

3

Soil Characteristics of the Everglades Peatland

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3.1 Introduction

The Everglades is a 700,000 ha subtropical wetland whose origin dates to approximately 5,000 years BP when the rate of sea level rise slowed and peat began to accumulate in the shallow embayment of the south Florida peninsula (Gleason and Stone 1994). For the next 4,900 years, the Everglades was a net sink for organic carbon as peat accreted to depths of 1–3 m over much of the embayment and up to 4 m in areas south of Lake Okeechobee. During the past 100 years, however, as the population of south Florida swelled from approximately 20,000 to more than 4,000,000 people, efforts to drain the Everglades led to loss of nearly 65% of the original acreage (Kushlan 1989). Furthermore, the historical hydrology and low nutrient regimes characteristic of the extant Everglades have been modified by the vast network of canals, levees, and pumping stations (Walters et al. 1992) and, in northern areas, by nutrient-enriched drainage from the Everglades Agricultural Area (EAA; Davis 1994).

This chapter describes some of the chemical and physical characteristics of the Everglades peatlands including the distribution of organic C and nutrients (N, P), historical and recent rates of peat accretion, nutrient accumulation, and the effects of anthropogenic hydrologic alteration and nutrient enrichment on these processes. Excellent reviews of the origin and development of the Everglades peatland have been written by Gleason et al. (1984) and Gleason and Stone (1994). The effects of eutrophication, especially P, on Everglades plant community structure and ecosystem processes have been described extensively (Belanger et al. 1989; Davis 1989, 1991; Koch and Reddy 1992; Craft and Richardson 1993a, 1995; Reddy et al. 1993; Qualls and Richardson 1995; Miao and Sklar 1998; Vaithyanathan and Richardson 1999; Chiang et al. 2000; Qualls and Richardson 2000). Likewise, review articles describing efforts to drain the Everglades and the ecological consequences of these efforts are described by Light and Dineen (1994) and in this book's Chaps. 2 and 8. The reader is referred to these papers to gain an in-depth understanding of the geological development and the effects of human activities on the Everglades peatlands.

3.2 Methods

We focused on chemical and physical characteristics of the peat, including organic C, N, and P in the rooting zone; peat accretion; and organic C, N, and P accumulation. Twenty peat cores (30–50 cm deep) were collected along a north-to-south gradient from the Loxahatchee National Wildlife Refuge (Loxahatchee NWR), through Water Conservation Areas (WCAs) 2A, 2B, and 3A, to Everglades National Park (ENP; Fig. 3.1). The north-to-south gradient roughly parallels the historical pattern of sheetflow of water that overflowed from Lake Okeechobee and moved southeast and then southwest into Florida Bay (Fennema et al. 1994). With the exception of northern WCA-2A, which is impacted by nutrient-enriched drainage from the EAA, cores were collected from areas currently unaffected by agricultural nutrient loadings. At all locations, soils were collected from sawgrass (*Cladium jamaicense*), the dominant plant community of the Everglades (Gunderson 1994). Ten cores were collected from unenriched interior areas far removed from levees, canals, and water control structures: Loxahatchee NWR ($n=1$), unenriched WCA-2A ($n=3$), WCA-2B ($n=2$), WCA-3A (3A) ($n=3$), and ENP ($n=1$) (Fig. 3.1). Ten cores were collected in areas proximal to canals and levees in enriched WCA-2A ($n=4$) and in WCA-3A (AA, 12A, 12C, $n=2$ for each location) (Fig. 3.1).

Cores were sectioned in 2 cm depth increments and analyzed for bulk density, organic C, N, and P. Depth increments from all 20 cores were analyzed for ^{137}Cs to calculate recent (30 years) rates of peat accretion and nutrient accumulation. Lead-210 was measured in depth increments of eight cores (Loxahatchee NWR, WCA-2A (enriched, $n=2$), WCA-2A (unenriched, $n=3$), WCA-3A, ENP) to quantify peat accretion and nutrient accumulation during the past 100 years. In several cores, subsurface peat was analyzed for ^{14}C to quantify historical (>500 years) rates of peat accretion. Detailed descriptions of the analytical methods and results are published in Craft and Richardson (1993a, b, 1998).

3.3 Results and Discussion

3.3.1 Everglades Peat Types

Much of the Everglades is underlain by peat. Two types, Everglades peat and Loxahatchee peat, encompass over 7,000 km² (Table 3.1). Other peat types include Okeechobee muck (130 km²) and Okeelanta peaty muck (105 km²), which are found along the southern and eastern shore of Lake Okeechobee in the EAA (Gleason and Stone 1994). Gandy peat (77 km²) is found associated with tree islands, usually atop Everglades Loxahatchee peat.

Of the two most abundant peat types, Everglades peat is thinner, higher in mineral content, and less decomposed than Loxahatchee peat. It forms mostly from partial

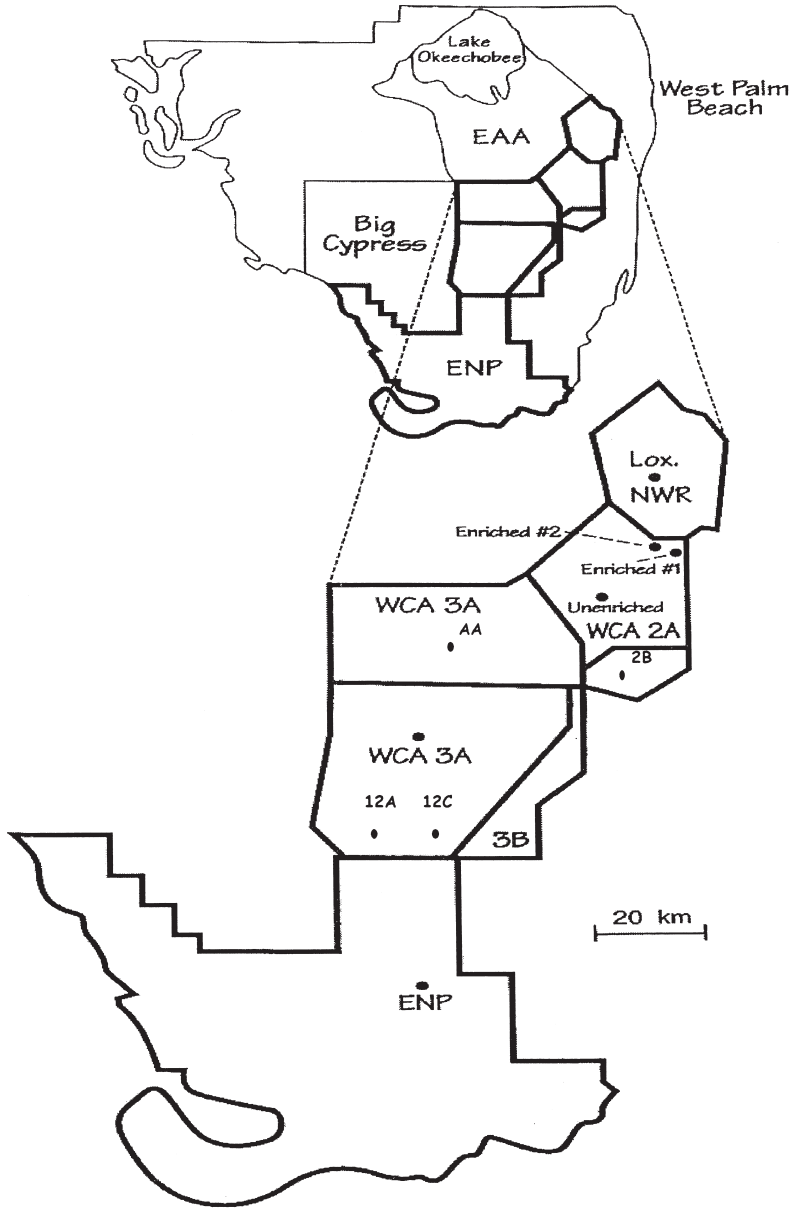


Fig. 3.1 Sampling locations where peat cores were collected along the north-to-south (e.g., downstream) gradient through the Everglades

decomposition of sawgrass, the dominant wetland plant species. Everglades peat underlies much of the central and southern Everglades (Gleason and Stone 1994). Loxahatchee peat is thicker, higher in organic content, N, and acidity and more decomposed than Everglades peat (Table 3.1; Gleason and Stone 1994). Loxahatchee

Table 3.1 Selected characteristics of the dominant types of peat in the Everglades

	USDA classification ^a	Area ^b (km ²)	Thickness ^b (m)	Origin ^b	pH ^c	Organic content ^e (%)
Everglades peat	Euic hyperthermic typic medihemist (Pahokee series) ^d	4,420	0.5–2.0	Sawgrass (<i>Cladium jamaicense</i>)	5.5–6.5	85–92
Loxahatchee peat	Euic hyperthermic typic medisaprist (Terra Ceia series)	2,950	2.0–3.0	Water lily (<i>Nymphaea odorata</i>)	5.0–6.5	92–92

^aSCS (1978)^bGleason and Stone (1994)^cJones (1948)^dAlso includes Terra Ceia, Lauderhill, and Dania series

peat forms from vegetation of sloughs, especially water lily. Loxahatchee peat underlies WCA-1 (Loxahatchee NWR) and northeastern areas of WCA-2A (Gleason and Stone 1994).

3.3.2 Surface Soil Bulk Density, Organic Carbon, Nitrogen, and Phosphorus

Bulk density (0–24 cm depth) exhibited a general increase from north to south along the gradient of historical sheetflow (Fig. 3.2a). Bulk density was $0.06 \pm 0.01 \text{ g cm}^{-3}$ in Loxahatchee NWR, $0.10 \pm 0.01 \text{ g cm}^{-3}$ in the WCAs, and $0.17 \pm 0.06 \text{ g cm}^{-3}$ in ENP. Increased bulk density from north to south corresponds to increased mineral content that is the result of decreasing thickness of the peat from north to south (see Table 3.1). As the peat thins from north to south, mineral material from the underlying bedrock mixes with the peat, resulting in an increase in bulk density and inorganic constituents (Al, Fe) along the north-to-south gradient (Craft and Richardson 1997). Soil organic C, which varied inversely with bulk density, generally decreased along the north-to-south gradient (Fig. 3.2b). Organic C was $51 \pm 4\%$ in Loxahatchee NWR, $44 \pm 2\%$ in the WCAs, and $43 \pm 5\%$ in ENP.

In contrast to bulk density and organic C, there was no apparent trend in N or P along the north-to-south gradient (Fig. 3.2c,d). Nitrogen concentrations were highest in Loxahatchee NWR ($4.1 \pm 0.5\%$) and areas of WCA-3A ($4.2 \pm 0.2\%$ at 3A and 12A) and lowest in WCA-2B ($3 \pm 0.1\%$) and ENP ($2.9 \pm 0.9\%$). Soil P was highly variable from north to south through the Everglades (Fig. 3.2d). Average phosphorus concentration was much higher in northern WCA-2A ($1,250 \mu\text{g g}^{-1}$) where

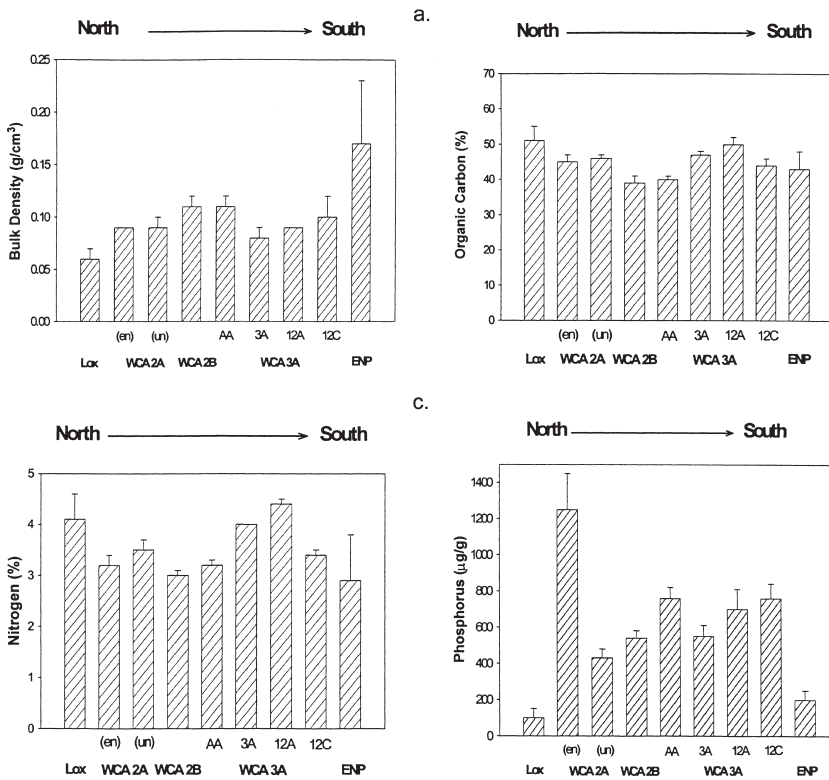


Fig. 3.2 Surface soil (a) bulk density, (b) organic carbon, (c) nitrogen, and (d) phosphorus along the north-to-south gradient through the Everglades. Bars represent mean values (± 1 standard error) of 2 cm depth increments from 0 to 24 cm. Values at locations AA (0–20 cm) and 12A (0–12 cm) represent the entire peat layer down to bedrock. En is the nutrient-enriched area of WCA-2A, Un is the unenriched area

nutrient-enriched agricultural drainage enters from pumping stations along the Hillsboro canal. The extreme northern and southern areas of the Everglades, Loxahatchee NWR, and ENP had the lowest P concentrations (Fig. 3.2d). Soil P was only $100 \pm 50 \mu\text{g g}^{-1}$ in interior areas of the Loxahatchee NWR and $200 \pm 50 \mu\text{g g}^{-1}$ in ENP. Loxahatchee NWR and ENP receive much of their water and nutrient inputs from rainfall (Light and Dineen 1994; Fennema et al. 1994). In contrast, depending on their proximity to canals, the WCAs receive at least some water and nutrients and, in some cases, substantial quantities of surface runoff from the network of canals that dissect the WCAs. Other locations in the WCAs had soil P concentrations that were intermediate ($620 \pm 60 \mu\text{g g}^{-1}$) between the nutrient-enriched area of WCA-2A and Loxahatchee NWR/ENP.

3.3.3 Bulk Density, Organic Carbon, Nitrogen, and Phosphorus as a Function of Depth

Bulk density, organic C, and nitrogen changed little with depth in the upper 30 cm of peat (Fig. 3.3a–c). Published studies from the Everglades report similar trends in bulk density, C, and N with depth (Craft and Richardson 1993a, b, 1998; Reddy et al. 1993). In the Everglades, peat is derived mostly from deposition of plant biomass (sawgrass, water lily) that contains a fixed proportion of C to N (Craft et al. 1995; Schlesinger 1997). As a result, accumulating peat typically

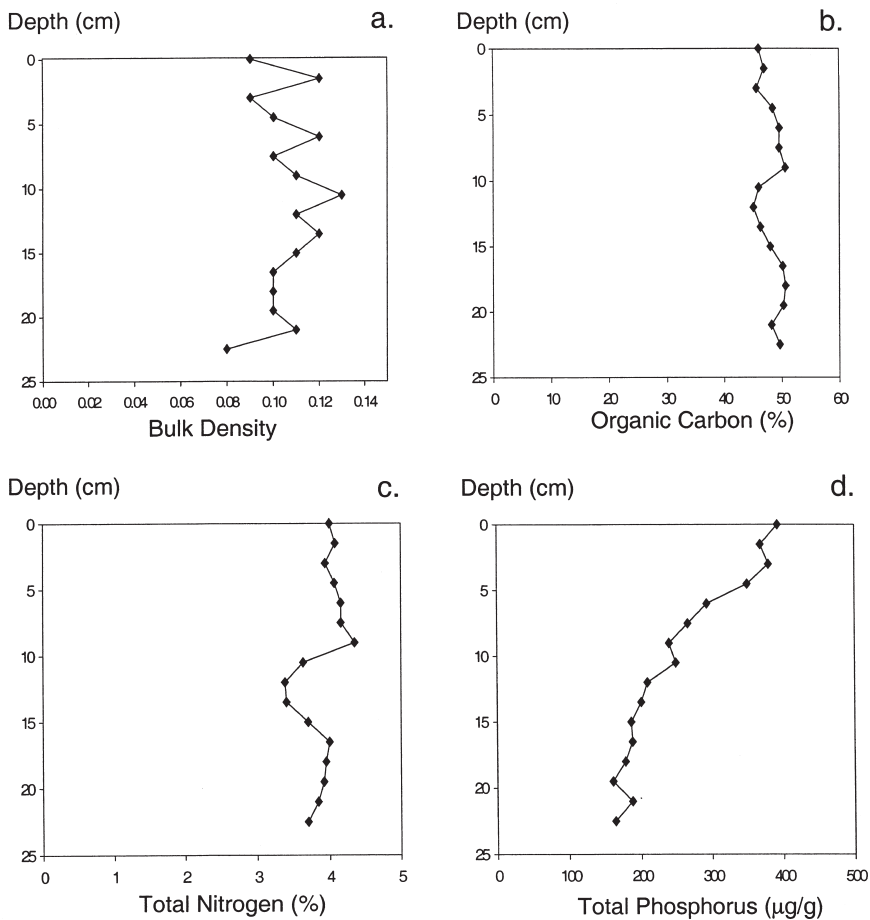


Fig. 3.3 Distribution of soil (a) bulk density, (b) organic carbon, (c) nitrogen, and (d) phosphorus with depth in the upper 30 cm of peat collected from Everglades National Park. Note that bulk density, organic C, and N are relatively constant with depth but most phosphorus is concentrated near the surface, in the zone of greatest biological activity

contains relatively constant concentrations of C and N with depth. In contrast to C and N, phosphorus exhibited a marked decrease with depth throughout the upper 30 cm of peat (Fig. 3.3d). Published studies throughout the Everglades also reported decreasing P with depth (Craft and Richardson 1993a, b, 1998; Reddy et al. 1993). High levels of P in surface peat often are evidence of wetland P limitation because the limiting nutrient, in this case P, is concentrated and maintained in the zone of greatest biological activity (Richardson and Marshall 1986; Walbridge 1991).

3.3.4 Thickness and Accretion of Peat

As discussed previously, peat thickness decreased from north to south through the Everglades (Table 3.2). Peat thickness ranged from 3 m in Loxahatchee NWR to less than 0.5 m in WCA-2B, WCA-3A, and ENP. In spite of the differences in the thickness of the peat, recent (^{137}Cs) rates of peat accretion were relatively uniform (Table 3.2). With the exception of the enriched area of WCA-2A, recent rates of accretion ranged from 0.8 to 3.2 mm year⁻¹. Recent peat accretion was lowest in the Loxahatchee NWR and ENP, 0.8 mm year⁻¹. Loxahatchee NWR and ENP receive most water and nutrient inputs from rainfall so that hydroperiod is shorter and nutrient inputs are lower at these locations as compared to the WCAs. Low nutrient inputs, especially P, lead to reduced NPP, organic C inputs to the soil and, hence, vertical accretion at these locations.

Table 3.2 Peat thickness and peat accretion along a north-to-south gradient in the Everglades

Location	Sample number	Peat thickness (m)	Accretion rate (mm year ⁻¹)		
			^{137}Cs	^{210}Pb	^{14}C
Loxahatchee NWR	$n = 1$ core	3.0	0.8	1.1	0.9
WCA-2A (nutrient enriched)	$n = 4$ for ^{137}Cs , $n = 2$ for ^{210}Pb ^a	2.4	5.3 ± 0.9	5.8 ± 1.4	–
WCA-2A (unenriched)	$n = 3$ for ^{137}Cs , $n = 3$ for ^{210}Pb	2.5	2.0 ± 0.6	2.0 ± 0.1	0.6
WCA-2B	$n = 2$ for ^{137}Cs	0.5	2.4 ± 0.4	–	–
WCA-3A (AA)	$n = 2$ for ^{137}Cs	0.3	2.0 ± 0	–	–
WCA-3A (3A)	$n = 3$ for ^{137}Cs , $n = 1$ for ^{210}Pb	0.6	1.7 ± 0.3	1.4	0.2
WCA-3A (12A)	$n = 2$ for ^{137}Cs	0.1	2.8 ± 0	–	–
WCA-3A (12C)	$n = 2$ for ^{137}Cs	0.4	3.2 ± 0.4	–	–
Everglades National Park	$n = 1$ core	0.4	0.8	1.9	0.2
Mean (excluding enriched)	$n = 20$ for ^{137}Cs , $n = 8$ for ^{210}Pb	2.0 ± 0.3	1.6 ± 0.2	0.5 ± 0.2	

^aAccretion rates based on ^{210}Pb encompass the period 1962–1994

Recent peat accretion was highest in the enriched area of WCA-2A, 5.3 ± 0.9 mm year⁻¹. Previously published studies also reported higher rates of peat accretion in northern WCA-2A as compared to other locations in response to P loadings from agricultural drainage (Craft and Richardson 1993a, b, 1998; Reddy et al. 1993). At the enriched location, recent (30 years) rates of peat accretion based on ²¹⁰Pb (5.8 ± 1.4 mm year⁻¹) were similar to rates determined using ¹³⁷Cs (5.3 ± 0.9 mm year⁻¹, Table 3.2). Unenriched areas of WCA-2A and WCA-3A also possessed similar rates of peat accretion based on ¹³⁷Cs (2.0 ± 0.9 mm year⁻¹ for WCA-2A, 2.4 ± 0.4 mm year⁻¹ for WCA-3A) and ²¹⁰Pb (2.0 ± 0.1 mm year⁻¹ for WCA-2A, 1.4 mm year⁻¹ for WCA-3A).

Carbon-14 dating of peat collected from similar depths (37–46 cm) of four cores revealed a gradient of decreasing peat accretion and increasing age of the peat along the north-to-south gradient. Subsurface peat (46 cm) in the Loxahatchee NWR and WCA-2A was deposited only 500 and 800 years BP, respectively (Table 3.3). In WCA-3A, peat collected from the same depth was deposited more than 2,000 years BP. Carbon-14 dating of basal peat (37 cm) collected from ENP indicated that, at this location, peat began to accumulate more than 2,500 years ago. Carbon-14 dating of basal peat from the EAA, Loxahatchee NWR, and northern WCA-2A indicates that peat accumulation began earlier in those areas, 4,500–4,800 years BP (McDowell et al. 1969; Gleason and Stone 1994). In southern WCA-2A, the onset of peat accumulation began 2,000–3,000 years BP.

The large difference in ¹⁴C age of peat collected from similar depths from the Loxahatchee NWR, WCA-3A, and ENP suggests that historical environmental factors differed greatly between the northern and southern Everglades. The underlying bedrock of southern Everglades consists of Miami limestone that is more permeable than the Fort Thompson formation that underlies areas of the northern Everglades (Gleason et al. 1984). The porous nature of the Miami limestone perhaps contributes to reduced hydroperiod and, consequently, increased fire frequency in the southern Everglades, leading to reduced peat accretion and thinner peat at these locations.

Carbon-14-based peat accretion ranged from 0.9 mm year⁻¹ in the Loxahatchee NWR to 0.2 mm year⁻¹ in interior areas of WCA-3A and ENP. The average rate of accretion based on ¹⁴C was 0.5 ± 0.2 mm year⁻¹. In the far northern Everglades, in what is now the Everglades Agricultural Area, ¹⁴C dating of basal (3.5 m depth) and subsurface peat (1.3 m depth) yielded accretion rates of 0.8 and

Table 3.3 ¹⁴C age of subsurface peat along a north-to-south gradient in the Everglades ($n = 1$ per location)

Location	¹⁴ C age (years BP)
Loxahatchee NWR ^a	530 ± 50
WCA-2A (unenriched) ^a	830 ± 60
WCA-3A (3A) ^a	2,060 ± 60
Everglades National Park ^b	2,550 ± 60

^aSubsurface peat (46 cm depth)

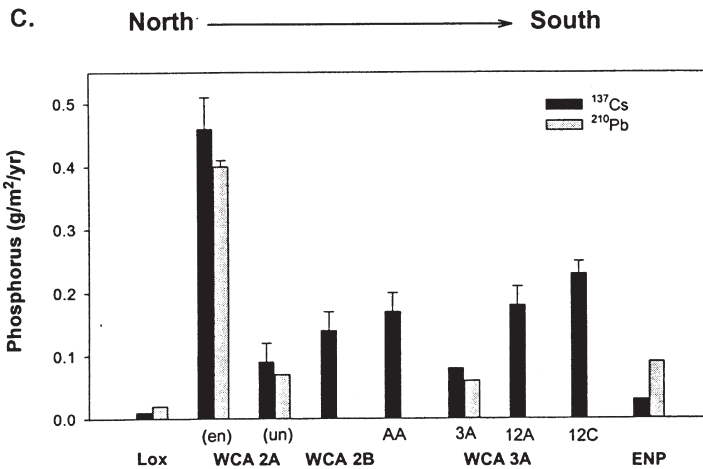
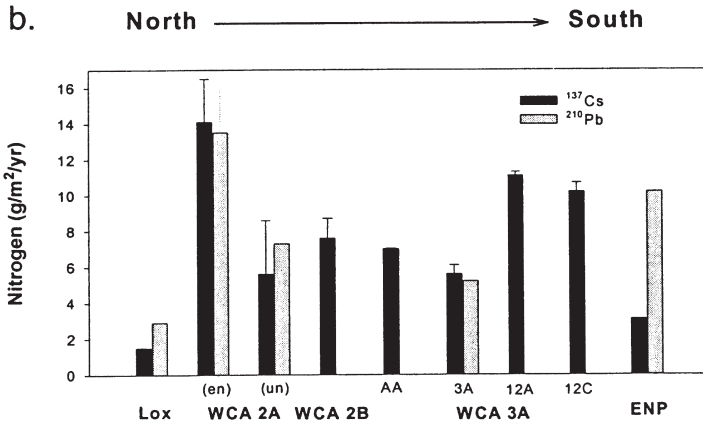
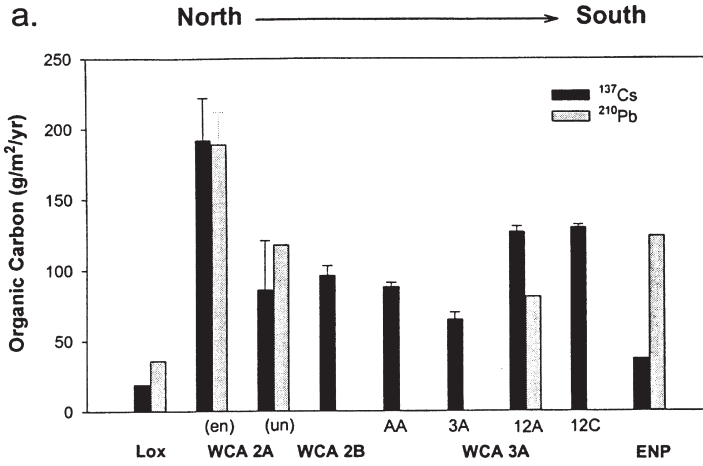
^bBasal peat (37 cm depth)

1.5 mm year⁻¹, respectively (McDowell et al. 1969). With the exception of Loxahatchee NWR, ¹⁴C peat accretion was much lower than long-term rates in the EAA area or our recent accretion measurements. In contrast to ¹³⁷Cs and ²¹⁰Pb that measure accretion during past 30–100 years, respectively, the ¹⁴C method measures peat accretion over a period of centuries to millennia (Table 3.3). Thus, the ¹⁴C method accounts for long-term decomposition, subsidence, and fire, all of which contribute to reduce vertical accretion over time. The similarity in ¹³⁷Cs, ²¹⁰Pb, and ¹⁴C peat accretion (0.9 ± 0.1 mm year⁻¹) in Loxahatchee NWR suggests that the rate of peat accretion in the least disturbed portion of northern Everglades has been relatively stable over time, perhaps due to fact that this is a rainfall-driven area (in the interior), and hydroperiod and fire frequency are more uniform compared to other hydrologically disturbed areas in the northern Everglades.

3.3.5 Organic Carbon, Nitrogen, and Phosphorus Accumulation

Like peat accretion, there was no clear gradient in organic C accumulation from north to south. Organic C accumulation was lowest in Loxahatchee NWR and ENP (28 ± 9 g m⁻² year⁻¹) and highest in the enriched area of northern WCA-2A (192 ± 30 g m⁻² year⁻¹) (Fig. 3.4a). Low recent organic C accumulation in Loxahatchee NWR and ENP probably reflects the isolated nature of these rainfall-driven locations as compared to the WCAs, where hydrology has been altered by canals and water control structures. Recent (30 years) organic C accumulation in enriched WCA-2A (192 g m⁻² year⁻¹) based on ¹³⁷Cs was more than double that of unenriched areas (86 ± 35 g m⁻² year⁻¹). Previous studies of nutrient-enriched areas of northern WCA-2A also reported much higher organic C accumulation as compared to unenriched areas of WCA-2A (Craft and Richardson 1993b; Reddy et al. 1993) as well as other areas in the WCAs (Craft and Richardson 1998). Long-term (100 years) organic C accumulation based on ²¹⁰Pb generally was comparable to recent (¹³⁷Cs) organic C accumulation (Fig. 3.4a). Long-term organic C accumulation was lowest in Loxahatchee NWR (36 g m⁻² year⁻¹) and highest in the enriched area of WCA-2A (189 g m⁻² year⁻¹). In Loxahatchee NWR and ENP, long-term organic C accumulation was two to three times higher than recent accumulation (Fig. 3.4a), perhaps reflecting extended hydroperiod at these interior locations prior to anthropogenic drainage efforts during the twentieth century.

With the exception of enriched WCA-2A, recent organic C accumulation was higher in areas of southern WCA-3A (12A, 12C) as compared to other locations (Fig. 3.4a). At these locations, hydroperiod was extended by construction of an east–west highway and levee across the Everglades during the twentieth century. Consequently, water pools along the north side of the levee in WCA-3A, resulting in extended hydroperiod (SFWMD 1992) and enhanced peat accretion and organic C accumulation at these locations (Craft and Richardson 1993a). Similarly, the combination of extended hydroperiod and increased P loadings accelerated organic



C accumulation in northern WCA-2A as compared to other areas of the Everglades (Craft and Richardson 1993a).

Nitrogen accumulation exhibited the same pattern as peat accretion and organic C accumulation. Recent (^{137}Cs) N accumulation was lowest in Loxahatchee NWR and ENP ($2.3 \pm 0.8 \text{ g m}^{-2} \text{ year}^{-1}$) and highest in the enriched area of WCA-2A ($14.1 \pm 2.4 \text{ g m}^{-2} \text{ year}^{-1}$) (Fig. 3.4b). Extended hydroperiod in southern WCA-3A (12A, 12C) also resulted in higher N accumulation as compared to other locations. Long-term (^{210}Pb) N accumulation was similar to recent accumulation, ranging from $2.9 \text{ g m}^{-2} \text{ year}^{-1}$ in Loxahatchee NWR to $13.5 \pm 2.5 \text{ g m}^{-2} \text{ year}^{-1}$ in the enriched area of WCA-2A. Like organic C, recent N accumulation in ENP ($3.1 \text{ g m}^{-2} \text{ year}^{-1}$) was much lower than long-term accumulation ($10.2 \text{ g m}^{-2} \text{ year}^{-1}$). In ENP, low N (and C) accumulation during the past 35 years may reflect reduced hydroperiod caused by drainage activities in the WCAs that reduced water flows to ENP (Light and Dineen 1994).

Phosphorus accumulation along the north-to-south gradient varied more than organic C and N accumulation (Fig. 3.4c). In unenriched areas, recent (^{137}Cs) P accumulation ranged from $0.01 \text{ g m}^{-2} \text{ year}^{-1}$ in Loxahatchee NWR to $0.20 \pm 0.03 \text{ g m}^{-2} \text{ year}^{-1}$ at locations 12A and 12C in southern WCA-3A. In unenriched areas, P accumulation was lowest in areas that primarily are rainfall-fed (e.g., Loxahatchee NWR and ENP) and highest in areas of extended hydroperiod and enhanced peat accretion, 12A and 12C in southern WCA-3A. Long-term (^{210}Pb) accumulation of P in unenriched areas was low, $0.06 \pm 0.01 \text{ g m}^{-2} \text{ year}^{-1}$, as compared to recent accumulation (Fig. 3.4c). Phosphorus accumulation in northern WCA-2A (enriched) was much higher than in unenriched areas of the Everglades (Fig. 3.4c). Since 1963, ^{137}Cs -based P accumulation in the enriched area ($0.46 \pm 0.05 \text{ g m}^{-2} \text{ year}^{-1}$) was three times higher as compared to unenriched areas of the WCAs ($0.15 \pm 0.02 \text{ g m}^{-2} \text{ year}^{-1}$) and 20 times higher than in Loxahatchee NWR and ENP ($0.02 \pm 0.01 \text{ g m}^{-2} \text{ year}^{-1}$). Likewise, ^{210}Pb -based P accumulation in enriched WCA-2A since the early 1960s ($0.40 \pm 0.0 \text{ g m}^{-2} \text{ year}^{-1}$) was seven times higher as compared to unenriched areas of the Everglades ($0.06 \pm 0.01 \text{ g m}^{-2} \text{ year}^{-1}$). Increased P accumulation in northern WCA-2A reflects increased loading of P and water to WCA-2A from the EAA during the past 50 years (Craft and Richardson 1993). Construction activities in the early 1960s resulted in complete impoundment by levees and by installation of four water control structures that replaced sheetflow across the fen (Light and Dineen 1994). Collectively, these hydrologic alterations accelerated eutrophication of WCA-2A while sparing areas downstream of WCA-2A from excessive phosphorus.

Fig. 3.4 Recent (30 years, ^{137}Cs) and long-term (100 years, ^{210}Pb) (a) organic carbon, (b) nitrogen, and (c) phosphorus accumulation along the north-to-south gradient through the Everglades. Bars represent mean values (± 1 standard error) of two to four peat cores collected from the same location (see Table 3.1 for details). *En* is the nutrient-enriched area of WCA-2A, *Un* is the unenriched area. At the enriched location, accumulation rates based on ^{210}Pb encompass the period 1962–1994

3.3.6 Effects of Increased Water and Nutrient Loading on Peat Accretion and Nutrient Accumulation

The effect of anthropogenic water and nutrient loadings on Everglades plant community structure and ecosystem processes has received much attention. Much of this research has focused on WCA-2A, particularly northern areas that receive vast quantities of nutrient-laden drainage water from the EAA. Between 1978 and 1987, an average of 459,000,000 m³ of water, 1,814 metric tons of N, and 60 metric tons of P was released annually into northern WCA-2A through four water control structures along the Hillsboro canal (SFWMD 1992). The combination of extended hydroperiod and increased P, the primary limiting nutrient in the Everglades (Steward and Ornes 1975b; Belanger et al. 1989; Craft et al. 1995), has led to a shift in plant community composition as cattail encroached into sawgrass and slough communities (Belanger et al. 1989; Urban et al. 1993; Davis 1994; Jensen et al. 1995; Bartow et al. 1996; Vaithiyathan and Richardson 1999; Richardson et al. 1999). Furthermore, P enrichment has contributed to increased net primary production (Davis 1989, 1991; Miao and Sklar 1998), decomposition (Davis 1991; Qualls and Richardson 2000) and enrichment of soil P pools (Koch and Reddy 1992; DeBusk et al. 1994; Qualls and Richardson 1995; Richardson et al. 1999) in northern WCA-2A.

The effects of increased water and P loading also enhanced peat and nutrient accumulation in northern WCA-2A. Since the early 1960s, peat accretion in the enriched area of WCA-2A more than doubled (5.3 ± 0.9 mm year⁻¹) as compared to unenriched areas in southern WCA-2A (Table 3.4). Prior to 1962, peat accretion in the enriched area (1.9 ± 0.2 mm year⁻¹) was similar to unenriched areas in southern WCA-2A (2.0 mm year⁻¹). Like P, organic C, and N accumulation in the enriched area since 1962 was twice that of unenriched areas of WCA-2A or the enriched area prior to 1962 (Table 3.4). Reddy et al. (1993) reported similar increases in peat accretion (6.0 ± 1.1 mm year⁻¹) and organic C (215 ± 38 g m⁻² year⁻¹) and N accumulation (14.1 ± 2.3 g m⁻² year⁻¹) in the enriched area using the ¹³⁷Cs method (Table 3.4). Phosphorus accumulation in the enriched area since the early 1960s was five to seven times higher (0.43 ± 0.03 g m⁻² year⁻¹) as compared to the period 1900–1960 (0.06 ± 0.0 g m⁻² year⁻¹) or to unenriched areas of southern WCA-2A (0.09 ± 0.03 g m⁻² year⁻¹). Reddy et al. (1993) also reported much higher P accumulation in the enriched northern area (0.53 ± 0.14 g m⁻² year⁻¹) as compared to southern WCA-2A (0.15 ± 0.02 g m⁻² year⁻¹). Thus, in addition to obvious shifts in plant species composition, increased water and P loading to northern WCA-2A have led to less obvious changes in soil processes such as peat accretion and nutrient accumulation.

3.3.7 Comparison with Other North American Peatlands

Organic C and nutrient accumulation in unenriched areas of the Everglades was compared to other North American peatlands (Table 3.5). Organic C accumulation

Table 3.4 Effects of increased water and phosphorus loadings on peat accretion and nutrient accumulation in nutrient-enriched and -unenriched areas of WCA-2A

Time interval (years)	Accretion rate (mm year ⁻¹)	Organic C (g m ⁻² year ⁻¹)	N (g m ⁻² year ⁻¹)	P (g m ⁻² year ⁻¹)
Enriched				
1964–1990 (¹³⁷ Cs) ^a	5.3 ± 0.9	192 ± 30	14.1 ± 2.4	0.46 ± 0.05
1964–1990 (¹³⁷ Cs) ^b	6.0 ± 1.1	215 ± 38	14.1 ± 2.3	0.53 ± 0.14
1962–1990 (²¹⁰ Pb) ^a	5.8 ± 1.4	189 ± 23	13.5 ± 2.5	0.40 ± 0.0
1900–1962 (²¹⁰ Pb) ^a	1.9 ± 0.2	111 ± 36	6.7 ± 2.2	0.06 ± 0.0
Unenriched				
1964–1990 (¹³⁷ Cs) ^c	2.0 ± 0.6	86 ± 35	5.6 ± 3.0	0.09 ± 0.03
1964–1990 (¹³⁷ Cs) ^d	3.6 ± 0.5	124 ± 21	7.7 ± 1.4	0.15 ± 0.02
1900–1990 (²¹⁰ Pb) ^c	2.0 ± 0.1	112 ± 6	7.0 ± 0.3	0.07 ± 0.01
Mean enriched (this study)	5.6 ± 0.2	190 ± 2	13.8 ± 0.3	0.43 ± 0.03
Mean unenriched (this study)	2.0 ± 0.0	99 ± 13	6.3 ± 0.7	0.08 ± 0.01

^a*n* = 4 for ¹³⁷Cs, *n* = 2 for ²¹⁰Pb^bReddy et al. (1993); (*n* = 6, one core each was collected from stations 10, 11A, 11B, 12, 13, and 14)^c*n* = 3 for ¹³⁷Cs, *n* = 3 for ²¹⁰Pb^dReddy et al. (1993); (*n* = 3, one core each was collected from stations 15–17)

in the Everglades ($98 \pm 13 \text{ g m}^{-2} \text{ year}^{-1}$), a southern fen (e.g., groundwater-fed, circumneutral pH), was greater than northern fens ($43 \pm 6 \text{ g m}^{-2} \text{ year}^{-1}$) but similar to precipitation-fed, acidic bogs ($96 \pm 16 \text{ g m}^{-2} \text{ year}^{-1}$). Nitrogen accumulation was much higher in the Everglades ($6.7 \pm 0.4 \text{ g m}^{-2} \text{ year}^{-1}$) as compared to bogs ($3.0 \pm 0.5 \text{ g m}^{-2} \text{ year}^{-1}$) and northern fens ($3.1 \pm 0.5 \text{ g m}^{-2} \text{ year}^{-1}$). Higher rates of N accumulation in the Everglades reflect increased N fixation by cyanobacteria that are abundant in the open water sloughs (Swift and Nicholas 1987; Craft and Richardson 1993a). Overall, fens and bogs had comparable P accumulation, $0.10 \pm 0.02 \text{ g m}^{-2} \text{ year}^{-1}$ for fens and $0.11 \pm 0.03 \text{ g m}^{-2} \text{ year}^{-1}$ for bogs. However, long-term (²¹⁰Pb measured) accumulation of P in the Everglades ($0.06 \pm 0.01 \text{ g m}^{-2} \text{ year}^{-1}$) is among the lowest reported North American peatlands (Table 3.5). Low P accumulation in the Everglades is a consequence of the historical low inputs and reflects the current role of P as the primary limiting nutrient in this oligotrophic peatland.

Table 3.5 Comparison of organic C, N, and P accumulation in unenriched areas of the Everglades with other North American peatlands

Peatland	Organic C (g m ⁻² year ⁻¹)	Nitrogen (g m ⁻² year ⁻¹)	Phosphorus (g m ⁻² year ⁻¹)
Fens			
Everglades (¹³⁷ Cs) ^a (FL)	81 ± 14	6.5 ± 1.2	0.12 ± 0.03
Everglades (¹³⁷ Cs) ^b (FL)	124 ± 21	7.7 ± 1.4	0.15 ± 0.02
Everglades (²¹⁰ Pb) ^a (FL)	90 ± 20	6.4 ± 1.6	0.06 ± 0.01
Mean	98 ± 13	6.7 ± 0.4	0.11 ± 0.03
Northern fens (¹³⁷ Cs) ^c (MI)	38 ± 10	2.6 ± 0.7	0.07 ± 0.02
Northern fens (²¹⁰ Pb) ^c (MI)	49 ± 15	3.5 ± 1.1	0.09 ± 0.04
Mean	43 ± 6	3.1 ± 0.5	0.08 ± 0.01
Bogs			
Okefenokee (²¹⁰ Pb) ^d (GA)	82	3.8	0.15
Pocosin (²¹⁰ Pb) ^e (NC)	127	3.0	0.06
Northern bogs (²¹⁰ Pb) ^f (MA, MD, PA, WV, MN)	79 ± 4	2.1 ± 0.3	0.11 ± 0.01
Mean (fens)	71 ± 28	4.9 ± 1.2	0.10 ± 0.02
Mean (bogs)	96 ± 16	3.0 ± 0.5	0.11 ± 0.03

^aThis study^bReddy et al. (1993); (*n* = 3, one core each was collected from stations 15–17 of WCA-2A)^cC.B. Craft, unpublished data (*n* = 2 fens)^dSchlesinger (1978) (*n* = 1 core)^eC.B. Craft, unpublished data (*n* = 1 core)^fHemond (1980, 1983) and Wieder et al. (1994) cited in Craft and Richardson (1998)

3.4 Conclusions and Lessons

The Everglades is a subtropical fen wetland underlain by deep (2–3 m) organic soils in the north that decrease in thickness and increase in mineral content to the south, along the direction of historical water flow. Recent (¹³⁷Cs) peat accretion (0.8 ± 0 mm year⁻¹) and organic C (28 ± 9 g m⁻² year⁻¹), N (2.3 ± 0.8 g m⁻² year⁻¹), and P (0.02 ± 0.01 g m⁻² year⁻¹) accumulation are lowest in interior areas such as the Loxahatchee NWR and ENP that are primarily rainfall-fed. Anthropogenic alteration of the hydrologic cycle has reduced organic C, N, and P accumulation in overdrained interior areas and increased accumulation in areas near canals where inundation is extended. Anthropogenic P loading from agricultural drainage has led to dramatically higher peat accretion (5.6 ± 0.2 mm year⁻¹) and organic C (190 ± 2 g m⁻² year⁻¹), N (13.8 ± 0.3 g m⁻² year⁻¹), and P (0.43 ± 0.03 g m⁻² year⁻¹) accumulation in eutrophic areas of the Everglades, especially northern WCA-2A. Unenriched areas of the Everglades possess some of the lowest rates of P accumulation (≤0.06 g m⁻² year⁻¹) of North American peatlands. The dramatic response of peat accretion and nutrient accumulation to P loadings reflects the importance of P in regulating ecosystem-level processes in this P-limited oligotrophic peatland. Our initial

long-term P accretion rates in the enriched areas provided a basis for estimating the number of storm water treatment areas (STAs) that would be needed to effectively remove P from the water column and store P permanently in the soil, mainly as organic P. Richardson and Craft (1993) calculated that more than 30,000 ha would be required to reduce P to levels close to background concentrations. An increased amount of STA wetland area is now being considered for construction by the SFWMD to meet the required $10\mu\text{g l}^{-1}$ criterion (SFWMD 2006).

