16:75–83

Hinkle RL, Mitsch WJ (2005) Salt marsh vegetation recovery at salt hay farm wetland restoration sites on Delaware Bay. Ecol Eng 25:240–251

Hsu PL (1938) Contributions to the theory of Student's t test as applied to the problem of two samples. Stat Res Mem 2: 1–24

KunSeop L, Short FT, Burdick DM (2004) Development of a nutrient pollution indicator using the seagrass, *Zostera marina*, along nutrient gradients in three New England estuaries. Aquat Bot 78:197–216

Leeds JA, Smith SM, Garrett PB (2002) Seedbanks and their potential role in the vegetation dynamics of a Northern Everglades Marsh. Fla Sci 65:16–34

Lindman HR (1974) Analysis of variance in complex experimental designs. W. H. Freeman & Co., San Francisco

McCormick PV, Newman S, Miao S, Gawlik DE, Marley D (2002) Effects of anthropogenic phosphorus inputs on the Everglades. In: Porter JW, Porter KG (eds) The Everglades, Florida bay and coral reefs of the Florida keys: an ecosystem sourcebook. CRC Press, Boca Raton, FL, p 83

Miao SL, Sklar FH (1998) Biomass and nutrient allocation of sawgrass and cattail along a nutrient gradient in the Florida Everglades. Wetl Ecol Manage 5:245–263

Mushet DM, Euliss NH Jr, Shaffer TL (2002) Floristic quality assessment of one natural and three restored wetland complexes in North Dakota, USA. Wetlands 22:126–138

Newman S, Grace JB, Koebel JW (1996) Effects of nutrients and hydroperiod on Typha, Cladium, and Eleocharis: implications for Everglades restoration. Ecol Appl 6:774–783

Newman S, Kumpf H, Laing JA, Kennedy WC (2001) Decomposition Responses to Phosphorus Enrichment in an Everglades (USA) Slough. Biogeochem 54:229–250

Newman S, McCormick PV, Miao SL, Laing JA, Kennedy WC, O'Dell MB (2004) The effect of phosphorus enrichment on the nutrient status of a northern Everglades slough. Wetl Ecol Manage 12:63–79

Noe GB, Childers DL, Edwards AL, Gaiser E, Jayachandran K, Lee D, Meeder J, Richards J, Scinto LJ, Trexler JC, Jones RD (2002) Short-term changes in phosphorus storage in an oligotrophic Everglades wetland ecosystem receiving experimental nutrient enrichment. Biogeochem 59: 239–267

Pietro K, Bearzotti R, Chimney M, Germain G, Iricanin N, Piccone T, SamFilippo K (2006) STA performance, compliance and optimization. Chapter 4. 2006 South Florida environmental report. South Florida Water Management District, West Palm Beach, FL

Posey MH, Alphin TD, Powell CM (1997) Plant and infaunal communities associated with a created marsh. Estuaries 20:42–47

RECOVER (2004) CERP Monitoring and assessment plan: part 1 monitoring and supporting research: restoration coordination and verification (RECOVER): Jacksonville, Fl, United States Army Corps of Engineers, and West Palm Beach, Fl, South Florida Water Management District. Available online: http://www.evergladesplan.org/pm/recover/recover_map.cfm

Rutchey K, Vilchek L (1999) Air photointerpretation and satellite imagery analysis techniques for mapping cattail coverage in a northern Everglades impoundment. Photogramm Eng Rem Sens 65:185–191

Sklar F, McVoy C, Zanzee R, Gawlik DE, Tarboton K, Rudnick D, Miao S (2002) The effects of altered hydrology on the Everglades. In: Porter JS, Porter KG (eds) The Everglades, Florida bay and coral reefs of the Florida keys: an ecosystem sourcebook. CRC Press, Boca Raton, FL, p 39

Smith SM, Newman S (2001) Growth of southern cattail (*Typha domingensis*, Pers.) in response to fire-related soil conditions in a northern Everglades marsh. Wetlands 21:363–369

Smith SM, Garrett PB, Leeds JA, McCormick PV (2000) Evaluation of a non-destructive field method for estimating live and dead aboveground biomass in monospecific wetland macrophyte stands using a hand-held digital camera. Aquat Bot 67:69–77

Smith SM, Newman S, Garrett PB, Leeds JA (2001) Effects of above- and below-ground fire on soils of a northern Everglades marsh. J Environ Qual 30:1998–2005

Stein ED, Ambrose RF (1998) A rapid impact assessment method for use in a regulatory context. Wetlands 18:379–392

Teal JM, Weishar L (2005) Ecological engineering, adaptive management and restoration management in Delaware Bay salt marsh restoration. Ecol Eng 25:304–314

United States Army Corps of Engineers (1994) Clean Water Act Section 404 Permit. No. 199404532. U.S. Army Corps of Engineers. Jacksonville District, Jacksonville, FL

Urban N, Davis SM, Aumen N (1993) Fluctuations in sawgrass and cattail densities in Everglades Water Conservation Area 2A under varying nutrient, hydrologic and fire regimes. Aquat Bot 46:203–223

van der Valk AG, Rosburg TR (1997) Seed bank composition along a phosphorus gradient in the northern Florida Everglades. Wetlands 17:228–236

Visser JM, Sasser CE, Chabrek RH, Linscombe RG (1999) Long-term vegetation change in Louisiana tidal marshes. Wetlands 19:168–175

Weieher E, Wisheu IC, Keddy PA, Moore DRJ (1996) Establishment, persistence, and management implications of experimental wetland plant communities. Wetlands 16:208–218

Weinstein MP, Balletto JH, Teal JM, Ludwig DF (1997) Success criteria and adaptive management for a large-scale wetland restoration project. Wetl Ecol Manage 4:111–127

Wigand C, McKinney RA, Cole ML, Thursby GB, Cummings J (2007) Varying stable nitrogen isotope ratios of different coastal marsh plants and their relationships with wastewater nitrogen and land use in New England, USA. Env Mon Assess 131:71–81

Wu Y, Sklar FH, Rutchey K (1997) Analysis and simulations of fragmentation patterns in the Everglades. Ecol Appl 7:268–276