Recent and Long-Term Organic Soil Accretion and Nutrient Accumulation in the Everglades

C. B. Craft* and C. J. Richardson

ABSTRACT

Organic soil accretion and nutrient accumulation were measured in the northern, central, and southern Everglades to evaluate the effects of anthropogenic nutrient and hydroperiod alterations on organic C and nutrient storage during the past century. Six soil cores (euic, hyperthermic Typic Medisaprists) were collected from nutrient-enriched (Water Conservation Area [WCA] 2A) and unenriched locations. Soil depth increments were analyzed for radionuclides (^{137}Cs, ^{210}Pb, ^{14}C), bulk density, and nutrients (C, N, P, S) to estimate recent (30-yr) and long-term (100-yr) organic soil accretion and nutrient accumulation. Since WCA 2A was completely impounded in the early 1960s, organic soil accretion in northern WCA 2A (5.8–6.7 mm yr^{-1}) increased by three to five times compared with before 1960 (1.9 mm yr^{-1}) or with unenriched areas within and outside of WCA 2A (1.4–1.6 mm yr^{-1}). Nutrient accumulation in the enriched area of WCA 2A since 1960 was two (184–223 g C m^{-2} yr^{-1}, 13.6–16.6 g N m^{-2} yr^{-1}) to eight (0.40–0.46 g P m^{-2} yr^{-1}) times higher than before 1960 (110 g C m^{-2} yr^{-1}, 6.6 g N m^{-2} yr^{-1}, 0.06 g P m^{-2} yr^{-1}) or in unenriched areas (65–90 g C m^{-2} yr^{-1}, 4.7–6.4 g N m^{-2} yr^{-1}, 0.06 g P m^{-2} yr^{-1}). Unenriched areas of the Everglades possess some of the lowest rates of P accumulation of peatlands in North America. Successful restoration of the Everglades will have to include the elimination of anthropogenic nutrient loadings to limit the P enrichment zone from expanding into existing unenriched interior areas and areas downstream of WCA 2A.

THE EVERGLADES is a 700 000-ha subtropical freshwater wetland dominated by sawgrass (*Cladium jamaicense* Crantz), open-water slough (*Eleocharis* spp., *Nymphaea* spp. *Utricularia* spp., *Nuphar advena* Aiton), wet prairie (*Eleocharis*, *Rhynchospora* spp.) and tree island [*Magnolia virginiana* L., *Persea borbonia* (L.), *Salix caroliniana* Michaux] communities (Loveless, 1959; Gunderson, 1994). During the past 5000 yr, the Everglades has developed into a vast freshwater organic soil system, underlain in some areas by up to 4 m of sapric material (Gleason and Stone, 1994).

Since the beginning of the 20th century, nearly 65% of the original Everglades has been drained for agriculture and urban–suburban development (Kushlan, 1989). Construction of canals, levees, and water control structures for flood control and to supply water for irrigation and municipal use has led to a general reduction in the depth and duration of inundation in the remaining Everglades (Light and Dineen, 1994). Some of the hydrologic and ecological alterations attributed to drainage include modification of surface water flow (e.g., increased pulsing from water control structures and pump stations), loss of wet prairie wetlands, ponding of water in some areas, and overdrainage in others (Walters et al., 1992; Light and Dineen, 1994).

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Historically, the Everglades developed as a low-nutrient or oligotrophic ecosystem, receiving most of its nutrients from rainfall and episodic overflow from Lake Okeechobee (Belanger et al., 1989; Davis, 1994). Phosphorus, in particular, has been shown to limit the productivity of sawgrass and other emergent species (Steward and Ornes, 1983; Davis, 1989, 1991; Craft et al., 1995). During the past 50 yr, areas of the northern Everglades have been affected by nutrient-enriched agricultural drainage from the 300 000-ha Everglades Agricultural Area (EAA) upstream (Davis, 1991, 1994). Changes in Everglades community structure and ecosystem function associated with nutrient enrichment are described in Table 1.

Nearly all of these studies have focused on the effects of P enrichment during the past 30 yr, while community structure and ecosystem processes in the Everglades prior to anthropogenic nutrient loadings have not been clearly documented. We measured recent (^{137}Cs) and long-term (^{210}Pb and ^{14}C) organic soil accretion and nutrient (C, N, P, and S) accumulation to assess whether, and to what extent, nutrient enrichment and anthropogenic drainage activities have affected organic soil accumulation and nutrient storage in the Everglades during the past century.

METHODS

Site Description

Soil cores were collected from six locations throughout the northern, central, and southern Everglades (26°N, 80.5°W) (Fig. 1). In the northern Everglades, one core was collected from WCA 1 (Loxahatchee National Wildlife Refuge [NWR]) and three cores were taken from WCA 2A. In WCA 2A, two cores were taken from a eutrophic area that has received nutrient (N and P) enriched agricultural drainage for at least the past 30 yr (Davis, 1991; Craft and Richardson, 1993b). One core (enriched no. 1) was taken 3.5 km downstream of the Hillsboro canal, the source of nutrient inflows to WCA 2A. The second core (enriched no. 2) was collected 1.4 km south of the Hillsboro canal. The third core was collected from an unenriched area, 10.5 km downstream of the Hillsboro canal. The remaining cores were collected in the central (WCA 3A) and southern (Everglades National Park [ENP]) Everglades. At unenriched locations, soil cores were taken from nearly monotypic stands of sawgrass while, at nutrient-enriched locations, cores were collected from cattail-dominated communities. Except for the nutrient-enriched cores, all cores were collected from interior areas of the Everglades, 10 km or more from the nearest canal or levee. The soils are classified as Terra Ceia series (euic, hyperthermic Typic Medisaprists; Soil Conservation Service, 1978).

Abbreviations: BP, before present; EAA, Everglades Agricultural Area; ENP, Everglades National Park; Loxahatchee NWR, Loxahatchee National Wildlife Refuge; WCA, Water Conservation Area.

Table 1. Changes in community structure and ecosystem processes associated with nutrient enrichment of the Everglades.

I.	Phosphorus enrichment of surface water, pore water, and peat.†
II.	Shifts in plant species composition, including loss of the *Utricularia*–periphyton mat in sloughs and cattail (*Typha domingensis* Pers.) encroachment into sawgrass and slough communities.‡
III.	Increased net primary production, tissue P concentration, and P storage by wetland vegetation.§
IV.	Increased litter decomposition.¶
V.	Increased organic soil accretion and nutrient (N and P) accumulation.#

† Koch and Reddy (1992), DeBusk et al. (1994), Qualls and Richardson (1995).
‡ Steward and Ornes (1975), Belanger et al. (1989), Davis (1991, 1994), Urban et al. (1993), Craft et al. (1995), Jensen et al. (1995).
§ Davis (1989), Craft et al. (1995).
¶ Davis (1991).
# Craft and Richardson (1993a,b), Reddy et al. (1993), Richardson et al. (1997).

Sample Collection and Analysis

Soil cores were collected using a 7.5 by 7.5 cm stainless steel box corer with a removeable side. Recognizable leaf litter (e.g., dead shoot material) was removed from the soil surface prior to sample collection. Compaction was minimized by removing one side of the corer, which allowed the core to expand outward during sample collection. Cores were visually inspected prior to removal from the soil to ensure that no compaction occurred and only those cores that did not exhibit any compaction were collected. The cores were sectioned into 1.5-cm (Loxahatchee NWR, WCA 2A enriched no. 1 and 2) or 2-cm (WCA 2A unenriched, WCA 3A, ENP) depth increments. The increments were air dried, weighed (for bulk density), ground, and passed through a 2-mm mesh diameter sieve.

Accretion rates were determined by analyzing the depth increments for ^{137}Cs and excess ^{210}Pb. Cesium-137 was determined by measuring the gamma emissions at 661.62 keV using a high-purity germanium detector (2.08% efficiency, EG&G Ortec, Oak Ridge, TN). Cesium-137 has been used to estimate recent (30-yr) rates of accretion in estuarine (Craft et al., 1993; Sharma et al., 1987) and freshwater wetlands (Hatton et al., 1983; Kadlec and Robbins, 1984). Cesium-137 is adsorbed onto clay, especially montmorillonite, and organic particles, uptake by vegetation is low, and diffusion usually is limited (Ritchie and McHenry, 1990). Even when diffusion does occur, such movement will not likely change the position of the ^{137}Cs horizon (Ritchie and McHenry, 1990). The ^{137}Cs technique, however, appears to be unreliable in acid organic soils (Oldfield et al., 1979; Clymo, 1983; C.B. Craft, 1996, unpublished data from North Carolina pocosins) because the cation-exchange sites are dominated by H^+ or Al species, which are preferentially sorbed instead of ^{137}Cs (Craft and Richardson, 1993a). Previous studies by Craft and Richardson (1993a,b) and Reddy et al. (1993) indicated that the ^{137}Cs technique is a reliable means to determine recent (30-yr) rates of organic soil accretion in the Everglades because of the high organic content (400–500 g kg^{-1} organic C; Craft and Richardson, 1993a), the presence of montmorillonite clay (Sawyer and Griffin, 1983), and circumneutral pH (Qualls and Richardson, 1995), all of which serve to enhance sorption of ^{137}Cs (Ritchie and McHenry, 1990).

Lead-210 was measured by alpha spectrometry of ^{210}Pb (and ^{209}Po) plated onto silver planchets after dissolution in HNO_3, HCl, $HClO_4$, and HF as described by Craft and Richardson (1993a). Chemical yield of ^{210}Pb was determined by adding ^{209}Po to the samples prior to digestion. Supported ^{210}Pb (^{210}Pb produced in the soil by radioactive decay of naturally occurring ^{238}U decay products) was estimated from total ^{210}Pb by assuming the background activity of total ^{210}Pb in the bottom portion of each core represented supported ^{210}Pb. The constant-activity model (constant accretion; CA) was used at unenriched sites and the constant rate of supply model (variable accretion; CRS) was used at the enriched sites to determine rates of organic soil accretion based on excess ^{210}Pb (Oldfield and Appleby, 1984; Bricker-Urso et al., 1989; Robbins and Herche, 1993). Excess ^{210}Pb (total minus supported ^{210}Pb) accumulates in depositional environments through atmospheric deposition and sedimentation (Brenner et al., 1994). Both the CA and CRS models assume a constant rate of supply of excess ^{210}Pb to the soil (Schelske et al., 1988). Additionally, the CA model assumes that the accretion rate is constant with time (Schelske

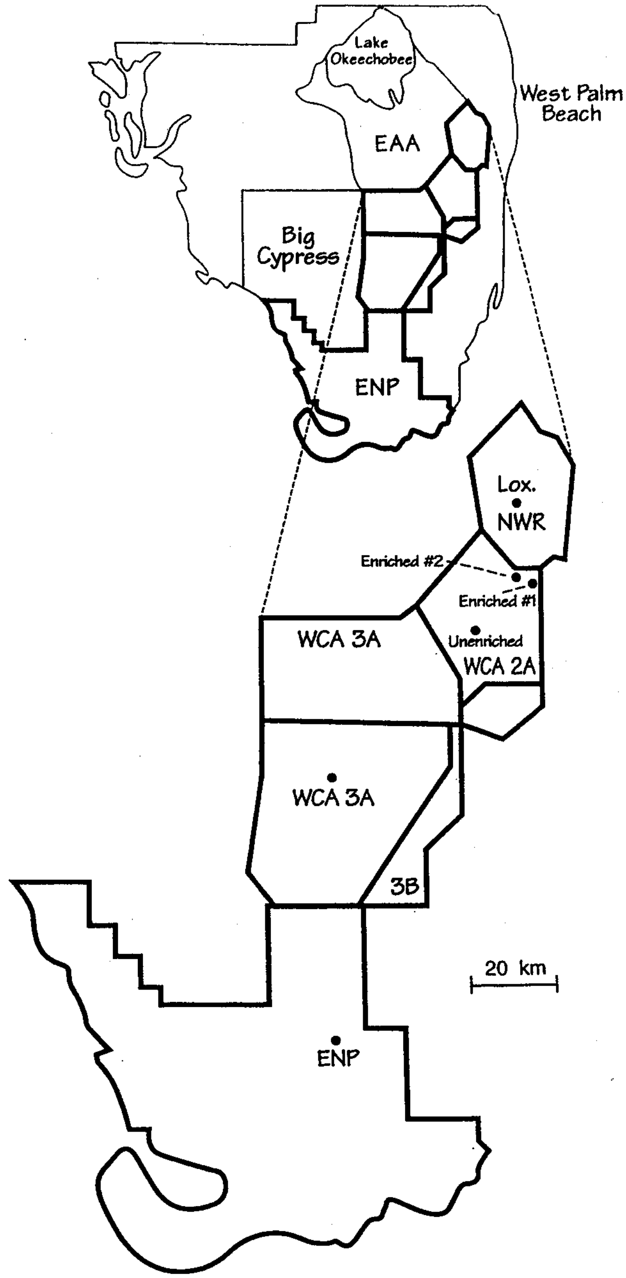

Fig. 1. Sampling locations (dots) where soil cores were collected in the northern (Loxahatchee National Wildlife Refuge [Lox. NWR] and Water Conservation Area [WCA] 2A), central (WCA 3A), and southern (Everglades National Park [ENP]) Everglades of South Florida (Everglades Agricultural Area [EAA]).

et al., 1988). We further assumed that there is no significant mixing of the surface layers by organisms, a phenomenon often observed in lake sediments (Schelske et al., 1988). This assumption is supported by the monotonic decrease in total ^{210}Pb with depth in cores collected from unenriched locations (see Fig. 3). Lead-210 is considered to be a more reliable means to estimate accretion than ^{137}Cs (Oldfield et al., 1979) because it is polyvalent and, thus, is bound more tightly to mineral and organic soil particles (Binford, 1990). In addition, ^{210}Pb can be used to estimate accretion during a longer time interval, up to 100 yr before present (BP), than ^{137}Cs. The distribution of excess ^{210}Pb with depth in soils and sediments has been widely used to estimate sedimentation and organic matter accumulation in wetlands (Oldfield et al., 1979; Sharma et al., 1987; Bricker-Urso et al., 1989; Novak et al., 1994; Wieder et al., 1994), including the Everglades (Craft and Richardson, 1993a; Rood et al., 1995; Bartow et al., 1996), and lake environments (Robbins and Edgington, 1975; Oldfield and Appleby, 1984; Schelske et al., 1988; Binford, 1990; Schelske and Hodell, 1995).

In this study, accretion rates determined using ^{137}Cs (6.7 ± 0.9 mm yr^{-1} at enriched locations, 1.4 ± 0.5 mm yr^{-1} at unenriched locations) agree well with rates determined using ^{210}Pb (enriched = 5.8 ± 1.4 mm yr^{-1}, unenriched = 1.7 ± 0.2 mm yr^{-1}). The close agreement between the two methods supports our contention that the ^{137}Cs technique is a reliable means to estimate organic soil accretion in the Everglades.

Carbon-14 dating of subsurface organic soil was measured to estimate longer term (centuries to millenia) rates of accretion. Subsurface depth increments from four cores (Loxahatchee NWR, WCA 2A unenriched, and WCA 3A, 46-cm depth; ENP, 37-cm depth) were analyzed for ^{14}C by accelerator mass spectrometry (Beta Analytic Inc., Miami, FL). These depths were chosen because they represented the lowermost increment of the soil core (Loxahatchee NWR, WCA 2A, and WCA 3A) or the layer of organic soil immediately above the limestone bedrock (ENP). The age of the depth increments, expressed as years before present (1990), were corrected using the ^{13}C/^{12}C of the sample and dendrocalibration.

Depth increments were also analyzed for total C, N, P, and S (WCA 2A enriched no. 2 and unenriched only). Carbon, N, and S were measured using a Perkin-Elmer 2400 CHNS analyzer. Total P was measured in HNO_3–$HClO_4$ digests following the method of Sommers and Nelson (1972). Bulk density and nutrient and radionuclide concentrations were expressed on a dry-weight basis by drying a 1.0-g subsample overnight at 75°C. The NIST standards were digested and analyzed along with the soil samples to ensure complete recovery of C, N, S (bituminous coal, SRM no. 1632b), and P (Buffalo River sediment, SRM no. 2704). The measured values for these standards were within 5% of the actual values.

RESULTS AND DISCUSSION

Recent (Cesium-137) and Long-term (Lead-210 and Carbon-14) Accretion

The distribution of ^{137}Cs with depth revealed well-developed peaks in all six cores (Fig. 2). Based on ^{137}Cs, the rate of accretion was lowest (0.8–1.2 mm yr^{-1}) in extreme northern (Loxahatchee NWR) and southern (WCA 3A and ENP) parts of the Everglades and highest (5.8–7.6 mm yr^{-1}) in nutrient-enriched areas of WCA 2A. The high rate of organic soil accretion in areas of WCA 2A that receive nutrient-enriched agricultural drainage has been documented by previous studies using ^{137}Cs (Craft and Richardson, 1993a,b; Reddy et al., 1993; Richardson et al., 1997).

The depth distribution of ^{210}Pb also revealed differences in organic soil accretion between nutrient-enriched and unenriched locations. At unenriched sites, total and excess ^{210}Pb decreased exponentially with depth (Fig. 3), indicating a relatively constant rate of accretion during the past 100 yr. At these locations, organic soil accretion ranged from 1.1 to 2.1 mm yr^{-1} (Fig. 4). At nutrient-enriched sites, however, the ^{210}Pb profiles indicated that accretion was substantially higher (4.4–7.2 mm yr^{-1}) during the past 30 yr than 70 to 100 yr ago (1.7–2.1 mm yr^{-1}; Fig. 3 and 4). The ^{137}Cs and ^{210}Pb methods yielded similar rates of accretion at the nutrient-enriched locations, averaging 6.7 ± 0.9 (^{137}Cs) and 5.8 ± 1.4 mm yr^{-1} (^{210}Pb). Of the two enriched sites, organic soil accretion was highest near the Hillsboro canal (enriched no. 2), the source of nutrient-enriched drainage to WCA 2A. At this site, 1.4 km downstream, ^{137}Cs and ^{210}Pb accretion rates were 7.6 and 7.2 mm yr^{-1}, respectively. Calculation of increment age vs. depth using the CRS model (Oldfield and Appleby, 1984; Bricker-Urso et al., 1989) indicates that nutrient enrichment at this site began about 1960 (Fig. 4). At the other enriched (no. 1) site, 3.5 km downstream, accretion rates were 4.4 mm yr^{-1} (^{210}Pb) and 5.8 mm yr^{-1} (^{137}Cs). Nutrient enrichment at this site also began about 1960 (Fig. 4). Increased organic soil accretion at enriched locations beginning around 1960 probably is due to increased water and nutrient loadings to WCA 2A during the early 1960s. Completion of the levees surrounding WCA 2A and installation of water control structures that release water from the Hillsboro canal into northern WCA 2A were completed in 1961 (Bartow et al., 1996), at about the same time that organic soil accretion accelerated (Fig. 4). The higher accretion rate at the site 1.4 km from the Hillsboro canal reflects greater P loadings, which stimulate plant productivity and organic matter deposition, as well as increased hydroperiod (Craft and Richardson, 1993b). At unenriched locations, accretion rates based on ^{137}Cs and ^{210}Pb were also similar (1.4 ± 0.5 and 1.9 ± 0.2 mm yr^{-1}, respectively), although at three of the four locations, the ^{137}Cs method yielded lower rates than ^{210}Pb (Fig. 2 and 4). The fourth unenriched location, WCA 2A, had a higher recent rate of accretion (2.7 mm yr^{-1}) than the other unenriched locations (0.8–1.2 mm yr^{-1}). This may be due to an extended hydroperiod from increased water storage in WCA 2A since it was impounded in the early 1960s (Light and Dineen, 1994).

Carbon-14 dating of subsurface (37–46 cm) organic soil collected from unenriched locations yielded accretion rates of 0.9 mm yr^{-1} (Loxahatchee NWR, 46-cm depth, 530 ± 50 yr BP), 0.6 mm yr^{-1} (WCA 2A, 46-cm depth, 830 ± 60 yr BP) and 0.2 mm yr^{-1} (WCA 3A, 46-cm depth, 2060 ± 60 yr BP; ENP, 37-cm depth, 2550 ± 60 yr BP). There was a gradient of decreasing ^{14}C accretion from north to south corresponding with increasing age of the subsurface organic soil. These rates are much lower than those determined using ^{210}Pb and ^{137}Cs, which is not surprising given the age (530–2550 yr BP) and

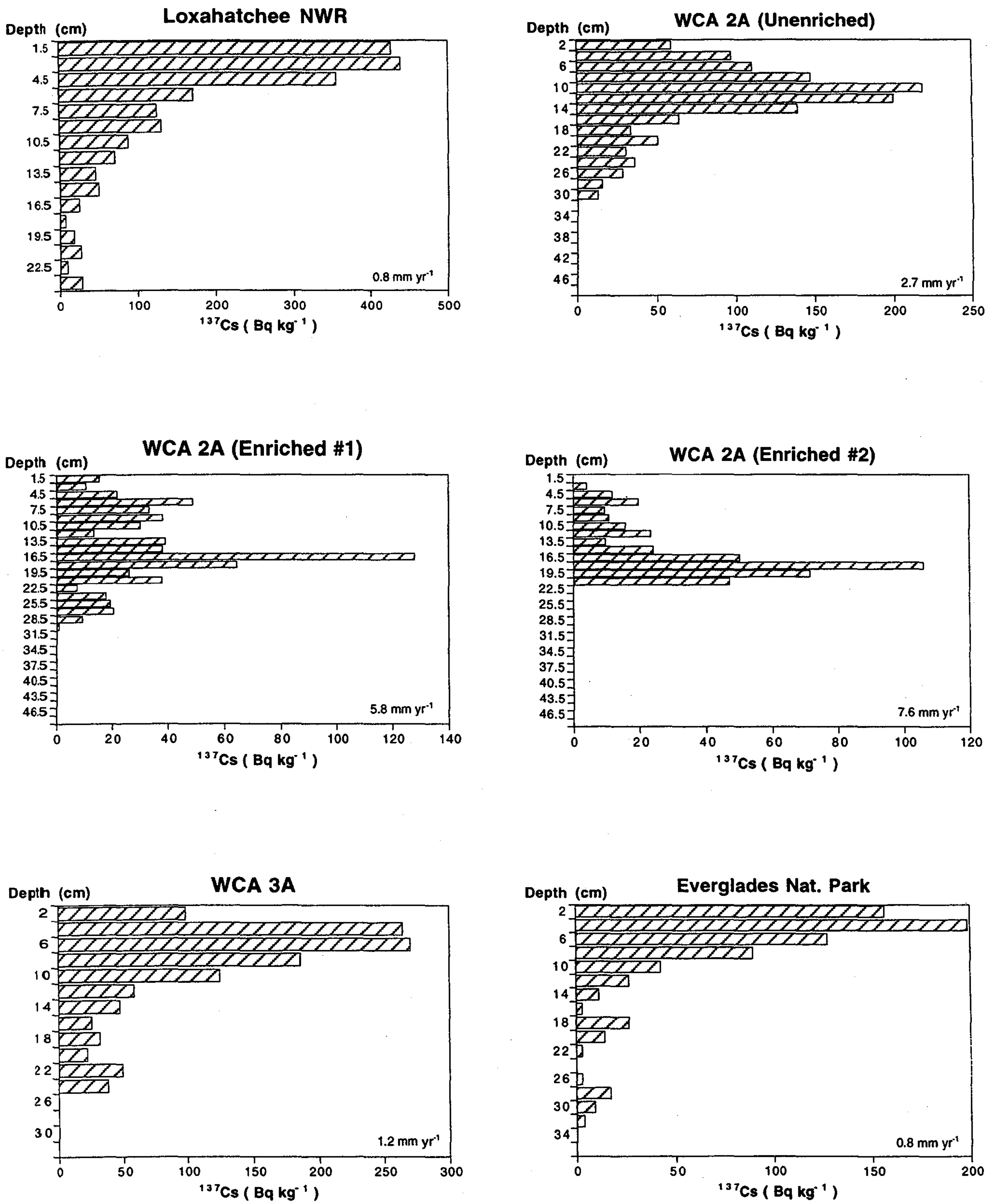

Fig. 2. Depth distribution of ^{137}Cs in soil cores collected from the northern (Loxahatchee National Wildlife Refuge [NWR], Water Conservation Area [WCA] 2A), central (WCA 3A), and southern (Everglades National Park) Everglades of South Florida.

time interval for accretion and autocompaction of this subsurface organic material. Our ^{14}C accretion rates also are lower than those measured by McDowell et al. (1969) using ^{14}C (0.8 mm yr^{-1} [3.5-m depth, 4400 yr BP] and 1.5 mm yr^{-1} [1.3-m depth, 1200 yr BP]). McDowell et al. (1969) dated basal organic material in the extreme northern Everglades, in the Everglades Agricultural Area. Prior to drainage, this region was part of the

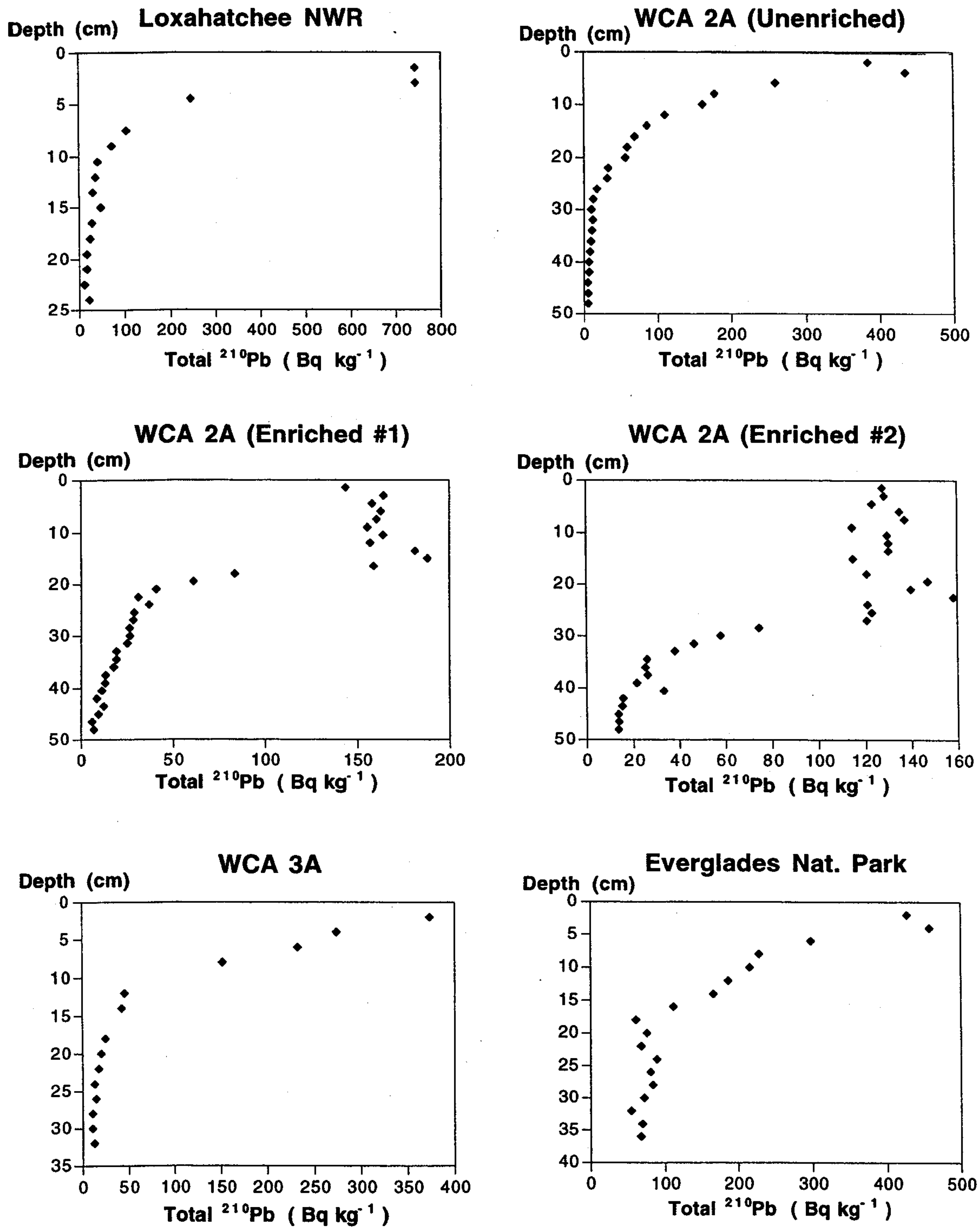

Fig. 3. Depth distribution of total ^{210}Pb in soil cores collected from the northern (Loxahatchee National Wildlife Refuge [NWR], Water Conservation Area [WCA] 2A), central (WCA 3A), and southern (Everglades National Park) Everglades of South Florida.

original Everglades ecosystem and contained the deepest (3.5–4 m) and oldest (4400–5000 yr BP) organic soils in the entire embayment (McDowell et al., 1969; Gleason et al., 1984). Our sampling locations, in contrast, are located farther south in areas where the organic soil is not as old or as thick, 3 m in the Loxahatchee NWR to <60 cm in WCA 3A and the ENP.

Bulk Density and Carbon, Nitrogen, Phosphorus, and Sulfur Concentrations

There was a gradient of increasing bulk density and decreasing C and N concentration from north to south through the Everglades (Fig. 5). Soil bulk density was lowest in the Loxahatchee NWR (0.05–0.07 Mg m^{-3}) and highest in the ENP (0.11–0.23 Mg m^{-3}). Carbon and

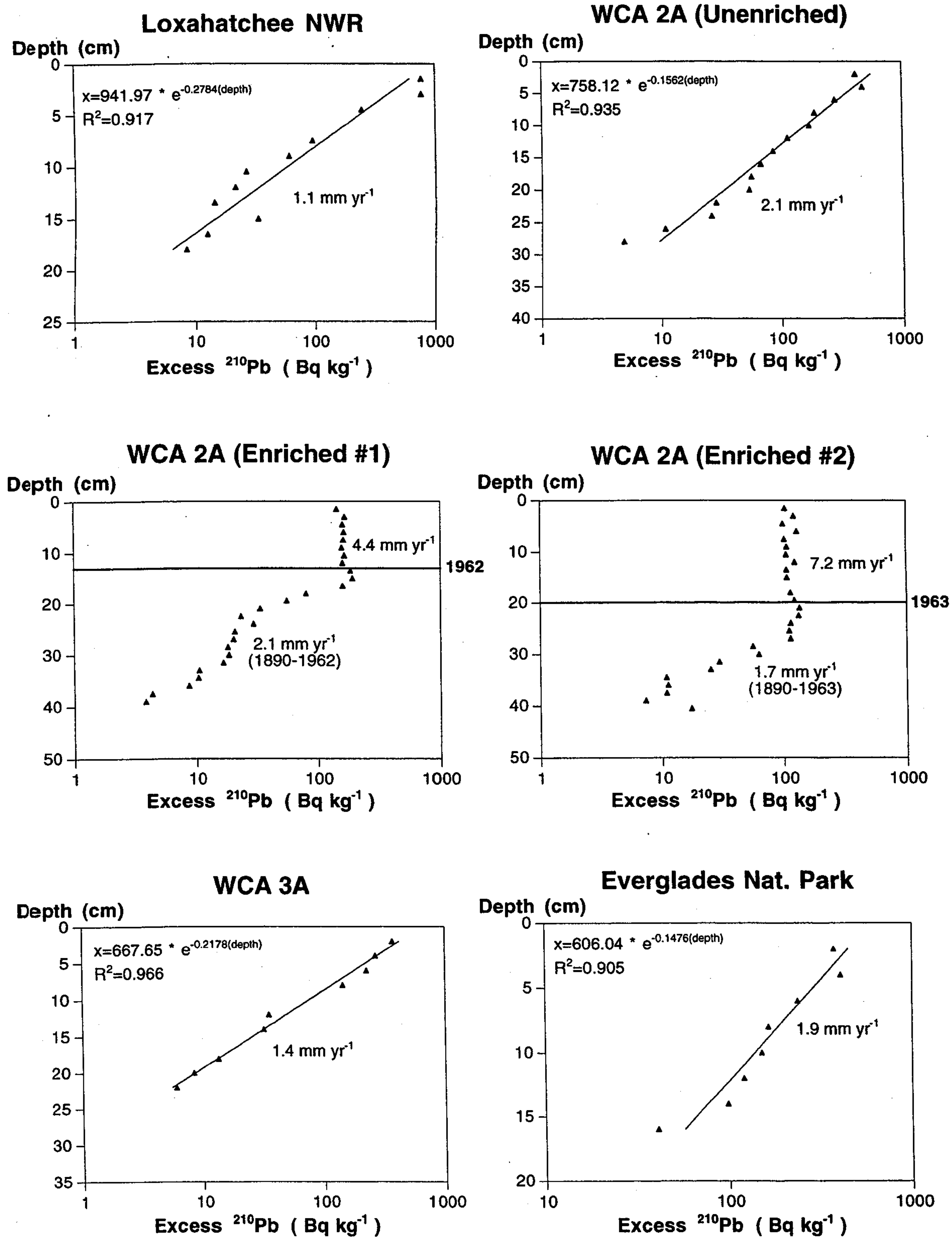

Fig. 4. Depth distribution of excess ^{210}Pb in soil cores collected from the northern (Loxahatchee National Wildlife Refuge [NWR], Water Conservation Area [WCA] 2A), central (WCA 3A), and southern (Everglades National Park) Everglades of South Florida. The 1962 (enriched no. 1) and 1963 (enriched no. 2) dates were calculated using the constant-activity model describing the relationship between soil increment age and depth (Bricker-Urso et al., 1989; Oldfield and Appleby, 1984).

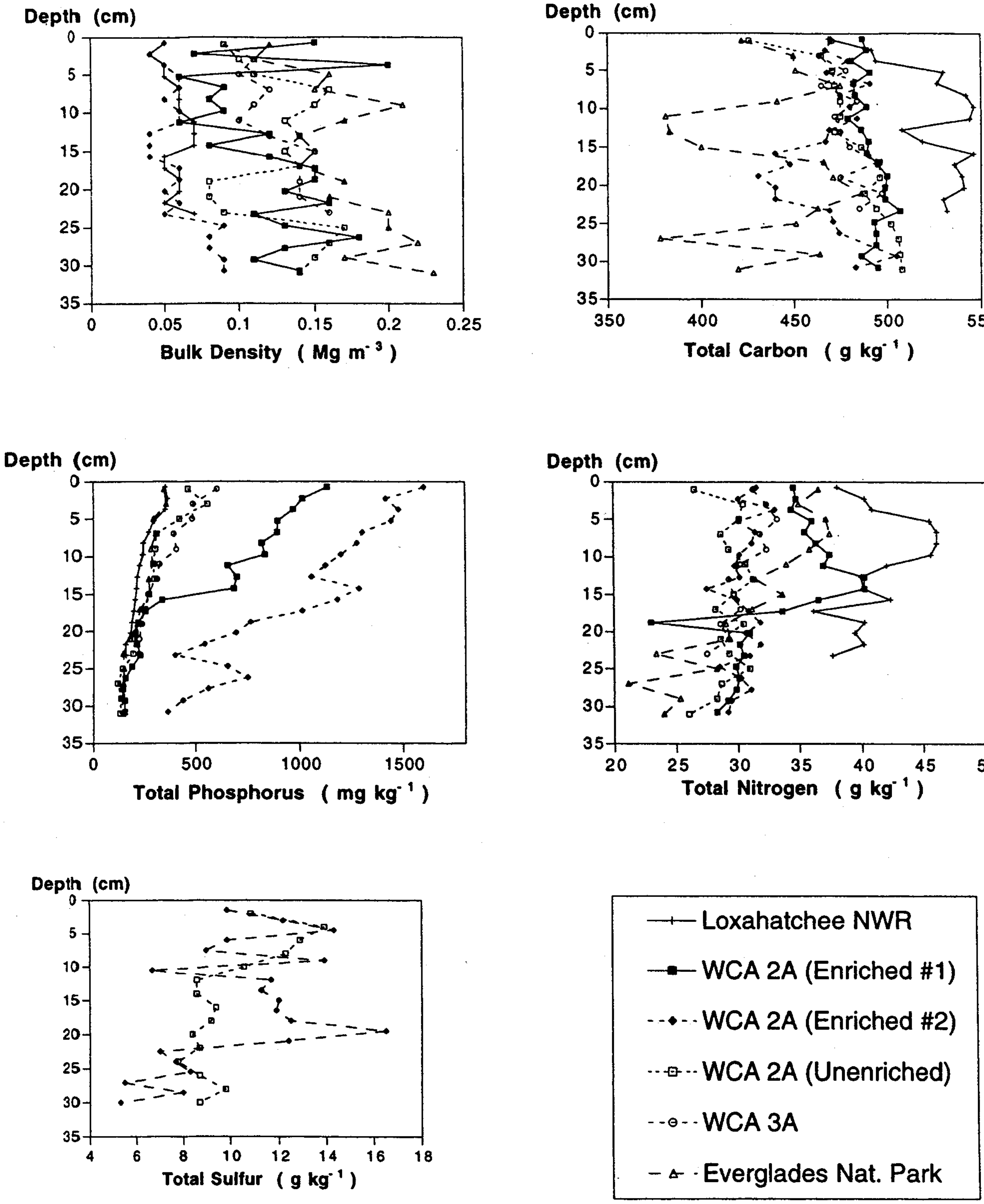

Fig. 5. Depth distribution of bulk density and total C, N, P, and S in soil cores collected from the northern (Loxahatchee National Wildlife Refuge [NWR], Water Conservation Area [WCA] 2A), central (WCA 3A), and southern (Everglades National Park) Everglades of South Florida.

N concentrations also were highest in the Loxahatchee NWR (470–550 and 36–46 g kg^{-1}) and lowest in the ENP (380–480 g C kg^{-1} soil, 21–38 g N kg^{-1}). There was no clear difference in C and N between nutrient-enriched and unenriched areas of the Everglades. These findings are supported by previous studies in enriched and unenriched areas of the northern and central Everglades (Craft and Richardson, 1993a,b; Reddy et al., 1993). There was, however, a pronounced increase in soil P in the enriched area, with P concentrations that were two to three times higher (700–1600 mg kg^{-1}) than unenriched areas (100–600 mg kg^{-1}) or than soil depos-

Table 2. Cesium-137-based C, N, P, and S accumulation in Everglades soils since approximately 1964. Accumulation rates were calculated based on the ^{137}Cs accretion rate (Fig. 2) and mean bulk density and nutrient concentrations (Fig. 5) in depth increments above and including the ^{137}Cs maximum.

Location	C	N	P	S
	g m^{-2} yr^{-1}			
Loxahatchee NWR	19	1.5	0.01	–
WCA 2A (enriched no. 1)	282	21.3	0.47	–
WCA 2A (enriched no. 2)	164	11.9	0.46	4.3
WCA 2A (unenriched)	149	9.4	0.14	4.0
WCA 3A	56	4.8	0.07	–
Everglades Natl. Park	37	3.1	0.03	–
Mean (enriched)	223 ± 59	16.6 ± 4.7	0.46 ± 0.01	4.3
Mean (unenriched)	65 ± 29	4.7 ± 1.7	0.06 ± 0.03	4.0

ited in the enriched area prior to 1950 (150–500 mg kg^{-1}; Fig. 5). The core collected from WCA 2A (enriched no. 2), which was closest to the Hillsboro canal, exhibited the highest soil P levels of all cores (Fig. 5). Other studies have documented the enrichment of soil P in the northern WCA 2A caused by agricultural drainage (Craft and Richardson, 1993a,b; Reddy et al., 1993; Richardson et al., 1997). There was no clear difference in total S between enriched (8–14 g kg^{-1}) and unenriched (6–16 g kg^{-1}) locations of WCA 2A (Fig. 5).

There was a trend of increasing bulk density and decreasing N and S with depth in most soil cores (Fig. 5), which probably is due to autocompaction of the organic soil with depth (bulk density), as well as N and S conservation in the surface layer. The distribution of C was relatively uniform with depth (Fig. 5). Soil P, however, exhibited a pronounced decrease with depth in all cores, especially the two cores collected from nutrient-enriched areas of WCA 2A (Fig. 5). The trend of decreasing soil P with depth in our unenriched cores has been observed in other ecosystems where P is limiting and biological cycling maintains higher levels of P in surface than subsurface layers (Richardson and Marshall, 1986; Walbridge et al., 1991). The decrease in P with depth in our enriched cores probably reflects both biological conservation as well as anthropogenic P enrichment at these locations during the past 30+ yr (Craft and Richardson, 1993a,b; Reddy et al., 1993).

Carbon, Nitrogen, Phosphorus, and Sulfur Accumulation

Recent (^{137}Cs) rates of C, N, and P accumulation were highest in nutrient-enriched areas of WCA 2A and lowest in the extreme northern (Loxahatchee NWR) and southern (ENP) portions of the Everglades (Table 2). The Loxahatchee NWR had the lowest rates of C (19 g m^{-2} yr^{-1}), N (1.5 g m^{-2} yr^{-1}), and P accumulation (0.01 g m^{-2} yr^{-1}). The central (WCA 3A) and southern (ENP) areas of the Everglades had higher C (37–56 g m^{-2} yr^{-1}), N (3.1–4.8 g m^{-2} yr^{-1}), and P (0.03–0.07 g m^{-2} yr^{-1}) accumulation but these rates were much lower than WCA 2A (Table 2). Within WCA 2A, nutrient accumulation at the unenriched location was two (N and P) to three (C) times greater than other unenriched areas of the Everglades. Higher nutrient accumulation at this location probably reflects an extended hydroperiod as a result of water management practices that increased water storage in WCA 2A during the 1960s and 1970s (Light and Dineen, 1994; Bartow et al., 1996).

Table 3. Lead-210-based C, N, P, and S accumulation in Everglades soils. Accumulation rates were calculated using the ^{210}Pb accretion rates (Fig. 4) and mean bulk density and nutrient concentrations (Fig. 5) in depth increments containing excess ^{210}Pb. Unless noted differently, nutrient accumulation rates are since approximately 1890.

Location	C	N	P	S
	g m^{-2} yr^{-1}			
Loxahatchee NWR	36	2.9	0.02	–
WCA 2A (enriched no. 1)				
>1962	213	16.0	0.39	–
<1962	146	8.8	0.06	–
WCA 2A (enriched no. 2)				
>1963	156	11.1	0.40	4.0
<1963	75	4.5	0.06	1.0
WCA 2A (unenriched)	118	7.3	0.07	2.5
WCA 3A	81	5.2	0.06	–
Everglades Natl. Park	124	10.2	0.09	–
Mean (enriched)	184 ± 29	13.6 ± 2.5	0.40 ± 0.01	4.0
Mean (unenriched)†	97 ± 16	6.5 ± 1.1	0.06 ± 0.01	1.8 ± 0.8

† n = 6 for C, N, and P; n = 2 for S.

Enriched areas of WCA 2A exhibited the highest ^{137}Cs rates of nutrient accumulation (Table 2). Phosphorus accumulation in the enriched area (0.46 g m^{-2} yr^{-1}) was three times higher than the unenriched area of WCA 2A (0.14 g m^{-2} yr^{-1}) and six to 46 times higher than the other areas we sampled (Table 2). Recent rates of C (156–213 g m^{-2} yr^{-1}), N (13.6–16 g m^{-2} yr^{-1}), P (0.39–0.40 g m^{-2} yr^{-1}), and S (4.0 g m^{-2} yr^{-1}) accumulation based on ^{210}Pb were similar to rates determined using ^{137}Cs (164–282 g C m^{-2} yr^{-1}, 11.9–21.3 g N m^{-2} yr^{-1}, 0.46–0.47 g P m^{-2} yr^{-1}, and 4.0–4.3 g S m^{-2} yr^{-1}). The accelerated rate of nutrient accumulation at our enriched locations probably is the result of anthropogenic nutrient loadings, especially P. Like ^{137}Cs, ^{210}Pb-based rates of nutrient accumulation at unenriched sites revealed that the Loxahatchee NWR had the lowest accumulation of C, N, and P, with higher accumulation in areas to the south (WCA 2A, WCA 3A, and ENP; Table 3).

Lead-210 rates of C, N, P, and S accumulation in nutrient-enriched areas of WCA 2A prior to enrichment were comparable to accumulation in other areas of the Everglades using ^{210}Pb (Table 3). Before about 1960, C, N, and P accumulation ranged from 75 to 146, 4.5 to 8.8, and 0.06 g m^{-2} yr^{-1}, respectively. These values are similar to ^{210}Pb-based measurements of C (36–124 g m^{-2} yr^{-1}), N (2.9–10.2 g m^{-2} yr^{-1}), and P (0.02–0.09 g m^{-2} yr^{-1}) accumulation at unenriched locations. Sulfur accumulation in WCA 2A prior to nutrient enrichment was 1.0 g m^{-2} yr^{-1} and was lower than recent (^{137}Cs) accumulation at enriched locations (4.0–4.3 g m^{-2} yr^{-1}) and long-term (^{210}Pb) accumulation at the unenriched location (2.5 g m^{-2} yr^{-1}).

Comparison with Other North American Peatlands

Organic soil accretion and C and S accumulation in unenriched areas of the Everglades were similar to other unenriched subtropical (Okefenokee swamp), temperate (pocosins of North Carolina), and northern organic soil wetlands (bogs and fens) of North America (Table

Table 4. Comparison of peat accretion and nutrient accumulation rates of various organic soil freshwater wetlands in the USA.

Type	Accretion rate	C	N	P	S
	mm yr^{-1}	g m^{-2} yr^{-1}			
Bogs (MA)†	4.3	90	1.2	–	–
(MD, PA, WV)‡	1.4–3.1	64–89	1.4–3.1	0.07–0.16	1.0–2.0
(MN)‡	2.4	79	–	–	0.5
Fens (MI)					
Unenriched§	0.9	42	3.0	0.11	–
Unenriched¶	–	–	–	0.30	–
Enriched¶	–	–	–	0.90	–
Pocosins (NC)#	2.6	127	3.0	0.06	–
Okefenokee (GA)††	–	82	3.8	0.15	–
Everglades (FL)‡‡					
Enriched					
^{137}Cs	6.7	223	16.6	0.46	4.3
^{210}Pb	5.8	184	13.6	0.40	4.0
Unenriched					
^{137}Cs	1.4	65	4.7	0.06	4.0
^{210}Pb	1.7	97	6.5	0.06	1.8

† From Hemond (1980, 1983). Carbon accumulation was calculated assuming soil organic matter is 500 g C kg^{-1}.
‡ Accretion rate from Wieder et al. (1994). Carbon was calculated assuming organic matter content is 500 g C kg^{-1}. Nitrogen and P accumulation were calculated using the accretion rate from Wieder et al. (1994) and bulk density (0.06 Mg m^{-3}) and N (16.5 g kg^{-1}) and P (867 mg kg^{-1}) concentrations (0–30 cm) from Wieder (1985). Sulfur accumulation is from Novak et al. (1994).
§ Accretion rate (^{137}Cs) from C.B. Craft (1997, unpublished data). Carbon, N, and P accumulation were calculated using the accretion rate of 0.9 mm yr^{-1} and soil bulk density (0.13 Mg m^{-3}), C (360 g kg^{-1}), N (25.4 g kg^{-1}), and P (900 mg kg^{-1}) from Richardson et al. (1978). Carbon (360 g kg^{-1}) was calculated from Richardson et al. (1978) assuming soil organic matter (72%) is 500 g C kg^{-1}.
¶ Richardson and Marshall (1986).
# Accretion rate (^{210}Pb) from C.B. Craft (1996, unpublished data). Bulk density (0.08 Mg m^{-3}), C (610 g kg^{-1}), N (14.4 g kg^{-1}), and P (308 mg kg^{-1}) concentrations (0–30 cm) from Bridgham and Richardson (1993).
†† Schlesinger (1978).
‡‡ This study (enriched $n = 2$; unenriched $n = 4$ [^{137}Cs] or $n = 6$ [^{210}Pb]).

4). However, N accumulation was higher (5–7 g m^{-2} yr^{-1}) and P accumulation was lower (0.06 g m^{-2} yr^{-1}) than other organic soil wetlands (1–4 g N m^{-2} yr^{-1}, 0.06–0.30 g P m^{-2} yr^{-1}). The high rate of N accumulation in the Everglades probably is the result of N_2-fixing cyanobacteria that are abundant in the open water sloughs (Craft and Richardson, 1993a). Based on limited data from the Everglades and northern fens, anthropogenic P inputs increased P accumulation three to eight times over unenriched areas (Table 4). Historically low P accumulation in the Everglades and other North American peatlands suggests that even small anthropogenic P loadings may alter organic soil accretion and nutrient accumulation of these freshwater wetlands.

In conclusion, ^{137}Cs and ^{210}Pb dating of Everglades organic soils revealed that anthropogenic nutrient loadings to northern WCA 2A during the past 30 yr have resulted in accelerated organic soil accretion and C, N, and P accumulation compared with unenriched areas of the Everglades. In the enriched area, organic soil accretion was three to five times higher and nutrient accumulation was two (C and N) to eight (P) times greater than in unenriched areas. In the enriched zone, ^{210}Pb-based accretion and nutrient accumulation prior to nutrient enrichment, about 1960, was similar to ^{137}Cs- and ^{210}Pb-based rates in unenriched areas. Our findings suggest that, since WCA 2A was impounded in the early 1960s, P loadings to the northern WCA 2A have resulted in accelerated rates of organic soil accretion and C, N, and P accumulation compared with unenriched areas of the Everglades or with the enriched area before 1960. At present, P enrichment is limited to WCA 2A and areas adjacent to canals along the northern periphery of the Everglades (DeBusk et al., 1994; Newman et al., 1997). Unenriched areas of the Everglades possess some of the lowest rates of P accumulation of peatlands in North America. In addition to restoring the predrainage hydrology of the wetland, successful restoration of the Everglades will have to include remediation of anthropogenic P loadings to limit expansion of the P enrichment zone into oligotrophic, ecologically sensitive areas outside of WCA 2A.

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