

Long-Term Nutrient Accumulation Rates in the Everglades

K. R. Reddy,* R. D. DeLaune, W. F. DeBusk, and M. S. Koch

ABSTRACT

Anthropogenic nutrient inputs to the northern Everglades of Florida during the last three decades have resulted in alteration of vegetation and soil nutrient storage. Due to the nutrient-limited status of this ecosystem, increased loading may have altered the capacity for long-term nutrient accumulation. Our study was conducted to determine the potential long-term nutrient accumulation rates for this ecosystem along a gradient of nutrient loading. Accumulation rates were calculated using the vertical peat accretion rates, as determined by ^{137}Cs dating, and nutrient concentration profiles. Intact soil cores were obtained along a 15-km transect and evaluated as a function of distance from the inflow structure. Soil cores were sectioned into 1-cm-depth increments and analyzed for ^{137}Cs , P, N, C, and selected cations. Vertical accretion rates of peat decreased logarithmically with distance from the inflow, with rates of 1.1 cm yr^{-1} at 0.3 km from the inflow to about 0.25 cm yr^{-1} in unimpacted sawgrass (*Cladium jamaicense* Crantz)-dominated areas. Phosphorus, N, and C accumulation rates in soil and floodwater total P concentrations also showed similar relationships. The P accumulation rates ranged from 0.54 to $1.14 \text{ g P m}^{-2} \text{ yr}^{-1}$ in cattail (*Typha* spp.)-dominated areas, and 0.11 to $0.25 \text{ g P m}^{-2} \text{ yr}^{-1}$ in sawgrass-dominated areas. The C/P and N/P accumulation ratios increased with distance from the inflow, suggesting that a greater proportion of P accumulated in the system, compared with C and N. Similar P retention coefficients were obtained when calculated using either changes in surface water total P concentration, or the long-term P accretion rates. These findings suggest that P was either directly adsorbed by soil or precipitated with Ca in the water column and deposited on the soil surface. This hypothesis was further supported by a highly significant correlation between P and Ca accretion rates, suggesting that Ca-bound P controls equilibrium concentrations in this ecosystem.

LONG-TERM NUTRIENT ACCUMULATION in wetland ecosystems is determined by the balance between inputs and outputs. Nutrients in wetlands undergo several biogeochemical transformations, some resulting in the loss of certain nutrients as gaseous end products or through leaching and discharge to outflow, while

others result in nutrient accumulation within the ecosystem. Nutrient accumulation can occur through sedimentation or organic matter accumulation. In peat-dominated wetlands, a major portion of the nutrients is stored in live and detrital plant tissue, microbial biomass, and stabilized soil organic matter. Nutrients stored in vegetation and microbial biomass can be readily released through natural die-off and decomposition (Davis, 1991). In herbaceous wetlands, nutrient storage in vegetation is usually short term (Reddy and DeBusk, 1987), while in forested wetlands incorporation of nutrients into woody tissue of trees can result in long-term storage (Richardson and Davis, 1987).

As C and N are cycled through a wetland, a portion can be lost as gaseous end products. For example, organic C is converted to CO_2 and CH_4 , and is lost from the system. This process is influenced by the hydrologic regime of the system, with frequent wet and dry cycles increasing decomposition rates and loss of C (Reddy and Patrick, 1975). In the EAA, oxidation of organic matter under drained conditions accounted for soil loss of about 3 cm yr^{-1} (Snyder et al., 1978). However, CO_2 fixation by vegetation and accumulation of detrital material in many wetlands usually offsets decomposition, resulting in a net C accumulation. Similarly, organic N is mineralized to $\text{NH}_4\text{-N}$, which is subsequently lost through nitrification-denitrification and NH_3 volatilization reactions (Reddy and Patrick, 1984). However, P released during decomposition is usually retained by the wetland through sorption and precipitation reactions (Howard-Williams, 1985).

Nutrients added to a wetland are rapidly incorporated into living and detrital plant material, and eventually incorporated into soil organic matter (Puriveth, 1980; Day, 1982; Davis and van der Valk, 1983; DeBusk and Reddy, 1987). Long-term nutrient retention by soil organic matter is affected by environmental factors such as temperature, hydroperiod and fire. Nutrient accumulation rates have been estimated for many wetland ecosystems using ^{137}Cs as a marker (DeLaune et al., 1978; Hatton et al., 1983; Kadlec and Robbins, 1984; Patrick and DeLaune, 1990). Peat

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Abbreviations: EAA, Everglades Agricultural Area; WCA, Water Conservation Area; ENP, Everglades National Park; SRP, soluble reactive P; TKN, total Kjeldahl N.

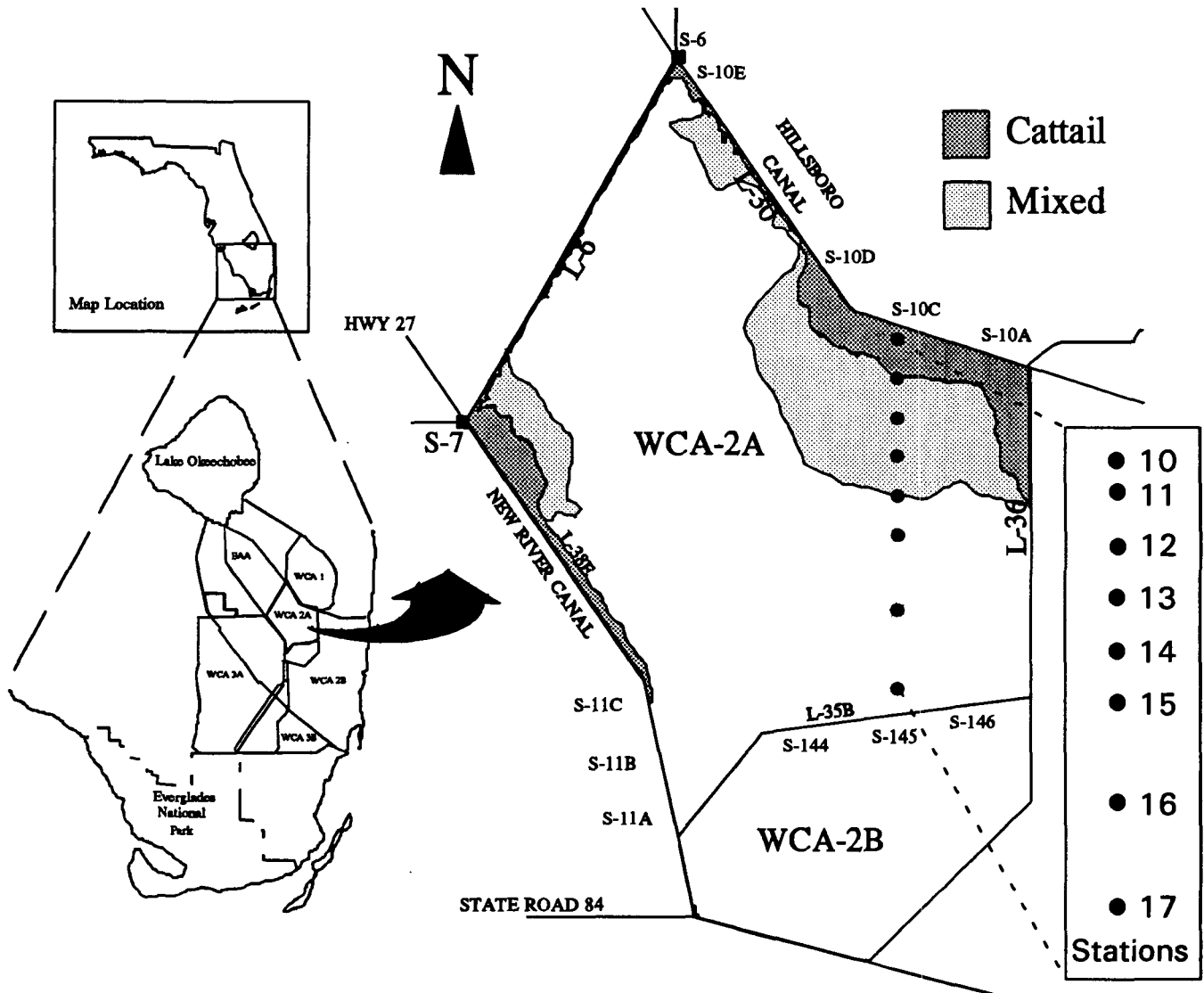


Fig. 1. A map of Water Conservation Area 2A showing sampling stations along a transect south of inflow structure S-10C.

accretion rates of 0.75 to 1.35 cm yr⁻¹ were measured in freshwater marshes of Louisiana (DeLaune et al., 1978). These rates represent C, N, and P accumulation rates of 200 to 300, 9, and 0.5 g m⁻² yr⁻¹, respectively (Hatton et al., 1982). Similarly, a P accumulation rate of 0.18 g P m⁻² yr⁻¹ was measured in oligotrophic areas of the Everglades (Davis, 1991), compared with <0.1 to 0.2 g P m⁻² yr⁻¹ for northern oligotrophic wetlands (Nichols, 1983).

The original Everglades consisted of a sawgrass marsh with occasional sloughs, swamps, and hammocks (Davis, 1943). Large areas of the northern and eastern Everglades have been drained for agricultural or urban land uses. The hydrology of the central Everglades is now regulated by pumps and canals. Historically, nutrient loading to the Everglades has been through atmospheric precipitation (Davis, 1943; Parker et al., 1955), as evidenced by the low nutrient status of the ecosystem. However, the point source inputs of agricultural drainage and associated nutrients from EAA has resulted in the spread of cattails into areas originally occupied by sawgrass (Davis, 1991).

Alterations in vegetation communities have been accompanied by changes in overall productivity and can potentially influence the long-term nutrient storage capabilities of the ecosystem (Davis, 1991). This study was conducted to evaluate long-term nutrient storage in Everglades wetland soil that is influenced by anthropogenic nutrient loading.

MATERIALS AND METHODS

Site Description

The Everglades area was historically a contiguous wetland, but is presently fragmented into the following hydrological units by a system of canals and levees: EAA, 245 930 ha; WCA-1, 58 900 ha; WCA-2, 54 700 ha; WCA-3, 237 000 ha; and ENP, 149 400 ha (Fig. 1). The EAA is currently used for growing sugarcane (*Saccharum officinarum* L.), vegetables, and sod. The soils in the EAA are highly managed by frequent draining during the cropping season. The hydrology of the WCAs and the ENP is regulated although these areas are flooded during most of the year. The WCAs were established in the early 1960s for the purpose of water supply, flood control, and wildlife habitat and creation. Thus, any intensive nutrient load-

ing to these systems has occurred during the past 30 yr. During predrainage conditions (hydrologic modifications began in the early 1800s), water flowed south by continuous sheet flow. At present, however, water flows southward from one hydrologic unit to the next through 2400 km of canals, 18 major pump stations, and hundreds of water control structures that are strictly regulated by predefined water schedules. Water is stored in WCAs in the upper end of the Everglades system for water supply during the dry season, and for backpumping excess storm drainage for flood control during the rainy season. The Everglades within the managed WCAs are loaded with storm water runoff from agricultural areas to the north. These events concomitantly add large amounts of P (2.28×10^5 kg P yr⁻¹) and N (8.17×10^6 kg N yr⁻¹) to the ecosystem.

About 58% of inflow water entering WCA-2 originates from the EAA (South Florida Water Management District, 1992). The soils in the EAA are artificially drained; the nutrient-enriched canal water enters north of the WCA-2 marsh via four water control structures (S-10A, S-10C, S-10D, and S-10E) located along Hillsboro Canal (Fig. 1). Minor discharge occurs from control structures located at the south end of WCA-2. Current research focuses on WCA-2A, which is impacted by these nutrient inputs as indicated by vegetation shifts and nutrient enrichment in soil and water. A distinct P concentration gradient in surface water south of the inflow structure of WCA-2A has been shown in data from the South Florida Water Management water quality monitor P network (South Florida Water Management District, 1992). The spatial characteristics of the soils and the distribution of nutrients along this nutrient gradient in surface water were reported by Koch and Reddy (1992) and Reddy et al. (1991). These data were used to identify the experimental sites along a transect south of the S-10C structure within WCA-2 (Fig. 1).

Soil Sampling and Analysis

Sampling stations south of the S-10C control structure were selected to represent three distinct vegetational zones. Visual observation indicated that Stations 10 and 11 were located in an area dominated by cattails, Stations 12 and 13 consisted of mixed populations of cattails and sawgrass, and Stations 14 to 17 were in a sawgrass-dominated area (Fig. 1). Eight stations along a transect south of the S-10C structure were selected for determination of ¹³⁷Cs and nutrient content. Intact soil cores were obtained by driving a thin-walled aluminum pipe (15-cm diam.) to a depth of 50 cm. The intact core was retrieved with negligible compaction or soil disturbance. The coring tube was capped on both ends and transported to the laboratory. At Station 11 (1.9 km from the inflow), duplicate soil cores were obtained, while at other stations only one soil core was obtained. Soil was extruded from the coring tube by slowly pushing from the bottom and was sectioned into 1-cm increments. Sectioned samples were dried at 70 °C for 72 h and weights were recorded. Soil subsamples were ground in a ball mill for analysis of ¹³⁷Cs, total P, N, and C, and selected metals.

Vertical accretion rates were determined from ¹³⁷Cs distribution in the soil profile (DeLaune et al., 1978). This method for determination of the peat accretion rate is based on a known date of atmospheric fallout of H-bomb-derived ¹³⁷Cs. The first significant fallout levels were detected during 1954, while peak concentrations were measured in 1963 and 1964 (Pennington et al., 1973). The ¹³⁷Cs activity in each section was determined by gamma counting oven-dried samples with a germanium detector and multichannel analyzer. Total P was determined by combusting a known amount of soil at 550 °C for 4 h. The ash was dissolved in 20 mL of 6 M HCl followed by analysis on an autoanalyzer (U.S. Environmental Protection Agency, 1983, Method 365.4). Total N and C in the samples were determined using a Carlo-Erba CNS analyzer (Haak-Buchler Instruments, Saddlebrook, NJ). The bulk density of soil for each depth increment was calculated using soil dry weight and volume.

Water Sampling and Analysis

The South Florida Water Management District has an extensive surface water quality monitoring network within WCA-2 (South Florida Water Management District, 1992). Surface water samples were obtained once every 2 wk by district staff during 1986 to 1991 and analyzed for SRP, total P, NH₄-N, NO₃-N, and TKN using standard methods (American Public Health Association, 1985). Water quality data obtained during 1986 to 1991 were used for comparison with long-term nutrient accumulation rates calculated using ¹³⁷Cs techniques.

Calculations

Peat accretion rates were calculated based on the assumption that there was no significant deposition of ¹³⁷Cs since 1964. Depth of peat accumulation above the peak ¹³⁷Cs activity gave an indication of accretion since 1964 (for the past 26 yr) and was calculated as follows:

$$\text{PAR} = \frac{{}^{137}\text{Cs peak depth (cm)}}{\text{Number of years since 1964}} \quad [1]$$

where PAR = peat accretion rates (cm yr⁻¹).

Nutrient accumulation rates were calculated as follows:

$$\text{NAR} = \frac{\sum(C\rho_b)}{n} \text{PAR} \times 10 \quad [2]$$

where NAR = nutrient accumulation rates (g m⁻² yr⁻¹); C = concentration of nutrient (mg g⁻¹); ρ_b = bulk density (g cm⁻³) in each depth increment; and n = number of 1-cm depth increments above the 1964 peak.

Phosphorus retention coefficients were calculated using the following first-order kinetic relationship:

$$-\frac{dC}{dX} = AC \quad [3]$$

where C = concentration of P in the water column (mg L⁻¹), X = distance from inflow (km), and A = P retention coefficient (km⁻¹). Two types of data were used to calculate P retention coefficients: (i) P concentration in the surface water column as a function of distance from inflow; and (ii) long-term P accumulation as a function of distance from inflow.

Integrating Eq. [3], the following relationship is obtained:

$$C_x = C_o \exp(-AX) \quad [4]$$

where C_o = concentration of total P in the water column at the inflow point (mg L⁻¹) and C_x = concentration of total P at distance X (km) from the inflow (mg L⁻¹).

Equation [4] is modified to calculate P retention coefficients from long-term P accumulation data:

$$(\text{NAR})_x = (\text{NAR})_o \exp(-AX) \quad [5]$$

where (NAR)_o = nutrient accumulation at or near inflow point (g m⁻² yr⁻¹); (NAR)_x = nutrient accumulation at distance X from the inflow (g m⁻² yr⁻¹). Equations [4] and [5] were solved by nonlinear least square fit using the Gauss-Newton method (SAS Institute, 1985). The values for A and C_o or (NAR)_o were obtained from these equations.

RESULTS

Surface Water Quality

Average N and P concentrations in the water column from 1986 to 1991 are shown in Table 1. Total and soluble P concentrations decreased exponentially as a

Table 1. Mean ($n = 87$) surface water quality characteristics at selected distances from the inflow station during 1986 to 1991 (South Florida Water Management District, 1992).

| Distance from inflow | SRP† | TP‡ | NH ₄ -N | NO ₃ -N | TKN§ |
|----------------------|----------------------|-----------|--------------------|--------------------|---------------|
| km | $\mu\text{g L}^{-1}$ | | | | |
| 1.6 | 134 ± 203 | 203 ± 249 | 160 ± 220 | 30 ± 80 | 3,420 ± 1,310 |
| 3.0 | 101 ± 178 | 154 ± 233 | 90 ± 180 | 10 ± 10 | 2,520 ± 850 |
| 4.4 | 34 ± 56 | 72 ± 76 | 20 ± 20 | 10 ± 10 | 2,280 ± 730 |
| 5.4 | 25 ± 61 | 52 ± 69 | 84 ± 363 | 8 ± 3 | 2,280 ± 820 |
| 6.4 | 7 ± 7 | 28 ± 42 | 30 ± 90 | 11 ± 8 | 2,190 ± 580 |
| 9.2 | 6 ± 3 | 11 ± 5 | 86 ± 144 | 13 ± 14 | 2,480 ± 679 |

† SRP = soluble reactive P.

‡ TP = total P.

§ TKN = total Kjeldahl N.

function of distance from the inflow. Soluble P accounted for 25 to 67% of the total P. Changes in forms of N showed no apparent relationship with distance, although elevated levels were observed near the inflow station.

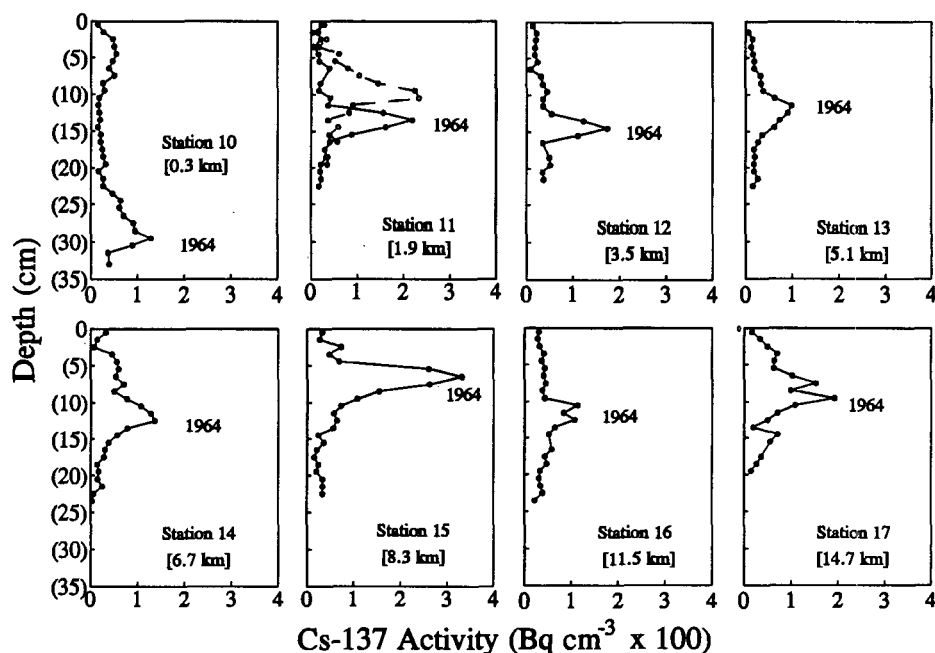
Peat Accretion

The distribution of ¹³⁷Cs in soil cores revealed distinct peaks at all stations and indicated that peat accretion had occurred during recent years in WCA-2A (Fig. 2). The depth at which the 1964 ¹³⁷Cs peak occurred varied with distance from the inflow. Maximum peat accretion occurred at the station located 0.3 km from the inflow structure (S-10C), an area dominated by cattails. Very little change in peat accretion was observed between stations at 1.9 and 6.7 km from the inflow and reached a minimum value at Station 15 (8.3 km from the inflow). Peat accretion rate at Station 10 (0.3 km from the S-10C structure) was 1.13 cm yr⁻¹, compared with 0.48 cm yr⁻¹ at Station 11, located 1.9 km from the inflow. Both stations (10 and 11) are located in an area now dominated by cattails where total P concentrations in surface water were >100 $\mu\text{g L}^{-1}$ (Table 1). Stations 12, 13, and 14

are located in an area with mixed stands of cattails and sawgrass. Average peat accretion rate in this area was 0.52 cm yr⁻¹. At Stations 15, 16, and 17, an area predominantly sawgrass marsh and sloughs with surface water P concentrations at background level, the average peat accretion rate was 0.39 cm yr⁻¹. Lowest peat accretion (0.27 cm yr⁻¹) was observed at Station 15 (8.3 km from inflow S-10C), which is least influenced by anthropogenic inputs of nutrients, while areas near Stations 16 and 17 were impacted by minor nutrient inputs from control structures south of WCA-2A.

Phosphorus

Total soil P content was generally higher in surface layers and decreased with depth (Fig. 3). Concentrations typically followed nutrient gradients of surface water and vegetation. At Station 10, P accumulation occurred throughout the profile, with a minimum concentration of 80 $\mu\text{g P cm}^{-3}$ observed at a depth of 30 cm where the ¹³⁷Cs peak was observed. At Station 11 (1.9 km from the inflow), a concentration of 80 $\mu\text{g P cm}^{-3}$ was observed at a depth of about 12 cm. At this station, P concentration steadily decreased with depth to about 20

**Fig. 2.** Depth distribution of ¹³⁷Cs in soil cores collected as a function of distance from inflow structure S-10C.

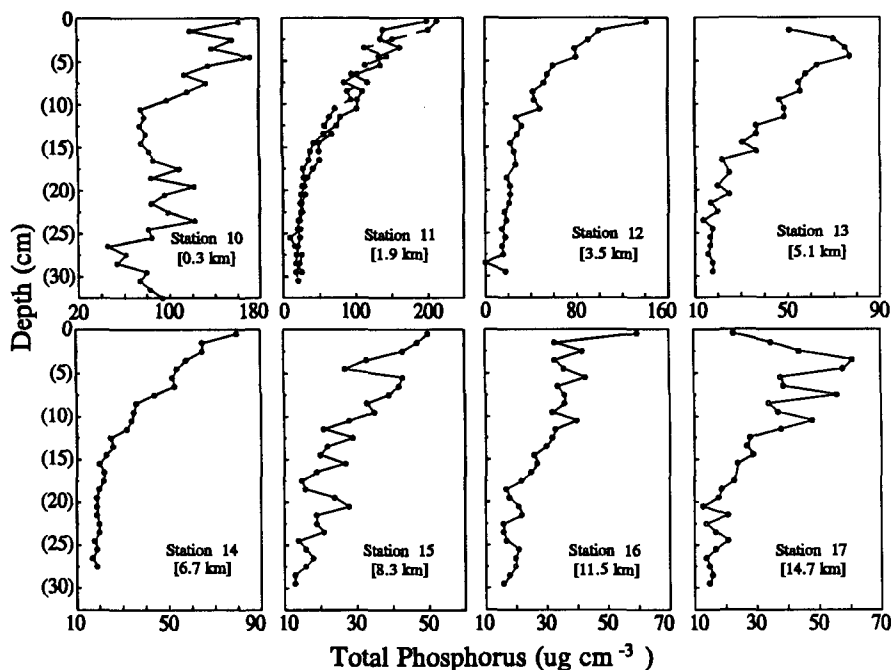


Fig. 3. Depth distribution of total P in soil cores collected as a function of distance from inflow structure S-10C.

cm and stabilized in the range of 17 to 24 $\mu\text{g P cm}^{-3}$ to a depth of 30 cm. At Station 12 (3.5 km from the inflow), 80 $\mu\text{g P cm}^{-3}$ was observed at a depth of about 5 cm, while at Stations 13 (5.1 km from the inflow) and 14 (6.7 km from the inflow), 80 $\mu\text{g P cm}^{-3}$ was measured in the top 1 cm of soil. At Station 15 (8.3 km from the inflow), total P concentration in the top 1 cm was 50 $\mu\text{g cm}^{-3}$, and steadily decreased with depth to 15 $\mu\text{g cm}^{-3}$.

Phosphorus accumulation rates decreased with distance ($r^2 = 0.945$; $P = 0.01$) from the inflow (Table 2). In the areas closer (0.3–1.9 km) to the inflow structure, P accumulation rates were in the range of 0.54 to 1.14 $\text{g P m}^{-2} \text{yr}^{-1}$ while, at a distance of 3.5 to 6.7 km from the inflow, P accumulation rates were 0.25 to 0.35 $\text{g P m}^{-2} \text{yr}^{-1}$. Phosphorus accumulation rates at 8 to 15 km from the inflow (areas dominated by sawgrass and sloughs) were in the range of 0.11 to 0.25 $\text{g P m}^{-2} \text{yr}^{-1}$.

Nitrogen and Carbon

Total N and C concentrations showed minimal trend through the 30-cm profile (Fig. 4 and 5). Nitrogen and

C accumulation rates were also higher near the inflow structure and decreased with distance. At stations closer to the inflow, accumulation rates were 11 to 24 $\text{g N m}^{-2} \text{yr}^{-1}$ and 163 to 387 $\text{g C m}^{-2} \text{yr}^{-1}$. In areas with mixed stands of cattails and sawgrass, accumulation rates were 9 to 13 $\text{g N m}^{-2} \text{yr}^{-1}$ and 140 to 208 $\text{g C m}^{-2} \text{yr}^{-1}$. Station 15, which is the least impacted area dominated by sawgrass, had N and C accumulation rates of 5 $\text{g N m}^{-2} \text{yr}^{-1}$ and 86 $\text{g C m}^{-2} \text{yr}^{-1}$, respectively.

Selected Cations

Calcium concentrations were high in the surface layer, and decreased with depth at stations near the inflow (Fig. 6). In areas dominated by sawgrass, a minimal trend with depth was observed. Calcium accumulation rates were in the range of 14 to 32 $\text{g Ca m}^{-2} \text{yr}^{-1}$ in cattail-dominated areas, compared with 4 to 8 $\text{g Ca m}^{-2} \text{yr}^{-1}$ in sawgrass areas (Table 3). Magnesium accumulation also showed similar trends. Accumulation of cations (Fe, Al, Mn, and Na) was high at the inflow station (0.3 km) but rapidly decreased at 1.9 km (Table 3). This was followed by minimal change in accumulation rate with distance.

Table 2. Net accumulation of peat, C, N, and P in soils of Water Conservation Area 2A as a function of distance from inflow structures. Accretion rates were calculated using ^{137}Cs peaks.

| Station | Distance | Peat | C | N | P | C/N/P |
|---------|----------|---------------------|----------------------------------|------|------|----------|
| | km | cm yr^{-1} | $\text{g m}^{-2} \text{yr}^{-1}$ | | | |
| 10 | 0.3 | 1.13 | 387 | 24.3 | 1.14 | 339:21:1 |
| 11A | 1.9 | 0.54 | 242 | 17.0 | 0.63 | 384:27:1 |
| 11B | 1.9 | 0.42 | 163 | 10.8 | 0.54 | 302:20:1 |
| 12 | 3.5 | 0.58 | 208 | 12.9 | 0.35 | 594:37:1 |
| 13 | 5.1 | 0.46 | 140 | 8.9 | 0.25 | 560:36:1 |
| 14 | 6.7 | 0.48 | 153 | 10.6 | 0.25 | 612:42:1 |
| 15 | 8.3 | 0.27 | 86 | 5.4 | 0.11 | 782:49:1 |
| 16 | 11.5 | 0.42 | 127 | 7.7 | 0.16 | 794:48:1 |
| 17 | 14.7 | 0.39 | 158 | 10.1 | 0.18 | 878:56:1 |

DISCUSSION

A series of biotic and abiotic processes regulate nutrient retention in WCA-2A and control nutrient concentrations in the overlying water column and in the soil. Carbon accumulation occurs because of an imbalance between production and decomposition of detritus. Detrital production is high in cattail-dominated areas, compared with sawgrass areas, reflecting differences in net primary productivity (Davis, 1991). Litter decomposition is governed by hydroperiod and supply of electron acceptors (such as O_2 , NO_3^- and SO_4^{2-}), which can stimulate the rate of decomposition (Reddy et al., 1986; Reddy and DeBusk, 1990). These processes result in loss of

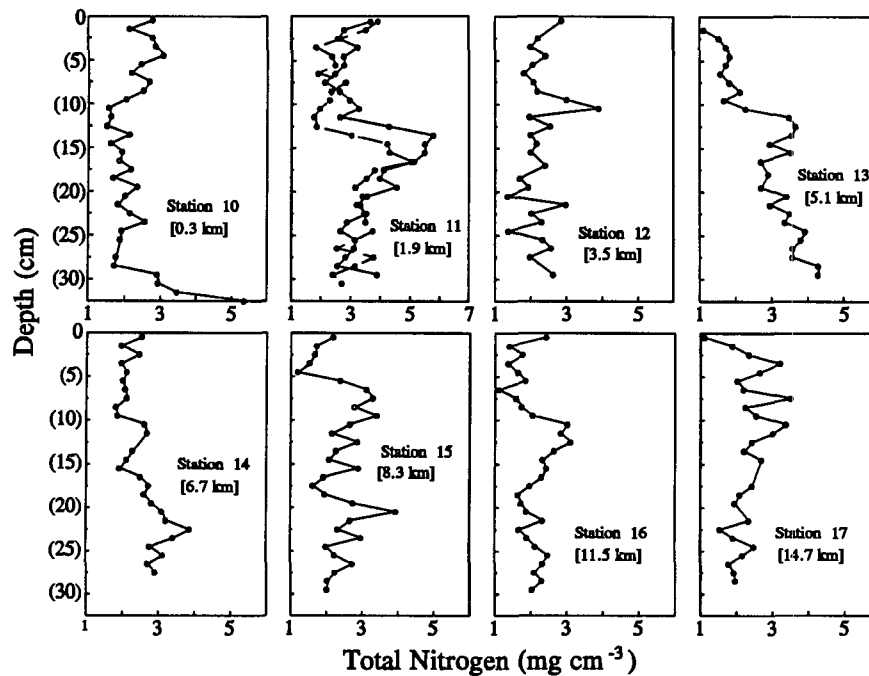


Fig. 4. Depth distribution of total N in soil cores collected as a function of distance from inflow structure S-10C.

organic C from the system as CO_2 , although the alkaline pH of WCA-2A soils can enhance the formation of bicarbonates (Reddy et al., 1991). Total C accumulation rates were in the range of 86 to $387 \text{ g C m}^{-2} \text{ yr}^{-1}$, with the high values measured in cattail areas and low values in sawgrass areas. The C accumulation rates observed for cattail-dominated areas of the Everglades are similar to those reported for freshwater wetlands of Louisiana (Smith et al., 1983). Davis (1991) measured accumula-

tion of organic matter at rates equivalent to 492 and $1160 \text{ g m}^{-2} \text{ yr}^{-1}$ in sawgrass and cattail areas of the Everglades, respectively. Assuming 40% C in the organic matter, net C accumulation rates would be 197 to $464 \text{ g C m}^{-2} \text{ yr}^{-1}$, values slightly higher than those measured with the ^{137}Cs technique. It should be noted that the values reported by Davis (1991) represent upper limits of C accumulation.

Field studies by Davis (1991) have shown that pro-

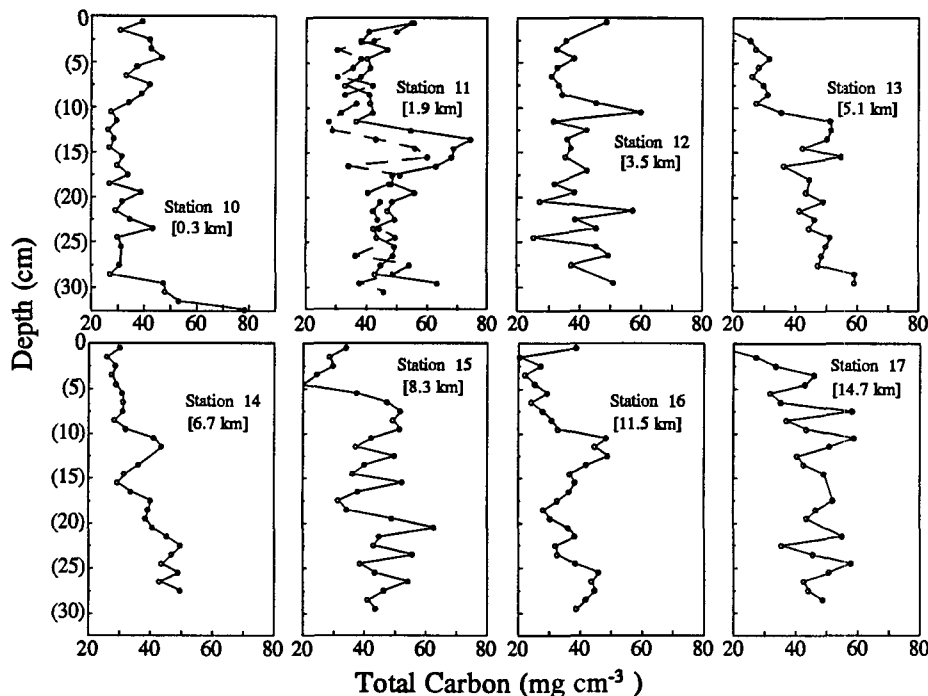


Fig. 5. Depth distribution of total C in soil cores collected as a function of distance from inflow structure S-10C.

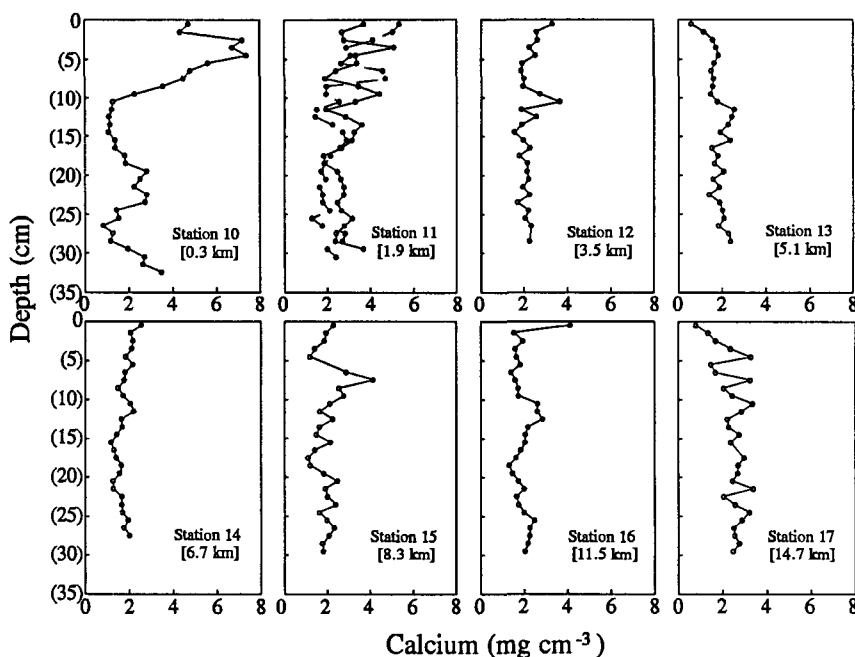


Fig. 6. Depth distribution of total Ca in soil cores collected as a function of distance from the inflow.

duction of detritus is higher than its decomposition, resulting in a net accumulation of organic material. Based on these experiments, Davis (1991) calculated N and P retention of 17 to 18 g N m⁻² yr⁻¹ and 1.1 to 1.4 g P m⁻² yr⁻¹ for mixed stands of cattails and sawgrass in the Everglades. These rates are similar to those estimated in our study for Stations 10 and 11 (Fig. 2) using the ¹³⁷Cs technique (Fig. 7). Both stations are dominated by cattails with a minimal cover of sawgrass. It should be recognized that the estimates made by this technique represent only net accumulation in the system, and do not give any indication of the extent of the losses of nutrients. Values reported by Davis (1991) for the Everglades represent upper limits for nutrient storage, while values estimated using ¹³⁷Cs provide a conservative estimate of nutrient accumulation. Long-term nutrient accumulation rates suggest that WCA-2A serves as a net sink for N and P. The N and P retention rates are similar to those reported by Nichols (1983) for northern oligotrophic wetlands and by Hatton et al. (1982) for a Louisiana backwater marsh.

The C/P and N/P ratios of the material accumulated in the soil increased with distance from inflow (Table

Table 3. Net accumulation of cations in soils of Water Conservation Area 2A as a function of distance from the inflow structure.

| Station | Distance km | g m ⁻² yr ⁻¹ | | | | | |
|---------|----------------|------------------------------------|------|------|------|-------|------|
| | | Ca | Mg | Fe | Al | Mn | Na |
| 10 | 0.3 | 32.1 | 5.62 | 3.41 | 4.78 | 0.034 | 3.92 |
| 11A | 1.9 | 16.7 | 1.38 | 0.70 | 0.52 | 0.016 | 0.67 |
| 11B | 1.9 | 14.3 | 0.94 | 0.34 | 0.26 | 0.008 | 0.41 |
| 12 | 3.5 | 13.2 | 1.46 | 0.87 | 0.65 | 0.008 | 0.46 |
| 13 | 5.1 | 7.0 | 0.80 | 0.44 | 0.41 | 0.013 | 0.21 |
| 14 | 6.7 | 9.5 | 1.05 | 0.53 | 0.62 | 0.054 | 0.28 |
| 15 | 8.3 | 4.2 | 0.50 | 0.27 | 0.32 | 0.013 | 0.20 |
| 16 | 11.5 | 8.0 | 0.97 | 0.48 | 0.52 | 0.012 | 0.24 |
| 17 | 14.7 | 7.4 | 0.90 | 0.55 | 0.48 | 0.007 | 0.23 |

1). Wider C/P and N/P ratios at Stations 12 to 17 clearly suggest that the system is P limited. The C/N ratios range from 14 to 16, compared with 339 to 878 for C/P ratios and 21 to 56 N/P ratios. Nitrogen accumulation in WCA-2A is influenced by mineralization of organic N to NH₄⁺, followed by loss due to either nitrification-denitrification reactions, or NH₃ volatilization (Reddy and Patrick, 1984). Distinct soil pore water NH₄⁺ gradients measured by Koch and Reddy (1992) for WCA-2A suggest upward diffusion from anaerobic zones to aerobic zones and into the overlying water. Ammonium flux from the soil in nutrient-enriched areas of WCA-2A was in the range of 2.9 to 5.6 mg N m⁻² d⁻¹, compared with 0.2 to 0.5 mg N m⁻² d⁻¹ in unimpacted areas (Koch and Reddy, 1992). Because of the high organic matter content of WCA-2A soils, it is likely that denitrification can play a significant role in reducing N accumulation. Similarly, high-pH conditions at the soil and floodwater interface can also increase the possibility for NH₃ volatilization (Reddy and Patrick, 1984).

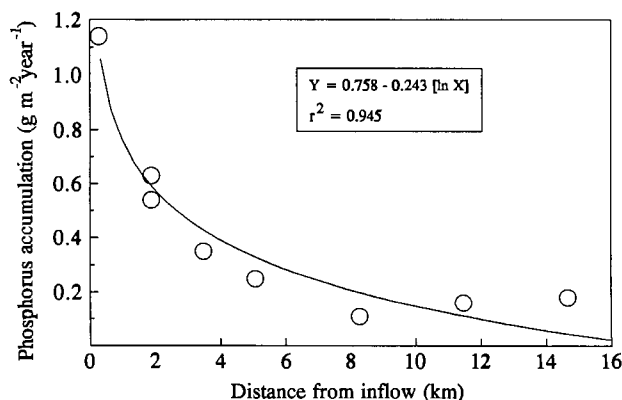


Fig. 7. Phosphorus accretion rates as a function of distance from inflow.

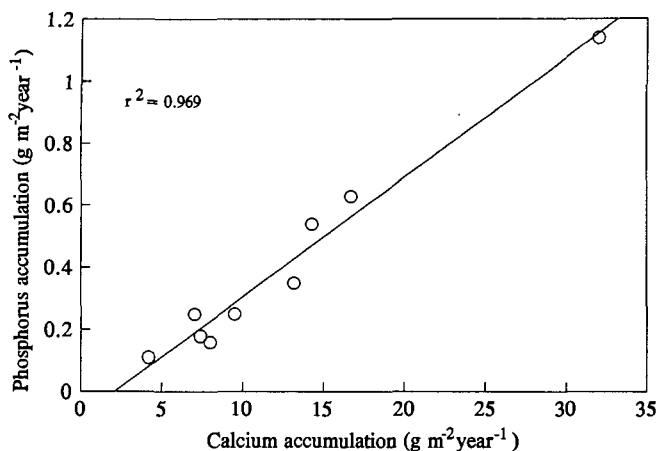


Fig. 8. Relationship between P accretion rates and Ca accretion rates.

A highly significant relationship was observed between P accumulation rates and Ca accumulation rates (Fig. 8), with Ca alone accounting for 97% of the variability. These results strongly support the hypothesis that Ca loaded to the system readily precipitates the P in the water column and is deposited on the soil surface. High pH in the water column (Koch and Reddy, 1992) associated with high periphyton activity and high Ca levels are ideal conditions for P coprecipitation with calcite (Otsuki and Wetzel, 1972). In a recent study, Diaz et al. (1991) observed rapid precipitation of P as Ca-P in water obtained from the Everglades, especially when the pH was at or higher than 8.0.

Unlike N and C, P mineralized from soil organic matter or imported from anthropogenic sources accumulates in the system, as indicated by the P enrichment in surface soil layers. Data on soil P fractionation (Koch and Reddy, 1992) indicate that Ca and Mg are the dominant factors regulating inorganic P dynamics in this system. In addition, detritus accumulation can result in a significant amount of P occurring as labile organic P. The relative availability of nonlabile pools, remineralization of labile organic P, and the factors regulating release and retention of P in these systems need further investigation.

Phosphorus retention coefficients (A in Eq. [4]) were calculated using a simple first-order kinetic relationship between P accumulation rates and distance from the inflow (Table 4). The P retention coefficient represents the P removal rate from the water column as a function of distance from inflow. This relationship is empirical and needs further evaluation to determine its mechanistic implications. The A value implies that P moving through the water column is retained by the soil, as mediated by settling, diffusion, uptake, and adsorption processes. Exponential decreases in both surface water total P concentration and P accumulation rates were used to calculate these relationships. The value for A using the changes in surface water total P was in the range of 0.201 to 0.486 km^{-1} . High A values during 1989 were due to severe drought conditions, resulting in high concentrations of P in the water column. Deleting 1989 data from the calculations gave an average A value of 0.232 km^{-1} . This value is about the same as the A value calculated using the data obtained on long-term P accumulation rates (Table 4). These similar A values for P retention

Table 4. Phosphorus assimilation coefficients calculated using a first-order kinetic relationship.

| Year | A (slope) km^{-1} | C_0 (intercept) mg L^{-1} | r^2 |
|---------------------|------------------------------------|--|-------|
| Water column P | | | |
| 1986 | 0.266 | 0.192 | 0.868 |
| 1987 | 0.383 | 0.382 | 0.984 |
| 1988 | 0.289 | 0.258 | 0.680 |
| 1989† | 0.572 | 2.011 | 0.987 |
| 1990 | 0.275 | 0.383 | 0.826 |
| 1991 | 0.372 | 0.151 | 0.958 |
| Average | 0.360 ± 0.105 | 0.563 ± 0.653 | |
| P accretion in soil | | | |
| 1964–1991 | 0.330 | $\text{g m}^{-2} \text{yr}^{-1}$ 1.20 | 0.959 |

† Drought conditions elevated the concentrations during 1989.

clearly suggest that P entering through the water column is either precipitated with a Ca-periphyton complex (Swift, 1984; Otsuki and Wetzel, 1972) and deposited on the soil surface, or directly sorbed into the surface soil and retained as Ca-P. These relationships were further substantiated by a highly significant relationship between Ca and P accumulation rates.

CONCLUSIONS

The ^{137}Cs data, as evidenced by distinct peaks corresponding to maximum ^{137}Cs fallout in 1964, are indicative of peat accretion in WCA-2A. Peat accretion decreased with distance from inflow structure S-10C. A similar response was also observed for C, N, and P retention based on soil analyses and accretion data. Nutrient retention in response to loading was higher in cattail-dominated areas than in sawgrass areas. The C/P and N/P accumulation ratios increased with distance from the inflow structure, suggesting that the system is P limited. Presence of a significant nutrient front (i.e., soil nutrient enrichment) from the S-10C structure raises the question of bioavailability of nutrients stored in surface layers of the peat. If the stored nutrients are readily released during organic matter decomposition, it may have a significant impact on the water quality of downstream areas. A number of factors such as hydroperiod, fire, physico-chemical condition at the soil-floodwater interface, uptake and release by vegetation, aquatic biota in the water column, and external nutrient loading influence nutrient release and retention. Results obtained in this study provide evidence for the significant long-term nutrient storage capability in WCA-2A. Future research should focus on short-term biogeochemical processes in the ecosystem and their impact on overlying water quality.

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