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Peat accretion and phosphorus accumulation along a eutrophication gradient in the northern Everglades

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Abstract. Recent rates of peat accretion (as determined by ^{137}Cs) and N, P, organic C, Ca and Na accumulation were measured along a 10 km eutrophication gradient in the northern Everglades area of Water Conservation Area 2A (WCA 2A) that has received agricultural drainage from the Hillsboro canal for the past 25—30 yrs. Rates of peat accretion were highest at sampling locations closest to the Hillsboro canal, 1.6 km downstream, (5.67 ± 0.50 mm/yr) and decreased to 2.01 ± 0.31 mm/yr at distances of 7.1 to 10.7 km downstream. Phosphorus and Na accumulation were a function of both peat accretion and soil P and Na concentrations. The concentration and accumulation of P in peat deposited in the past 26 years was highest near the Hillsboro canal (1478 ± 67 ug/g, 0.66 ± 0.06 g/m^2/yr) and decreased to 560 ± 20 ug/g and 0.10 ± 0.02 g/m^2/yr at distances of 8.8 to 10.7 km downstream. Like phosphorus, the concentration and rate of Na accumulation was highest near the Hillsboro canal (3205 ± 1021 ug/g, 1.48 ± 0.53 g/m^2/yr). Although sodium enrichment of the peat was limited to 1.6 km downstream of the Hillsboro canal, increased rates of Na accumulation penetrated 5.2 km downstream of the Hillsboro canal, the extent of the area of enhanced peat accretion.

In contrast to P and Na, there was no difference in the concentration of soil organic C, N and Ca along the eutrophication gradient. However, there was a gradient of organic C, N and Ca accumulation corresponding to the area of enhanced peat accretion. The highest rates occurred 1.6 km south of the Hillsboro canal (212 ± 5 g organic C/m^2/yr, 14.1 ± 0.4 g N/m^2/yr, 22.1 ± 5.2 g Ca/m^2/yr). Accumulation of organic C, N and Ca at distances of 7.1—10.7 km downstream averaged 87 ± 11, 6.3 ± 0.7 and 6.5 ± 0.9 g/m^2/yr, respectively.

The areal extent of enhanced peat accretion and organic C, N, Ca and Na accumulation encompasses approximately 7700 ha of the northern part of WCA 2A. The area of enhanced P accumulation is larger, covering 11,500 ha or 26% of the total area of WCA 2A. The 11,500 ha area has functioned as a sink for P for the past 25—30 yr removing 74% (49.3 MT/yr) of the 67 MT/yr that enters via agricultural drainage and rainfall. Moreover, P accumulation along the gradient was related to mean (1989—1990) surface water P concentration, decreasing as surface water P decreases. These findings suggest that P accumulation is dependent on the P concentration in the water column and that decreasing P loadings per unit area result in less P storage per unit area. The potential long-term equilibrium of the 11,500 ha area as a sink for P is based on a mean annual loading of 67 metric tons P/yr. Input rates exceeding this loading rate could result in an expansion of the 11,500 ha area until a new equilibrium size is reached.

Introduction

The Everglades is a 500,000 ha freshwater wetland dominated by sawgrass (*Cladium jamaicense* Crantz), wet prairie (*Eleocharis-Rhynchospora-Panicum*) and shallow water sloughs (*Nymphaea-Nymphoides-Nuphar*) (Loveless 1959; Davis 1989). Historically the Everglades extended 150 km from the southern shore of Lake Okeechobee south of Florida bay (Davis 1943). However, since the turn of the century, 65% of the original Everglades has been drained for agricultural and urban-suburban development (Kushlan 1989). The remaining Everglades consists of the 350,000 ha Water Conservation Areas (WCAs), which have been impounded and managed for flood control and water supply, and approximately 150,000 ha is in the Everglades National Park (ENP) (Belanger et al. 1989; Davis 1989; SFWMD 1992).

The Everglades is believed to have evolved in a low nutrient, especially low P, environment (Belanger et al. 1989; SFWMD 1992). The low P concentration in sawgrass tissue suggests that this species requires less P to support healthy growth as compared other Everglades macrophytes which have higher tissue P concentrations (Steward & Ornes 1975a, 1975b; Davis 1989, 1991).

In the last several decades, nitrogen (N) and phosphorus (P) enriched agricultural drainage from the 291,000 ha Everglades Agricultural Area (EAA) has been pumped into northern areas of the WCAs (Davis 1991; SFWMD 1992). The record of nutrient enrichment of the northern Everglades dates back to the 1950's when Parker et al. (1955) reported that canal water draining the EAA contained relatively high levels of dissolved solids. However, it is likely that significant nutrient inputs did not occur until the early 1960's when construction of the water control structures and the levees surrounding the WCAs was completed. It was not until the early 1970's that nutrient enrichment of the WCAs became a concern. At this time, several investigations reported higher concentrations of N, P and dissolved solids in canals draining the EAA as compared to other surface waters in southeastern Florida (McPherson 1973; Gleason 1974; Waller & Earle 1975). In the late 1970's, long-term water quality monitoring of the Everglades watershed was initiated by the South Florida Water Management District.

The Loxahatchee National Wildlife Refuge (WCA 1) and WCA 2A, in particular, have received the bulk of the nutrient enriched agricultural drainage (SFWMD 1992). Between 1978 and 1987, an average of 1814 metric tons of N and 60 metric tons of P (in 459,000,000 m^3 of water) were released each year into the northern part of WCA 2A through four water control structures, the S10-A, C, D and E gates, on the Hillsboro canal (SFWMD 1992). As a result, a gradient of P enrichment, characterized by high concentrations of P in surface- and porewaters, vegetation and soil, has developed in the northern part of WCA 2A (Belanger et al. 1989; Craft & Richardson 1993a; Davis 1989, 1991; Koch & Reddy 1992; Qualls & Richardson 1992; SFWMD 1992). Concentrations of P are highest near the Hillsboro canal and decrease in the downstream direction (Davis 1989; Koch & Reddy 1992; Qualls & Richardson 1992; SFWMD 1992). Concurrent with this enrichment and enhanced surface flow has been a shift in plant species composition in the first 3—4 km south of the inflow structures from a community dominated by willow, sawgrass and slough species to one consisting primarily of cattail, *Typha domingensis* Pers. (Belanger et al. 1989; Davis 1991; SFWMD 1992).

Other changes in community structure that have been attributed to nutrient enrichment of WCA 2A include an increase in net primary productivity (NPP) of macrophytes (Davis 1989) and an increase in the density and diversity of macroinvertebrates (Rader & Richardson 1993). Davis (1989) observed that NPP of both sawgrass and cattail was higher in the enriched area of WCA 2A as compared to unenriched areas in the southern part of WCA 2A. Rader & Richardson (1993) found that the density of macroinvertebrates was 6 times greater in the enriched area of WCA 2A as compared to unenriched areas. Macroinvertebrate diversity also was higher in the enriched area. One hundred and two taxa were recorded from the enriched area while 77 taxa were found in unenriched areas in the southern part of WCA 2A (Rader & Richardson 1993).

Although changes in community structure have occurred in response to alterations in water flows and nutrient enrichment, the effects of agricultural drainage on ecosystem level processes, such as nutrient storage capacity, have not been quantified. Peat accretion and nutrient accumulation are processes that are particularly susceptible to changes in water flow and nutrient regimes. Nutrient enrichment, especially P, may stimulate net primary production (NPP) of Everglades macrophytes resulting in an increase in peat accretion in enriched areas as compared to unimpacted areas that do not receive agricultural drainage. In fact, preliminary estimates of peat accretion and nutrient accumulation in the northern and central Everglades suggests that these processes have increased in areas of WCA 2A that receive agricultural drainage (Richardson & Craft 1993; Craft & Richardson 1993a). However, enrichment also may increase litter decomposition rates (Valielia et al. 1982), negating any increase in peat accretion that might occur as a result of nutrient additions.

The primary objective of this study was to characterize recent (26 yr) rates of peat accretion and nutrient accumulation and storage along a eutrophication gradient in WCA 2A that has received agricultural drainage for the past 25—30 yr. We hypothesized that rates of nutrient accumulation would increase in response to increasing nutrient loadings as a result of higher peat accretion rates and incorporation of nutrients into the peat. Additional objectives were to determine the magnitude and extent of nutrient enrichment in the northern part of WCA 2A and to quantify the efficiency of the enriched area as long-term sink for phosphorus. Although the enriched area has functioned effectively as a sink for phosphorus for the past 25 yr, there is concern that the efficiency of P removal will decrease over time, resulting in a 'front' of P enrichment penetrating further south into the Everglades ecosystem and eventually reaching Everglades National Park (SFWMD 1992). Quantifying the phosphorus storage capacity for this area will also be useful in determining the amount of area required for the Everglades Nutrient Removal Project, a proposed multimillion dollar plan to build constructed wetlands on organic soils to remove P in agricultural drainage before releasing it into the Everglades ecosystem (SFWMD 1992).

Methods

Site location

Three transects (10A, 10C, 10D) were established along a nutrient enrichment gradient in WCA 2A that has received agricultural drainage for the past 30 yr (Fig. 1). Each transect originated near the S10-A, -C and -D water control structures that release water from the Hillsboro canal into WCA 2A (Fig. 1). Between 1978 and 1988, an average of 1814 metric tons of N and 60 metric tons of P were released in 459,000,000 m^3 of water annually through the S10 water control structures into the northern part of WCA 2A (SFWMD 1992), resulting in a gradient of phosphorus enrichment and increased water flow. Each transect contained six sampling locations, varying in distance from 1.4 to 10.8 km downstream of the Hillsboro canal. Distances were determined using the Global Positioning System (Magellan 5000D; Magellan Systems Corp., San Dimas, CA). The peat soils along the gradient are classified as Terra Ceia mucks, euic, hyperthermic, Typic Medisaprists (UDSA 1978).

Soil sampling and analyses

One soil core was collected from each transect point in June 1990 using a 7.5 × 7.5 cm by 60 cm deep stainless steel box corer with a removeable fourth side (C. J. Richardson, unpublished design). Compaction of the core was minimized by pushing the three sided corer into the peat, sliding

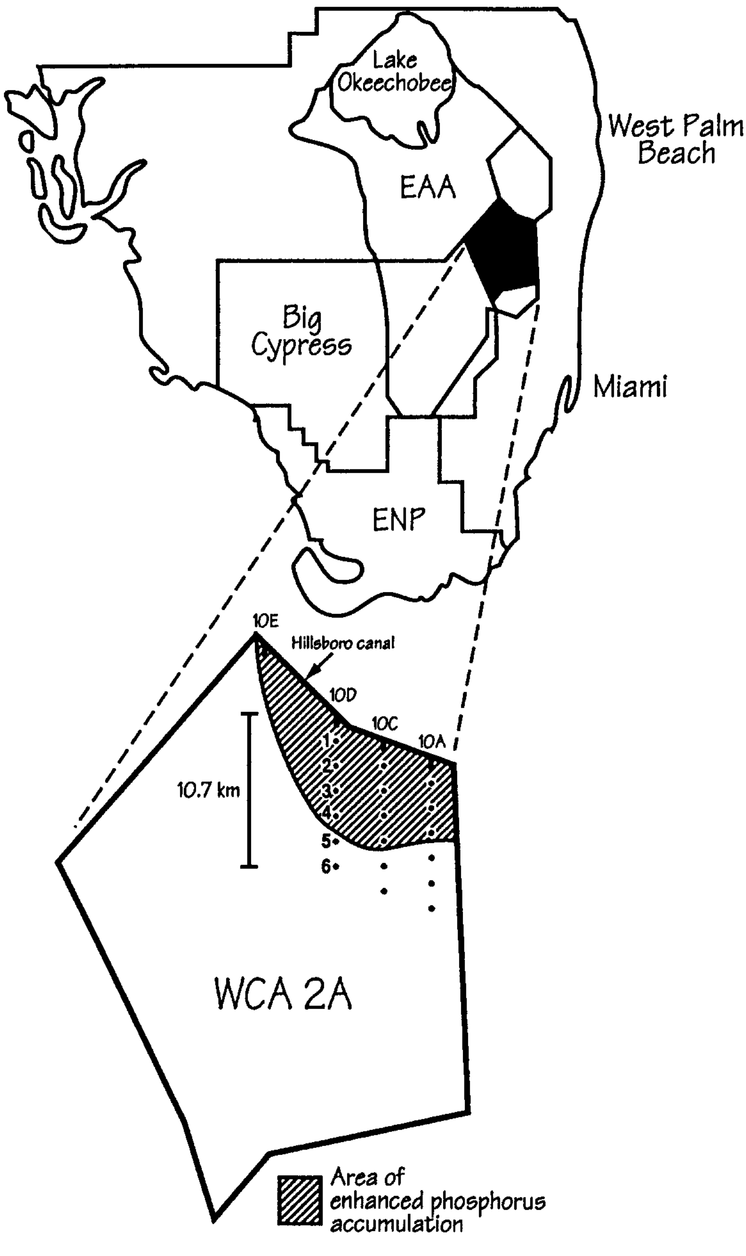

Fig. 1. Location of the three transects and the 11,500 ha area of enhanced phosphorus accumulation along a eutrophication gradient in Water Conservation Area 2A of the northern Everglades.

the fourth side in, then removing the intact peat core. Cores were sectioned into 1.5 cm depth increments and the increments were air-dried, weighed and ground to pass a 2 mm mesh sieve.

Rates of peat accretion were determined by measuring Cesium-137 in soil depth increments. The ^{137}Cs maximum in the soil profile corresponds to the soil surface in approximately 1964, the period of maximum deposition of ^{137}Cs from aboveground thermonuclear weapons tests. Accumulation of peat above this ^{137}Cs maximum represents the net accretion of peat over the past 26 years. The ^{137}Cs technique has successfully been used to estimate accretion rates in Everglades peat and was verified with ^{210}Pb analyses (Craft & Richardson 1993a). Cesium-137 activity was measured in soil samples by counting gamma emissions at 661.62 keV. Samples were counted for 8 hr using a high purity germanium (2.08% efficiency) detector (EG&G Ortec, Oak Ridge TN). Counting efficiency was determined by counting a ^{137}Cs standard of the same matrix (Everglades peat) and geometry.

Total N, P, organic C, Ca and Na were measured in each depth increment. We chose these nutrients because preliminary data (Richardson et al. 1991) suggested that these elements were accumulating at higher rates in areas receiving agricultural drainage than in areas that do not receive nutrient enriched drainage. The presence of carbonates in the soil samples was tested by adding several drops of 2 N HCl to a subsample and observing effervescence. Samples containing carbonates were treated with 2 N HCl prior to analysis for organic C. Organic C and total N were measured in 10 to 15 mg samples using a Perkin-Elmer 2400 CHNS analyzer (Perkin-Elmer, Norwalk, CN). Total P was determined by digesting 100 mg of soil in nitric/perchloric acid (Sommers & Nelson 1972) and measuring phosphate in the digests using a TRAACS 800 autoanalyzer (method no. 781-86T, Branne-Luebbe Inc., Elmsford, NY). Total Ca and Na were measured in the same digests using flame atomic absorption spectrometry (Perkin-Elmer model no. 2380). Soil bulk density, ^{137}Cs and nutrients were expressed on a dry weight basis by oven-drying 1.0 g subsamples overnight at 75 °C.

Two standards (pine needles, NBS # 1575, n = 8; river sediment, NBS # 2704, n = 6) were digested and analyzed for P, Ca and Na using these same methods. Bituminous coal (NBS # 1632b, n = 10) was employed as the standard for organic C and total N. The measured values for these NBS standards were within 4% of the actual value.

Results and discussion

Accretion rates

There was a well defined ^{137}Cs maximum at depth in nearly all of our Everglades peat cores (Fig. 2). The depth of the ^{137}Cs peak ranged from 0 cm (10C-5) to 17.25 cm (10C-1 and 10A-2) (10A-2 data not shown). We collected additional cores from the 10A-2, 10C-1 and 10C-5 sites in June 1991 to verify the location of the ^{137}Cs peak at these sites. The midpoint depth of the ^{137}Cs maximum in these cores was similar to the cores collected in 1990 (Fig. 2), yielding average accretion rates of 6.2 ± 0.4 mm/yr, 7.1 ± 0.5 mm/yr and 0.6 ± 0.3 mm/yr for the 10A-2, 10C-1 and 10C-5 sites, respectively.

We analyzed two cores (10C-6, 10A-2) for excess ^{210}Pb (C. B. Craft, unpublished data) to determine the reliability of the ^{137}Cs dating technique. At the 10C-6 location. ^{137}Cs and ^{210}Pb (constant activity model, Bricker-Urso et al. 1989; Oldfield & Appleby 1984) yielded accretion rates of 2.50 (260 g peat/m^2/yr) and 1.92 mm/yr (230 g/m^2/yr), respectively. The ^{210}Pb accretion rate reported here is similar to our earlier ^{210}Pb accretion measurement (1.83 mm/yr) in the interior of WCA 2A (Craft & Richardson 1993a). At the 10A-2 location, the absence of an exponential decrease in ^{210}Pb with depth required us to use the constant flux model (Bricker-Urso et al. 1989; Oldfield & Appleby 1984) to estimate accretion. This model revealed two distinct periods of peat accretion: (1) a relatively high rate of peat accretion (4.9 mm/yr, 588 g peat/m^2/yr) from approximately 1970 to the present, and (2) a much lower rate of peat accretion (2.2 mm/yr, 302 g/m^2/yr) prior to 1970. The ^{137}Cs technique, which is used to estimate recent (1964-present) rates of peat accretion, also yielded a high accretion rate (6.1 mm/yr, 594 g peat/m^2/yr) at this location. The similarities in peat accretion rates using the ^{137}Cs and ^{210}Pb dating techniques indicate that the ^{137}Cs technique provides a reliable estimate of peat accretion in Everglades soils.

There was a significant ($p = 0.001$) negative correlation between the rate of peat accretion and distance from the Hillsboro canal (Table 1). Peat accretion was highest near the Hillsboro canal, the source of the nutrient enriched water and decreased in the downstream direction (Table 2). The highest mean rate of accretion (5.90 ± 0.42 mm/yr) occurred within 3.5 km of the water control structures, at sites A1, C1, D1 and A2. The rate of peat accretion was constant at distances of 7.1 to 10.7 km downstream, averaging 2.01 ± 0.31 mm/yr, $n = 9$). These values are similar to our earlier estimates of peat accretion (2.33 ± 0.24 mm/yr) in unenriched areas of the WCA's (Craft & Richardson 1993a). Our

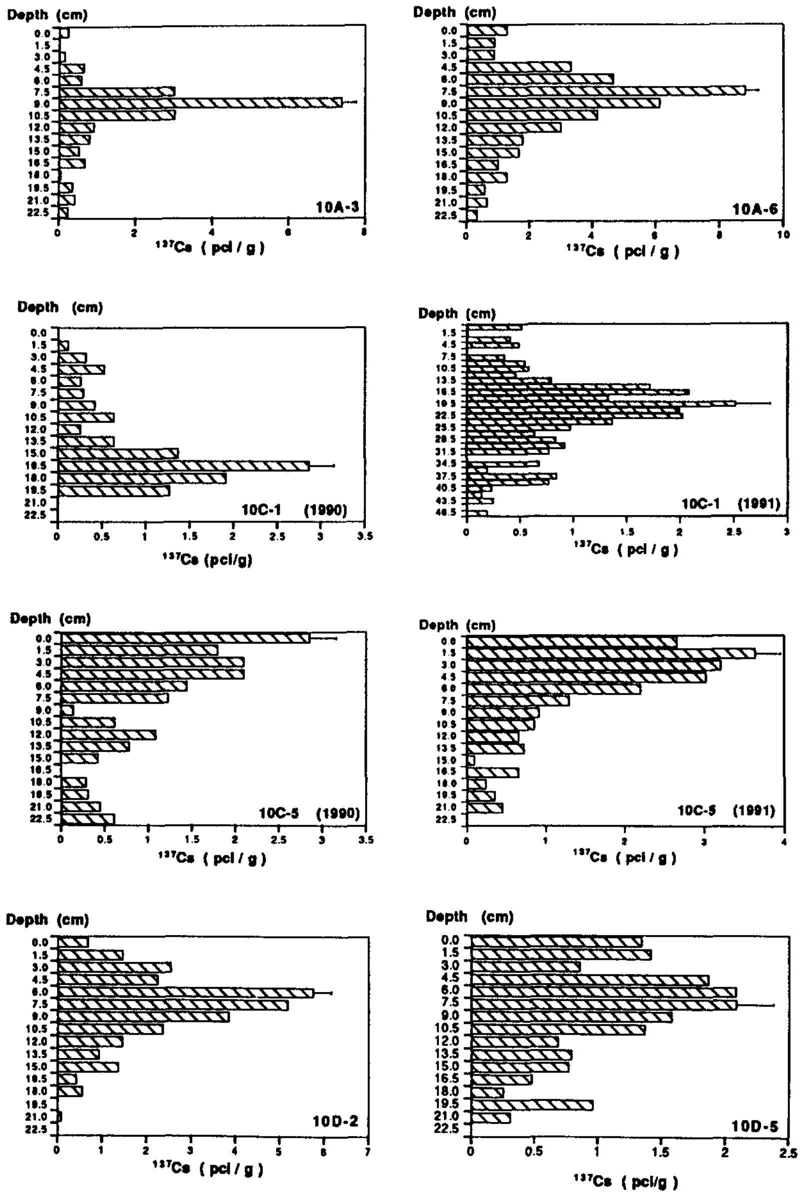

Fig. 2. Depth distribution of ^{137}Cs in representative soil cores collected along a eutrophication gradient in Water Conservation Area 2A of the northern Everglades. The error bar on the 1964 peak represents the counting error (1SD).

Table 1. Pearson correlation coefficients for soil physicochemical properties and distance from the Hillsboro canal, the source of nutrient enriched drainage water for WCA 2A (n = 18). The correlation coefficients were calculated from the data in Table 2 using Statistical Analysis Systems (1982).

	AR	BD	OC	N	P	Ca	Na
Dist.	−0.71 (***)	0.22	−0.02	0.24	−0.93 (****)	−0.34	−0.52 (*)
AR		0.53 (*)	0.21	−0.20	0.65 (**)	0.05	0.50 (*)
BD			0.03	0.35	−0.06	0.19	−0.24
OC				0.53 (*)	−0.03	−0.36	−0.27
N					−0.31	−0.52 (*)	−0.45
P						0.52 (*)	0.62 (**)
Ca							0.63 (**)

* : $p \leqslant 0.05$
** : $p \leqslant 0.01$
*** : $p \leqslant 0.001$
****: $p \leqslant 0.0001$

measured rates of peat accretion in unenriched areas of the Everglades are comparable to the 1—2 mm/yr reported for European and North American freshwater wetlands (Mitsch & Gosselink 1986).

Soil nutrient concentrations

The concentration of phosphorus in peat deposited during the past 25 yr was significantly (p = 0.0001) and inversely correlated with the distance from the Hillsboro canal, the source of the nutrient input to WCA 2A (Table 1). Phosphorus concentrations were highest 1.6 km south of the Hillsboro canal (1478 ± 67 ug/g) and decreased in the downstream direction (Table 2). Phosphorus enrichment in surface peat was evident at a distance of 7.1 km south of the Hillsboro canal. Surface soil P concentrations at distances of 8.8 and 10.7 km downstream were similar (560 ± 20 ug/g) to other unenriched areas to the south in WCA 2B and WCA 3A (Craft & Richardson 1993a) and probably have not been affected by nutrient enrichment. Total P concentrations in unenriched Everglades

Table 2. Peat accretion rate (AR) and mean bulk density (BD), phosphorus, sodium, organic carbon (OC), nitrogen and calcium concentrations in peat deposited between 1964 and 1990 along a eutrophication gradient in WCA 2A in the northern Everglades. (Means were calculated using the depth increments down to and including the ^{137}Cs maximum (0.75—17.25 cm).

Distance (km)[1]	AR (mm/yr)	BD (g/cm^3)	P	Na	OC	N	Ca
			----- (ug/g) -----		------------ (%) ------------		
1.8 (10A-1)[2]	5.5	0.07	1401	1396	50.87	3.33	3.17
1.4 (10C-1)	6.6	0.07	1611	4929	45.93	3.08	4.74
1.5 (10D-1)	4.9	0.09	1423	3289	45.76	3.03	6.70
3.5 (10A-2)	6.6	0.09	1114	1376	52.31	3.76	2.63
3.5 (10C-2)	3.8	0.09	1292	1264	46.45	3.13	3.67
3.2 (10D-2)	2.6	0.11	1252	2324	47.69	3.18	4.54
5.3 (10A-3)	3.8	0.11	996	1484	51.42	4.13	3.10
5.1 (10C-3)	3.8	0.09	924	2110	44.60	3.84	2.75
5.1 (10D-3)	3.2	0.09	934	1109	48.86	3.27	3.30
7.3 (10A-4)	1.4	0.13	700	820	49.85	4.02	2.92
6.9 (10C-4)	2.0	0.09	954	1778	46.96	3.33	3.66
7.0 (10D-4)	1.4	0.13	1201	1764	46.58	3.64	5.31
9.0 (10A-5)	2.0	0.08	537	1236	49.73	3.82	2.93
8.8 (10C-5)	0.3	0.10	568	1358	46.46	3.46	3.66
8.7 (10D-5)	3.2	0.08	546	1404	46.97	3.08	2.97
10.8 (10A-6)	3.2	0.06	570	1303	48.69	3.65	3.00
10.5 (10C-6)	2.6	0.10	495	1683	47.03	3.22	3.74
10.7 (10D-6)	2.0	0.10	646	1602	46.18	3.34	4.04

[1] Distance from the Hillsboro canal as determined by analysis of GPS coordinates for each location.
[2] Transect lines (see Fig. 1).

peats are intermediate between acidic ombrotrophic pocosin peatlands in North Carolina (300 P ug/g) and minerotrophic fen peatlands in Michigan (700 ug P/g) (Richardson & Marshall 1986; Faulkner & Richardson 1989).

Phosphorus enrichment varied both spatially along the gradient and with depth in the soil profile. The depth of P enrichment in the profile was greatest at locations nearest to the Hillsboro canal and decreased with distance (Fig. 3). Enriched P concentrations extended to depths of 18 to 20 cm at the locations within 1.6 km of the Hillsboro canal (Fig. 3). The depth of enrichment progressively decreased with distance from the Hillsboro canal. At distances of 3.4, 5.2 and 7.1 km downstream, the zone of enrichment penetrated to depths of 12 to 18, 10 to 12 and 3 to 6 cm,

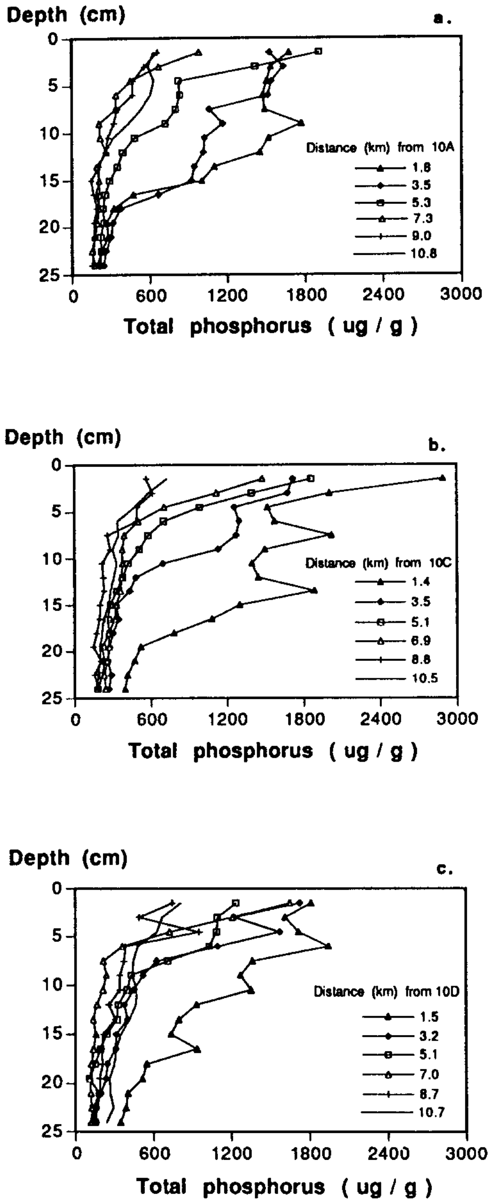

Fig. 3. Depth distribution of total soil phosphorus along the (a.) 10A, (b.) 10C and (c.) 10D transects in Water Conservation Area 2A of the northern Everglades. See Fig. 1 for the 6 locations on each transect.

respectively (Fig. 3). Total P concentrations decreased with depth at all locations (Fig. 3), even in the unenriched areas far from the Hillsboro canal, suggesting biological cycling of P in the upper soil layers (e.g. acrotelm zone) where most microbes and macrophyte roots are active (Richardson & Marshall 1986). Carignan & Flett (1981) observed that total P concentrations in freshwater lake sediments also were highest at the sediment/water interface and decreased with depth. These researchers reported that the surface sediment total P maxima resulted from precipitation of Fe phosphates in the oxidized surface layer. However, this mechanism does not appear likely in Everglades peats because of the low total Fe concentration (1600 ug/g (0—10 cm) vs 60000 ug/g (0—8 cm) in lake sediments (Carignan & Flett 1981)), the uniform distribution of Fe with depth (C. B. Craft, unpublished data) and the circumneutral (pH = 7.0—7.1) soil pH.

Like P, the concentration of Na in surface peat was inversely correlated (r = 0.52) with distance from the Hillsboro canal outflow (Table 1). However, the relationship was not as strong and the extent of Na enrichment was not as widespread as P. The concentration of Na in peat deposited during the past 25 yr was much higher at 10C-1 and 10D-1 (3289—4929 ug/g) than at other locations (820—2324 ug/g) (Table 2). At these two locations, Na concentrations were consistently higher throughout the profile (0—24 cm) as compared to other sites (Figs. 4a and b).

The high soil Na concentration at the 10D-1 and 10C-1 locations probably is due to the large inputs of Hillsboro canal water which contains elevated levels of dissolved minerals (sodium, calcium, chloride, bicarbonate) as well as N and P (SFWMD 1992). The origin of the Na (and other dissolved minerals) is believed to be connate seawater in marine sediments underlying the organic soils of the EAA and northern WCAs (Gleason 1974; SFWMD 1992). The excavation of canals through the EAA and northern Everglades during the past century released this saline groundwater, enabling it to mix with the overlying groundwater and surface water in the canals (SFWMD 1992). It is likely that sodium enrichment of the peat at 10D-1 and 10C-1 reflects ponding and evaporation of Hillsboro canal water, resulting in an increase in soil Na concentrations at these locations.

Most of the soil Na at the 10D-1 and 10C-1 locations is associated with the solid phase. Porewater Na (0.21—0.29 g/m^2; R. G. Qualls, pers. comm.) accounted for only 9—10% of the total soil Na (2.3—3.0 g/m^2; 0—15 cm depth) at these locations. It is likely that most of the solid phase Na is bound to cation exchange sites on the peat matrix. Sodium, generally, is not an essential plant nutrient (Brady 1984) and, therefore, is not assimilated by marsh vegetation and incorporated into the peat. Precipitation of Na at the peat surface by evaporation also appears unlikely since peats in the enriched area usually are water saturated (90% wet weight; C. B. Craft, unpublished data) and there is no evidence of a surface peat Na maxima at our Na enriched locations (Figs. 4a, b).

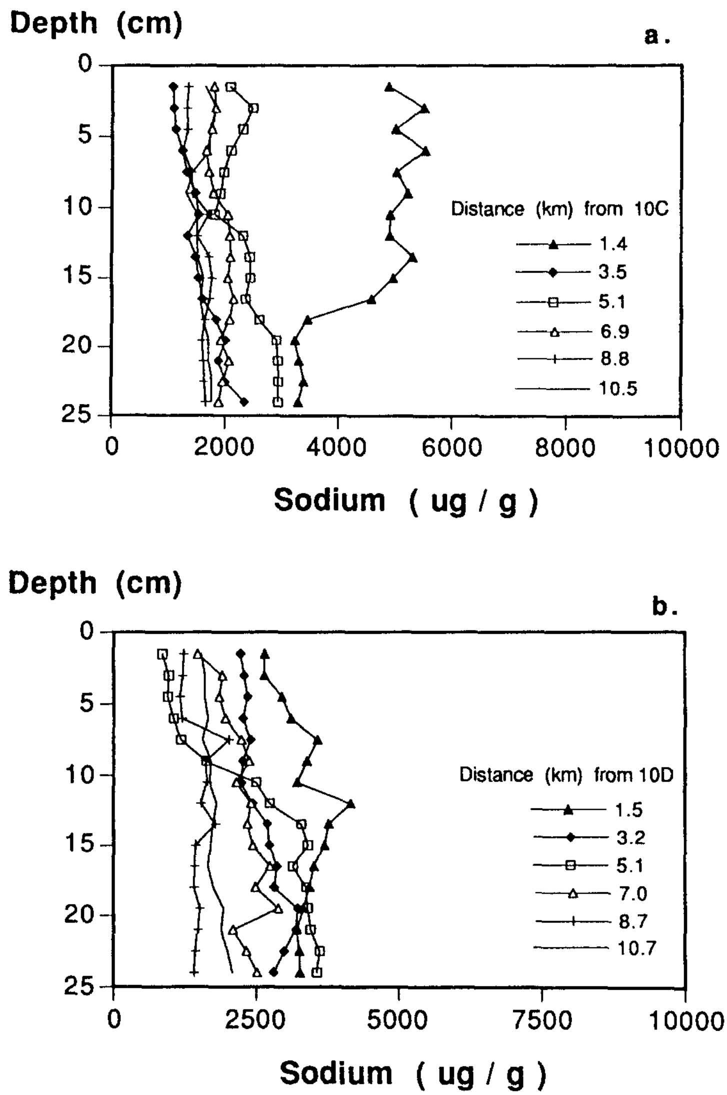

Fig. 4. Depth distribution of total soil sodium along the (a.) 10C and (b.) 10D transects in Water Conservation Area 2A of the northern Everglades. See Fig. 1 for the 6 locations on each transect.

There was no evidence of Na enrichment along the 10A transect, on the eastern edge of WCA 2A (Table 2). The absence of a sodium enrichment gradient (and the somewhat lower P concentrations) along this transect is a result of differential inputs of water through the S10 water control structures. Between 1979 and 1988, the 10A structure accounted for only 23% of the 459,000,000 m^3 of water released by the four water control structures (28% for 10C, 37% for 10D, 12% for 10E) (SFWMD 1992). Thus, this transect has received less water and nutrients and, has been impacted to a lesser degree, than the 10C and 10D transects.

Sodium concentrations in surface peat were positively correlated with total Ca (r = 0.63) and P (r = 0.62) and the rate of peat accretion (r = 0.50) (Table 1). These findings reflect the large inputs of Na, P and Ca in agricultural drainage as well as the enhanced rate of peat accretion in the nutrient enriched area.

In contrast to P and Na, soil bulk density, organic C, total N and Ca were not significantly correlated with distance from the Hillsboro canal (Tables 1 and 2). The bulk density of peat deposited during the past 25 years ranged from 0.6 g/cm^3 at 10A-6 to 0.13 g/cm^3 at 10A-4 and 10D-4 (Table 3). Organic C and total N and Ca in surface peat varied from 44.60% to 52.31%, 3.03% to 4.13% and 2.63% to 6.70%, respectively (Table 2). Soil bulk density of Everglades peats was comparable to fen peatlands in Michigan (0.22 g/cm^3) and pocosin soils in North Carolina (0.07 g/cm^3) (Richardson & Marshall 1986; Faulkner & Richardson 1989). However, total N concentrations were substantially higher in Everglades peats as compared to fen peatlands (2.2% N) and pocosins (1.4% N) (Richardson & Marshall 1986; Faulkner & Richardson 1989).

The uniform distribution of soil Ca along the eutrophication gradient is somewhat surprising because canals draining the EAA contain elevated levels of Ca and other dissolved minerals (Gleason 1974; SFWMD 1992). In fact, surface water Ca concentrations in areas near the Hillsboro canal (72 mg/l) are almost twice that of interior areas of WCA 2A (38 mg/l) (Richardson et al. 1991). It is likely that Ca enrichment in WCA 2A is limited to areas near the Hillsboro canal. Richardson et al. (1991) reported Ca enrichment of the surface peat at locations within 0.5 km of the S10-C and S10-D water control structures. At these locations, surface peat Ca concentrations averaged 7.7% to 10.1%, respectively, as compared to 3.2—4.3% at locations 3.2—10.7 km downstream (Richardson et al. 1991).

Accumulation rates of P, Na, Ca, organic C and N

Rates of nutrient accumulation generally were highest near the Hillsboro

Table 3. Accumulation rates of P, Na, organic C, total N and Ca along a eutrophication gradient in WCA 2A in the northern Everglades.

Distance (km) from the Hillsboro canal	P	Na	OC (g/m²/yr)	N	Ca
1.8 (10A-1)	0.56	0.56	205	13.4	12.8
1.4 (10C-1)	0.78	2.39	223	14.9	23.0
1.5 (10D-1)	0.65	1.50	209	13.9	30.6
$\bar{X}$ 1.6	0.66	1.48	212	14.1	22.1
SE 0.1	0.06	0.53	5	0.4	5.2
3.5 (10A-2)	0.63	0.78	296	21.2	14.9
3.5 (10C-2)	0.46	0.45	167	11.2	13.2
3.2 (10D-2)	0.36	0.66	136	9.1	13.0
$\bar{X}$ 3.4	0.48	0.63	200	13.8	13.7
SE 0.1	0.08	0.10	49	3.7	0.6
5.3 (10A-3)	0.43	0.64	221	17.8	13.3
5.1 (10C-3)	0.32	0.73	154	13.2	9.5
5.1 (10D-3)	0.28	0.33	141	9.7	9.8
$\bar{X}$ 5.2	0.34	0.57	172	13.6	10.9
SE 0.1	0.04	0.12	25	2.3	1.2
7.3 (10A-4)	0.12	0.15	89	7.2	5.2
6.9 (10C-4)	0.17	0.33	86	6.1	6.7
7.0 (10D-4)	0.21	0.31	81	6.4	9.3
$\bar{X}$ 7.1	0.17	0.26	85	6.6	7.1
SE 0.1	0.03	0.06	2	0.3	1.2
9.0 (10A-5)	0.08	0.19	75	5.8	4.5
8.8 (10C-5)	0.02	0.04	14	1.0	1.1
8.7 (10D-5)	0.14	0.36	121	7.9	7.6
$\bar{X}$ 8.8	0.08	0.20	70	4.9	4.4
SE 0.1	0.03	0.09	31	2.0	1.9
10.8 (10A-6)	0.12	0.27	100	7.5	6.2
10.5 (10C-6)	0.13	0.43	120	8.2	9.6
10.7 (10D-6)	0.13	0.33	95	6.9	8.3
$\bar{X}$ 10.7	0.13	0.34	105	7.5	8.0
SE 0.1	0.00	0.05	8	0.4	1.0

canal and decreased with distance (Table 3). Two factors can result in a higher accumulation rate of an element: (1) higher rates of peat accumulation and (2) a higher concentration in the peat deposited. Phosphorus and sodium accumulation were a function of both higher soil P and Na concentrations and higher rates of peat accretion (Tables 2 and 3). As expected, the extent of enhanced P accumulation in WCA 2A corresponded to the area characterized by enriched soil P concentrations. Rates of P accumulation averaged 0.66 $\pm$ 0.06 g/m^2/yr 1.6 km south of the Hillsboro canal and decreased to 0.10 + 0.02 g/m^2/yr 8.8 to 10.7 km downstream (Table 3). The average rate of P accumulation in the enriched area was 0.44 $\pm$ 0.06 g/m^2/yr (n = 11) which is similar to previous estimates by Craft & Richardson (1993a) (0.46 $\pm$ 0.12 g/m^2/yr, n = 2). Preliminary research by Craft & Richardson (1993a) (n = 3 cores) in unenriched areas of WCA 2A also yielded P accumulation rates (0.06 $\pm$ 0.03 g/m^2/yr) comparable to the 0.10 + 0.02 g/m^2/yr found in this expanded study.

Like phosphorus, rates of Na accumulation were highest at the locations closest to the Hillsboro canal (1.48 $\pm$ 0.53 g/m^2/yr) and decreased in the downstream direction. Areas of maximum Na accumulation (10C-1, 10D-1) corresponded to areas where soil Na concentrations were the highest (Tables 2 and 3). Enhanced rates of Na accumulation did not extend as far downstream as the area of increased P accumulation. Instead, increased rates of Na accumulation occurred only as far as 5.2 km downstream, the extent of enhanced peat accretion. The rate of Na accumulation was constant at a distance of 7.1 to 10.7 km south of the Hillsboro canal, averaging 0.27 $\pm$ 0.04 g/m^2/yr (Table 3).

Like P and Na, rates of Ca, organic C and N accumulation decreased with distance from the Hillsboro canal (Table 3). However, accumulation of these elements were primarily a function of the rate of peat accretion since there was no difference in soil Ca, organic C and N concentrations along the gradient (Table 2). Calcium accumulation was highest (22.1 $\pm$ 5.2 g/m^2/yr) 1.6 km south of the Hillsboro canal and decreased to 6.5 $\pm$ 0.9 g/m^2/yr at distances of 7.1 to 10.7 downstream (Table 3). Rates of organic C and N accumulation averaged 212 $\pm$ 5 and 14.1 $\pm$ 0.4 g/m^2/yr 1.6 km south of the Hillsboro canal and decreased to 87 $\pm$ 11 and 6.3 $\pm$ 0.7 g/m^2/yr, respectively, at distances of 7.1 to 10.7 km downstream.

Organic carbon storage

Net annual primary production (NAPP) of macrophytes and organic C accumulation were compared along the eutrophication gradient to determine the effect of nutrient additions on the balance between NAPP and decomposition. The percentage of NAPP buried annually as peat was highest near the Hillsboro canal and decreased with distance (Table 4). At a distance of 1.6 km south of the Hillsboro canal, 23% of the NAPP was buried each year. The amount buried decreased to 17% and 15% at

Table 4. Net annual primary production (NAPP), organic C accumulation and percentage of NAPP buried as peat along a eutrophication gradient in WCA 2A in the northern Everglades.

Distance (km) from the Hillsboro canal	NAPP[1]	Organic C[2]	% buried
	------------ ($g\ C/m^2/yr$)	------------	
1.4—1.5[3]	913	209—223	23—24
3.2—3.5	882	136—167	15—19
6.9—7.0	524	81—86	15—16

[1] From Davis (1989). Dry weight values were converted to organic C by multiplying by the organic C content (45%) of live aboveground sawgrass tissue (Craft & Richardson, unpublished data).
[2] Data from the S10-C and S10-D transects were used for comparison with Davis (1989) NAPP data (see footnote # 3).
[3] NAPP was measured by Davis (1989) at distances of 1.6, 3.2 and 6.4 km south of the Hillsboro canal between the S10-C and S10-D structures.

distances of 3.4 km and 7.0 km, respectively. Other studies suggest that nutrient enrichment may increase rates of litter decomposition (Valielia et al. 1982), resulting in reduced rates of peat accretion and nutrient accumulation. However, our findings indicate that the increase in NAPP over the past 25 to 30 yr more than compensates for any increase in decomposition that may occur as a result of the enrichment process with nearly 3 times more organic C being stored in enriched area as compared to the unenriched area (Table 4).

Phosphorus storage efficiency of WCA 2A

The effectiveness of Everglades peatlands as a sink for P was evaluated by comparing P inputs and accumulation rates in the enriched area of northern WCA 2A. Using the spatial distribution of soil total P (0—10 cm) in WCA 2A (Reddy et al. 1991, Fig. 2—10) and our P accumulation data (Table 3), we used planimetry to determine the area of enhanced P accumulation in the northern part of WCA 2A using USGS topographic maps (Fort Lauderdale-2 SE, -2 SW and -2 NW). We chose an accumulation rate of 0.15 g $P/m^2/yr$ as the boundary delineating the area of enhanced P accumulation from areas characterized by background (unenriched) rates of P accumulation. In areas to the west of our transects that were not sampled during this study, we used a total soil P concentration of $\geqslant$ 600 ug/g (0—10 cm depth; from Reddy et al. 1991) to delineate areas of enhanced P accumulation. This value is similar to our measured concentrations of 495—646 ug P/g in surface peat collected from unenriched areas 8.8 to 10.7 km downstream of the Hillsboro canal and in other areas of WCA 2B and WCA 3A (Craft & Richardson 1993a). Based on the 0.15 g P/m^2/yr and $\geqslant$ 600 ug/g isopleths, we estimate that increased rates of P accumulation occur in approximately 11,500 ha of northern WCA 2A (see Fig. 1). The areas of enhanced peat accretion and Na accumulation are smaller, approximately 7700 ha.

Phosphorus accumulation along the gradient was a function of mean annual surface water P concentration as both surface water P and P accumulation in peat decreased with distance from the Hillsboro canal (Figs. 5a, b). In general, this process follows a first order model as described by Howard-Williams (1985). However, year to year variations in surface water P concentrations due to differences in rainfall and P loadings may reduce the relationship to long-term accumulation rates for individual year water concentrations. To estimate overall P storage efficiency for the entire area and to properly weigh the storage rate per unit area, we divided the area of enhanced P accumulation into zones of high (0.65—0.90 g/m^2/yr), moderate (0.40—0.65 g/m^2/yr) and low (0.15—0.40 g/m^2/yr) storage (based on the P accumulation and soil P isopleths) using the methods described previously. The maximum rate of P accumulation (0.90 g/m^2/yr) was estimated using a polynomial regression model (see Fig. 5b). The high storage area, which encompassed 2500 ha, removed the largest amount of P, 18.0 MT P/yr (Table 5). The moderate storage area was somewhat larger (2800 ha) and removed 14.6 MT P/yr. The low storage area was the largest (6200 ha) and removed 16.7 MT P/yr. Although the three zones removed comparable amounts of P, the area required to remove P increased as the P concentration in the water decreased (Figs. 5a, b, Table 5). These findings suggest that as mass loadings of P per unit area decrease, the storage rate decreases. Our results support earlier work that suggests that peatlands are not efficient P sinks and that large areas are required to sustain effective P removal (Richardson 1985; Richardson & Marshall 1986).

The entire 11,500 ha area receives an average of 67 metric tons of P each year (Table 5). Nearly 90% of the input is through the three water control structures on the Hillsboro canal. Seventy four percent of the P input to this 11,500 ha area accumulated in the peat (49.3 MT/yr) with an integrated accumulation rate of 0.43 g/m^2/yr (Table 5). This integrated rate of accumulation is similar to our measured mean (n = 11) rate of P accumulation (0.44 $\pm$ 0.06 g/m^2/yr) in the P enriched area of WCA 2A.

Most of the P that accumulates in the 11,500 ha enriched area is stored as recalcitrant compounds that are not easily decomposed or taken up by organisms (Qualls & Richardson 1993). Over 85% of the soil P in the

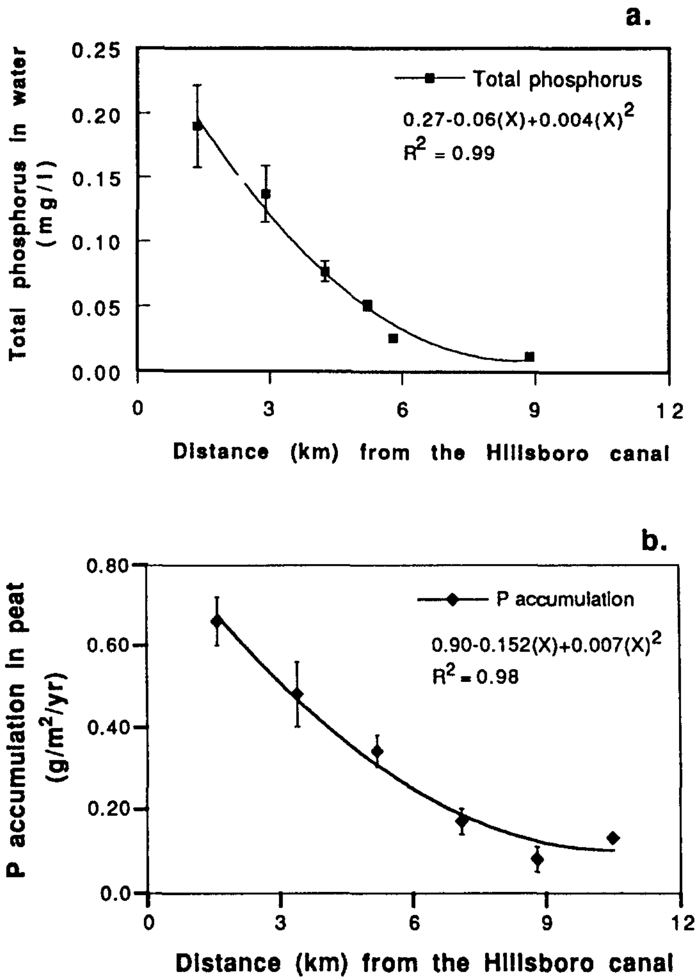

Fig. 5. (a) Mean surface water total phosphorus concentration and (b) mean phosphorus accumulation ($n = 3$) as a function of distance along a eutrophication gradient in WCA 2A. (Total P concentrations in surface water are data collected by the SFWMD during the years 1986, 1987, 1988, 1989 and 1990 (The numbers of samples collected from each location range from 50 to 64). The drawn curves represent the model fit using least squares regression (Statistical Analysis Systems 1982).

enriched area exists as refractory compounds such as low solubility organic P compounds (65%), calcium phosphates (13%) and Fe and Al phosphates (7%) (Qualls & Richardson 1993). Thus, most of the P accumulating in the enriched area is permanently sequestered in the peat matrix and, under current conditions, is unlikely to be released back into the water column and exported downstream.

Table 5. Phosphorus storage efficiency in the 11,500 ha nutrient enriched area of WCA 2A.

	Total P (metric tons/yr)	
Input: S10-A, -C, -D and -E gates[1]	60.0	
Rainfall (0.06 g/m²/yr)[1]	7.0	
Total	67.0	
Storage: high (2500 ha, 21%)[2] (0.65—0.90 g/m²/yr)	18.0	
moderate (2800 ha, 24%)[2] (0.40—0.65 g/m²/yr)	14.6	
low (6200 ha, 55%)[2] (0.15—0.40 g/m²/yr)	16.7	
Total	49.3	
Percent efficiency		74%
Integrated rate of accumulation (g/m²/yr) (Storage (49.3)/Area (11,500))		0.43

[1] From SFWMD (1992).
[2] Calculated using the mean rates of 0.72 (high efficiency; cores 10C-1 and 10D-1), 0.52 (moderate efficiency; cores 10A-1, 10A-2, 10A-3, 10C-2) and 0.27 (low efficiency; 10C-3, 10C-4, 10D-2, 10D-3 and 10D-4) g P/m²/yr.

Total soil P along the eutrophication gradient was positively correlated with the rate of peat accretion ($r = 0.65$) and soil Ca concentration ($r = 0.52$) (Table 1), suggesting that increased deposition of P enriched detritus and calcium bound P are the primary mechanisms controlling P storage in the enriched area. Qualls & Richardson (1993) found that refractory organic P (humic acid P, $r = -0.75$; residual P, $r = -0.87$) and calcium P ($r = 0.81$) (0—5 cm depth) were inversely correlated with distance along the gradient. Sixty five percent of the soil P in the enriched area existed as low solubility organic compounds while 13% was associated with calcium (mean of 4 locations; 0—5 cm depth; Qualls & Richardson 1993). In unenriched areas, refractory organic P and Ca bound P accounted for only 52% and 11%, respectively, of the soil P ($n = 4$; Qualls & Richardson 1993). Likewise, Koch & Reddy (1992) reported that organic P and calcium-P were the major soil P pools in nutrient enriched and unenriched areas of WCA 2A. Organically bound P and Ca-P accounted for 70% and 25%, respectively, in the enriched area and 78% and 14% in the unenriched area (0—40 cm, Koch & Reddy 1992).

It is likely that the higher percentage of refractory organic P in the enriched area is the result of increased NPP and P uptake by emergent vegetation. Davis (1989, 1991) observed an increase in macrophyte (sawgrass and cattail) NPP and tissue P concentration in the enriched area as compared to unenriched locations in the interior of WCA 2A. Furthermore, cattail, which has replaced sawgrass as the dominant emergent in the enriched area, has higher NPP and tissue P content than sawgrass (Craft & Richardson 1993b; Davis 1989, 1991). The increase in Ca bound P in the enriched area probably is due to high concentrations of both phosphorus and calcium in drainage water entering WCA 2A. There was no difference in the amount of Fe and Al bound P along the eutrophication gradient (Qualls & Richardson 1993), which suggests that Fe and Al are not important in sequestering P in these circumneutral (soil pH = 7.0—7.1) peatlands. In fact, total soil Fe (1100 ug/g) and Al (1600 ug/g) concentrations in the enriched area (0—10 cm depth) were 20—30 times lower than the Ca concentration (37,000 ug/g) (C. B. Craft, unpublished data). These findings emphasize the importance of Ca in sequestering P in circumneutral peatlands such as the Everglades. In contrast, sorption and precipitation of P with Fe and Al, generally, is the primary chemical mechanism controlling P retention in acidic mineral soil wetlands and peatlands (Richardson 1985).

Our data concerning long-term P storage in Everglades peat suggest that P can be sequestered at an average rate of 0.44 $g/m^2/yr$. These data are invaluable in determining the wetland area needed to remove P in peat based wetlands. The South Florida Water Management District is proposing to construct approximately 16,400 ha of wetland buffer areas on former agricultural land to remove P from agricultural drainage prior to release into the WCAs (Burns & McDonnell 1993). The District estimates that a wetland of this size could be used to remove approximately 220 metric tons of P annually, depending on the effectiveness of agricultural best management practices. However, our field research on long-term P accumulation in WCA 2A suggests that an area more than three times the size (50,000 ha) of the proposed 16,400 ha will be needed to effectively and permanently remove the 220 MT P/yr in agricultural drainage.

Conclusions

Long-term (25—30 yr) additions of nutrient enriched agricultural drainage to WCA 2A have resulted in increased rates of peat accretion and nutrient (P, Na, organic C, N, Ca) accumulation downstream from the Hillsboro canal, the source of the nutrient and water input. Increased rates of P and Na accumulation were attributed to both greater peat accretion and higher soil P and Na concentrations. Phosphorus enrichment of the soil occurred up to 7.1 km downstream of the Hillsboro canal while Na enrichment was found only within 1.5 km of the Hillsboro canal. Increased rates of organic C, N and Ca accumulation were due only to increased peat accretion. The area of enhanced peat accretion (and organic C, N, Ca and Na accumulation) extended 5.2 km downstream of the Hillsboro canal and covered approximately 7700 ha in northeastern WCA 2A. The area of enhanced P accumulation (and enriched soil P concentrations) extended 7.1 km downstream and covered approximately 11,500 ha.

The 11,500 ha area of enhanced P accumulation removed 74% (49.3 MT) of the 67 MT P/yr that enters via agricultural drainage and rainfall. However, P accumulation in the enriched area decreases as the mean annual (1986—1990) surface water P concentration decreases along the gradient. These findings suggest that P accumulation is dependent on the P concentration in the water column and that decreasing P loads per unit area result in less P storage per unit area.

The 11,500 ha area in WCA 2A has functioned effectively as a sink for P for the past 25—30 yr. Our findings of low P accumulation rates and an understanding of the mechanisms controlling P storage in WCA 2A will be useful in determining the sizing of peat based wetland systems which can be used to efficiently remove P from agricultural drainage, wastewater and other anthropogenic sources.

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References

Belanger TV, Scheidt DJ & Platko JR II (1989) Effects of nutrient enrichment on the Florida Everglades. Lake and Reservoir Management 5: 101—111

Brady NC (1984) The Nature and Properties of Soils. Macmillan Publishing Co., New York, New York

Bricker-Urso S, Nixon SW, Cochran JK, Hirschberg DJ & Hunt C (1989) Accretion rates and sediment accumulation in Rhode Island salt marshes. Estuaries 12: 300—317

Burns & McDonnell (1993) Modified conceptual plan for the Everglades Protection Project, prepared for the South Florida Water Management District, May 10, 1993

Carignan R & Flett RJ (1981) Postdepositional mobility of phosphorus in lake sediments. Limnol. Oceanogr. 26: 361—366

Craft CB & Richardson CJ (1993a) Peat accretion and N, P and organic C accumulation in nutrient-enriched and unenriched Everglades peatlands. Ecol. Appl. 3: 446—458

Craft CB, Vymazal, J & Richardson CJ (1993b) Response of Everglades plant communities to nitrogen and phosphorus additions. Aquatic Botany. In prep.

Davis JH (1943) The natural features of southern Florida. The Florida Geological Survey, Bulletin no. 25. Tallahassee, Florida

Davis SM (1989) Sawgrass and cattail production in relation to nutrient supply in the Everglades. In: Sharitz RR & Gibbons JW (Eds) Freshwater Wetlands and Wildlife (pp 325—341). CONF-8603101, DOE symposium series no. 61, USDOE Office of Scientific and Technical Information, Oak Ridge, Tennessee

Davis SM (1991) Growth, decomposition and nutrient retention of *Cladium jamaicense* Crantz and *Typha domingensis* Pers. in the Florida Everglades. Aquat. Bot. 40: 203—224

Faulkner, SP and Richardson CJ (1989) Physical and chemical characteristics of freshwater wetland soils. In: Hammer DA (Ed) Constructed Wetlands for Wastewater Treatment (pp 41—72). Lewis Publishers, Chelsea, Michigan

Gleason PJ (1974) Chemical quality of water in conservation area 2A and associated canals. Technical report 74-1, South Florida Water Management District, West Palm Beach, Florida

Gleason PJ, Cohen AD, Smith WG, Brooks HK, Stone PA, Goodrick RL & Spackman W Jr (1984) The environmental significance of Holocene sediments from the Everglades and saline tidal plain. In: Gleason PJ (Ed) Environments of South Florida: Present and Past II (pp 297—351). Miami Geol. Soc., Coral Gables, Florida

Howard-Williams C (1985) Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective. Freshwater Biology 15: 391—431

Kushlan JA (1989) Wetlands and wildlife, the Everglades perspectives. In: Sharitz RR & Gibbons JW (Eds) Freshwater Wetlands and Wildlife (pp 773—790). CONF-8603101, DOE symposium series no. 61, USDOE Office of Scientific and Technical Information, Oak Ridge, Tennessee

Koch KR & Reddy KR (1992) Distribution of soil and plant nutrients along a trophic gradient in the Florida Everglades. Soil Sci. Soc. Amer. J. 56: 1492—1499

Loveless CM (1959) A study of the vegetation in the Florida Everglades. Ecology 40: 1—9

McPherson BF (1973) Water quality in the conservation areas of the Central and Southern Florida Flood Control District, 1970—1972. Open-file report 73014, US Geological Survey, Tallahassee, Florida

Mitsch WJ & Gosselink JG (1986) Wetlands. Van Nostrand Reinhold Co., New York

Oldfield F & Appleby PG (1984) Empirical testing of ^{210}Pb models for dating lake sediments. In: Haworth EY & Lund JWG (Eds) Lake Sediments and Environmental History (pp 93—124). University of Minnesota Press, Minneapolis, Minnesota

Parker GG, Ferguson GE & Love SK (1955) Water resources of southeastern Florida with special reference to the geology and groundwater of the Miami area. Water Supply Paper 1255, US Geological Survey, US Government Printing Office, Washington, DC

Qualls RG & Richardson CJ (1993) Forms of soil phosphorus along a nutrient enrichment gradient in the northern Everglades. Soil Science. In review

Rader RB & Richardson CJ (1993) Changes in invertebrates and small fish along a nutrient enrichment gradient in the Everglades. Wetlands. In review

Reddy KR, DeBusk WF, Wang Y, DeLaune R & Koch M (1991) Physico-chemical properties of soils in Water Conservation Area 2 of the Everglades. Final report to the South Florida Water Management District, West Palm Beach, Florida

Richardson CJ (1985) Mechanisms controlling phosphorus retention capacity in freshwater wetlands. Science 228: 1424—1427

Richardson CJ & Craft CB (1993) Effective phosphorus retention in wetlands: fact or fiction? Proceedings of the International Symposium on Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Inc., Chelsea, Michigan. In press

Richardson CJ & Marshall PE (1986) Processes controlling movement, storage and export of phosphorus in a fen peatland. Ecol. Monogr. 56: 279—302

Richardson CJ, Craft CB, Qualls RG, Rader RB & Johnson RR (1991) Effects of nutrient loadings and hydroperiod alternations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of south Florida. Annual report to the Everglades Agricultural Area Environmental Protection District. Duke Wetland Center publication no. 91-08. Duke University Durham, North Carolina

Sawyer RK & Griffin GM (1983) The source and origin of the mineralogy of the northern Florida Everglades. In: Raymond R Jr. & Andrejko MJ (Eds) Mineral Matter in Peat: Its Occurrence, Form and Distribution (pp 189—198). Los Alamos National Laboratory, Los Alamos, New Mexico

Sommers LE & Nelson DW (1972) Determination of total phosphorus in soils: a rapid perchloric acid digestion procedure. Soil Sci. Soc. Amer. Proc. 36: 902—904

South Florida Water Management District (1992) Surface water improvement and management plan for the Everglades. Supporting information document. South Florida Water Management District, West Palm Beach, Florida

Statistical Analysis Systems (1982) SAS User's Guide: Statistics. SAS Institute Inc., Cary, North Carolina

Steward KK & Ornes WH (1975) Assessing a marsh environment for wastewater renovation. J. Water Pollut. Control Federation 47: 1880—1891

Steward KK & Ornes WH (1975) The autecology of sawgrass in the Florida Everglades. Ecology 56: 162—171

USDA, Soil Conservation Service (1978) Soil Survey of Palm Beach County Area of Florida. US Government Printing Office, Washington, DC

Valiela I, Howes B, Howarth R, Giblin A, Foreman K, Teal JM & Hobbie JE (1982) Regulation of primary production and decomposition in a salt marsh ecosystem. In: Gopal B, Turner RE, Wetzel RG & Whigham DF (Eds) Wetlands Ecology and Management (pp 151—169). National Institute of Ecology and International Scientific Publications, Jaipur, India

Waller BG & Earle JE (1975) Chemical and biological quality of water in part of the Everglades, southeastern Florida. Water Resources Investigations 56—75, US Geological Survey, Tallahassee, Florida