Spatial Distribution of Soil Nutrients in a Northern Everglades Marsh: Water Conservation Area 1

S. Newman,* K. R. Reddy, W. F. DeBusk, Y. Wang, G. Shih, and M. M. Fisher

ABSTRACT

The Florida Everglades developed as a nutrient-poor, rain-fed ecosystem. However, for the past 30 yr, the Everglades have received nutrient-enriched surface water runoff from the adjacent Everglades Agricultural Area (EAA). This study examines the response of a pristine wetland, Water Conservation Area 1 (WCA 1), part of the northern Florida Everglades, to nutrient loading as documented by soil nutrient concentrations. During 1979 to 1988, WCA 1 received 138 t total P (TP) and 4919 t total N (TN), retaining 53% of the TP load and 58% of the TN load. Analyses of the spatial distribution of soil N and P showed steep gradients of TP along the western canal boundary, adjacent to inflow points importing EAA runoff. Surficial soils (0–10 cm depth) at interior marsh sites had a mean TP concentration of 368 mg kg^{-1}, compared with 1028 mg kg^{-1} measured at sites adjacent to the western canal. Similar trends were observed for soil Ca and Mg, while C and N did not show the same boundary effects on spatial enrichment. Nutrient-enriched sites also had higher porewater soluble reactive P (SRP; 0.15 mg L^{-1}) and NH_4-N (1.65 mg L^{-1}) than unenriched sites (SRP = 0.02 mg L^{-1}, NH_4-N = 0.85 mg L^{-1}). Of the 90 sites sampled, 66 sites consisted of sloughs and sawgrass (*Cladium jamaicense* Crantz); the remaining 24 sites were either cattail (*Typha* spp.) dominated or had a significant cattail presence. These 24 cattail sites were closest to the nutrient inflow areas and had the highest soil nutrient concentrations.

The function and community structure of wetlands is dependent on the source, quantity, and quality of the water supply (Mitsch and Gosselink, 1986). The Everglades wetland ecosystem evolved with rain as the primary nutrient input and thus supports vegetation communities adapted to nutrient-limited and fluctuating hydroperiod environments (Davis, 1943; Parker, 1984). The historic Everglades encompassed approximately one million hectares and was described as a mosaic of shallow sawgrass plains interspersed with aquatic sloughs and dotted with tree islands (Davis, 1943). Starting in the early 1880s, large parts of the northern and eastern Everglades were drained for agricultural and some urban development. The present Everglades encompasses 500 000 ha and is divided into two distinct regions, consisting of WCA in the north and Everglades National Park in the south. The WCA are shallow diked marshes maintained for flood control, water supply, and environmental restoration, with vegetation communities still dominated by those species observed in the historic and remnant Everglades.

The northern boundary of the Everglades area is dominated by the EAA (290 000 ha) and a series of canals and water management structures used to direct flow for urban and agricultural use. Channelization has significantly altered the hydrology of the Everglades and also impacted the nutrient-limited status because much of the water entering the WCA is laden with nutrients from agricultural runoff (South Florida Water Management District, 1992). The combination of hydrological alteration and nutrient change, specifically P, has contributed to shifts in species composition of flora and fauna within this ecosystem (South Florida Water Management District, 1992). The most noticeable impact is observed in northeast and west WCA 2a, where ≈10 000 ha of cattails have appeared since the 1970s (Koch and Reddy, 1992; Jensen et al., 1995). This change is thought to be primarily due to the ability of cattail to outcompete sawgrass under increased nutrient loads (Davis, 1991; Koch and Reddy, 1992).

Nutrient inputs to wetlands are primarily stored in the soil because nutrient storage in vegetation is relatively short-term. Therefore, it is important to establish the spatial distribution of soil nutrients as a means of assessing nutrient impacts to these systems. Previous studies have shown the spatial patterns of nutrient enrichment in the soils of WCA 2a of the Everglades ecosystem (Koch and Reddy, 1992; DeBusk et al., 1994). This study assesses the influence of nutrient loading in WCA 1, the Arthur R. Marshall Loxahatchee National Wildlife Refuge, on soil nutrient enrichment. The objectives of this study were to (i) determine the spatial distribution of some soil chemical properties likely to be affected by external nutrient loading, (ii) determine TP storage in the soil as a result of external P loading, and (iii) quantitatively relate soil nutrient enrichment to the spatial composition of the plant community.

MATERIALS AND METHODS

Site Description

Water Conservation Area 1, encompassing 59 000 ha of the northern-most remnant of Everglades habitat (Fig. 1), was established as a Wildlife Refuge in 1951. Enclosed within 90 km of levees and canals, rain represents the major water inflow into the area, accounting for 54% of the surface water budget (South Florida Water Management District, 1992). The remainder is input from the northern tip, via pump station S-5A (30%) and from the west, by pump station S-6 (15%; Fig. 1). Therefore, ≈45% of the water budget for WCA 1

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Abbreviations: ANOVA, analysis of variance; EAA, Everglades Agricultural Area; SRP, soluble reactive P; TP, total P; TOP, total organic P; TIP, total inorganic P; WCA, Water Conservation Area; TN, total N; TC, total C.

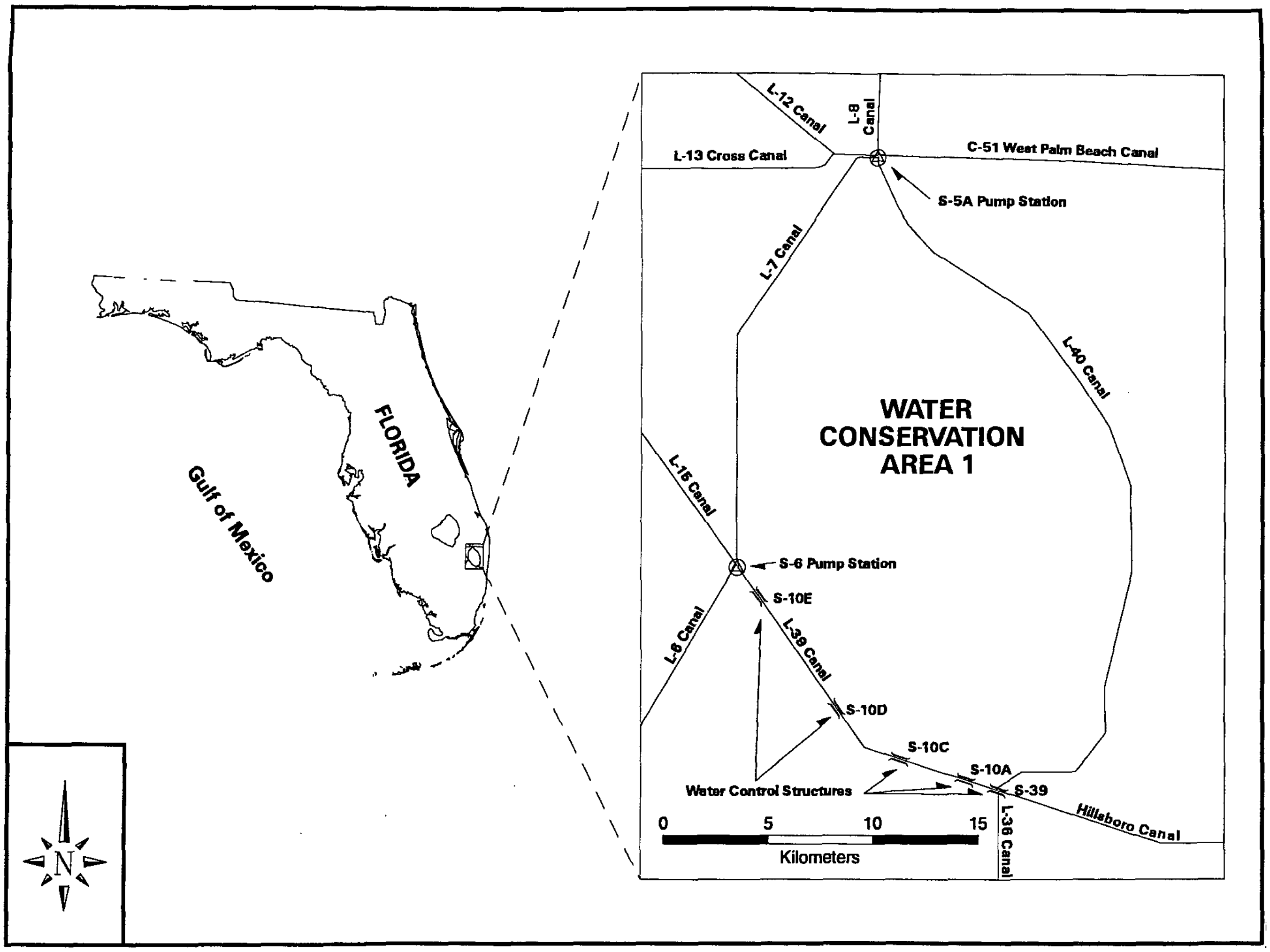

Fig. 1. Location of Water Conservation Area 1 in southern Florida.

originates from agricultural runoff from the adjacent EAA (South Florida Water Management District, 1992). The majority of water exits the area through a series of water control structures, the S-10s, at the south end of WCA1 (Fig. 1).

A topographical map developed in 1987 by Richardson et al. (1990) defines the average elevation as 4.58 m above sea level with a range of 3.36 to 5.00 m. There is a north–south slope of 2.55 cm km^{-1}. In addition, the internal perimeter canal drains the northern end and tends to direct inflows around the marsh rather than through it. Coupled with the current management of the system, this tends to cause ponding in the southern zone and drying in the northern zone.

The vegetation of WCA 1 is a mosaic of sawgrass marsh, wet prairies, aquatic sloughs, and tree islands and was recently mapped using SPOT satellite imagery and ground truthing (Richardson et al., 1990). This map delineates a zone of cattail along the western boundary, near the inflow points and fringing the perimeter canal (Fig. 2). In 1960, cattail represented 1% of the total vegetation population; in 1987, it had increased to 4% (South Florida Water Management District, 1992). Almost all the cattails are found within 1 km of the canal (Richardson et al., 1990). Soils within WCA 1 are Histosols. The predominant soil in the study area is a member of the Terra Ceia series (Euic, hyperthermic Typic Medisaprist; McCollum et al., 1976). Gleason et al. (1984) referred to the same soil in this study area as Loxahatchee Peat.

Soil Sampling and Analysis

Richardson et al. (1990) collected more than 100 soil samples from the surface 0- to 10-cm soil depth throughout WCA 1. The spatial representation (contour map) of these data were used in the sampling design for this study. This contour map was imported into a computer program that systematically calculated the slopes of Mehlich-extractable P within known windows (squares of known area) on the map. The size of each window increased until the entire area of WCA 1 was accounted for, and 90 sampling points representing areas with the greatest change in Mehlich-extractable P were determined. Soil cores were collected at 90 sites during 4 to 6 Sept. 1991 (Fig. 2). A float helicopter was used to access the sites, therefore minimizing disturbance and reducing sampling time. Loran C and global positioning system (GPS) navigation (Trimble Navigation, Sunnyvale, CA) were used to locate sites. Sampling occurred in both marsh and slough communities, no sampling was conducted in tree islands.

Soil cores were collected by driving a plastic polyvinyl chloride (PVC) coring tube (7.5 cm i.d.) into the soil and extracting the tube with the core intact. Any cores that contained large rhizomes were discarded. Small roots were not removed from the soil cores and were included in the nutrient analyses. The cores were sectioned in the field into depth increments of 0 to 10 and 10 to 20 cm, placed in sealed plastic bags, and stored

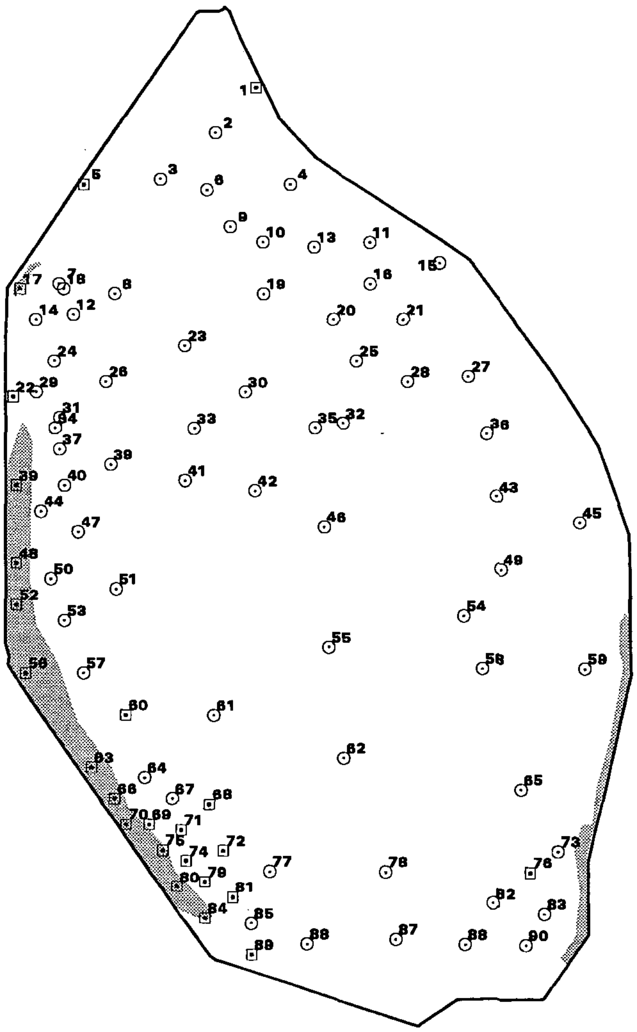

Fig. 2. Location of soil sampling sites (squares indicate cattail sites, circles indicate typical Everglades vegetation). Shaded area indicates cattail distribution established by Richardson et al. (1990).

at 4°C prior to analysis. A sub-sample of soil was weighed and dried at 70°C for 72 h or until a constant weight was obtained. Percentage dry weight, water content, and bulk density were determined. A sub-sample of moist soil was also used to determine pH. The remainder of the soil samples were analyzed for porewater ammonium (NH_4-N) and porewater SRP, HCl-extractable P, KCl-extractable NH_4-N and NO_x (NO_3 + NO_2-N), TP, TN, and total C (TC). Porewater was extracted by centrifuging a portion of fresh soil, maintained under a N_2 atmosphere, decanting the supernatant, and then filtering through a 0.45-μm membrane filter. The filtrate was analyzed for NH_4-N and SRP (Methods 351.2 and 365.1, U.S. Environmental Protection Agency, 1983). Phosphorus extracted with HCl (1:50 soil to solution ratio) was used as an estimate of total inorganic P (TIP). One-half gram of air-dry soil was extracted with 1 *M* HCl for 3 h, then filtered through a 0.45-μm membrane filter. The filtrate was analyzed for inorganic P (Method 365.1, U.S. Environmental Protection Agency, 1983), Ca, Mg, Fe, and Al (Method 200.7; U.S. Environmental Protection Agency, 1983). Total P was determined by combusting soil samples at 550°C for 4 h in a muffle furnace, followed by dissolution in 6 *M* HCl (Anderson, 1976). The digestate was analyzed for P (Method 365.4; U.S. Environmental Protection Agency, 1983). Total organic P (TOP) was calculated as the difference between TP and TIP. Total C and TN were determined from finely ground soil samples using a Carlo-Erba NA1500 C–N–S Analyzer (Haak-Buchler Instruments, Saddlebrook, NJ).

Water Sampling and Analysis

Surface water inflows through the pump stations S-5A and S-6 were sampled biweekly for water quality from 1979 through 1988 as part of the South Florida Water Management District regional water quality monitoring program (Germain, 1994). Data for samples collected while the pumps were operating are presented. In addition, water samples were collected from 16 interior sites by the South Florida Water Management District on an infrequent basis during 1978 to 1983 (Millar, 1981; South Florida Water Management District, unpublished data; Swift and Nicholas, 1987). Samples were also collected at points within the perimeter canal during the same time period. All samples were analyzed for TN, TP, SRP, NO_x, NH_4-N, conductivity, pH, and alkalinity using methods listed above.

Data Analyses

The spatial patterns of soil constituents were assessed using geostatistical analyses. Contour plots were produced for concentrations of N and P: TN (0–10 and 10–20 cm), TP (0–10 and 10–20 cm), porewater NH_4-N (0–10 and 10–20 cm), and porewater SRP (0–10 and 10–20 cm). The spatial structure of the data were investigated using GS+ software (Version 2.11, Gamma Design Software, Inc., Plainwell, MI), and it was determined that only TP and TN at the 0- to 10-cm soil depth had spatial autocorrelation or spatial structure at the sampling interval used. Therefore, optimal interpolation weights were derived from the semivariograms for these two parameters and used in the kriging algorithm to produce interpolated lattices from which contour plots were constructed. The remaining six parameters and depths were interpolated using inverse distance weighting. Comparisons among soil properties and nutrient concentrations were based on soil depth increments and also the dominant vegetation species at the site. Statistical differences between means were obtained by ANOVA analysis followed by Tukey-Kramer comparisons. All statistical analyses were performed using SAS (SAS Institute, 1989).

Sampling sites were grouped into two categories based on vegetation composition. The vegetation map developed by Richardson et al. (1990) was used in conjunction with field observations to categorize the sites based on cattail occurrence; 66 absent, 4 present, 15 significant presence but not a monoculture, 5 cattail monoculture. Because of the limited number of cattail categories, all cattail sites were collapsed into one category, resulting in two site classifications: cattail (24) or interior (66). Mean values were compared using ANOVA analysis followed by Tukey-Kramer comparisons (SAS Institute, 1989).

RESULTS

Depth and Spatial Distribution of Soil Nutrients

A summary of mean values of physical and chemical properties of WCA 1 soils is shown in Table 1. Bulk density, Al, and TC increased with soil depth, while TP, TIP, TOP, and extractable NH_4-N had significantly greater concentrations in the surface soil. The concentrations of all other parameters measured were not sig-

Table 1. Selected physical and chemical characteristics of soil samples collected in Water Conservation Area 1 (mean ± SE, *n* = 90). Soil samples were collected during 4 to 6 Sept. 1991.

Parameter†	0–10 cm depth	10–20 cm depth
Bulk density, g cm^{-3}	0.06 ± 0.003*	0.08 ± 0.002
pH	5.4 ± 0.06	5.5 ± 0.06
Water content, g g^{-1}	93 ± 0.3	92 ± 0.2
Ash content, g g^{-1}	10 ± 1	8.61 ± 1
Total C, g kg^{-1}	438 ± 5*	460 ± 5
Total N, g kg^{-1}	30 ± 1	30 ± 1
Total P, mg kg^{-1}	544 ± 41*	313 ± 28
TOP, mg kg^{-1}	375 ± 27*	217 ± 12
TIP, mg kg^{-1}	169 ± 18*	95.8 ± 20
Ca, mg kg^{-1}	21901 ± 2723	21641 ± 2670
Mg, mg kg^{-1}	1786 ± 94	1840 ± 112
Fe, mg kg^{-1}	416 ± 23	419 ± 33
Al, mg kg^{-1}	460 ± 38*	527 ± 27
Extractable NH_4–N, mg kg^{-1}	66 ± 4*	44 ± 3
Extractable NO_x, mg kg^{-1}	5.1 ± 0.6	5.4 ± 0.6
Porewater SRP, mg L^{-1}	0.05 ± 0.02	0.04 ± 0.01
Porewater NH_4–N, mg L^{-1}	1.06 ± 0.11	0.84 ± 0.09

* Values within the same row are significantly different at 0.05 probability level according to Tukey-Kramer comparisons.
† TOP = total organic P; TIP = total inorganic P; SRP = soluble reactive P.

nificantly different between the 0-to 10- and 10- to 20-cm depths.

The spatial distributions of N and P were also evaluated using kriging techniques. Elevated levels of porewater NH_4–N and SRP were found in areas adjacent to the pump stations where agricultural runoff is pumped into the system (Fig. 3 and 4). Similar trends of enrichment near the western canal boundary were also determined for P storage within this system. Results showed steep gradients of P along the western boundary (Fig. 5), with the zone of P enrichment extending further from the canal into the interior marsh in the surface 0- to 10-cm soil depth than in the 10- to 20-cm soil depth. On average, TP storage was higher in the surface 0 to 10 cm, but the contributions of inorganic and organic P to the TP pool were equivalent, 30 and 70%, respectively. Some spatial correlation in the ratio of inorganic to organic P was apparent, particularly at the western and southwest portions at 10- to 20-cm depth (data not shown). Carbon to P ratios showed a twofold increase with depth with ratios increasing from >1000 (0–10 cm) to >2000 (10–20 cm). Lower ratios tended to occur at the western boundary. In contrast, C/N ratios were the same magnitude at both depths without evidence of a gradient at the western boundary. Spatial gradients of TN were not as distinct as those for TP and the distribution range was much smaller (Fig. 6).

A comparison of soils data based on vegetation composition showed that cattail sites were typically associated with elevated nutrient concentrations. Extractable Al and NH_4–N and bulk density were the only parameters that were not significantly different in cattail vs. interior sites (Table 2). Porewater nutrient concentrations exhibited the greatest difference between the two regions, with porewater SRP concentrations being almost tenfold higher in cattail sites vs. interior sites. Total P, Ca, Mg, and porewater NH_4–N concentrations were approximately twice as high in cattail vs. interior sites, although ranges overlapped. Soils in interior sites were more acidic, with only half the ash content of soils in the cattail zone.

Surface Water Nutrients

Biweekly monitoring of the two major inflows, pump stations S-5A and S-6, during a 10-yr period (January 1979 through December 1988) showed TP and TN concentrations entering WCA 1 averaged 0.21 mg TP L^{-1} and 6.9 mg TN L^{-1} at S-5A and 0.15 mg TP L^{-1} and 5.5 mg TN L^{-1} at S-6 (Table 3). Greater than 50% of TP was present as SRP, while >50% of TN was organic. Nitrate–N was the dominant form of inorganic N in waters entering WCA 1. The range of nutrient concentrations was greater in water entering through S-5A

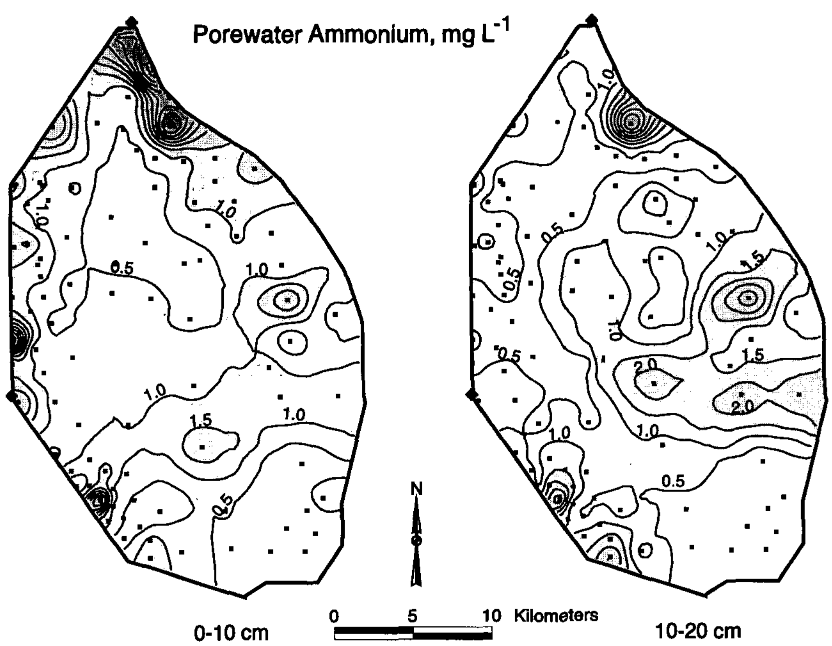

Fig. 3. Spatial distribution of porewater NH_4–N in soils cores from 90 sites in WCA 1, sampled during 4 to 6 Sept. 1991. Diamonds indicate the locations of the pump stations.

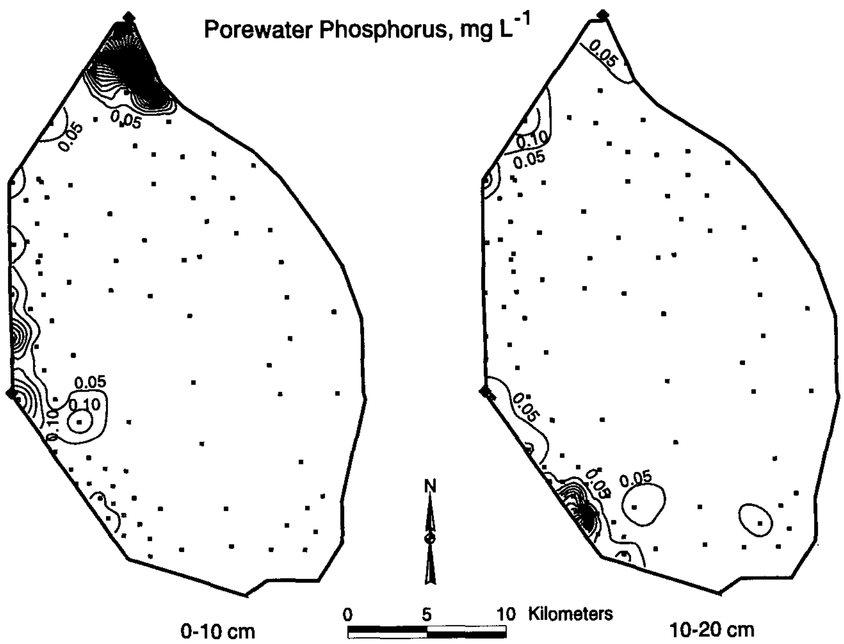

Fig. 4. Spatial distribution of porewater SRP in soils cores from 90 sites in WCA 1, sampled during 4 to 6 Sept. 1991. Diamonds indicate the locations of the pump stations.

than that measured through S-6. Combined inflows from pump stations S-5A and S-6 contributed 76%, or 106 t, of the TP load entering WCA 1 from 1979 to 1988 (South Florida Water Management District, 1992), with 56% of the TP load attributed to S-5A. The TN loads were fortyfold higher, but similar proportions of the TN load were contributed by the two pump stations, 84%, 4140 t. Typically, WCA 1 acts as a sink for these nutrients. Areal loads and retention of TP in WCA 1 during 1979 to 1988 were 0.23 and 0.12 g m^{-2}, respectively (South Florida Water Management District, 1992). Loads and retention of TN were 8.37 and 4.83 g m^{-2}, respectively (South Florida Water Management District, 1992).

Nutrient concentrations were generally higher in the canals than in the marsh interior (Table 4). Both SRP and NO_x–N were frequently determined to be at or below detection limits.

DISCUSSION

When a significant nutrient load is distributed through discrete water control structures, water flow patterns will influence the spatial distribution of nutrients. During periods of low water, the water entering WCA 1 generally flows south along the perimeter canals and does not infiltrate the interior marsh due to the slightly raised ground elevations at the center of WCA 1 (Swift

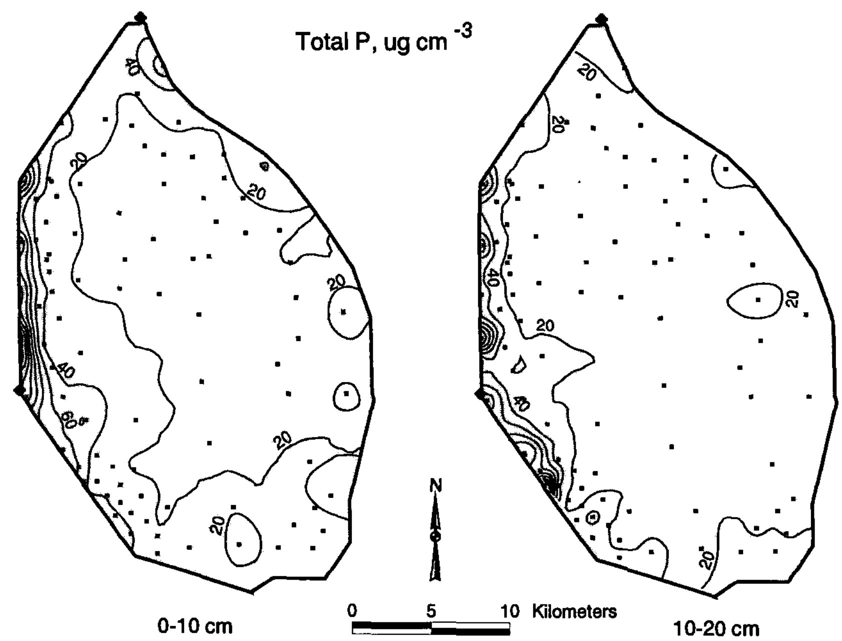

Fig. 5. Spatial distribution of Total P in soils cores from 90 sites in WCA 1, sampled during 4 to 6 Sept. 1991. Diamonds indicate the locations of the pump stations.

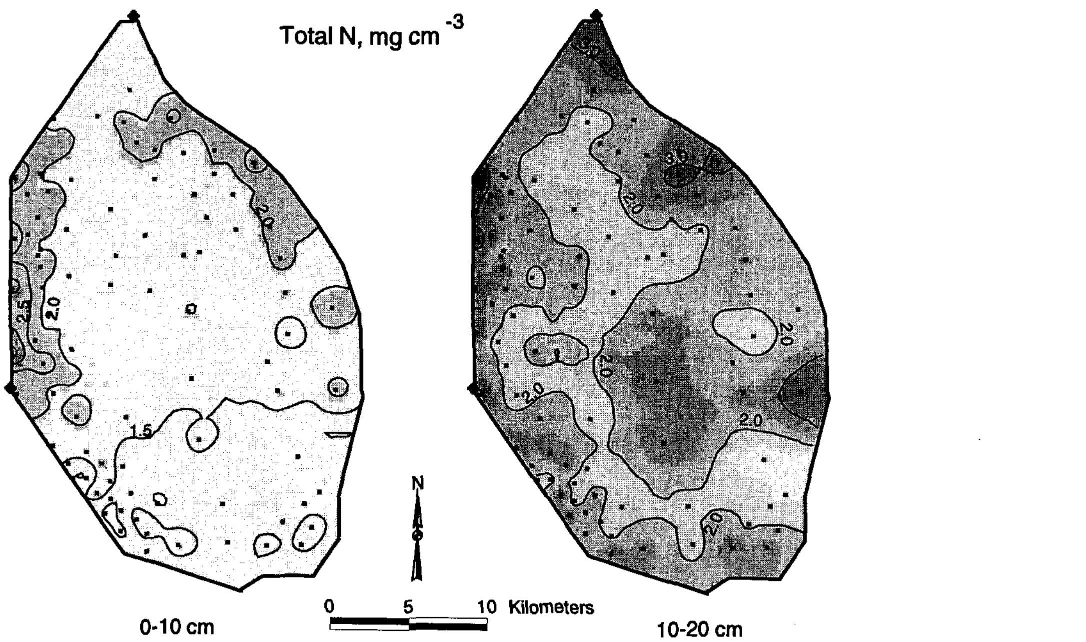

Fig. 6. Spatial distribution of Total N in soils cores from 90 sites in WCA 1, sampled during 4 to 6 Sept. 1991. Diamonds indicate the locations of the pump stations.

and Nicholas, 1987). Therefore, at low stage, nutrient inputs to the interior marsh of WCA 1 are primarily through rainfall, while areas adjacent to the boundary will be influenced by hydraulic and nutrient loads from the surrounding canal. Consequently, many water chemistry characteristics differ between interior and peripheral sites (Table 4). The marsh interior has lower conductivity and alkalinity and a slightly acidic pH. The peripheral sites have a circumneutral pH (7.3) similar to that observed in WCA 2A (7.1) and WCA 3A (7; Swift and Nicholas, 1987). In contrast, the majority of WCA 1 sites are pH 6. During high water periods, the marsh stage is elevated in response to increased pumping and rainfall. Thus, water from the canals is able to mix with water of the interior marsh (Millar, 1981).

Table 2. Selected physical and chemical characteristics of soils (0–10 cm) by vegetation zones in Water Conservation Area 1 (mean ± SE). Soil samples were collected during 4 to 6 Sept. 1991.

Parameter†	Cattail (n = 24)	Interior (n = 66)
Bulk density, g cm^{-3}	0.07 ± 0.009	0.06 ± 0.002
pH	6.2 ± 0.1*	5.3 ± 0.05
Water content, g g^{-1}	92 ± 1*	94 ± 0.2
Ash content, g g^{-1}	17 ± 2*	7 ± 0.2
Total C, g kg^{-1}	402 ± 12*	450 ± 4
Total N, g kg^{-1}	27 ± 1*	31 ± 1
Total P, mg kg^{-1}	1028 ± 93*	368 ± 13
TOP, mg kg^{-1}	670 ± 68*	268 ± 8
TIP, mg kg^{-1}	358 ± 49*	100 ± 6
Ca, mg kg^{-1}	42002 ± 8990*	14591 ± 605
Mg, mg kg^{-1}	2609 ± 211*	1486 ± 75
Fe, mg kg^{-1}	254 ± 36*	475 ± 24
Al, mg kg^{-1}	464 ± 62	459 ± 46
Extractable NH_4–N, mg kg^{-1}	73 ± 10	64 ± 4
Extractable NO_3, mg kg^{-1}	7.1 ± 1.2*	4.4 ± 0.6
Porewater SRP, mg L^{-1}	0.15 ± 0.07*	0.02 ± 0.01
Porewater NH_4–N, mg L^{-1}	1.65 ± 0.33*	0.85 ± 0.09

* Values within the same row are significantly different at 0.05 probability level according to Tukey-Kramer comparisons.
† TOP = total organic P; TIP = total inorganic P; SRP = soluble reactive P.

The significance of elevated nutrient loading to soil chemistry in WCA 1 is dependent on how much of each nutrient is retained within the system. Net accumulation of NO_3–N and organic N in inflow waters of the WCA occurs following conversion to NH_4–N and vegetative uptake and deposition (Davis, 1991; Reddy et al., 1993). However, N is often lost from wetlands through many microbial and physico-chemical mechanisms, such as ammonia volatilization and denitrification (Reddy and Patrick, 1984). Unlike N, P is not subject to the same loss mechanisms; therefore, P tends to accumulate. Described as a P-limited system, increases in P concentrations and P storage within the Everglades are of particular concern to the natural functioning of this pristine habitat. Previous studies in WCA 2A have shown that distinct P gradients develop adjacent to inflow points (Davis, 1991; Koch and Reddy, 1992; Urban et al., 1993; DeBusk et al., 1994; Qualls and Richardson, 1995). Elevated soil and surface water P concentrations in WCA 2A extend 5 to 7 km into the marsh from the inflow structures (Urban et al., 1993; Qualls and Richardson, 1995). Although the extent of the nutrient gradient in WCA 1 is less, there are distinct differences between peripheral and interior marsh sites (Tables 2 and 4; Swift and Nicholas, 1987). The mechanisms of P retention are influenced by the form of P in the inflow water as well as soil properties. Greater than 50% of TP in the canal water is in the form of SRP; thus, conversion from soluble P to insoluble P is essential for P retention. This may occur through mechanisms such as biological uptake, sorption, and precipitation. Typically, P-enriched zones in WCA 1 soils have higher Ca and Mg concentrations than interior sites. In sites immediately adjacent to the canal, this may be partially attributed to the mixing of canal waters with mineral-rich groundwater inflows (Gleason, 1974; Waller and Earle, 1975; Lutz, 1977). The chemical precipitation of Ca phosphates is suggested to

Table 3. Selected chemical concentrations in surface water from pump stations S-5A and S-6, collected during a 10-yr period (1979–1988).

Pump station	TN†	TKN†	NO_3-N	NH_4-N	SRP†	TP†
	mg L^{-1}					
S-5A						
mean	6.85	3.98	2.84	0.39	0.123	0.21
std dev	2.72	1.26	1.94	0.50	0.092	0.10
min	1.38	1.09	0.09	0.01	0.005	0.06
max	18.68	7.71	11.80	2.27	0.465	0.58
median	6.71	3.93	2.54	0.12	0.106	0.19
n	141	142	140	108	137	140
S6						
mean	5.46	3.79	1.58	0.46	0.105	0.15
std dev	2.57	1.03	1.89	0.37	0.130	0.13
min	2.09	1.86	0.08	0.01	0.004	0.01
max	15.85	6.95	10.03	1.46	0.849	0.87
median	4.66	3.66	0.88	0.42	0.062	0.11
n	111	111	110	94	100	108

† TN = total N; TKN = total Kjeldahl N; SRP = soluble reactive P; TP = total P.

be an important factor controlling P retention in WCA 2A soils (DeBusk et al., 1994; Qualls and Richardson, 1995). In Everglades slough communities with abundant calcareous periphyton mats, P precipitation is attributed to co-precipitation with Ca (Swift and Nicholas, 1987). However, the sites near the inflow structures of WCA 1 are not a suitable habitat for calcareous algal mats. A recent study in WCA 2A demonstrated the loss of calcareous algal mats as a direct result of P enrichment (McCormick and O'Dell, 1996). Therefore, it is more likely that the Ca phosphate formation at P-enriched sites adjacent to the canal is attributable to high, often near saturation, concentrations of Ca and CO_3^{2-} in the surface water (Swift, 1984). In contrast, the acidic soils of the marsh in the interior of WCA 1 are not conducive to Ca-dominated P storage because they experience minimal mixing with the mineral-rich groundwater inflows of the canals and any Ca phosphate precipitation would tend to redissolve at lower pH (Diaz et al., 1994).

Although Ca phosphates may contribute to some P storage in the WCA, the majority of P in Everglades soils is stored as organic P (this study; DeBusk et al., 1994; Reddy et al., 1994b; Qualls and Richardson, 1995). Phosphorus pools in these soils indicate that ≈70% of TP is organic. The form of organic P in WCA 1 soils varies dependent on sampling site location. Recalcitrant P forms dominate the storage of P in enriched areas of WCA 1, while less resistant forms are present in the unenriched interior (Reddy et al., 1994a). This spatial distribution is probably due to the difference in vegetation types and resultant humic substances produced in these two areas. The lignin content of sawgrass and cattail are similar (Reeder and Davis, 1983), but the aquatic slough and sawgrass communities within the marsh interior have higher densities of associated algae. Algae do not have the complex lignins associated with macrophytes and therefore will tend to produce less complex organic endproducts (Francois, 1990), e.g., fulvic acids as opposed to humic acids.

The mean TP storage in the surface 0 to 10 cm is 8.0 and 2.2 g m^{-2} in enriched and interior areas, respectively. A similar range in TP storage in unenriched vs. enriched sites was measured in WCA 2A (3–12 g m^{-2}; DeBusk et al., 1994). Net accumulation of soil P was calculated based on the following assumptions. The average TP content of 37.4 μg cm^{-3} in surface (0–10 cm depth, Table 2) soils was used in the calculations. It was assumed that the surface 0 to 10 cm was impacted by external P loading to the system. The minimal TP content (10.5 μg cm^{-3}) measured within the marsh interior was used as an indication of background levels, it was assumed that soils at the interior site were not influenced by external nutrient loading. Thus, net TP accumulation could be calculated as

$$P_{acc} = ([TP]_{avg} - [TP]_{min})D(0.1) \quad [1]$$

where $[TP]_{avg}$ is the average TP content (μg cm^{-3}) for the entire area of WCA 1 as estimated from all 90 sampling sites; $[TP]_{min}$ is the minimum P content of the soils measured in the marsh interior (μg cm^{-3}); D is soil depth in which P accumulation has occurred (10 cm); 0.1 is the conversion factor; and P_{acc} is net TP accumulation (g m^{-2}).

With the above equation, TP accumulation in WCA 1 soils was estimated to be 1582 metric tons or 27 kg TP ha^{-1} in the surface 10 cm of soil. With the assumption of an annual TP retention of 1.2 kg ha^{-1} yr^{-1} (South Florida Water Management District, 1992), the net accumulation in the surface 0 to 10 cm soil represents 22 yr of loading.

The ecological impact of nutrient enrichment is often dependent on the bioavailability of the nutrient forms, with porewater P the most labile and bioavailable por-

Table 4. Characteristics of surface water in Water Conservation Area 1 collected from 1978 to 1983 (mean ± SE, values in parentheses = *n*). Units are mg L^{-1} unless otherwise noted.

Parameter	Canal	Marsh Interior
pH	7.30 ± 0.03 (104)*	6.00 ± 0.06 (118)
Alkalinity, meq L^{-1}	4.47 ± 0.16 (104)*	1.84 ± 0.12 (207)
Conductivity, μS cm^{-1}	1051 ± 235 (104)*	561 ± 129 (15)
Total P	0.09 ± 0.01 (104)*	0.03 ± 0.00 (204)
Total soluble P	0.06 ± 0.01 (74)*	0.01 ± 0.00 (163)
Soluble reactive P	0.05 ± 0.01 (104)*	<0.004 (208)
Total N	3.48 ± 0.21 (104)*	2.72 ± 0.11 (200)
NH_4-N	0.11 ± 0.02 (104)	0.09 ± 0.02 (207)
NO_3-N	0.51 ± 0.10 (104)*	<0.01 (205)
Ca	74.9 ± 2.6 (104)*	27.6 ± 1.8 (207)
Mg	22.1 ± 1.0 (104)*	9.6 ± 0.7 (207)

* Values within the same row are significantly different at 0.05 probability level according to Tukey-Kramer comparisons.

tion of soil P. In WCA 1, the highest porewater P concentrations occur at sites closest to the canal, in association with the cattail fringe (Richardson et al., 1990). *Typha domingensis* (Pers.), the dominant species of cattail in the Everglades, has been shown to be highly competitive within a regime of high water levels and elevated nutrient concentrations (Davis, 1991; Urban et al., 1993; Newman et al., 1996). Thus, the distribution of cattail along the canal may also be attributed to the fluctuating hydroperiod. Richardson et al. (1990) compared soil nutrient concentrations and hydroperiod vs. cattail distribution. Through canonical analysis, they concluded soil P concentration is the primary factor controlling cattail distribution in WCA 1. As expected, the cattail zone mapped by Richardson et al. (1990) also falls within the zone of TP enrichment delineated in this study.

The mean soil TP concentrations in enriched (1028 mg kg^{-1}) and interior (368 mg kg^{-1}) sites in WCA 1 are quite similar to enriched (1340 mg kg^{-1}) and interior (470 mg kg^{-1}) areas in WCA 2A (DeBusk et al., 1994). Both enriched areas are dominated by cattail stands, while interior sites support only a sparse distribution of cattail, suggesting a threshold concentration above which cattails may proliferate. This is also indicated by a recent probability model used to test the effect of water depth and soil TP concentrations on cattail invasion in WCA 2A (Wu et al., 1997). Wu et al. (1997) determined that a soil TP of 650 mg kg^{-1} is the threshold at which accelerated cattail invasion occurs in WCA 2A. Established cattail stands may perpetuate the enrichment in the areas they inhabit. Cattails remove relatively high concentrations of P within their aboveground biomass and then release it rapidly upon decomposition, this may result in a localized recycling of elevated P concentrations compared with a species such as sawgrass. Sawgrass is typically associated with environments characterized as nutrient-poor and subject to periods of drought (Steward and Ornes, 1983). This species, along with openwater sloughs and tree islands, dominate the interior sites, which characteristically have low porewater nutrient, especially P, concentrations.

In conclusion, distinct zones of soil nutrient enrichment were found associated with the perimeter canal of WCA 1. These zones did not extend into the marsh interior and appear to arise from the influence of the higher hydraulic and nutrient loads from the adjacent canals vs. the reduced loading reaching the marsh interior. Phosphorus and Ca concentrations exhibited the most distinct gradients. Storage data suggest that a significant portion of TP added to WCA 1 through external inputs is stored within the soils. Twenty-seven kg TP ha^{-1} were calculated to have accumulated within the surface 0- to 10-cm soil depth during the past 22 yr. The majority of P was stored in the organic form, indicating the importance of a recalcitrant organic P pool in long-term P storage.

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