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RESEARCH ARTICLE

Assessing Impacts of Hydropattern Restoration of an Overdrained Wetland on Soil Nutrients, Vegetation and Fire

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Abstract

Restoring hydrology to overdrained wetlands can facilitate restoration of degraded ecosystems. In the northern Everglades, the Rotenberger Wildlife Management Area (RWMA) became a rain-driven system as historic overland inflows were redirected. Consequently, the soil experienced severe drying, resulting in frequent muck fires, oxidation and a shift in vegetation composition. In July 2001, the RWMA hydropattern restoration began utilizing discharge from Stormwater Treatment Area 5 (STA-5), a constructed wetland. As a result, predischarge hydroperiods averaging 124 days increased to an average of 183 days. Soil total phosphorus (TP) concentrations in the topsoil layer did not significantly change from predischarge (637 mg/kg) to postdischarge (633 mg/kg) concentrations. Muck fires appear to be the catalyst for rapid alterations in the bioavailability and solubility of P. Prior to muck fires, soil P pools were 88% organic P and 12% inorganic P, shifting to 49% organic P and 51% inorganic P measured after a muck fire. Sawgrass (*Cladium jamaicense*, OBL) and Cattail (*Typha domingensis*, OBL) cover approximately 75% of the RWMA area as dominant or codominant species. Predischarge vegetation community composition documented obligate (OBL) and facultative wetland (FACW) species, each composing 46% of all species surveyed. Postdischarge vegetation compositions shifted to 59% OBL and 39% FACW species. In addition, there were significant elevations in tissue nutrient concentrations, TP, and total nitrogen, between pre- and postdischarge samples. An adaptive management approach to inflow and outflow operations will be an important part of successful wetland restoration.

Key words: everglades, hydropattern restoration, oxidation, phosphorus, soil, vegetation composition, wetlands.

Introduction

Rehydration of overdrained wetlands initiates the process of ecosystem restoration (Zedler 2000; Bruland et al. 2003). In the northern Everglades, historic flows have been greatly reduced, discontinued, or redirected due to anthropogenic influences. As a result, hydrology, soil oxic state, and vegetation have been dramatically altered. Shortened hydroperiods, that is, water depth and duration, directly affect soil properties, such as moisture and nutrient content, and vegetation composition (Kushlan 1990). Soils that once experienced infrequent drawdowns (water levels below the soil surface) can transition from anaerobic to aerobic conditions. During frequent and prolonged dry periods, organic wetland soils oxidize and cannot retain sufficient soil moisture to prevent soil combustion during a wildfire (muck or peat fire) (Wade et al. 1980; Gunderson & Snyder 1994). This increase in fire frequency and severity affects soil nutrient composition (Newman et al. 1998), resulting in significant shifts in nutrient storage pools (Faulkner & De La Cruz 1982; Smith et al. 2001). For example, nitrogen (N) can be volatilized and lost from the system, whereas phosphorus (P) can be mineralized from recalcitrant forms, organic to labile inorganic forms (Reddy et al. 1998).

Changes in hydrology and soil nutrient content, particularly P enrichment, are a few of the many driving factors shifting vegetation composition in wetlands, including the Everglades (van der Valk et al. 1994; Craft and Richardson 1997; Kellogg & Bridgham 2002). Historically oligotrophic wetlands can become eutrophic through high nutrient loading as a result of soil oxidation and muck fires, concentrating inorganic P (Smith et al 2001). Preimpact vegetation composition may shift in response to these nutrients and environmental factors through (1) the increased occurrence of upland plants replacing existing obligate wetland species or (2) the replacement of one wetland community by another wetland community, such as Sawgrass (*Cladium jamaicense*) encroaching into sloughs (Davis et al. 1994), and (3) the replacement of previously existing Sawgrass communities by Cattail (*Typha domingensis*) (Jordan et al. 1990; McCormick

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et al. 2002). Generally, plants adapted to low P environments such as Sawgrass are out competed and replaced by Cattail (Miao & Sklar 1998).

The Rotenberger Wildlife Management Area (RWMA), part of the northern Florida Everglades, is an extensively overdrained wetland. Since the 1950s, surface water inflows were redirected from the RWMA, resulting in a rainfall-driven system (SFWMD 2001). Consequently, the RWMA ecosystem has experienced marked disturbances and soil loss as a result of decreased hydroperiods, oxidation, and muck fires, elevating the soil P content (Newman et al. 1998). Historic landscape patterns indicate that the northern portion of the RWMA was probably a Sawgrass-dominated community and the southern portion was a ridge (Sawgrass) and slough spikerush (*Eleocharis* spp.) and water lily (*Nymphaea* spp.) community (C. McVoy, 2003, SFWMD, personal communication). Hydroperiod alterations facilitated the transition from obligate wetland species to less flood–tolerant higher-nutrient marsh plant species (Tobe et al. 1998). These plants are documented as occurring in overdrained, high-nutrient areas by aerial photography and vegetation maps of the Everglades (K. Rutchey, unpublished vegetation map)

The state of Florida identified the RWMA for hydropattern restoration using discharges from a Stormwater Treatment Area (STA). STAs are constructed filter marshes, designed to remove nutrients (particularly phosphorus) from agricultural and urban run-off prior to discharging into downstream areas. The South Florida Water Management District (District) began diverting discharges from STA-5 into the RWMA in July 2001 to initiate hydropattern restoration in accordance with the 1994 Everglades Forever Act (EFA). The EFA promotes Everglades restoration through improved water quality and hydrology. The average discharge total phosphorus (TP) concentrations from STA-5 were 74 ppb depending on inflow concentrations. Although water quality is not specifically a criterion for restoration success in RWMA, hydropattern restoration is dependent on meeting historic hydroperiods. To estimate the historic hydroperiods, initial RWMA stage targets were established using the district's Natural Systems Model (NSM), which simulates the hydrologic response of the predrainage Everglades based on a 36-year period of record for rainfall and climate data. In addition, the district incorporated an adaptive management approach to hydropattern restoration in RWMA, allowing managers the flexibility to adjust hydropattern components (stage levels and inflow and outflow operations) based on ongoing monitoring and research program data to attain NSM stage targets.

A monitoring and research program was implemented 3 years prior to reestablishing flows into RWMA to characterize the predischarge ecology of the ecosystem and document ecosystem response once hydropattern restoration was implemented. This program focused on the hydrology, water quality (primarily P species), soil nutrients and vegetation community structure. Long-term monitoring programs, in conjunction with an adaptive management approach, have been identified as the appropriate tools providing required data to institute program changes in order to meet desired restoration goals (Weinstein et al. 1997; Kentula 2000). The objectives of this paper are to (1) document predischarge (July 1999 to June 2001) marsh conditions and (2) report the initial postdischarge response (years 0–3, July 2001 to July 2004) to hydropattern restoration, focusing on changes in hydroperiods, soil biogeochemistry (i.e., specifically P species storage pools), and the vegetation community.

Study Area

The RWMA (Fig. 1) encompasses 11,784 ha within the Everglades Agricultural Area immediately north of WCA-3, west of the Miami Canal and 27 km south of Lake Okeechobee. Inflows into the RWMA are through the G-410 pump, located in the south end of the STA-5 discharge canal. Outflow from the RWMA is via the G-402 (A–D) gated culverts discharging into the Miami Canal. Currently, the RWMA contains remnant Sawgrass and tree island communities interspersed with monospecific stands of Cattail. There are widespread areas of

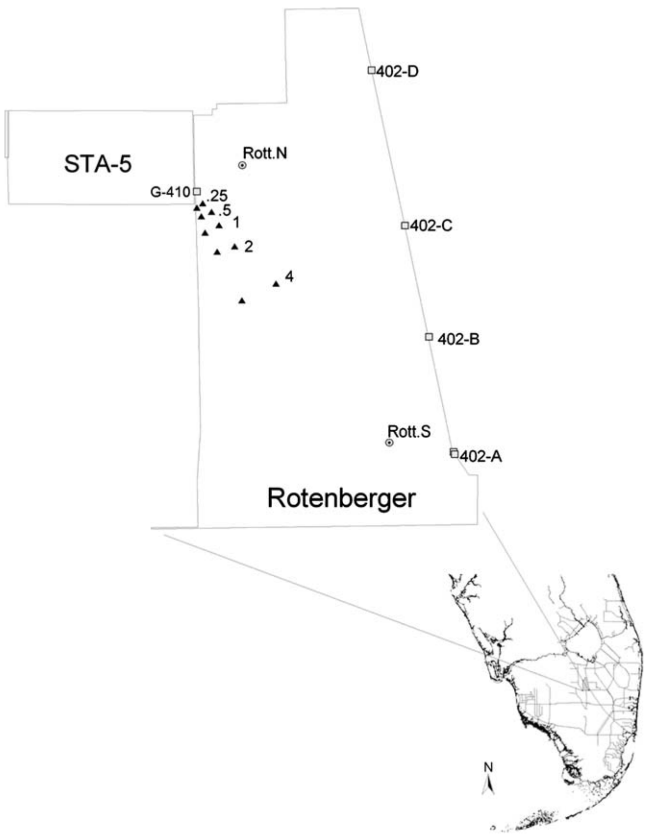

Figure 1. Map of the RWMA in South Florida showing field monitoring (triangles), stage gauge (Rott.N and Rott.S), and inflow and outflow sites. Inflow to RWMA from STA-5 is through the G-410 pump structure and outflow through the 402 A–D gated culverts structures.

grasses, panic grass (*Panicum* spp.), and woody species such as Carolina willow (*Salix caroliniana*) and Water primrose (*Ludwigia peruviana*), both of which are associated with disturbed, high-nutrient soils (Tobe et al. 1998). In addition, upland vegetation is widespread throughout much of the RWMA area.

Between 1980 and June 2001, the RWMA experienced 23 fires throughout the marsh. Ten events were classified as wildfires, eight were muck fires and five were prescribed burns to reduce the amount of the vegetation in an attempt to prevent muck fires. The wildfires and muck fires were ignited by lightening strikes associated with frequent summer thunderstorms. All fires were left to self-extinguish, with the exception of the June 1999 muck fire, which was of such extent and intensity, the district pumped in Miami canal water to extinguish the burn. Prior to 1999, culverts along the southern border created a southerly flow pattern draining the northern portion of RWMA. Thus, a majority of muck fires occurred in the north and west portion of the RWMA.

To detect water quality and soil nutrient gradients that may develop in response to STA-5 inflow, two monitoring transects were established immediately downstream from the G-410 inflow pump in 1997. Both transects extend in a southeasterly direction (flow path) away from the G-410 toward the marsh interior (Fig. 1). The northern transect travels in a more easterly trajectory toward the G-402B outflow structure, whereas the southern transect trends toward the G-402A structure. Five sampling platforms were established at 0.25, 0.5, 1.0, 2.0, and 4.0 km in each transect for sample collection.

Monitoring Methods

Hydrology

Mean internal water levels were determined by averaging values from two district remotely monitored stage gauges, Rotenberger North (Rott.N) and Rotenberger South (Rott.S) (Fig. 1). Internal RWMA stage elevation, used to dictate inflow and outflow operations, was reported as a combined monthly mean derived from both stations. The annual hydropattern restoration target for the RWMA was based on the target monthly stage elevations determined by the NSM (SFWMD 2001, Rotenberger Operations Manual), which was calibrated using a 31-year basin flow dataset (1965–1995). Monthly mean pre- and postdischarge marsh stage levels were compared to the NSM target stage levels to monitor when hydropattern targets were achieved.

Water Quality

When water depths were greater than 10 cm, monthly surface water samples were collected from the north (upstream) side of each sample platform using a peristaltic pump. Grab and autosampler composite water samples at the RWMA inflow and outflow structures were only collected when the structures were open. Inflow and outflow samples were analyzed for TP. Samples collected at the internal sites were analyzed for 18 parameters (Table 1), including the in situ physical parameters measured with the Hydrolab water quality multiprobe (Hach Environmental, Loveland, CO, U.S.A.). All sample collection and analyses have been conducted in accordance with analytical methods approved by either U.S. Environmental Protection Agency (USEPA 1993) or American Public Health Association (APHA 1989). Samples that required laboratory analysis were shipped overnight to the Florida Department of Environmental Protection laboratory.

Fire

From 1980 until 1996, the Florida Fish and Wildlife Conservation Commission (FFWCC) recorded fire occurrences within the RWMA. After each fire was extinguished, FFWCC mapped the extent of the burned areas, recording the burn outline via a global positioning system (GPS) device. Fire severity was noted, designating wildfires where only vegetation burned or a muck fire that included both vegetation and soil. In 1997, the district began mapping fires in RWMA by applying a similar protocol. However, the fire data collected by both agencies only produced a gross estimate of the percentage of vegetation or soil burned based on the burned area that was mapped versus unburned areas.

Soil Nutrients

Triplicate soil cores were collected annually within 50 m of each monitoring platform, using a 10-cm-diameter coring device to a depth of 20 cm. Each core was sectioned into 0–2, 2–10 and 10–20 cm portions, then transported to the laboratory for analysis of TP, total nitrogen (TN), total carbon (TC), bulk density, and ash content. Soil samples collected in 1998 and 2004 were further characterized using an inorganic phosphorus (iP) fractionation (Page et al. 1982; Reddy et al. 1998) scheme run on all core sections.

Emergent Macrophytes

Presence/absence plant surveys were conducted at each monitoring platform during the dry (March/April) and wet season (September/October), producing an annual species list for each monitoring site. Habitat designations were assigned to each species according to Tobe et al. (1998) and U.S. Fish and Wildlife Services National Wetlands Inventory wetland plant species list (Cowardin et al. 1979). Percentages of obligate wetland (OBL), facultative wetland (FACW), and facultative (FAC) species were determined at each site based on the total number of plants divided by the occurrence of OBL, FACW, or FAC plants per site. In an effort to document temporal and spatial changes in the vegetation community, permanent 0.25 m^2 plots were established at each of the 0.25, 1.0, and 4.0 km sites to monitor long-term changes in species

Table 1. Units and overall means with associated standard deviations of predischarge and initial marsh response period for surface water parameters collected monthly in the RWMA.

	RWMA Surface Water	
	Predischarge	*Postdischarge*
Parameter	*July 1998 to June 2001*	*July 2001 to June 2004*
Number of sampling events (months)	10	23
Temperature (°C)	25.2 ± 3.9	22.7 ± 4.5
Dissolved oxygen (mg/L)	4.5 ± 2.7	2.3 ± 1.3
Potential hydrogen (pH units)	7.6 ± 0.5	7.1 ± 0.2
Specific conductivity (μhos/cm)	278 ± 137	467 ± 174
SRP (mg/L)	0.007 ± 0.009	0.009 ± 0.010
Total DP (mg/L)	0.030 ± 0.030	0.015 ± 0.012
TP (mg/L)	0.072 ± 0.094	0.032 ± 0.020
Dissolved organic carbon (mg/L)	30.3 ± 16.2	22.0 ± 5.7
Ammonium (mg/L)	0.542 ± 1.402	0.035 ± 0.035
Nitrate (mg/L)	0.010 ± 0.020	0.004 ± 0.001
Nitrate/nitrite (mg/L)	0.012 ± 0.017	0.020 ± 0.072
Total dissolved nitrogen (mg/L)	2.5 ± 1.6	1.4 ± 0.4
TN	2.8 ± 2.2	1.4 ± 0.5
Dissolved sulfate (mg/L)	14.0 ± 38.3	6.7 ± 7.0
Alkalinity (mg/L)	139.6 ± 55.2	172.0 ± 55.5
Dissolved chloride (mg/L)	9.8 ± 14.7	47.8 ± 28.5
Dissolved calcium (mg/L)	57.3 ± 27.1	59.3 ± 17.2
Dissolved iron (mg/L)	261.8 ± 213.8	203.3 ± 147.2
Dissolved magnesium (mg/L)	5.1 ± 2.7	6.7 ± 2.6
Dissolved potassium (mg/L)	1.4 ± 1.7	3.2 ± 1.8
Dissolved sodium (mg/L)	6.5 ± 8.6	34.6 ± 20.7
Dissolved silica (mg/L)	3.6 ± 2.5	4.0 ± 3.28

composition. Tissue nutrients (TP and TN) were analyzed in live leaves and roots from Sawgrass and Cattail plants in triplicate for each sample plot.

Statistical Analysis

Water quality, soil, and macrophyte tissue nutrient data were analyzed using SAS Jump (version 5; SAS Institute, Inc., Cary, NC, U.S.A.). A one-way analysis of variance (ANOVA) was performed to test for significant differences in pre- versus postdischarge. For water quality, soil, and tissue nutrient data, all years comprising pre- and postdischarge periods were pooled. The soil data were separated by soil core layer, then combined all years together into pre- and postdischarge categories. Due to inconsistent sampling events from lack of water or logistical problems, spatial differences were determined by pooling the north and south transect values in the pre- and postdischarge years. Where ANOVA factors were significant, a post hoc Dunnett's test was used to identify significant treatment means. A significance level of $\alpha = 0.05$ was used for all analysis.

Results

Predischarge Conditions (July 1999 to June 2001)

Hydrology. The predischarge hydroperiod averaged 124 days ranging from 92 days during the 1999 drought year to 157 days in 2001. The monthly mean stage ranged from 3.3 m (National Geodetic Vertical Datum [NGVD], dry season) to 3.9 m (NGVD, wet season) (Fig. 2). These mean values were consistently below the NSM interim stage level targets for the RWMA, which ranged from 3.7 m (NGVD, dry season) to 4.1 m (NGVD, wet season) (Fig. 2). Corresponding stage level water depths ranged from 37 cm below the soil surface during the dry season to a high of 26 cm above the soil surface in the wet season. The primary water source was direct rainfall totaling

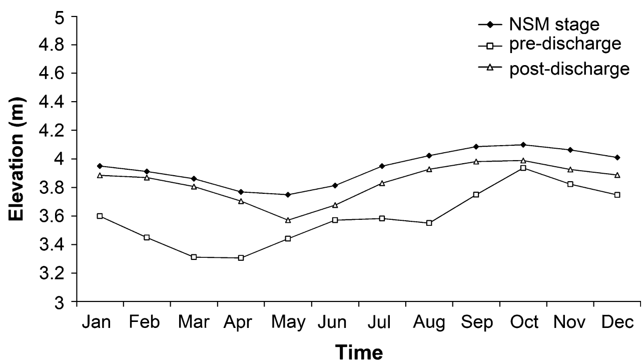

Figure 2. NSM stage regulation schedule for the RWMA compared to the monthly average stage elevations (NGVD) for stations Rott.N and Rott.S for predischarge (July 1999 to June 2001) and postdischarge (July 2001 to June 2004) periods.

411 cm. In June 1999, additional emergency water was pumped in from the Miami canal to extinguish an extensive muck fire burning a large tract of land within the RWMA. However, due to logistical constraints, water quality samples of the pumped Miami Canal water could not be collected.

Water Quality. Due to shallow water depths (<10 cm), only 10 sampling events occurred (out of a possible 42) during the predischarge period. Spatial differences in mean TP, mean dissolved phosphorus (DP), and soluble reactive phosphorus (SRP) concentrations were not significant. Therefore, all surface water samples collected each year and at all transect sites were pooled, yielding a mean TP of 0.071 mg/L (Fig. 3), DP concentration of 0.030 mg/L (Table 1), and SRP concentration of 0.007 mg/L (Table 1). A statistical summary for all water quality parameters pooled over sampling station by sampling period is provided in Table 1.

Soils. Bulk density did not vary significantly temporally or spatially. Mean TP soil concentration for the 0–2 cm section (631 mg/kg) was significantly greater than TP concentrations for the 2–10 cm (352 mg/kg) and 10–20 cm (173 mg/kg) sections. The 2–10 and 10–20 cm sections were not significantly different from each other (Fig. 4). TP, TN, and TC exhibited a spatial gradient, with significantly higher concentrations at the inflow (0.25 and 0.5 km) sites compared to the downstream sites (1.0, 2.0, and 4.0 km) in all soil layers. In contrast, the spatial gradient for percent ash content was significantly lower at inflow sites compared to downstream sites. Percent ash content and TC and TN concentrations were not significant between soil layers (Table 2).

Results of the inorganic phosphorus fractionation from 1998 are listed in Table 3. There were no significant differences between the different inorganic P storage pools spatially or with depth. Therefore, results were combined.

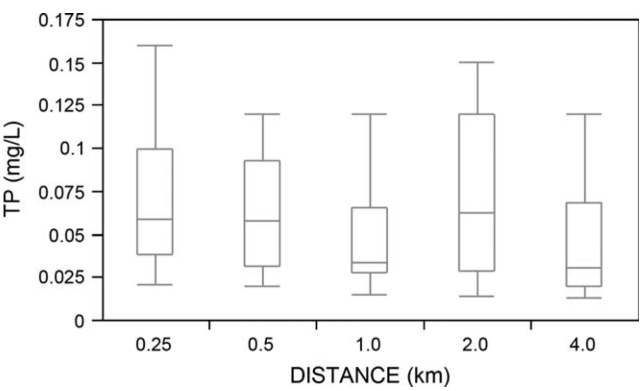

Figure 3. Predischarge mean TP concentrations in surface water at monitoring transect stations; all years are pooled for the predischarge period (July 1999 to June 2001). Whiskers represent the 5 and 95 percentiles, and the internal bar represents the sample median.

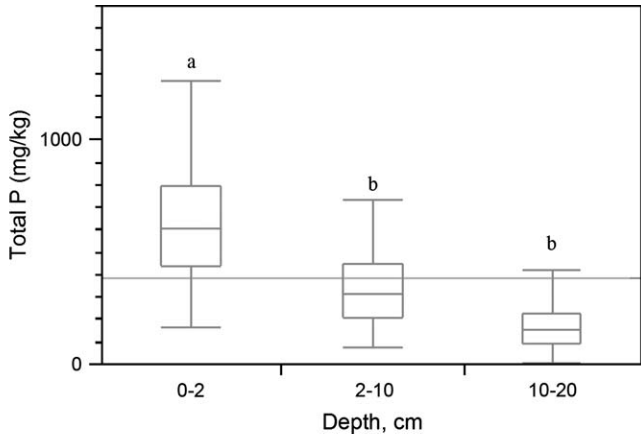

Figure 4. Overall mean TP soil content in mg/kg in 0–2, 2–10, and 10–20 cm layers; the line represents the average of all three layers. All years and all sampling stations pooled for the predischarge period from July 1999 to June 2001.

Additionally, the inorganic P pools were combined to represent the entire inorganic layer, then compared to the organic layer to show changes in these storage pools over time (Fig. 5). The inorganic phosphorus fractionation from 1998 shows that the organic P pool (bound, unavailable P) was the dominant P storage (88%) compared with the inorganic (bioavailable) storage pool (12%).

Emergent Macrophytes. The percentages of OBL (45.8%), FACW (46.2%), and FAC (7.9%) did not significantly vary either spatially or temporally; therefore, all data were pooled to represent predischarge conditions (Fig. 6). Although Sawgrass and Cattail (both OBL) were present at each site, the community was indicative of a system transitioning to an upland habitat. For example, grass

Table 2. Units and overall means of pre- and postdischarge periods for measured parameters of annually collected soil cores in the RWMA.

	Soil Depth (cm)		
Parameter	*0–2*	*2–10*	*10–20*
Predischarge			
Bulk density (mg/cm^3)	0.400a	0.280a	0.295a
TP (mg/kg)	637b	351a	176a
TN (mg/kg)	23,502	24,214	20,263
TC (mg/kg)	311,113	335,756	296,911
Ash content (%)	45.4	41.6	50.1
Postdischarge			
Bulk density (mg/cm^3)	0.335	0.325	0.392
TP (mg/kg)	644b	371a	161a
TN (mg/kg)	23,170	21,375	17,219
TC (mg/kg)	306,612	298,433	254,087
Ash content (%)	46.0	50.0	57.7

The years comprising pre- and postdischarge periods were pooled. Significant differences are between depths in the pre- and postdischarge data. Values with the same letter are not significantly different at $\alpha = 0.05$.

Table 3. Percentages of inorganic and organic phosphorus (oP) pools in RWMA soil were averaged for all layers and monitoring sites for 1998 and 2004.

	1998	*2004*
HCLSRP (Ca/Mg iP)	2.78	13.04
KCLSRP (Fe/Al iP)	0.03	0.05
NAOHSRP (readily available iP)	1.33	6.05
NAOHTP (Alkali extractable iP)	7.57	32.05
Residual P (oP)	88.28	48.81

species such as *Panicum* spp. (FACW) and broom grass (*Andropogon* spp.) (FACW), which can tolerate short-term flooded conditions, were prevalent at many sites. Facultative species such as Dog fennel (*Eupatorium capillifolium*), Butterweed (*Senecio glabellus*), American germander (*Teucrium canadense*), and Daisy fleabane (*Erigeron quercifolius*) were abundant at all sites and are typically found in disturbed drained soils at sites S.5, S1, S2, N1, and N2. However, a few species indicative of wet prairies and sloughs such as lance-leaf arrowhead (*Sagittaria* spp.), pickerelweed (*Pontederia* spp.), *Eleocharis* spp., and beak rush (*Rhynchospora* spp.) were present. No presence of bladderwort (*Utricularia* spp.), a species associated with low P environments typically found in Everglades sloughs, was recorded (Busch et al. 1998).

Sawgrass and Cattail nutrient concentration data were highly variable, and no significant differences were found spatially or temporally. Therefore, all data collected at each monitoring station and for each year were pooled and presented by species and plant component representative of the predischarge time period. Total P concentration in Cattail live leaves was 674 mg/kg, which was greater than the 420 mg P/kg in Sawgrass. Root TP concentrations were similar for each species, 358 and 338 mg/kg for Cattail and Sawgrass, respectively. Mean TN concentrations measured were 10,440 mg/kg within cattail live leaves and 11,054.8 mg/kg in Sawgrass. Root TN for Cattail and Sawgrass were 7,131 and 7,171 mg/kg, respectively.

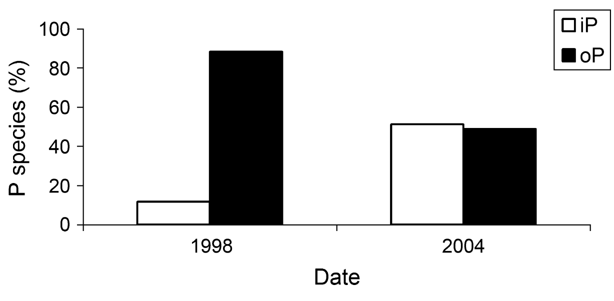

Figure 5. Inorganic (iP) and organic phosphorus (oP) percentage for soils collected in 1998 and 2004.

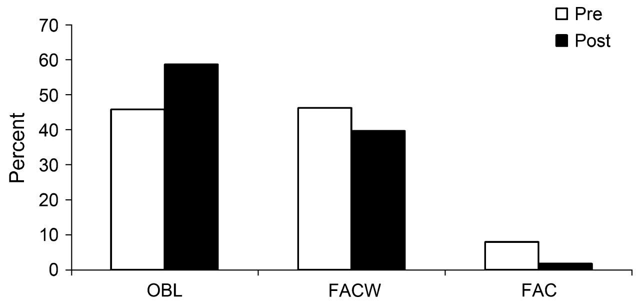

Figure 6. Percentage of obligate (OBL), facultative wetland (FACW), and facultative (FAC) plants for the pre- and postdischarge time periods.

Postdischarge Response (July 2001 to June 2004)

Hydrology. Inflow to the RWMA was primarily from rainfall totaling 364 cm, with an additional 109 cm of water discharged from STA-5 through the G-410 pump structure (SFWMD 2004). Water depths increased 27 cm compared to predischarge water depths. The marsh was flooded an average 182 days, ranging from 90 days to a high of 250 days. Monthly mean stage averaged 3.56 m (NGVD) and 3.98 m (NGVD) in the dry and wet season, respectively, which was slightly below the NSM interim stage targets (Fig. 2). These stages translate to water depth ranging from below the soil surface (−10.6 cm, dry season) to a high of 31.4 cm (wet season) and a mean depth of 20.2 cm.

Water Quality. Twenty-three surface water sampling collections were made out of a possible 36 months. The 0.25 km sites had significantly higher TP (0.057 mg/L) (Fig. 7), DP (0.030 mg/L), and SRP (0.021 mg/L) concentrations versus all other stations combined (0.5, 1.0, 2.0, and 4.0 km) for TP, DP, and SRP concentrations of 0.026, 0.011, and 0.007 mg/L, respectively. A complete listing of all surface water quality parameters for all stations is found in Table 1.

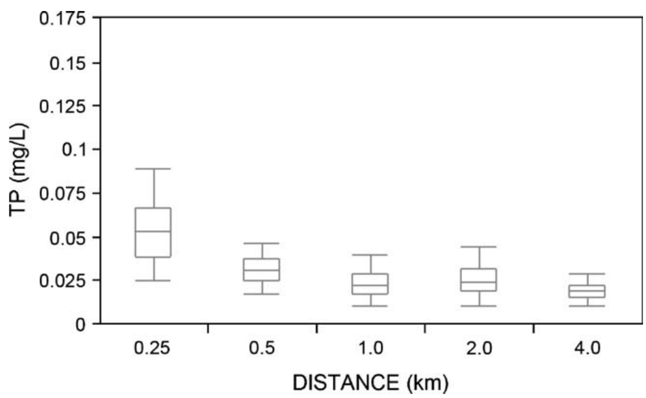

Figure 7. Spatial representation of postdischarge mean TP concentrations in mg/L from surface water measurements during the period from July 2001 to June 2004; all years are pooled. Whiskers represent the 5 and 95 percentiles, whereas the internal bar represents the sample median.

Fire. Due to the increase in hydroperiod from STA-5 discharges, the RWMA experienced increased periods of inundation with less severe soil drying during drawdowns. Soils remained moist, greater than 65% moisture content, throughout much of the dry season. Thus, fire frequency was reduced and no muck fires occurred. Throughout the entire postdischarge period, only one wildfire occurred in 2004, which burned approximately 90% of the marsh.

Soils. When all years were combined for each soil layer, the 0- to 2-cm section had significantly higher TP content (637 mg/kg) than the 2–10 cm (368 mg/kg) and 10–20 cm (162 mg/kg) layers (Fig. 8). Mean bulk density, percent ash, TN, and TC did not exhibit similar relationships with depth (Table 2). However, TN, TC, and TP were significantly higher when all soil layers and years were pooled at the 0.25 and 0.5 km (upstream) sites versus the 1.0, 2.0, and 4.0 km (downstream) sites. Percent ash and bulk density at the 0.25 and 0.5 km sites were lower in concentration than those at the 1.0, 2.0, and 4.0 km sites.

Results of the inorganic phosphorus fractionation from 2004 are listed in Table 3. There were no significant differences between the different inorganic storage pools spatially or with depth. Therefore, results were combined, representing the entire inorganic pool. The inorganic and organic P pools were then compared to show the changes in these storage pools over time. The results show that the inorganic P pool (bioavailable P) was the slightly dominant P storage (51%) (Fig. 5) compared with the organic P (bound, unavailable) storage pool (49%).

Emergent Macrophytes. The presence of OBL such as Cattail, Sawgrass, *S. lancifolia*, and *Pontederia cordata* increased in frequency at each monitoring site. Obligate wetland plant percentages increased to 58.6%, whereas

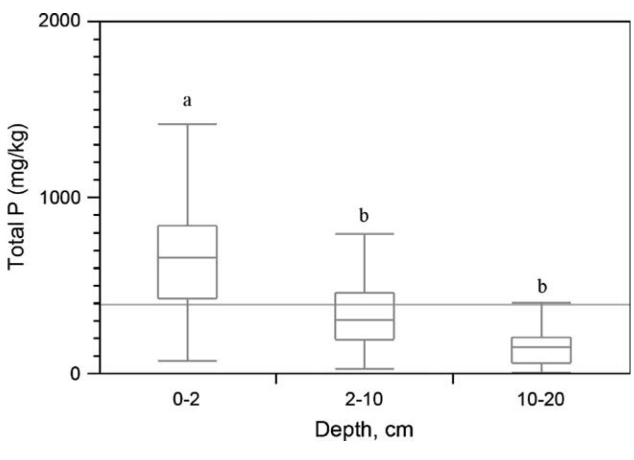

Figure 8. Overall mean TP concentrations in mg/kg separated by depth, 0–2, 2–10, and 10–20 cm layer for the postdischarge annual soil collections during the period from July 2001 to June 2004; all years and sampling stations are pooled. Line represents the average TP concentration of the three core depths combined. Different letters represent significant differences.

FACW and FAC plants both decreased to 39.6% and 1.73%, respectively (Fig. 6). Other obligate species such as *Utricularia foliosa* were noted sporadically. Cattail and Sawgrass remained the dominant vegetation present, collectively representing about 70–75% of the community. In addition, a mix of grasses (*Panicum* spp. and *Andropogon* spp.) and FACW species (*Solidago* spp., *T. canadensis* and *S. glabellus*) together comprised 25–30% of the remaining area. An increase was noted in the occurrence of *Salix caroliniana* and *Ludwigia peruviana*, both of which are associated with disturbed soils and considered successional species (Ewel 1990).

Mean TP concentrations in roots and leaves of Sawgrass and Cattail were significantly greater compared to those in the predischarge period. Cattail roots had a TP concentration of 1,039.5 mg/kg, whereas Sawgrass had a significantly higher root TP concentration of 1,340.0 mg/kg. Overall root TP concentrations were significantly higher than TP concentrations in live leaves of both species, with values of 933 and 506 mg/kg, for Cattail and Sawgrass, respectively.

Discussion

Hydrology

Changes to the operation and management of the hydrologic system were required to protect the natural resource value of this northern Everglades marsh. The internal stage gauge readings indicated that the system had no standing water much of the year, which led to low soil moisture content during the dry season. This combination of shortened hydroperiods and loss of soil moisture created an environment suitable for the combustion of organic soils and muck fires (Wade et al. 1980; Kushlan 1990), typically occurring at the end of the dry season (May/June in South Florida). Usually muck fires are ignited by lightening strikes associated with frequent thunderstorms.

Hydropattern restoration began in July 2001 with STA-5 discharges to RWMA. The NSM stage levels used to trigger the inflow and outflows from STA-5 were anticipated to maintain flooded or saturated soils for a majority of the year. Postdischarge stage data compared to predischarge data indicate a significant increase in hydroperiod, from 124 to 182 days. Associated water levels in postdischarge conditions increased approximately 24 cm, with a corresponding increase in soil saturation and moisture content.

Despite these improvements in hydrology, the RWMA still experiences a lack of flooded conditions in the late dry season. Water discharges from STA-5 have improved soil moisture content (>65%), preventing soil conditions conducive to muck fires. For example during the dry season in March/April 2004, a wildfire burned approximately 90% of the marsh; however, no muck fires were reported. The postdischarge response period is only 3 years to date.

Extended monitoring is required to determine if the changes in hydrology will continue to affect the fire frequency and intensity long term. Further adjustments to inflow and outflow operations may be required.

Soils

Previous studies have shown that oxidation and muck fires are the primary factors increasing soil P concentrations in the RWMA marsh (Faulkner & De La Cruz 1982; Newman et al. 1998). The soil monitoring data indicate that prior to STA-5 discharges the topsoil layers, considered the most reactive with the overlying water column containing the highest concentrations of P. Comparison of pre- and postdischarge soil nutrient concentrations revealed no significant changes either temporally or spatially. It should be noted that the predischarge sampling period was relatively short (4 years) compared to the amount of time in which the soils have been overly drained (approximately 60 years). Therefore, an increase in hydroperiod would be required to begin the process of attenuating P accretion stemming from years of muck fires and soil oxidation. An extended time period may be required to detect a significant reduction in soil nutrient concentrations.

iP Fractionation

Phosphorus storage in the sediment underwent significant shifts in storage pools due to physical and chemical influences. Between 1998 and 2004, the soil P storage pools in RWMA, shifted from bound organic residual P (unavailable to plants) to more labile bioavailable forms of inorganic P. The shift in soil P forms may have been initiated by reduced hydroperiods, causing oxidation and/or the occurrence of muck fires. A study by Smith et al. (2001) attributed the June 1999 muck fire as the catalyst for the rapid shift in P storage forms from organic P to inorganic P. This conclusion was based on comparing iP soil fractionation results conducted on muck burned soils collected within 1 week of the 1999 muck fire to the soil fractionation results in 1998.

In addition, Olila et al. (1997) showed that soil drainage and oxidation can promote significant shifts in the sediment storage pools of P from organic to inorganic forms through the mineralization of organically bound P into Ca/Mg- or Fe/Al-bound inorganic P.

From 2000 to 2004, no muck fires have occurred in RWMA. During this time, there has been an increase in organic P content and a decrease in inorganic P. Generally, significant changes in soil nutrient concentrations are a slow process, except during extreme events such as muck fires. Although soil oxidation may have contributed to gradual increases in soil TP concentrations, muck fires appear to be the primary factor in large increases in TP and bioavailable forms of P in the RWMA marsh.

The associated ecological impacts from a shift of recalcitrant unavailable P to more soluble bioavailable forms of P include (1) the potential for a perpetual cycle of eutrophication as more soluble forms of P continually flux into the water column (Reddy et al. 1998), (2) the promotion of Cattail growth especially in muck burned soils, and (3) facilitating shifts in vegetation community composition from low-P plants indicative of Everglades ecosystems to higher P–tolerant transition species such as *Salix caroliniana* and *Ludwigia peruviana*.

Emergent Macrophytes

According to Newman et al. 1998, the recent Cattail expansion in RWMA is driven primarily by the P content of the soil. Lowered soil elevations or depressions approximately 3–5 cm deep throughout the northwestern portion of the marsh were result of the 1999 muck fire. These depressions contained a more soluble, readily available form of P (inorganic) versus non–muck burned soils that were predominately organic P (Reddy et al. 1998; Smith et al. 2001). Dense Cattail stands quickly grew in the muck burned areas in response to the elevated bioavailable P (Shaver & Melillo 1984; DeBusk et al 1994). In non–muck burned soils, Cattail is present, although more widespread and less dense.

Increases in hydrology, as a result of STA-5 discharges, reduced the occurrence of less flood–tolerant plants, whereas obligate wetland plants became more prevalent. This shift to more typical Everglades wetland plant composition is supported by the increase in percentages of obligate plants in the postdischarge period compared to the predischarge period, despite increases in bioavailable P in the soil. It should be noted that the occurrence and density of Cattail stands also increased but were largely restricted to the areas it had previously occurred. However, this increase may also be contributing to the increase in obligates in postdischarge macrophyte surveys. A notable slough species, *Utricularia foliosa*, was recorded in 2003 after hydropattern restoration began; however, this has been, to date, the only occurrence possibly as a direct consequence of increased standing water.

The total TP content of Sawgrass live leaves and roots in RWMA was similar to the TP content in Sawgrass growing in moderately enriched areas of the Everglades that contain comparable soil TP concentrations (Miao & Sklar 1998). Cattail nutrient concentrations were comparable to those in Cattail plants growing in areas of the Everglades with low soil P content greater than 350 mg/kg (Miao & Sklar 1998), even though the RWMA soils are considered moderately enriched for the Everglades. One possible explanation is that Cattail may not be storing P due to the constant supply in the soil (Shaver & Melillo 1984). However, upon removal of, or a diminishing supply of, nutrients, Cattail may uptake and store P from the soil. The latter action, due to the uptake of P, could possibly reduce the rate of movement of a P front further into the marsh interior.

Predischarge macrophyte surveys in RWMA documented species that are less tolerant of flooded conditions and are defined by shorter hydroperiods. In some cases, these species are associated with higher soil nutrient concentrations. Traditional Everglades wetland species such as *Sagittaria* spp., *Pontederia cordata*, and *Rhyncospora* spp. were not as prevalent and slough species such as *Nymphaea odorata*, *Eleocharis* spp., and *Utricularia* spp. were no longer present. Although Sawgrass was a dominant species throughout much of the marsh, other taxa such as *Eupatorium* spp., *E. quercifolius*, and *Senecio glabellas* that are associated with shorter hydroperiods and disturbed drier soils were common. Additionally, several grasses such as *Panicum* spp. and *Andropogon* spp. were widespread at the monitoring sites and at several sites became the dominant or codominant species with Sawgrass and Cattail. All indications were the vegetation composition over time was transitioning into upland.

Postdischarge vegetation surveys documented an expansion of Cattail and increased stand densities most likely in response to the P storage pool changes in the soil when compared to predischarge surveys. Compared to low-P and P-impacted areas of the Everglades, Sawgrass live leaf and root TP concentrations equaled or exceeded concentrations levels in Sawgrass plants in impacted soils (Miao & Sklar 1998). Similar comparisons were made for Cattail tissue TP concentrations in live leaves and root concentrations equaling tissue levels of these plants found in impacted areas (Miao & Sklar 1998). Overall TP tissue nutrient concentrations in Cattail and Sawgrass significantly increased from predischarge to postdischarge collections, especially in root TP content of both species, possibly suggesting that more P is available for uptake.

Conclusions

The main goal of hydropattern restoration in the RWMA is to attenuate hydrology conditions that are conducive to muck fires, preventing further increases in soil P concentrations and the loss of organic soil matter. In addition, changes in hydroperiod will create conditions favorable for traditional Everglades marsh species and facilitate a shift in vegetation composition resembling this. These preliminary data indicate that this was successful for the short term. However, the data are preliminary and represent short-term trends. Long-term monitoring will be required to determine if these trends continue.

An adaptive management approach is currently used in RWMA, allowing the flexibility to manipulate inflows (STA-5 discharges) and outflows to obtain the desired stage levels and corresponding depths. Adaptive management recognizes that there are uncertainties with ecological restoration and ecosystems are complex. The premise is the process that allows for changes in restoration activities to be implemented when undesirable impacts have been identified. Such impacts can be detected, for example, with long-term monitoring programs. Therefore, additional operations adjustments will be required to achieve or maintain desired stage levels resembling historic hydrology then monitored for subsequent effects. Ecological data collected from the ongoing RWMA monitoring program will continue to assess the marsh response to reflooding and recommend changes, if necessary, in the operation of the system, thus facilitating wetland restoration.

Implications for Practice

- The alterations in hydrology had a cascading effect, driving changes in soil oxic state and vegetation community structure both sequentially and simultaneously.
- Rapid shifts in soil organic and inorganic P content were driven by muck fires, facilitating the spread of Cattail in these areas.
- Primary wetland vegetation community composition responses were to hydropattern restoration and secondary response to soil P forms evident in the transition to predominant obligate species in postdischarge and reductions in facultative wetland species.

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