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Recent Cattail Expansion and Possible Relationships to Water Management: Changes in Upper Taylor Slough (Everglades National Park, Florida, USA)

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Abstract Recent appearance of cattail (*Typha domingensis*) within a southern Everglades slough—Upper Taylor Slough (Everglades National Park)—suggests ecosystem eutrophication. We analyze water quality, nutrient enrichment, and water management operations as potential drivers of eutrophication in Upper Taylor Slough. Further, we attempt to determine why surface water phosphorus, a parameter used commonly to monitor ecosystem health in the Everglades, did not serve as an early warning for eutrophication, which has broader implication for other restoration efforts. We found that surface water total phosphorus concentrations generally were below a 0.01 mg L^{-1} threshold determined to cause imbalances in flora and fauna, suggesting no ecosystem eutrophication. However, assessment of nutrient loads and loading rates suggest Upper Taylor Slough has experienced eutrophication and that continued total phosphorus loading through a point-source discharge was a major driver. These nutrient loads, combined with increases in hydroperiods, led to the expansion of cattail in Upper Taylor Slough. We recommend other metrics, such as nutrient loads, periphyton and arthropod community shifts, and sediment core analyses, for assessing ecosystem health. Monitoring surface water alone is not enough to indicate ecosystem stress.

Keywords Everglades · Cattail · Water quality · Total phosphorus · Eutrophication · Point source

Introduction

Surface water quality and various pollutant standards have been used extensively to identify, monitor, and reduce aquatic ecosystem eutrophication (Lovett and others 2007; Wazniak and others 2007; Robarts and others 2008). Because surface water quality monitoring is relatively inexpensive and the methodologies well-established, natural resource managers rely heavily on these surface water data to make decisions about protecting and enhancing ecosystem health. Pollutant standards generally are designed to protect flora, fauna, and human health with the aim of preserving ecosystem integrity in the face of pressures from urban and agricultural development.

The Everglades developed as an ultra-oligotrophic freshwater marsh with flora and fauna adapted to low nutrient and ion conditions (Maie and others 2005; Wright and others 2009) and surface water quality is often used to monitor its health. One of the major pollutants in the Everglades is total phosphorus (TP) and much research has been conducted to establish surface water TP thresholds and standards (Craft and Richardson 1993a, 1993b; Craft and others 1995; McCormick and others 1996). The Everglades is the center of the world's largest and most expensive restoration efforts. A major portion of these efforts is designed to reduce TP concentrations discharged to Everglades wetlands from urban and agricultural runoff. Based on an extensive monitoring and research program, a TP criterion of 0.01 mg L^{-1} was established as a threshold beyond which imbalances in native flora and fauna occur (Florida Administrative Code, Rule 62-302.540). Throughout the northern Everglades, surface water TP concentrations exceed this criterion, resulting in

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large areas of cattail (*Typha domingensis,* Newman and others 1997; Weisner and Miao 2003; Hagerthey and others 2008) and other nutrient-related impacts.

The presence of dense cattail stands in the Everglades indicates nutrient enrichment, shifts in hydrology, direct physical disturbance, or some combination of each (Newman and others 1998; Weisner and Miao 2003; Boers and Zedler 2008). Cattail expansion is considered one of the final stages of Everglades nutrient enrichment, usually resulting from years to decades of TP enrichment of sediments, and generally preceded by more rapid changes in more sensitive components of the ecosystem such as periphyton (Hagerthey and others 2008). In the northern Everglades' Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge), nutrient enrichment (Harwell and others 2008) and decreased variability in water depths—a feature of managed water levels—led to cattail expansion from naturally sparse patches to dense stands of cattail at the perimeter canal and marsh interface (Newman and others 1997). Similarly, in an area just south of the Refuge—Water Conservation Area 2A—nutrient enrichment (Hagerthey and others 2008; McCormick and others 2009) and decreased water depth variability (McCormick and others 2009) have resulted in dense monotypic cattail through much of the area. In both of these areas, inflow TP concentrations are well above the TP criterion.

In the southern Everglades, Everglades National Park (ENP), TP concentrations in water delivered to Taylor Slough (Fig. 1) generally have been well below the TP criterion, except during extreme weather events and dry-downs. Despite these low inflow TP concentrations, cattail expansion was discovered recently in Upper Taylor Slough (Sadle 2008). The discovery of these recently formed cattail stands suggests the system has been experiencing detrimental impacts for years to decades and that surface water quality alone did not serve as an early warning indicator. The objective of this study was two-fold: (1) to determine potential causative factors of the recent cattail expansion; and (2) to determine if there were missed early warning signs that could have shown problems in advance of cattail expansion.

Methods

Study Area

The Taylor Slough watershed is a 40,900-ha (Armentano and others 2006) wetland, underlain by the Miami Oolite Formation (Randazzo and Jones 1997; Sutula and others 2001), and extends from the L31W canal to Florida Bay (Fig. 1). The upper reaches of Taylor Slough are narrow and are bordered to the northwest and southeast by marshes

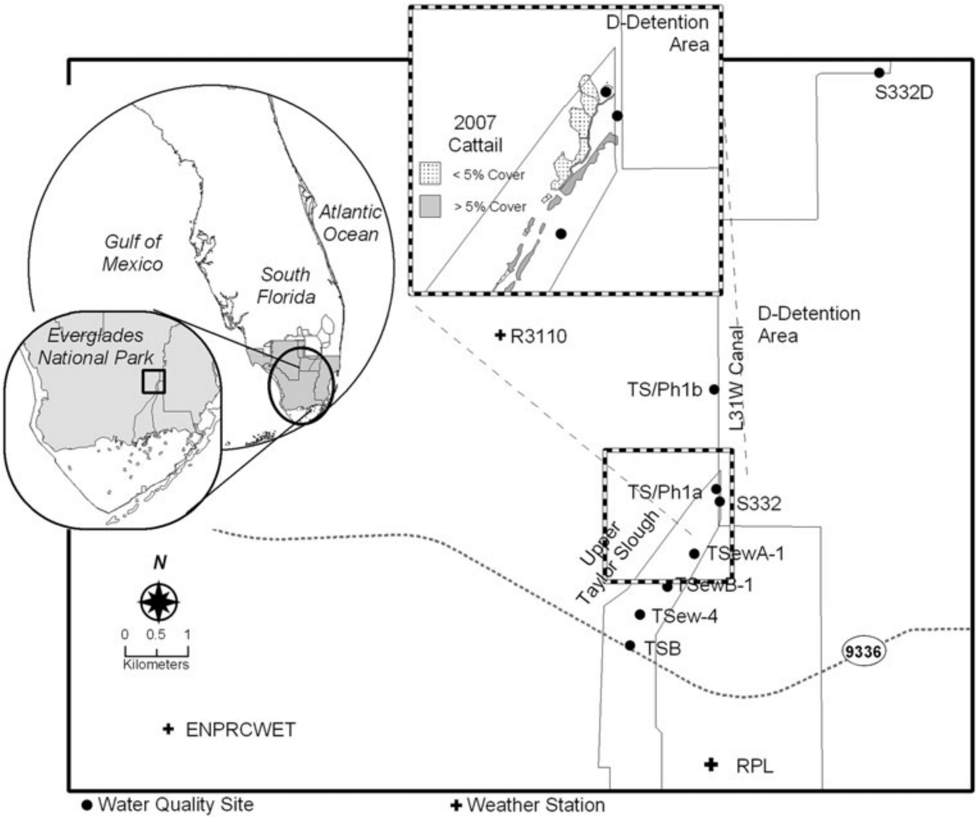

Fig. 1 Upper Taylor Slough surface water quality and weather monitoring sites. Upper inset shows the cattail expansion in 2007. Stage gages are located at the TSB and S332 water quality sites

10 to 30 cm higher in elevation (Armentano and others 2006). Prior to implementation of flood-control project construction in the mid-1900s, Taylor Slough was much like a river, delivering water to Florida Bay. Since the construction, significant losses of water from Taylor Slough have occurred (Van Lent and others 1993). Since the 1960 s, the system has been characterized by flora (e.g., muhly grass, sawgrass, spikerush, etc.; Armentano and others 2006) adapted to oligotrophic freshwater conditions (Maie and others 2005; Wright and others 2009).

This study focuses on Upper Taylor Slough (~200 ha), which extends from S332, a decommissioned discharge pump for L31W, southwest 2.7 km to Taylor Slough Bridge (TSB). The slough receives water from rainfall, upstream sheet and subsurface flow, and direct discharges (until 1999) from L31W (Harvey and others 2000). Taylor Slough subsurface flow is eastward, primarily due to low canal stages at the eastern boundary of ENP (Van Lent and others 1993; Harvey and others 2000). In the early 1980s, marsh sheet flow, serving as the headwaters to Taylor Slough, was almost eliminated as a result of this easterly subsurface flow (Van Lent and others 1993).

Beginning in 1999, three detention areas were constructed along ENP's eastern boundary as hydrologic barriers to reduce this eastward groundwater seepage from ENP marshes (SFNRC 2005; Brown and Caldwell 2007). The D-Detention Area, located at the head of Upper Taylor Slough, contains a variety of emergent vegetation including cattail, and soil TP concentrations since 2006 are greater than 600 mg kg^{-1}. Outflows from the D-Detention Area to L31W and ultimately Upper Taylor Slough occur infrequently as unmeasured sheetflow over a degraded levee at the western boundary of the detention area and north of S332 (HydroGeologic 2010, Fig. 1) when detention area water levels are high enough. Model results suggest that inflows into the northern reach of the D-Detention Area seep westward into L31W and short-circuit surface flows over the remainder of the D-Detention Area (HydroGeologic 2010). Hydrologic and TP transport modeling of the detention area further indicates most of the detention area groundwater and TP drains eastward away from Upper Taylor Slough (HydroGeologic 2010). Some westerly flow occurs with high canal inflows, but most is to the east.

Water Management Periods

We examined nutrient enrichment and water management changes over three periods: Period I—1985 through 1991; Period II—1992 through 1999; and Period III—2000 through 2008. Around 1980, the S332 pump began operation, directly discharging L31W canal water at a maximum rate of 4.7 m^3 s^{-1} into Upper Taylor Slough. The purpose of this discharge was to replace marsh sheet flow that used to hydrate the slough in the previous decade (Van Lent and others 1993). Previously, L31W water rarely entered the slough via overtopping the L31W bank at high canal stages or seepage through the bank. Although 1980 would have been the logical beginning of Period I, consistent water quality data only extend back to 1985. Period II begins when S332 discharge capacity tripled, from 4.7 to 14.2 m^3 s^{-1}, in an effort to restore a more natural hydroperiod to Taylor Slough. Based on 12-month, flow-weighted mean TP concentrations measured from late 1995 through 1998 at S332 and two adjacent structures, it was determined that tripling S332's capacity would not have adverse impacts on Taylor Slough water quality (Bearzotti 1999). Period III begins when the upstream detention areas were constructed, S332 was decommissioned, and the new pump station (S332D) began discharging upstream canal water into the D-Detention Area (Fig. 1).

From 1984 through at least 1992, an experimental drawdown of L31W and surrounding canals was implemented to facilitate agricultural operations east of L31W (Van Lent and others 1993). During dry periods, when upstream water sources were scarce—especially during the experimental drawdown—water deliveries to L31W were largely from local sources, including runoff from agricultural lands east of ENP (Van Lent and others 1993). At such times, nutrient concentrations in runoff from these surrounding agricultural areas were higher than those in water from upstream (Xue and Hill 2008).

Sampling Sites

Water quality sampling sites were located in the canal (at S332 and S332D) and slough (TS/Ph1a and b, TsewA-1, TsewB-1, Tsew-4, and TSB) (Fig. 1). Canal data were analyzed from S332 during periods I and II, and from S332D (discharge structure to D-Detention Area) during Period III after S332 was decommissioned. Even though S332 was decommissioned in 2000, TP data continued to be collected there until 2006. Because TP data from S332 and S332D during this overlap period (2000 through 2006) did not show significant differences, S332D data only were used from 2000–2009. Water was collected by grab sampling biweekly at S332 and S332D.

In the slough, the TSB site was monitored monthly with grab samples collected over all three periods, and had the longest period of record (1985 through 2009) of all slough sites. Three slough sites (TsewA-1, TsewB-1, and Tsew-4) were monitored monthly during part of Period II and III, with monthly grab samples collected between 1997 and 2006 (data provided by the South Florida Water Management District). The two remaining slough sites (TS/Ph1a and TS/Ph1b) were <0.3 km west of L31W and were monitored biweekly in Period III, and samples were collected by autosampler as time-proportional composite samples.

Rainfall, Atmospheric Deposition, Stage, Flow, and Water Quality Data

Rainfall, wet deposition, stage, flow, and water quality data were obtained from the South Florida Water Management District's data portal—DBHYDRO (http://my.sfwmd.gov/dbhydroplsql). Rainfall was the average of daily totals measured at the RPL and R3110 rainfall stations (Fig. 1). Wet atmospheric deposition was measured at the wet precipitation collector at the ENP research center (ENPRC-WET) (Fig. 1). Median values of rainfall TP concen trations were calculated to reduce the influence of extreme values due to bird droppings, insects, and other sources of contamination. Canal and marsh stage daily values were measured at S332 and TSB, respectively. Hydroperiods at TSB were calculated from daily difference between water stage and marsh elevation, and then determining the frequency of values greater than zero in each year. The marsh elevation at TSB (1.07 m) was determined from the United States Geological Survey's digital elevation model (USGS 2007). Upper Taylor Slough inflow is reported as daily flow from S332 for Period I and II. There was no discharge from S332 to the slough in Period III. Upper Taylor Slough outflow is measured biweekly at TSB for all three periods.

Grab samples were stored on ice and transported to the laboratory within four hours of collection. Time-proportional autosampling occurred once every three days, and samples were a composite of four 250 mL subsamples drawn every 18 hours. Most grab and autosampler samples were analyzed for TP by the South Florida Water Management District laboratory, and a smaller number of samples (sites TS/Ph1a and TS/Ph1b from 1999 through 2008) analyzed by the Florida International University laboratory. All water quality samples were collected and analyzed using state-certified, quality assurance/quality control procedures. Both laboratories are accredited through the National Environmental Laboratory Accreditation Program and certified by the Florida Department of Health, and both have a quality manual that follows the National Environmental Laboratory Accreditation Conference guidelines. In addition, both laboratories perform similarly in the Florida Department of Environmental Protection's annual laboratory comparison test (http://www.dep.state.fl.us/water/sas/everglades/), which is particularly important at the low TP concentrations analyzed in this study.

Temporal and Spatial Cattail Expansion

Although the occurrence of extensive cattail stands in Upper Taylor Slough was first documented by field surveys in 2007, digital aerial images collected in 1994, 1999, 2004, and 2009 were analyzed retrospectively to spatially map any temporal changes in cattail coverage. These images were photointerpreted and delineated into polygons utilizing a Datem digital photogrammetric workstation. Ground-truthing was performed on the 2009 image by using more than 260 Upper Taylor Slough field photographs to delineate major vegetation types including cattail, willow (*Salix caroliniana*), common reed (*Phragmites australis*), and other (everything else). These vegetation types and ground-truthing were applied to the previous images (1994, 1999, and 2004). We used these photointerpreted images and the 2007 field survey data (cattail characterized as greater than 5% cover) to estimate the expansion of cattail over time in Upper Taylor Slough.

Statistical Analysis

A cross-correlation analysis was performed on water quality data (TP, conductivity, chloride, sulfate, and total nitrogen) to screen for outlying values, and these outliers were removed (<1% of the data). Everglades nutrient concentrations, particularly TP, typically are at or near minimum detection limits (MDL). The TP MDL decreased from 0.01 to 0.004 mg L^{-1} in 1980, then to 0.002 mg L^{-1} in 2002 because of analytical improvements (Miller and others 2004). Values below the MDL were set equal to the detection limit minus 0.0001 mg L^{-1} to distinguish them from values that equal the MDL (Walker 1991). Twenty-three percent of TP data were below the MDL at TSB, 10% at S332, and <1% at S332D.

Nonparametric statistics were used for TP data because of non-normal distributions. Difference analyses among the three time periods were performed using the Mann-Whitney statistical test ($\alpha = 0.05$; XL-Stats 2010). Total phosphorus trends were analyzed over the three periods using modified seasonal Kendall's Tau analyses developed by Helsel and Hirsh (1991) for censored data. The magnitude of change in trends (MGT) of constituent concentrations through time was determined using the Akritas Theil-Sen trend line equation (Akritas and others 1995) obtained from the seasonal Kendall's Tau analysis. Percent rate of change was determined as:

$$MGT = \left(\frac{y_i - y_{i-1}}{y_{avg}}\right) * 100,$$

$$y_i = mx_i + b,$$

$$y_{i-1} = mx_{i-1} + b,$$

where y_i = constituent concentration at time t, y_{avg} = average of all y_i, m = Sen's slope, b = intercept, and x_i = date.

Total phosphorus loads were calculated as the product of discharge and concentration. Flow data are daily and represent a complete time-series dataset over the entire period of record. The TP concentration dataset is incomplete with missing data, thus we use piece-wise linear interpolation to estimate missing daily values (Shih and others 1998). Monthly loads were determined as the sum of daily loads for months in which there was flow. Loads were multiplied by appropriate flows to determine flow-weighted mean (FWM) concentrations. Total phosphorus loads from S332D could not be used to determine loads to Upper Taylor Slough, because S332D flows did not represent actual discharges downstream due to infiltration in the detention areas downstream.

Change-point analysis (Change-Point Analyzer V2.3, Taylor 2001; Gavit and others 2009) was applied to TP concentrations and loads to identify shifts over time. Kendall tau correlation analysis was applied to TP, flow, and stage data. Analysis of covariance (ANCOVA; Statistical Analysis Software) was used to test slope differences between cumulative annual rainfall and cumulative annual flow presented in a double-mass plot. The plot was used to show the effect that L31W discharges to Upper Taylor Slough had on TSB flows.

Seasons were defined as wet (June through October) and dry (November through May) based on Taylor Slough rainfall patterns. These periods correspond to the wet and dry seasons analyzed by Armentano and others (2006).

Results

Rainfall and Atmospheric Deposition

Monthly rainfall generally remained below 40 cm, with few exceptions. The median annual rainfall over the three time periods was 144 cm. The median for Period I was lower ($p < 0.1$) than Period II and III medians. Summary statistics for rainfall are presented in Table 1.

Median annual TP concentration in wet deposition was 0.005 mg L^{-1} from 1987 through 2009. Based on wet deposition TP and annual rainfall from 1961 through 2008, we estimated a TP wet deposition rate of approximately 0.007 g m^{-2} yr^{-1}. Measurement of dry deposition TP concentrations is problematic because of sampling apparatus contamination, but likely is similar in magnitude to wet deposition (Redfield 2002), suggesting total (wet plus dry) TP deposition rates of less than 0.02 g m^{-2} yr^{-1}. This approach to estimating total atmospheric loading rates provides a result similar to that observed by Ahn (1999; 0.04 g m^{-2} yr^{-1}). Richardson and Huvane (2008) estimated a TP concentration of 0.011 mg L^{-1} in wet and dry deposition. If this concentration is applied to estimate loading rate, it results in values ($\sim$0.015 g m^{-2} yr^{-1}), similar to those estimated in this study. These approaches to estimate total TP deposition rates yield annual loads that are much lower than surface water TP loads (see below).

Flow

Annual flows during Period II and III were higher ($P < 0.01$) than flows during Period I at S332 (Table 1). Annual flows in Period II at TSB were greater than Period I and III ($P < 0.01$). A double-mass plot of cumulative rainfall versus cumulative flow at TSB indicates a significant increase in slope (ANCOVA; $P < 0.01$) at the end of Period I. Higher Period II and III annual flows relative

Table 1 Summary statistics of relevant environmental conditions in Upper Taylor Slough

Environmental Parameter	Period	Unit	Median	Minimum	Maximum	Mean
Rainfall	I	cm	113	92	147	119
	II	cm	151	110	192	149
	III	cm	144	121	177	147
Flow - S332	I	m^3 yr^{-1}	4.7×10^7	3.7×10^7	6.3×10^7	4.8×10^7
	II	m^3 yr^{-1}	15.8×10^7	7.5×10^7	25.1×10^7	5.0×10^7
Flow - TSB	I	m^3 yr^{-1}	2.6×10^7	0.9×10^7	10.4×10^7	3.5×10^7
	II	m^3 yr^{-1}	10.1×10^7	4.0×10^7	10.4×10^7	8.6×10^7
	III	m^3 yr^{-1}	8.5×10^7	1.9×10^7	1.1×10^7	7.8×10^7
Stage - S332	I	m	1.05	0.42	1.75	1.06
	II	m	1.25	0.57	1.94	1.24
	III	m	1.35	0.31	1.99	1.34
Stage - TSB	I	m	1.04	0.07	1.62	0.96
	II	m	1.18	0.19	1.77	1.12
	III	m	1.04	0.05	1.69	1.02
Hydroperiod - TSB	I	months	3.5	2.6	5.5	3.9
	II	months	7.6	5.1	9.7	7.6
	III	months	5.6	3.1	7.4	5.6

to Period I are a result of management operations and not changes in rainfall, as observed in the double-mass plot of cumulative rainfall versus cumulative flow at TSB (Fig. 2).

Stage

Daily canal stages in L31W exceeded the bank elevation (1.63 m; Fig. 3) more frequently (30%) in Period III than Period I (0.1%) and II (1%). Stages in L31W (Table 1) were lowest in Period I, coinciding with the experimental drawdown operations, and increased in Period II and Period III. Stages at TSB in Periods II and III (Table 1) were higher than in Period I ($P < 0.01$). Period II and III TSB stages were greater than Period I ($P < 0.01$). Change-point analysis shows canal and TSB stages increased after 1991, near the end of the experimental drawdowns.

Hydroperiods

The median hydroperiod at TSB was longer in Periods II ($P < 0.01$) and III ($P < 0.05$) than in Period I (Table 1). Period I hydroperiods at TSB ranged from 2.6 to 5.6 months; Period II hydroperiods ranged from 5.1 to 9.7 months; and Period III hydroperiods ranged from 3.1 to 7.4 months. The longer hydroperiods in Period III relative to Period I at TSB are linked to higher canal stages maintained along the eastern boundary of ENP.

Total Phosphorus

Concentrations. Median TP concentration at S332 during Period I were higher ($P < 0.05$) than at S332 and TSB during Period II and Period III (Table 2). Median TP concentration at TSB during Period I were greater

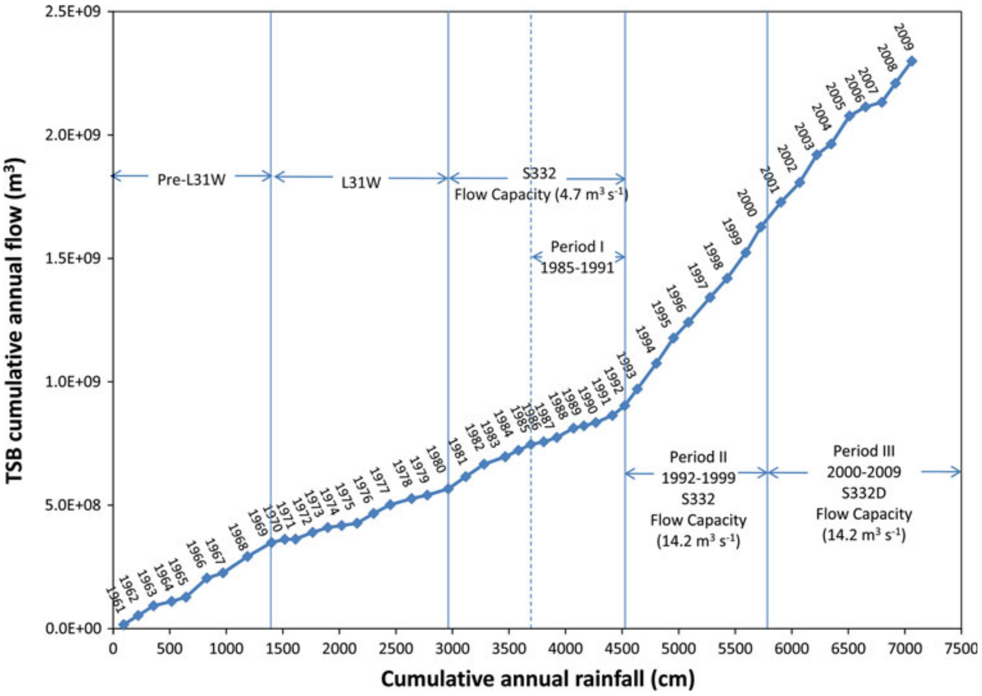

Fig. 2 Cumulative TSB annual flow versus cumulative annual rainfall in Upper Taylor Slough

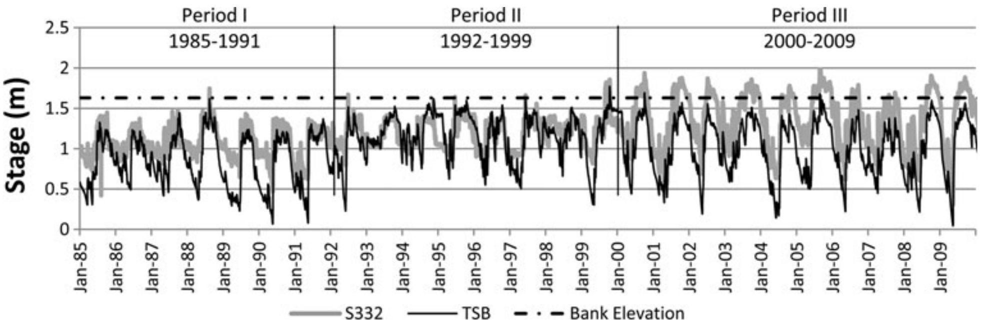

Fig. 3 Daily stage at S332 and TSB. The estimated L31W western bank elevation and the weir elevation (Period III only) also are plotted to show the potential for water to overflow the L31W bank toward Upper Taylor Slough

Table 2 Summary statistics of TP concentrations and loads in Upper Taylor Slough

Period	Station	TP				TP Loads			
		Median mg L^{-1}	Minimum	Maximum	Mean	Median kg	Minimum	Maximum	Mean
L31W Canal									
I (1985–1991)	S332	0.009a[1]	0.004	0.057	0.011	515a	301	586	453
II (1992–1999)	S332	0.007b	0.003	0.038	0.008	1,276b	769	2,098	1,324
III (2000–2009)	S332D	0.007b	0.003	0.029	0.007	–	–	–	–
UTS Marsh									
I (1985–1991)	TSB	0.005a	0.004	0.08	0.01	139a	64	332	160
II (1992–1999)	TSB	0.004b	0.002	0.028	0.006	429b	297	633	441
III (2000–2009)	TSB	0.004b	0.002	0.028	0.006	320c	71	476	304
Intermediate Marsh									
1997–2006	TsewA-1	0.005	0.004	0.026	0.007	–	–	–	–
1997–2006	TsewB-1	0.004	0.004	0.008	0.005	–	–	–	–
1997–2006	Tsew-4	0.004	0.004	0.014	0.006	–	–	–	–
III (2000–2009)	TS/Ph1a[2]	0.005	0.001	0.044	0.007	–	–	–	–
III (2000–2009)	TS/Ph1b[2]	0.006	0.001	0.048	0.008	–	–	–	–

[1] Values followed by unique letters in each column are significantly different as determined by the Mann–Whitney test ($P < 0.05$; $n \geq 44$)

[2] Collected via autosample

The letter comparisons are specific to the canal, marsh, or reference sites

($P < 0.01$) than in Period II and Period III. In Period III, median TP concentrations at TS/Ph1a and TS/Ph1b were between S332 and TSB concentrations. Total phosphorus concentrations at TSB were greater than TP concentrations at the intermediate sites (TSewA-1, TSewB-1, and TSew-4) infrequently.

Total phosphorus concentrations at S332 and TSB during Period I were greater than 0.01 mg L^{-1} 29 and 42% of the time, respectively. These elevated TP concentrations were related to the experimental drawdowns and elevated TP discharges in local agricultural runoff in the late 1980s and early 1990s. The frequency of exceeding TP concentrations of 0.01 mg L^{-1} decreased substantially in Period II for TSB (23%), and in Period III in the canal (S332D; 17%) and at TSB (14%). In Period III, the frequency of exceeding TP concentrations of 0.01 mg L^{-1} at TS/Ph1a and TS/Ph1b was 23 and 17%. Average annual TP concentrations at S332 were above the 0.01 mg L^{-1} threshold less than 1% of the time in Period II and were consistently below the threshold at TSB during Periods II and III.

Correlations and Trends

Total phosphorus concentrations at S332 had weak negative correlations ($P < 0.01$) with flow and stage at S332 during Period I, and with flow at S332 in Period II (Table 3). Total phosphorus concentrations at TSB had moderate to weak negative correlations ($P < 0.01$) with: stage and flow at S332 and stage at TSB during Period I; stage and flow at S332 and TSB in Period II; and stage and flow at S332 and TSB in Period III. Correlations between TSB TP and stage were strongest in Period I and III relative to Period II. Total phosphorus concentrations at TS/Ph1a in Period III were positively correlated ($P < 0.01$) with flow ($r = 0.092$; $n = 355$) in L31W, unlike patterns observed in the canal and at TSB. A declining trend in TP concentrations was observed in L31W (1.8% yr^{-1}) and at TSB (2.0% yr^{-1}) (seasonal Kendal; $P < 0.01$). Change-point analysis at S332 shows TP concentrations declined from an average of 0.018 mg L^{-1} to values generally below 0.01 mg L^{-1} after 1990,

Table 3 Correlations between TP and flow and between TP and stage over the three periods

Site	Period	Parameter	S332 TP	TSB TP
S332	I	Flow	−0.113	−0.257
S332	II	Flow	−0.071	−0.129
S332	I	Stage	−0.103	−0.247
S332	II	Stage	−0.001	−0.179
TSB	I	Flow	–	−0.166
TSB	II	Flow	–	−0.150
TSB	III	Flow	–	−0.405
TSB	I	Stage	–	−0.403
TSB	II	Stage	–	−0.191
TSB	III	Stage	–	−0.444

and declined at TSB from an average of 0.021 mg L^{-1} to an average of 0.006 mg L^{-1} after 1991.

Loads

Median annual TP loads from S332 in Period II were more than twice Period I loads (Table 2; $P < 0.05$). Median annual TP loads from TSB in Period II and III were more than three and two times greater ($P < 0.05$) than Period I, while Period II loads were 1.3 times greater than in Period III. A time-series plot of monthly TP loads exhibits a wet-dry season pattern, with flows and loads greatest in the wet seasons (Fig. 4). Change-point analysis shows average monthly TP loads increased after 1993 from S332 and in 1992 from TSB.

Period I and II TP loading rates (0.17 and 0.40 g m^{-2} y^{-1}; Table 4) were above those rates associated with probable eutrophication determined by an interagency Everglades science team (0.05 to 0.1 g m^{-2} y^{-1}; RECOVER 2007). Loading rates were determined for each period based on the difference between Upper Taylor Slough inflow loads and TSB outflow loads, minus potential aerial deposition, all divided by the Upper Taylor Slough area (200 ha). These rates may be slight overestimates, because no load exports from Upper Taylor Slough via sheet flow are considered, however, these export sheet flow loads are likely balanced with unmonitored loads in import sheet flow from upstream.

Cattail Expansion

Cattail (>5% cover) was first observed in Upper Taylor Slough by field measurements in 2007 (Sadle 2008), and occurred across 5.7 ha, while cattail <5% cover occurred

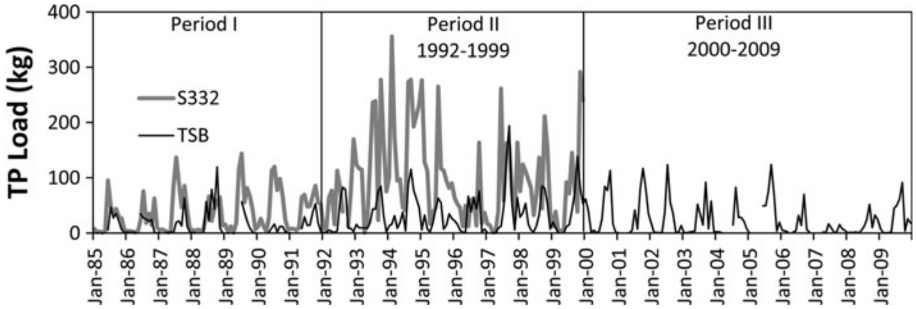

Fig. 4 Monthly TP loads at S332 and TSB

Table 4 Timeline of Upper Taylor Slough eutrophication

Time	Parameter	Indication
1985–1991	TP loading rates	TP loading rates to Upper Taylor Slough 0.17 g m^{-2} yr^{-1}, above restoration targets (0.05–0.1 g m^{-2} yr^{-1})
1992–1999	TP loading rates	TP loading rates to Upper Taylor Slough 0.4 g m^{-2} yr^{-1}, above restoration targets (0.05–0.1 g m^{-2} yr^{-1})
1992	TP load	Monthly TP loads at TSB increased from an average of 16 to 30 kg
1993	TP load	Monthly TP loads at TSB increased from an average of 41 to >77 kg
1995–1996	Soil TP	Soil TP concentrations > 600 mg kg^{-1} and as high as 800 mg kg^{-1} (USGS 2007)
1998–2002	Midge community changes	Increase in nutrient-tolerant species <0.05 km from L31W (Trexler and others 2003)
2002	Periphyton % cover	Reduced to <5 from >70% cover in 2000 near L31W (CH2MHILL 2002, Gaiser and others 2006)
2002–2003	Periphyton tissue TP concentration	Increased from 150 to ~250 μg g^{-1} < 0.1 km from L31W (Right and others 2004)
2004	Cattail expansion	Observed in aerial imagery (8.1 ha)
2005	Periphyton	Periphyton disappeared <0.02 km from L31W (Trexler and others 2009)
2007	Cattail expansion	First observed in field measurements to have dense cover (>5%) of 5.7 ha and sparse cover (<5%) of 8.9 ha
	Periphyton	Periphyton disappeared <0.07 km from L31W (Trexler and others 2009)
	Soil TP	Concentrations >800 mg kg^{-1} in cattail-infested area and farther south in the slough (Reddy and Osborne 2007)
2009	Cattail expansion	Observed in aerial imagery (7.9 ha)

across an additional area of 8.9 ha (Fig. 1). Subsequent to the first field observations, archived aerial imagery was obtained and photointerpreted to determine when appreciable amounts of cattail first appeared. No cattail was observed in the aerial imagery collected in 1994 and 1999. In the 2004 image, 8.1 ha of cattail were identified as the dominant vegetation in Upper Taylor Slough. The extent of cattail decreased in the 2009 image very slightly to 7.9 ha as a result of willow displacement.

Discussion

Increased nutrient loading, high soil TP concentrations (SFWMD 2000; Chambers 2001, 2002, 2003, 2007; Childers and others 2003; Reddy and Osborne 2007; Scheidt and Kalla 2007; USGS 2007; Tables 4, 5), changes in periphyton and midge communities (CH2MHILL 2002; Trexler and others 2003; Right and others 2004; Gaiser and others 2006; Trexler and others 2009; Table 4), and recent cattail expansion indicate Upper Taylor Slough is becoming eutrophic. Nutrient enrichment, coupled with increased hydroperiods, likely created conditions that led to the recent cattail expansion. However, nutrient enrichment of Upper Taylor Slough was not obvious from surface water TP concentrations, especially in Periods II and III. In the nutrient-sensitive, phosphorus-limited Everglades ecosystem, surface water TP concentration is a poor metric for early warning of eutrophication because: (1) any excess available phosphorus in surface water is taken up very rapidly by biota; (2) monthly or bi-weekly grab sampling employed at many of the sites might have missed episodic events that can convey high concentrations and loads of TP; (3) average TP concentrations in surface water generally were below the threshold TP concentration of 0.01 mg L^{-1}, especially in Periods II and III; and (4) TP concentrations in surface water generally exhibit declining trends over time.

In Period I, point-source discharge and surface water TP concentrations in Upper Taylor Slough often were well above the 0.01 mg L^{-1} TP threshold now known to cause ecosystem changes. These higher concentrations were correlated with lower slough depths, a result of experimental drawdowns in the 1980s and early 1990s. These lower depths likely concentrated excess surface water TP and/or increased TP exchange from the sediments to the water column. In addition to these high TP concentrations, construction and operation of the S332 pump tripled annual discharges to Upper Taylor Slough and created a point source of nutrient-enriched water largely from local agricultural runoff (Van Lent and others 1993). The TP loading rate in Period I was 0.17 g $\text{m}^{-2}\ \text{yr}^{-1}$ (Table 4), much higher than the restoration target of 0.05 to 0.1 g $\text{m}^{-2}\ \text{yr}^{-1}$. Although this period is likely the beginning of nutrient enrichment in Upper Taylor Slough, the easterly drainage pattern likely prevented the hydrologic conditions necessary for cattail to thrive. In fact, the hydrologic conditions promoted short-hydroperiod (2–3 months; Table 1) vegetation such as *Muhlenbergia capillaries* (Armentano and others 2006).

In Period II, surface water discharge and slough TP concentrations declined and were infrequently observed above the TP threshold. However, maximum TP concentrations in Taylor Slough inflows occasionally were 2 to 3-times higher than the threshold concentration of 0.01 mg L^{-1}. During Period II, the correlation between surface water TP concentrations and stage was much weaker than in Period I (Table 3) and hydroperiods were much longer

Table 5 Upper Taylor Slough soil TP data and sources

Year	Reference	Study	TP mg kg^{-1}	Comments
1995–1996	Scheidt and Kalla 2007	Regional Environmental Monitoring and Assessment Program	<200	Two sample sites
	USGS 2007	Sediment TP data collected at sites in Upper Taylor Slough	658–917	Two sample sites Highest concentration <0.5 km from L31W
1999	Childers and others 2003	Sediment TP data collected along transects	175–590	Five sample sites Highest concentration in the center of the cattail expansion area <1 km from L31W
2000	SFWMD 2009	Sediment TP data collected as part of surface water TP compliance development	93–498	Eight sample sites south of the slough Highest concentration <0.1 km from L31W
2001–2007	Chamber 2001, 2002, 2003, 2007	Sediment TP data collected near TSB	<150–217	One sample site collected near TSB 24 sample sites in the slough
2007	Reddy and Osborne 2007	Sediment TP data collected as part of transect sampling	71–1230	Concentrations >800 mg kg^{1} throughout the slough

than in Period I or III. However, the volume of canal water discharged to Upper Taylor Slough was triple that of Period I (Table 1) and more than 12-times higher than pre-Period I. As a result, TP loads delivered to Upper Taylor Slough more than doubled (Table 2) and hydroperiods also doubled (Table 1)—prime conditions for cattail expansion (Newman and others 1996). However, cattail was not observed to expand during this period. Regardless, eutrophication was occurring as evidenced by increased TP loads and loading rates (0.40 g m^{-2} yr^{-1}) and increases in soil TP concentrations to levels known to represent nutrient enrichment (400 to 500 mg kg^{-1}; Table 5; Qian and others 2004; RECOVER 2007). Thus, it is likely that, although cattail expansion was not evident during Period II, the environment was becoming more favorable for cattail expansion.

In Period III, discharges from S332 were discontinued, and TP concentrations in the canal and slough were at their lowest of any time during this study. Period III hydroperiods were shorter than in Period II, but canal stages were higher and slough hydroperiods were longer than in Period I. Nutrient loading continued through this period as evidenced by periphyton and arthropod community changes and elevated soil TP concentrations (Table 5). Increased TP concentrations and loads in Period II, coupled with favorable hydroperiods in Periods II and III, likely resulted in the cattail expansion observed in Period III.

Unrelated research conducted along the western boundary of L31W shows nutrient impacts in sediments and in periphyton, macrophyte, and midge communities. Sediment TP data have been collected by multiple investigators at many sites between 1995 and 2007, with a wide range of values measured for sediment bulk density and TP concentrations. Since at least 1995, sediment TP concentrations have been measured in Upper Taylor Slough at $\geq$500 mg kg^{-1} in the upper 10 cm (Tables 4, 5). In one study from 1995 through 1996, TP concentrations (< 200 mg kg^{-1}; Scheidt and Kalla 2007) were within background concentrations (<400 mg; Qian and others 2004) as identified for historically oligotrophic areas of the Everglades, but Orem (2005) found concentrations ranging from 660 to 920 mg kg^{-1}, with the highest concentrations near L31W. Childers and others (2003) found TP concentrations in 1999 ranging from 175 to 590 mg kg^{-1}, with the highest concentration observed on the edge of a willow stand within 1 km of L31W. In 2000, sediment TP ranged from 100 to 500 mg kg^{-1}, with the highest concentrations observed near L31W; however, relatively high concentrations (>400 mg kg^{-1}) also were observed near TSB. Between 2002 and 2005, additional sediment samples had TP concentrations <300 mg kg^{-1} (Scheidt and Kalla 2007). Sediments collected in 2007 had TP concentrations ranging from 250 mg kg^{-1} (0.6 km southwest of L31W) to 1,200 mg kg^{-1} (1.5 km southwest of L31W) (Reddy and Osborne 2007). When bulk densities were reported, there were significant differences, making comparisons between studies and sample locations difficult. Hydropattern and water quality dynamics can result in heterogeneous soil bulk densities, which influence TP concentrations reported based on soil mass rather than soil volume (Corstanje and others 2006; Scheidt and Kalla 2007), further complicating soil TP comparisons. Regardles of these complications, it is clear that since at least 1996, Upper Taylor Slough sediment has been enriched with TP and the enrichment is consistent with proximity to the TP source—L31W.

Upper Taylor Slough periphyton cover and TP concentrations have changed within 0.1 km of L31W (Table 4). From 1999 through 2000, periphyton cover was between 70 and 90% (Gaiser and others 2006). In 2002, periphyton cover in the first 0.1 km of slough downstream from L31W declined to 5% or less, but beyond 0.1 km downstream, periphyton cover remained greater than 70% (CH2MHILL 2002). Periphyton tissue TP concentration in the first 0.1 km of slough downstream L31W increased from 150 mg g^{-1} in 2000 to approximately 250 mg g^{-1} in 2002 to 2003 (Right and others 2004). In 2005, periphyton was absent completely between the canal and 0.02 km into the slough. Further, periphyton tissue TP concentrations declined in the slough from 250 to 100 mg g^{-1} between 0.02 and 0.1 km downstream. By 2007, periphyton was completely absent from 0.01 to 0.07 km into the slough, and beyond 0.08 km, periphyton tissue TP concentrations increased to 250 mg g^{-1} (Trexler, personal communication, January 2009). These shifts in cover and composition are consistent with previous findings that show shifts in periphyton composition, followed by increases then losses of periphyton biomass under conditions of pulsed and long-term elevated TP exposure (McCormick and Scinto 1999).

Midge community changes occurred in the slough near L31W since at least 2001 (Table 4). In 2001, midge communities in the slough within 0.03 km of L31W shifted from nutrient-intolerant to nutrient-tolerant species (Trexler and others 2003). This shift decreased with distance from canal.

Although our retrospective analysis reveals several indicators of nutrient enrichment in Upper Taylor Slough, surface water TP concentrations alone were not sufficient to serve as an early warning, despite relative high TP concentration spikes in Period I. In fact, long-term temporal trends in marsh TP concentrations suggest an improvement in water quality (Hanlon and others 2010; Kauffman and others 2010). The failure of surface water TP concentrations to serve as a warning sign is problematic, as this metric is relied on extensively as part of Everglades water quality monitoring networks. For example, compliance targets relying on surface water TP have been established in a settlement agreement and consent decree resulting from litigation (United States vs. SFWMD and others 1988; Case No. 88-1886-CIV-MORENO). In addition, surface water TP is monitored throughout the Everglades for compliance with state numeric water quality standards.

Surface water TP concentrations also do not provide information on phosphorus loads (Mayer 2005), and changes in the mass or loading rate can be an important indicator of potential changes to the ecosystem (Wazniak and others 2007). However, determination of TP loads to Upper Taylor Slough are now difficult because of the change from a point source discharge (via a pump) to a more diffuse discharge over a large area, making cross-sectional area measurements and discharge calculations almost impossible.

When considered in isolation, declining TP concentration trends and relatively stable TP concentrations at less than the 0.01 mg L^{-1} threshold in water discharged to Upper Taylor Slough since the mid 1990 s suggest water quality improvement (Miller and others 2004; Hanlon and others 2010)—a finding we believe that is incomplete. In hindsight, and with our improved understanding of Everglades ecosystem responses to nutrient enrichment, there were a number of additional metrics that could have provided natural resource managers with indications of nutrient enrichment well before the observance of cattail expansion (Table 4). In fact, these types of data, such as soil TP concentrations and periphyton tissue TP concentrations (CH2MHILL 2002; Right and others 2004; Gaiser and others 2006), were being collected under various research projects designed for other purposes. A limitation of this study is that it has to rely on multiple sources of data pulled from a variety of these studies designed for other purposes.

These problems with appropriate metrics, study design, and sampling spatial distribution are not unique to the Everglades, and various researchers have used biogeochemical analysis of dated sediment cores to address these shortcomings. Surratt and others (2008) attempted to identify the impacts of reduced freshwater and sea-level rise on a northern Florida estuary, but water quality monitoring networks were limited by short periods of record and spatial cover. They used biogeochemistry (Redfield ratio and C and N stable isotopes) of dated sediment cores to assess shifts in nutrient deposition and impacts on present ecosystem structure. Engstrom and others (2006) used sediment core TP concentrations to determine when eutrophication of Lake Okeechobee (Florida, USA) began because historic water quality records were being used to argue that the lake always received nutrient-enriched water. The lake's water quality records extended back to 1973, but the sediment cores extended the nutrient profile back to the late 1880s, showing a clear signal of anthropogenic influence beginning in the late 1950s. Yasuhara and others (2007) assessed eutrophication of Osaka Bay in Japan using sediment cores to overcome limitations of short time periods and poor spatial resolution covered by the water quality monitoring networks. In Upper Taylor Slough, biogeochronological analysis of dated sediment cores would be useful to look for breakpoints in ecosystem changes (von der Heyden and New 2004; Surratt and others 2008), although complications exist because of bioturbation distortion of subsurface features (Merkel and Hickey-Vargas 2000).

In order to prevent potentially irreversible ecological damage due to missed early warning signs of nutrient enrichment, monitoring designs should include those metrics now known to be most sensitive to early stages of enrichment, particularly in nutrient-sensitive ecosystems like the Everglades. A wide range of media (e.g., surface water, sediment, periphyton/phytoplankton, invertebrates, macrophytes, etc.) should be sampled. Ideally, the network design should include pre-impact conditions (baseline data), and this pre-impact monitoring should span several years to capture annual and inter-annual variability. Further, the network design should insure that data collected in the baseline period are actually representative of the historical condition of the ecosystem (Dodd and Barichivich 2007). Post-impact monitoring should be established at appropriate spatial and temporal scales. For example, in Taylor Slough, the nearest sampling site to new discharge points was 20 km downstream. This analysis has shown us that sampling network design may need to be on the scale of meters for appropriate spatial coverage near discharge points. Sampling frequency of periphyton composition or nutrient concentrations should be performed at useful intervals. In this study, even though monitoring did not begin until 1999 or later, even annual measurements of periphyton tissue nutrient content provided useful information about point source impacts on the receiving basin.

In conclusion, the early warning signs of nutrient enrichment in Upper Taylor Slough were missed, resulting in an unexpected expansion of cattail — a secondary ecological response to eutrophication in the Everglades. Although the early warning signals were present in data collected at various temporal and spatial scales for other purposes, these types of data collection were not part of the central monitoring network intended to monitor the nutrient status of Upper Taylor Slough. Considering the past decade's focus on aquatic ecosystem restoration efforts around the globe, it is important to include relevant monitoring of an appropriate suite of ecological indicators (e.g., nutrient and mineral loads, microphytes, macrophytes, invertebrates, and vertebrates) to help assess ecosystem trajectories and restoration success

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