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Biogeochemical Response of the Everglades Landscape to Eutrophication

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Abstract: The response of soil biogeochemical properties to external nutrient loading may serve as sensitive indicators of eutrophication in wetland ecosystems. We investigated the effects of nutrient loading on the distribution of soil C, N and P in four wetlands of the Florida Everglades: Water Conservation Area (WCA)-1, WCA-2a, WCA-3a and Taylor Slough. The nutrient-impacted zones extended from water-inflow points into interior areas and varied greatly between wetlands, from 0.5 km in WCA-1, 7 km in WCA-2a, 3 km in WCA-3a and 12 km in Taylor Slough. Nutrient loading effects on soil properties were similar among all wetlands regardless of background nutrient levels. Total P levels in oligotrophic areas varied considerably, from 205 to 619 mg kg^{-1} for floc and from 200 to 553 mg kg^{-1} for soil (0-3 cm). Floc had greater assimilative capacity for P than underlying soil. Assessment of the impacts of eutrophication indicated that P-related parameters were best suited as indicators. The most sensitive indicator with the greatest response to nutrient loading was $NaHCO_3$-P*i* (labile P). Labile P was 1973% greater in floc and 727% greater in soil for impacted compared to oligotrophic areas. Soil C and N properties were more indirectly related to nutrient loading through the influence of plant production and organic matter dynamics. Delineation of impacted and oligotrophic wetland areas in the Everglades ecosystem may serve as a baseline to assess future responses of biogeochemical properties to eutrophication.

Key words: Eutrophication · Everglades · Peatlands

INTRODUCTION

The Florida Everglades wetlands developed as nutrient-poor and supported vegetation adapted to these conditions [1]. In the past century, the Everglades was drained and separated into distinct hydrologic units where water movement and storage were regulated, including the Everglades Agricultural Area (EAA), Water Conservation Area-1, WCA-2a, WCA-3a and Taylor Slough of the Everglades National Park. Runoff and drainage of the EAA contributed to nutrient loading in northern Everglades wetlands, the impacts of which are best documented in the distribution of floodwater and soil total P in WCA-2a [2-4]. The extent of impacts in wetlands is primarily observed in locations proximal to water-inflow points or canals, thus the periphery is nutrient-impacted while interior areas of the wetlands are considered less impacted or oligotrophic [5].

Nutrient runoff from the EAA in addition to altered hydrologic conditions are implicated in altering the Everglades ecosystem by increasing soil nutrient levels, particularly P, which promoted shifts in vegetation community dynamics [1,5,6]. The harmful effects of nutrient loading on Everglades ecosystem structure and function are readily observed through changes in the indigenous sawgrass (*Cladium jamaicense*) slough ecosystem to a cattail (*Typha domingensis*) dominated ecosystem [5,7]. Nutrient loading into these wetlands also enhances organic matter decomposition and microbial activity, which increases nutrient concentrations in floodwater [8,9]. This internal cycling may serve as an important source of nutrients to oligotrophic areas of these wetlands in the future.

An understanding of the impacts of nutrient loading on changes in soil properties is important as organic matter decomposition and cycling depend on the chemical

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and physical composition of soil, microbial activity and nutrient availability. The addition of limiting nutrients to ecosystems increases the productivity of vegetation and stimulates microbial processes. However, soil biogeochemical properties may be more sensitive or respond more readily to increased nutrient levels than shifts in vegetation patterns and may thus serve as early warming indicators of eutrophication or changes in environmental conditions. Changes in vegetation may take years to be observed [10,11], while biogeochemical indicators may be altered after minimal exposure to elevated nutrient levels [12,13]. The objectives of this study were to determine the geographic extent of nutrient loading across the Everglades landscape, identify sensitive indicators of eutrophication and assess the response of biogeochemical properties.

MATERIALS AND METHODS

Site Description: The location of sampling sites within WCA-1, WCA-2a, WCA-3a and Taylor Slough of the Everglades National Park are shown in Fig. 1 and Table 1. Water Conservation Area-1 encompasses 59000 ha of the northern Everglades. Rainfall is a major water input while other sources include P-enriched runoff from the EAA. Elevated soil total P levels have been observed in areas adjacent to water-inflow points and *Typha* dominates the vegetation community in P-impacted areas while *Cladium*, open sloughs and tree islands are common in oligotrophic, interior areas. Two transects, encompassing a range of soil total P concentrations, were sampled in the southwestern section of WCA-1 from the S-6 water pump station extending into the oligotrophic interior.

Water Conservation Area-2a (54700 ha) receives drainage from WCA-1 in addition to discharge water from the EAA. The impacted areas of WCA-2a are much broader and extend much further into the interior compared with WCA-1, thus P impacts on vegetation community structure are more evident in WCA-2a [14]. Samples were taken along nutrient gradients extending from the S10-C water inflow structure to the interior of the wetland, encompassing *Typha*-dominated areas near the inflow and *Cladium* and periphyton communities in the interior.

Water Conservation Area-3a (233000 ha) receives drainage from northern wetlands, particularly WCA-2a and the Big Cypress National Preserve through the L-28 gap. Tree islands and wet *Cladium* prairies comprise the vegetation and are interspersed with sloughs, as this

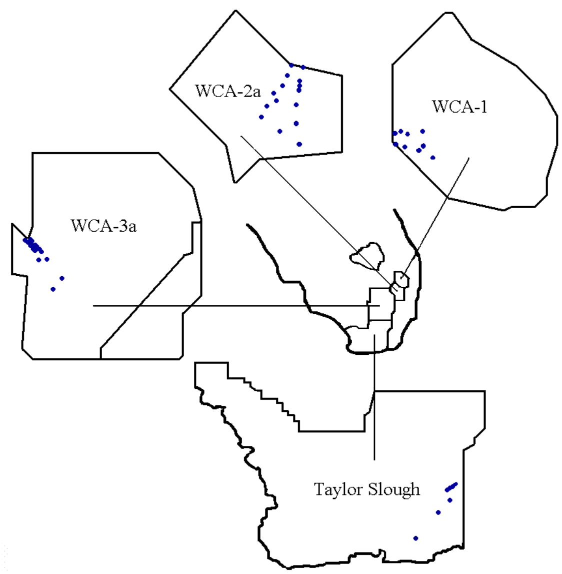

Fig. 1: The location of wetlands in the Everglades landscape and sampling sites along nutrient enrichment gradients in Water Conservation Area-1 (WCA-1), WCA-2a, WCA-3a and Taylor Slough

Table 1: Sampling locations in Water Conservation Area-1 (WCA-1), WCA-2a, WCA-3a and Taylor Slough with distance from the primary water-inflow points for each wetland

WCA-1		WCA-2a		WCA-3a		Taylor Slough	
Site	km	Site	km	Site	km	Site	km
X1	0.5	E1	2.3	E-05	0.6	E-05	0.3
X2	1.3	E2	3.3	E-10	1.5	E-1	1.0
X3	2.2	E3	4.2	E-15	2.4	E-15	1.7
X4	4.4	E4	7.0	E-20	3.0	W-05	0.4
Y4	3.2	E5	10.1	E-40	6.3	W-1	1.1
Z1	0.3	F1	1.8	W-05	0.7	W-15	1.7
Z2	1.1	F2	3.8	W-10	1.2	2-3	2.3
Z3	2.2	F3	5.6	W-15	2.2	2-4	2.5
Z4	3.1	F4	6.8	W-20	2.9	3-3	6.5
		F5	8.2	W-40	5.8	3-4	6.5
		U1	14.5	N-meso	12.9	N-meso	12.0
		U2	12.6	S-meso	15.5	S-meso	24.1
		U3	10.8				

wetland is characterized by a ridge and slough landscape oriented in the direction of water flow. Sampling sites extended to 15.5 km from the L-28 Gap.

Taylor Slough (40900 ha), a broad shallow basin located in Everglades National Park, serves as a conduit of water from northern uplands to Florida Bay. Taylor Slough receives water from WCA-3a through the L31W and C-111 canals. Vegetation includes *Cladium* marshes in northern areas and *Rhizophora* in southern areas. Sampling sites were selected along a gradient encompassing a range of soil total P from the C-111 canal to the interior of Taylor Slough.

Soil Sampling and Analysis: Triplicate soil samples were taken at each site using a 10 cm diam. corer. The top 0-3 cm was collected along with overlying floc, which consisted of suspended sediments and benthic periphyton assemblages. All samples were stored at 4°C until analysis. Water Conservation Area-1 was sampled in October 1998, WCA-2a in September 1998, WCA-3a in November 2000 and Taylor Slough in December 2000.

Total P was determined using the ashing method [15] followed by colorimetric analysis [16]. Total inorganic P was measured after extraction with 1 *M* HCl for 3 hr and the labile P fraction by extraction with 0.5 *M* $NaHCO_3$ for 16 hr, followed by colorimetric analysis [13,17]. Loss on ignition (LOI) was determined as the mass loss of soil after ashing for 4 hr at 550°C. Soil total C and N were measured after drying (70°C) with a Carlo-Erba NA 1500 CNS Analyzer (Haak-Buchler Instruments, Saddlebrook, NJ). Extractable organic C was measured by extraction with 0.5 *M* K_2SO_4 [8] and analysis with a Dohrmann total organic C analyzer (Rosemount Analytical, Santa Clara, CA). Extractable NH_4 was determined by extraction (2 *M* KCl) and colorimetric analysis [8].

Sampling sites along nutrient gradients in each wetland were grouped for statistical comparisons. Delineation between areas designated as eutrophic and oligotrophic within respective wetlands were based on significant differences in floc total P concentrations as a function of distance from primary water inflow points using a one-way ANOVA model at $P<0.05$. A three-way ANOVA model was used to determine main effects of wetland, site (impacted and oligotrophic) and soil depth. Treatment comparisons were based on a Fisher's LSD at $P<0.05$ [18]. Relationships between chemical indicators were determined using Pearson's correlation coefficients at $P<0.05$.

RESULTS AND DISCUSSION

Phosphorus Indicators: Transects were established near major water-inflow points which extended into the interior of the wetlands. Samples taken along transects encompassed a wide range of total P concentrations from nutrient-impacted areas in the wetland periphery to oligotrophic areas in the interior (Fig. 1). The nutrient gradients generally corresponded to patterns of water flow through the wetlands, such that future changes in nutrient levels can be used to determine the extent of external nutrient loading or internal cycling. The decreases in floc and soil total P with increasing distance from primary water inflow points for the four wetlands are shown in Fig. 2.

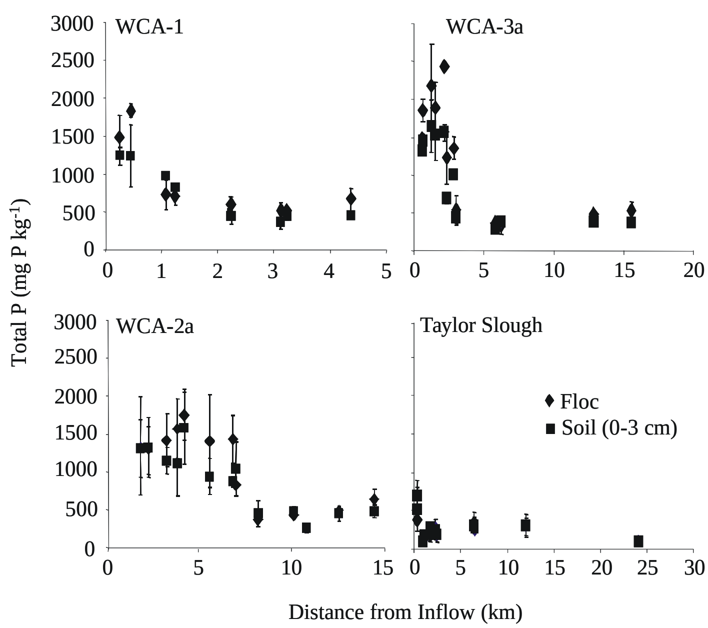

Fig. 2: Floc and soil total P concentrations in the water conservation areas and Taylor Slough as a function of distance from the primary water-inflow points

Table 2: Properties of floc and soil from impacted and oligotrophic areas of Water Conservation Area-1 (WCA-1) and WCA-2a. Significant differences between sites were noted by * (P<0.05) and NS (not significant)

		WCA-1			WCA-2a		
Parameter	Units	Impacted	Oligotrophic		Impacted	Oligotrophic	
Floc							
Total P	mg P kg^{-1}	1670	619	*	1410	497	*
Total inorganic P	mg P kg^{-1}	713	217	*	489	173	*
Labile P	mg P kg^{-1}	13	5	NS	50	2	*
Loss on ignition	%	84	88	NS	84	78	NS
Total C	g C kg^{-1}	417	426	NS	420	393	NS
Extractable organic C	g C kg^{-1}	7	14	*	4	6	*
Total N	g N kg^{-1}	36	37	NS	30	28	NS
Extractable NH_4-N	mg N kg^{-1}	663	608	NS	81	117	*
Soil (0-3 cm)							
Total P	mg P kg^{-1}	1220	553	*	1140	519	*
Total inorganic P	mg P kg^{-1}	494	194	*	349	189	*
Labile P	mg P kg^{-1}	37	5	*	38	7	*
Loss on ignition	%	82	91	*	85	80	NS
Total C	g C kg^{-1}	406	444	*	426	405	NS
Extractable organic C	g C kg^{-1}	3	6	*	4	3	NS
Total N	g N kg^{-1}	31	36	NS	28	26	NS
Extractable NH_4-N	mg N kg^{-1}	317	266	NS	127	116	NS

The delineation between impacted and oligotrophic areas was abrupt for all wetlands except Taylor Slough (Fig. 2). Impacts of nutrient loading in WCA-1 extended up to 0.5 km from the water inflow structure. Sites farther than 0.5 km from the inflow point did not differ in total P, but all had significantly lower total P than sites <0.5 km. The effects of nutrient loading extended much farther into the interior of WCA-2a compared to other wetlands, with impacted sites located up to 7 km from the S10-C water inflow structure. The impacted areas of WCA-3a extended 3 km from the L-28 gap. Due to lower total P levels and less exposure to P loads, Taylor Slough exhibited greater spatial variability, making the delineation of the impacted and oligotrophic area more difficult. The total P of Taylor Slough was significantly highest at sites within 0.4 km of the C-111 canal, but levels fluctuated at sites up to 12 km from the inflow. The site 24 km from the inflow had the lowest total P along the gradient and represented the oligotrophic, reference area. Possible low-level nutrient loading may have occurred in Taylor Slough as this wetland serves as a conduit for water flow from the northern water conservation areas into Florida Bay. Furthermore, hydrologic conditions and water levels fluctuate considerably in Taylor Slough which may influence nutrient loads from surface waters [19]. Since Taylor Slough did not directly receive water inputs from the EAA, but rather water previously filtered through the water conservation areas, it historically received lower nutrient loading and thus exhibited lower soil P levels.

Floc consisted of sediments, algae, periphyton assemblages, or particulate organic matter present on the soil surface or suspended in the water column [20]. This layer was more exposed to nutrient loading than underlying soil. Periphyton and floc often exhibit greater sensitivity to changes in environmental conditions than underlying soil [12,21]. Soil represented accumulated organic matter derived from decomposed periphyton and plant residues previously exposed to nutrient loading, thus soil P often approximated levels of floc P for nutrient-impacted areas. Total P was higher for floc than soil for the impacted areas of the four wetlands but not for the oligotrophic areas (Table 2 and 3). Background total P levels in oligotrophic areas varied considerably among the wetlands. Floc total P ranged from 205 to 619 mg kg^{-1} and soil total P from 200 to 553 mg kg^{-1}. Floc and soil total P were highest in WCA-1 and lowest in Taylor Slough. For impacted floc, WCA-1 and WCA-3a had higher total P than WCA-2a and Taylor Slough.

Total inorganic P represents the acid-soluble inorganic fraction of soil total P and commonly indicates P associated with Ca [17,22]. Total inorganic P concentrations increased in response to nutrient

Table 3: Properties of floc and soil from impacted and oligotrophic areas of Water Conservation Area-3a (WCA-3a) and Taylor Slough. Significant differences between sites were noted by * (*P*<0.05) and NS (not significant)

		WCA-3a			Taylor Slough		
Parameter	Units	Impacted	Oligotrophic		Impacted	Oligotrophic	
Floc							
Total P	mg P kg^{-1}	1720	452	*	258	205	*
Total inorganic P	mg P kg^{-1}	683	186	*	104	81	*
Labile P	mg P kg^{-1}	146	5	*	1	1	NS
Loss on ignition	%	88	78	*	41	51	NS
Extractable organic C	g C kg^{-1}	13	15	NS	6	6	NS
Total C	g C kg^{-1}	439	409	*	244	374	*
Total N	g N kg^{-1}	39	35	*	13	32	*
Extractable NH_4-N	mg N kg^{-1}	468	360	*	136	137	NS
Soil (0-3 cm)							
Total P	mg P kg^{-1}	1280	371	*	306	200	*
Total inorganic P	mg P kg^{-1}	446	125	*	122	75	*
Labile P	mg P kg^{-1}	60	5	*	4	0	*
Loss on ignition	%	81	77	NS	30	38	*
Extractable organic C	g C kg^{-1}	6	5	NS	3	2	*
Total C	g C kg^{-1}	389	412	NS	205	331	*
Total N	g N kg^{-1}	31	34	NS	10	27	*
Extractable NH_4-N	mg N kg^{-1}	168	94	*	68	44	*

loading for all wetlands and soil depths and floc concentrations were 2 to 3 times higher for impacted than oligotrophic areas (Table 2 and 3). Averaged across wetlands except Taylor Slough, floc total P was 211% and total inorganic P 226% greater for impacted than oligotrophic sites. Similarly, soil total P was 162% and total inorganic P 166% greater for impacted than oligotrophic areas. Total inorganic P was highest in the water conservation areas and lowest in Taylor Slough and contributed approximately 37% of the total P, indicating the importance of this pool to P dynamics and the significance of Ca for P sequestration. The proportion of total P as inorganic P did not differ between wetlands or between impacted and oligotrophic areas within wetlands. Total inorganic P was significantly related to total P (r=0.92).

Labile P represents the most available P fraction to vegetation and microbial communities [17] and is often the most responsive P fraction and sensitive to eutrophication [2,22]. For all wetlands except Taylor Slough and WCA-1 floc, labile P concentrations were increased by nutrient loading (Table 2 and 3). Labile P was 1973% greater in floc and 727% greater in soil for impacted than oligotrophic areas, which were considerably greater differences than observed for the total P and total inorganic P fractions. Concentrations of labile P in floc and soil were generally <7 mg kg^{-1} for oligotrophic areas. For impacted areas, WCA-3a floc and soil had the highest labile P and Taylor Slough the lowest. No depth effects occurred for oligotrophic areas of wetlands and only in WCA-3 was labile P greater in floc than soil. For WCA-1 and Taylor Slough, the labile P fraction of floc and soil contributed <1% of total P. For WCA-2a and WCA-3a, labile P was 4 and 9%, respectively, of total P in impacted areas. Labile P was significantly related to total P (r=0.73) and total inorganic P (r=0.62).

All four wetlands exhibited increases in floc and soil total P due to nutrient loading. However, the extent of the impacted zones varied among wetlands. Based on total P, impacted areas of WCA-1 were located within 0.5 km of water inflow points. However, in WCA-2a, the extent of nutrient loading covered a much larger geographic scale, extending up to 7 km from the inflow. The extent of P movement may result from water flow through wetlands and mass nutrient loading [6,7]. Water flow in WCA-2a is generally in a north to south direction from impacted areas adjacent to water inflow points to the oligotrophic interior [5]. Enhanced organic matter accumulation resulting from nutrient enrichment of impacted areas within several km of the S-10C water inflow point of WCA-2a [9,23] may have retarded water movement through this area, channelizing water around impacted areas and into sites beyond 5.6 km from the inflow. Internal nutrient cycling may also explain the greater extent of nutrient impacts in WCA-2a. Nutrient regeneration from organic soils may be as important as external nutrient loading, as internal wetland processes are important factors related to nutrient cycling in the Everglades [24,25]. The high accumulation rates of organic matter in impacted areas can result in the exposure of surface soil during periods of drought and low water levels, thus stimulating aerobic organic matter degradation and nutrient regeneration [26] and increasing the supply of nutrients down-gradient to oligotrophic areas in the interior of WCA-2a.

The limited extent of the impacted area in WCA-1 may be due to the lack of water flow from the periphery to the interior of the wetland, as the hydrology in this wetland is primarily driven by rainfall. The impacted areas of WCA-3a also exhibited smaller geographical zones than WCA-2a, primarily because it was not been subjected to intensive nutrient loading as had WCA-2a. Assessment of impacted areas in Taylor Slough was difficult due to low background total P levels, which is indicative of limited exposure to nutrient loading.

Carbon and Nitrogen Indicators: The LOI represents the soil organic matter content and exhibited mixed response to nutrient loading (Table 2 and 3). The LOI tended to be higher in impacted than oligotrophic areas of WCA-2a and WCA-3a, but higher in oligotrophic than impacted areas of WCA-1 and Taylor Slough. No significant changes with depth were observed for any wetland except for Taylor Slough, which had lower LOI in soil than floc. The floc LOI was significantly higher for the water conservation areas (85%) than Taylor Slough (46%). The same trend occurred for soil, which had higher LOI (83%) for the water conservation areas than Taylor Slough (34%). The LOI was not directly affected by nutrient loading, but rather the stimulation of plant production by nutrient enrichment increased organic matter accumulation [14] thereby increasing LOI. However, the presence of calcareous periphyton in oligotrophic wetlands [20] can significantly confound LOI dynamics by increasing the proportion of $CaCO_3$ in soil, which decreases LOI. Thus, organic matter content were indirectly affected by nutrient loading through changes in vegetation, microbial and organic matter dynamics and therefore was not a sensitive indicator of eutrophication.

Extractable organic C represents the labile C fraction and is generally a better indicator of available C than LOI or total C. In floc, extractable organic C often showed inverse relationships with nutrient loading, with lower concentrations in impacted areas near water-inflow points than oligotrophic areas (Table 2 and 3). Nutrient enrichment of wetland soils increases microbial activity and organic matter decomposition rates [9,13], thus higher extractable C was expected in impacted areas. Extractable organic C may accumulate when heterotrophic microbial activity is limited by nutrient availability as occurs in oligotrophic wetlands [26], hence higher levels in oligotrophic than impacted areas most affected by nutrient enrichment. Water Conservation Area-3a had higher extractable organic C than other wetlands, while Taylor Slough exhibited the lowest extractable organic C. Extractable organic C was not related to P parameters, but was significantly correlated with total N (r=0.37) and extractable NH_4 (r=0.65).

Similar to extractable organic C, total C and N exhibited a mixed response to nutrient loading. Total C and N were generally not affected by nutrient loading except for Taylor Slough, where levels in floc and soil were higher for oligotrophic than impacted areas (Table 2 and 3). Total C was significantly related to total N (r=0.93) and LOI (r=0.98). Extractable NH_4 was generally higher in impacted than oligotrophic areas and for all wetlands higher in floc than soil. Ammonium concentrations were approximately five times higher in WCA-1 than other wetlands, likely a result of receiving drainage water from the EAA. Nutrient loading from the EAA and restricted water flow into the interior of WCA-1 may have been responsible for elevated NH_4 levels in the peripheral areas.

The most sensitive indicators of nutrient loading in floc and soil were P-related chemical properties, such as total P, total inorganic P and labile P, while C and N parameters did not consistently respond to nutrient loading. Nutrient levels were highest in floc and decreased in underlying soil. Similar decreases with depth have been reported for Everglades soils [7,8]. The floc was partly comprised of calcareous periphyton, while soil consisted primarily of partially-consolidated and decomposed plant material. The higher substrate quality of the floc contributed to greater microbial biomass and organic matter decomposition compared to underlying soil [27], which in turn likely enhanced nutrient regeneration and increased concentrations.

The northern wetlands were more directly impacted by nutrient loading than the southern wetlands, such as Taylor Slough, which had the lowest background total P of all wetlands and thus experienced limited exposure to nutrient loading. Atmospheric nutrient deposition to Taylor Slough was reportedly greater than loading from surface waters [19]. Nutrient loading into the initially low P soils of Taylor Slough provoked a less significant response than observed for other wetlands. However, the response of biogeochemical properties to nutrient loading in Taylor Slough may be used to indicate the potential effects of nutrient loading to oligotrophic, interior areas of other Everglades wetlands having low P levels. Since changes in plant community composition occurred when soil total P exceeds certain thresholds [11], soil properties can used to predict potential changes to components of the Everglades ecosystem. The response of periphyton and heterotrophic microbial communities to P enrichment [13,20] demonstrated the potential importance of using soil biogeochemical properties for assessing changes in wetland ecosystems.

CONCLUSIONS

Nutrient loading led to the development of distinct gradients in floc and soil total P across the Everglades landscape, extending from water-inflow points to oligotrophic, interior areas. However, the geographic extent of nutrient loading on soil properties differed among wetlands. The northern wetlands receiving runoff and drainage from the EAA showed the highest P levels, while the southern wetlands, such as Taylor Slough, had less exposure to nutrient loading and subsequently had the lowest P levels. The most sensitive indicators of eutrophication were P-related parameters such as total P, total inorganic P and labile P, with labile P showing the greatest response. Soil C and N pools were generally not sensitive to eutrophication, as they were more dependent on organic matter cycling and decomposition dynamics. The identification of impacted and oligotrophic areas of the wetlands in the Everglades ecosystem should allow for determination of the impacts of future nutrient loading on changes in biogeochemical properties and P cycling. Changes in soil P fractions, especially labile P, may serve as early warning indicators of eutrophication.

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