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Historical rates of sediment and nutrient accumulation in marshes of the Upper St. Johns River Basin, Florida, USA

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Abstract

We used ^{210}Pb-dated sediment cores from wetlands and Blue Cypress Lake, in the Upper St. Johns River Basin (USJRB), Florida, USA, to measure historical accumulation rates of bulk sediment, total carbon (C), total nitrogen (N), and total phosphorus (P). Marsh cores displayed similar stratigraphies with respect to physical properties and nutrient content. Wetland sediments typically contained > 900 mg organic matter (OM) g^{-1} dry mass, > 500 mg C g^{-1}, and 30–40 mg N g^{-1}. OM, C, and N concentrations were slightly lower in uppermost sediments of most cores, but displayed no strong stratigraphic trends. Total P concentrations were relatively low in bottommost deposits (0.01–0.11 mg g^{-1}), but ranged from 0.38–2.67 mg g^{-1} in surface sediments. The mean sediment accretion rate in the marsh since ~ 1900, 0.33 ± 0.05 cm yr^{-1}, was calculated from ten ^{210}Pb-dated cores. All sites displayed increases in accumulation rates of bulk sediment, C, N, and P since the early part of the 20th century. These trends are attributed to recent hydrologic modifications in the basin combined with high nutrient loading from agricultural, residential, and urban sources.

Introduction

Sediments in wetland ecosystems preserve historical records of environmental change. Paleoecological studies provide long-term perspectives on ecosystem perturbations and enable comparisons between modern environmental conditions and predisturbance, baseline conditions. Various types of information can be gleaned from wetland sediment records, including the history of marsh vegetation (Bartow et al., 1996), rates of heavy metal deposition (Rood et al., 1995), and rates of nutrient input and storage (Craft & Richardson, 1993a, 1993b, 1998; Reddy et al., 1993).

We used paleoecological methods to study historical rates of nutrient accumulation in aquatic ecosystems of the Upper St. Johns River Basin (USJRB), Florida (Figure 1). Wetlands in the region once covered nearly 1800 km^2 and were the primary water source for the north-flowing St. Johns River, that traverses nearly 500 km before discharging into the Atlantic Ocean near Jacksonville, Florida (Figure 1). Because local wetlands possess nitrogen-rich histosol soils, they were increasingly exploited for ranching, citrus production, and row crops. Draining of local marshlands began around 1900, and by the mid-1940s the floodplain area in the USJRB had been reduced to ~ 1270 km^2 (Sincock, 1958). By 1957 the floodplain area had shrunk to 725 km^2. Eight years later, under drought conditions, the floodplain was reduced to only ~ 260 km^2 (Hall, 1987). By 1980, nearly 80% of the 3720 km^2 in the USJRB had been converted to pasture (70.6%), agricultural use (5.0%), urban development (3.4%) or silviculture

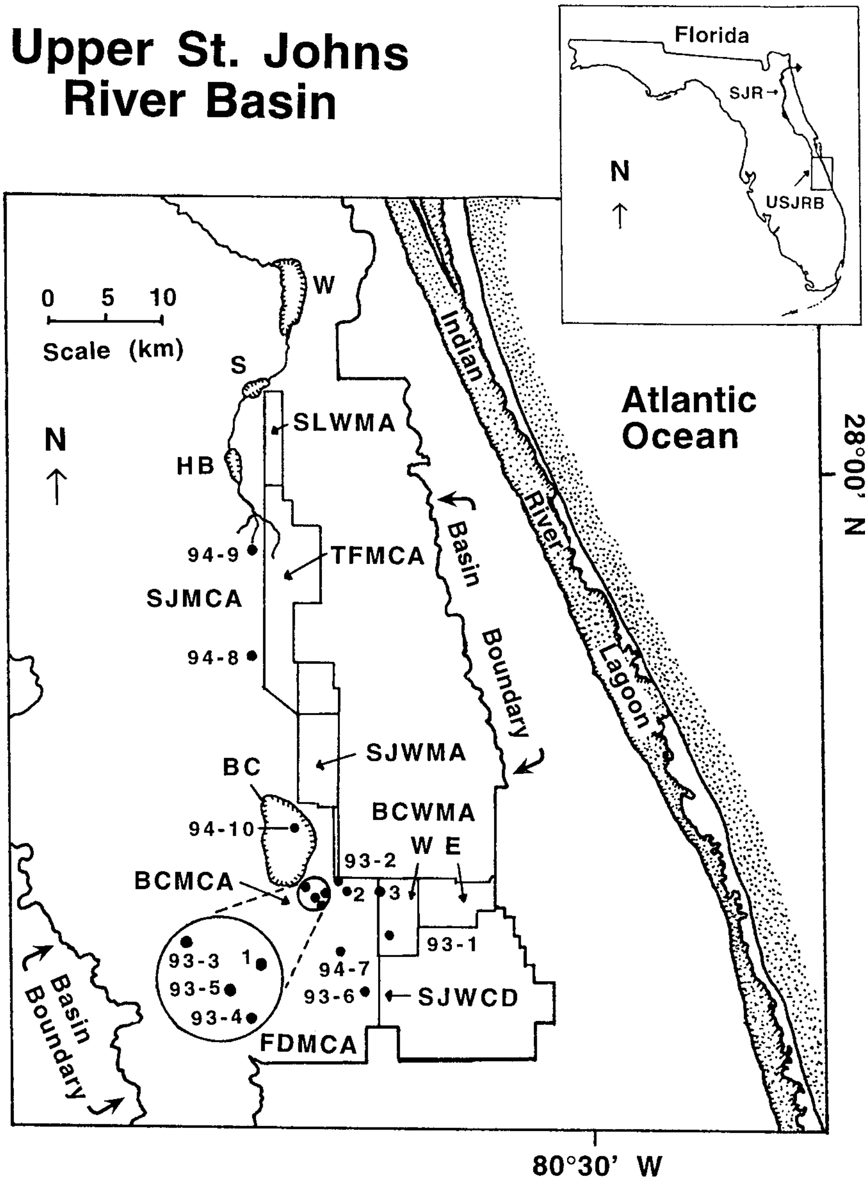

Figure 1. Map of the Upper St. Johns River Basin (USJRB), Florida, USA, showing the principal conservation and water management areas from south to north: FDMCA (Fort Drum Marsh Conservation Area), SJWCD (St. Johns Water Control District), BCMCA (Blue Cypress Marsh Conservation Area), BCWMA W/E (Blue Cypress Water Management Area – West/East), SJWMA (St. Johns Water Management Area), SJMCA (St. Johns Marsh Conservation Area), TFMCA (Three Forks Marsh Conservation Area), and SLWMA (Sawgrass Lake Water Management Area). Lakes in the USJRB include, from south to north, BC (Blue Cypress), HB (Hell 'n' Blazes), S (Sawgrass), and W (Washington). Core sites are indicated by black dots with designations as in Table 1. Nutrient-rich water from the western BCWMA enters the BCMCA, and flows northward into the St. Johns River. Inset map shows the location of the Upper St. Johns River Basin (USJRB), and the north-flowing St. Johns River (SJR), that discharges into the Atlantic Ocean at Jacksonville, Florida.

(0.1%), with the balance in wetlands (18.5%) or open water (2.3%) (SJRWMD 1980). The disappearance of local wetlands was accompanied by rapid population growth. Between 1930 and 1990, the combined population of Brevard and Indian River Counties grew from 20,000 to > 489,000. Remaining wetlands in the USJRB were impacted by runoff from ranches, agricultural areas, and roads.

In the 1970s, the St. Johns River Water Management District began a comprehensive study of the USJRB. Today, the Upper St. Johns River project involves investigation of several wetlands including the Blue

Cypress Marsh Conservation Area (BCMCA), the Fort Drum Marsh Conservation Area (FDMCA), the St. Johns Marsh Conservation Area (SJMCA), and several other water management and conservation areas (Figure 1). Management of these wetlands became necessary because the vast floodplain marsh was subjected to increasing human disturbance. Regional hydrology was altered by the construction of levees, canals and water control structures (e.g., weirs, culverts, and spillways). Road construction, particularly east-west routes, impeded south-to-north sheetflow of surface waters. Lacustrine and wetland ecosystems in the region received increased nutrient inputs in runoff and airborne particulates from agricultural fields.

We used sediment cores from marshes in the USJRB and Blue Cypress Lake (Figure 1) to test whether recent hydrologic modifications and increases in nutrient loading had altered the rate of sediment accretion and nutrient (C, N, P) accumulation in these aquatic ecosystems. We assessed anthropogenic impacts on nutrient sequestering by evaluating the historical trajectory of nutrient burial at widely spaced sites in the watershed, and by comparing predisturbance nutrient accumulation rates with recent nutrient accumulation rates.

Field methods

Coring sites (Table 1) were selected based on proximity to a point source of high nutrient loading. Nutrients enter the low-nutrient, western Blue Cypress Marsh Conservation Area (BCMCA) through a gap in the levee that separates the BCMCA from the nutrient-rich eastern end of the Blue Cypress Water Management Area (BCWMA) (Figure 1). Phosphorus concentrations in the BCWMA were frequently > 100 μg l^{-1} while values in the BCMCA were typically 30–40 μg l^{-1}. The gap in the levee was about 150 m from an agricultural discharge pump, used periodically to drain a large citrus grove. The pump discharges 378 l (100 gallons) per min and discharge water often had total P concentrations > 300 μg l^{-1} (SJRWMD, unpublished data). Core site 3 was located nearest the discharge site (Figure 1). Other coring sites (2, 93-2, 1, and 93-3) were located at increasing distances from the nutrient point source (Figure 1). Sites 93-5 and 93-4 were placed perpendicular to the direction of discharge flow and upstream (i.e. south) from the natural, northward sheetflow. Coring sites 93-6, 93-7, 94-8, 94-9, and 94-10 were located throughout the basin to measure temporal shifts in nutrient accumulation over a large area.

Table 1. Core designations, coring locations and core lengths for sediment profiles collected in the marshes of the USJRB and Blue Cypress Lake. Cores 1A, 1B, 2A, 2B, 3A, and 3B were collected at site 1, 2, and 3 in Phase I of the study. A and B indicate replicate cores taken at each site (1, 2, 3), and were ~ 50 m apart. Cores taken in Phase II are named by date (day-month-year) and site number. Latitude and longitude were obtained with a Global Positioning System (GPS)

Site/Core	Latitude (N)	Longitude (W)	Total length (cm)
1A	27 °41′ 38.3″	80 °43′ 28.6″	70
1B	27 °41′ 38.3″	80 °43′ 28.6″	89
2A	27 °41′ 43.6″	80 °42′ 12.8″	80
2B	27 °41′ 43.6″	80 °42′ 12.8″	90
3A	27 °41′ 47.9″	80 °40′ 51.6″	72
3B	27 °41′ 47.9″	80 °40′ 51.6″	86
2-XII-93-1	27 °39′ 24.2″	80 °39′ 58.1″	84
2-XII-93-2	27 °41′ 49.6″	80 °42′ 30.0″	84
2-XII-93-3	27 °41′ 36.9″	80 °44′ 08.9″	76
2-XII-93-4	27 °40′ 48.2″	80 °43′ 24.2″	72
2-XII-93-5	27 °41′ 05.6″	80 °43′ 39.1″	84
2-XII-93-6	27 °36′ 48.0″	80 °41′ 12.1″	92
21-I-94-7	27 °38′ 38.3″	80 °42′ 25.8″	92
21-I-94-8	27 °52′ 12.8″	80 °46′ 49.3″	64
21-I-94-9	27 °57′ 02.0″	80 °46′ 46.3″	60
8-II-94-10	Blue Cypress Lake (east-central basin)		96

In Phase 1 of the study, duplicate sediment/water interface cores were taken at each of three sites (1, 2, and 3) on 23 September 1992 in the Blue Cypress Marsh Conservation Area (BCMCA). Phase I was designed to assess the feasibility of ^{210}Pb dating the marsh sediments and to determine whether duplicate cores would yield replicable ^{210}Pb profiles. Site 1, the most westerly of the three stations, was farthest from the point source of nutrient loading and was presumed to be least affected. Site 3, the most northeasterly station, probably received the greatest nutrient load from pump discharge.

In Phase II, six cores were collected on 2 December 1993 and three cores were taken on 21 January 1994. Cores were collected from the Blue Cypress Marsh Conservation Area (BCMCA), the Fort Drum Marsh Conservation Area (FDMCA), and the St. Johns Marsh Conservation Area (SJMCA) (Figure 1). One core was collected in ~ 3 m of water in the east-central part of Blue Cypress Lake (Figure 1) on 8 February 1994. All cores in the study were assigned the project appelation 'BCM' (Blue Cypress Marsh), regardless of provenance.

Sediment profiles were retrieved using a piston corer with a 7.6-cm diameter, clear polycarbonate core barrel (Fisher et al., 1992). The corer was employed, as originally designed, to sample soft, poorly consolidated

Blue Cypress Lake deposits. The Blue Cypress Lake core (8-II-94-10) was sampled in a vertical position to prevent sediment mixing. The profile was extruded by pushing upward with a piston, and sectioned at 4-cm intervals into a PVC tray mounted on top of the core tube (Fisher et al., 1992). To sample the dense marsh peats, the coring 'head' was replaced with a PVC cap through which the piston cable passed. This cap was hammered with a rubber mallet to drive the core barrel into the deposits. Marsh cores were transported to the laboratory in a vertical position.

Laboratory methods

Marsh cores were stored in the laboratory at 4 °C, and extruded 24–48 h after collection. Cores 1A, 1B, 2A, 2B, 3A and 3B from sites 1, 2, and 3 (Figure 1) were sampled at 2-cm intervals. All other cores were sectioned at 4-cm intervals. Percent dry mass was calculated by weighing wet samples, drying, and re-weighing. Dried samples were ground and organic matter (OM) content was estimated by weight loss on ignition at 550 °C (Håkanson and Jansson, 1983). Sediment bulk density (g dry mass cm^{-3}) was calculated from the proportion of dry mass in wet sediment and the organic/inorganic proportion of dry sediment (Binford, 1990).

Total carbon (C) and total nitrogen (N) content were measured on a Carlo-Erba C/N/S analyzer. Total phosphorus (P) content was determined using a Bran & Luebbe Autoanalyzer II with a single-channel colorimeter, following digestion of dry sediment samples in H_2SO_4 and $K_2S_2O_8$ (Schelske et al., 1986).

Cores 1B, 2B and 3B, from sites 1, 2, and 3, were selected for ^{210}Pb dating in Phase I. Cores 1A, 2A and 3A had radionuclide activities measured at broader intervals to test the replicability of radioisotope stratigraphies, but were not dated. Samples near the core tops had low bulk density, necessitating the combining of sediment from two or more contiguous levels to provide sufficient dry mass for analysis. Dry material from every 4-cm section in the ten Phase II cores was prepared for dating. Radioisotope activities (^{210}Pb, ^{226}Ra [^{214}Bi], ^{137}Cs) were measured by gamma counting (Appleby et al., 1986) using two EG&G Ortec GWL High Purity Germanium coaxial well detectors attached to a 4096-channel pulse height analyzer (Schelske et al., 1994).

In Phase I, supported ^{210}Pb activity was estimated from the mean ^{210}Pb activity below the unsupported/supported ^{210}Pb boundary. This mean value was subtracted from the total ^{210}Pb activities at each level to obtain unsupported ^{210}Pb activities. For datable cores in Phase II, unsupported ^{210}Pb activity was calculated by subtracting measured supported ^{210}Pb (^{226}Ra) activity at each depth from the corresponding total ^{210}Pb activity. The two approaches for computing unsupported ^{210}Pb yielded virtually identical results because supported ^{210}Pb (^{226}Ra) activity was low in marsh samples. Dates were calculated using the constant-rate-of-supply (crs) model (Appleby & Oldfield, 1978, 1983; Oldfield & Appleby, 1985).

Nutrient accumulation rates were computed by multiplying the bulk sediment accumulation rate times the corresponding nutrient concentration in dry sediment for each dated interval. In cores 1B, 2B, and 3B, C and N concentrations were measured in every other stratigraphic sample, so accumulation rates were computed by interpolating nutrient concentrations for unanalyzed sediment depths. Interpolation introduced little error because C and N concentrations varied little between adjacent analyzed samples. Total P concentrations in Phase I cores were interpolated below 30 cm depth, where alternate samples were analyzed. Interpolation was justified because P concentrations varied little below 30 cm depth.

We employed an alternative, conservative approach to assess temporal shifts in sediment and nutrient accumulation, and compared the mean accumulation rate since the most recent date in the 1970s (i.e. roughly the last two decades of accumulation), to the accumulation rate around 1920. There were several rationales for using this method to evaluate long-term changes in sediment and nutrient accumulation. First, sediments deposited around 1920 are unaffected by 'too-old' dating error that affects calculated ages for older deposits (Binford, 1990). Second, in the early part of the 20th century, nutrient accumulation rates were relatively unaffected by human disturbance and fairly stable. Third, by computing the mean nutrient accumulation rate for the last ~ 20 years, we avoided the undue influence of topmost samples that may display high nutrient concentration as a consequence of dense algal abundance or lack of sediment diagenesis, and thus yield high calculated nutrient accumulation rates. Lastly, with the exception of core 21-I-94-8, mean nutrient accumulation rate since the 1970s was based on rates over three or four stratigraphic samples, thereby damping the effect of any single, extreme value.

Results

Retrieved sediment cores varied in total length from 60–96 cm (Table 1). Bulk density was low near the sediment surface and generally increased with depth, reflecting compaction and dewatering of deeper deposits. Excluding core 21-I-94-8, which came from a relatively dry area, topmost samples from marsh cores had bulk densities between 5 and 39 mg cm^{-3}, whereas bulk density in bottom deposits from the marsh cores was 73–135 mg cm^{-3}.

Organic matter in the marsh sediments exceeded 800 mg g^{-1} and most samples contained > 900 mg g^{-1}. Most marsh cores showed a slight increase in OM with increasing depth in the profile, but the trend was not strong. Concentrations of OM in the Blue Cypress Lake core (8-II-94-10) were lower than values in the marsh cores, and ranged between ~ 390 and 700 mg g^{-1}. Total carbon represents a nearly constant proportion of sediment organic matter, so only total C concentrations are shown (Figure 2). In marsh sediments, total C content ranged from ~ 390 to 560 mg C g^{-1}, and most values were > 500 mg g^{-1}. Similar to OM, total C generally showed a slight increase with depth in the profiles, particularly near the tops of cores. Total C concentrations in the Blue Cypress Lake core were mostly lower than those measured in marsh sediments, varying from 216–418 mg C g^{-1}. Total N content in marsh cores ranged between ~ 22 and 46 mg N g^{-1}, but was typically between 30 and 40 mg N g^{-1} (Figure 3). The Blue Cypress Lake core had lower total N, varying between 15 and 30 mg N g^{-1}. Lowest OM, C, and N concentrations in the lake core were associated with sand-rich depths.

Total P concentrations in Blue Cypress Marsh sediments generally declined with increasing depth in the cores (Figure 4). Phosphorus concentrations in surface deposits ranged from 0.38–2.67 mg P g^{-1}. Bottom samples in marsh profiles possessed between 0.01 and 0.11 mg P g^{-1}. The Blue Cypress Lake core also displayed increasing total P content toward the surface of the section and topmost sediment contained 0.99 mg P g^{-1}. The lake core had more total P in basal deposits (0.22 mg P g^{-1}) than did marsh cores.

Most cores displayed declines in total ^{210}Pb activity with increasing sediment depth (Figure 5), though these decreases were not always monotonic. In some cases activities in topmost samples were lower than activities in underlying levels. Topmost deposits typically had total ^{210}Pb activities between 10 and 25 dpm g^{-1}. Cores 21-I-94-7 and 21-I-94-9 showed little change in total ^{210}Pb activity with depth (Figure 5) and were not dated.

All marsh cores displayed low ^{226}Ra activity, i.e. supported ^{210}Pb activity, indicating that ^{210}Pb in the sediments came predominantly from the atmosphere. Of 246 marsh samples, only 27 yielded ^{226}Ra activities > 1 dpm g^{-1}. The highest value in the marsh deposits was recorded at 0–4 cm depth in core 2-XII-93-1 (3.45 dpm g^{-1}). Radium-226 activity was generally higher in Blue Cypress Lake sediments, ranging between 1.6 and 3.6 dpm g^{-1}. ^{226}Ra activity was very low in deeper deposits and tended to increase near the sediment surface (Figure 5). Many cores failed to display a sharp ^{137}Cs peak (Figure 5), and in some cases ^{137}Cs activity was measured at depths with low unsupported ^{210}Pb activities, i.e. in sediments > 100 years old.

Total integrated unsupported ^{210}Pb from the ten marsh sites varied between 11.5 and 23.8 dpm cm^{-2} (Figure 6). Mean and standard deviation for integrated unsupported ^{210}Pb activity were 17.9 ± 3.7 dpm cm^{-2}. The mean ^{210}Pb fallout rate for the ten marsh sites was 0.56 dpm cm^{-2} yr^{-1}. The Blue Cypress Lake core had an integrated unsupported ^{210}Pb value of 48.3 dpm cm^{-2}, yielding a fallout rate of 1.5 dpm cm^{-2} y^{-1}.

The crs ^{210}Pb dating model yields artificially 'too-old' dates in sediments deposited > 100–150 years ago (Binford, 1990) and error terms on these old dates are large. We therefore calculated material accumulation rates for sediments deposited since ~ 1900. Most profiles demonstrated increased linear accretion (cm yr^{-1}) near the core tops, which is attributed, in part, to relatively low compaction in recent, uppermost deposits. Mean accretion rates since ~ 1900 were calculated to provide an estimate of long-term sediment accumulation at the sites. Mean accretion rates for the ten dated sites ranged from 0.24–0.40 cm yr^{-1} (mean and s.d. = 0.33 ± 0.05 cm yr^{-1}). During the 20th century, accretion at the Blue Cypress Lake core site averaged 0.40 cm yr^{-1}.

Because recent shifts in accretion rates reflect, in part, changes in sediment compaction, we evaluated mass-based bulk sediment and nutrient accumulation rates. Recent bulk sediment accumulation rates in the cores were consistently higher than rates deeper in the profiles. Cores typically displayed increasing mass accumulation through time (Figure 7). Total C accumulation rates in the cores also demonstrated a generally increasing trend over time, as did total N accumulation rates (Figures 8 & 9). All eleven dated cores showed relatively pronounced increases in total P accumulation through time (Figure 10).

For the eleven dated cores, bulk sediment accumulation ca. 1920 ranged between 9 and 27 mg cm^{-2} yr^{-1}.

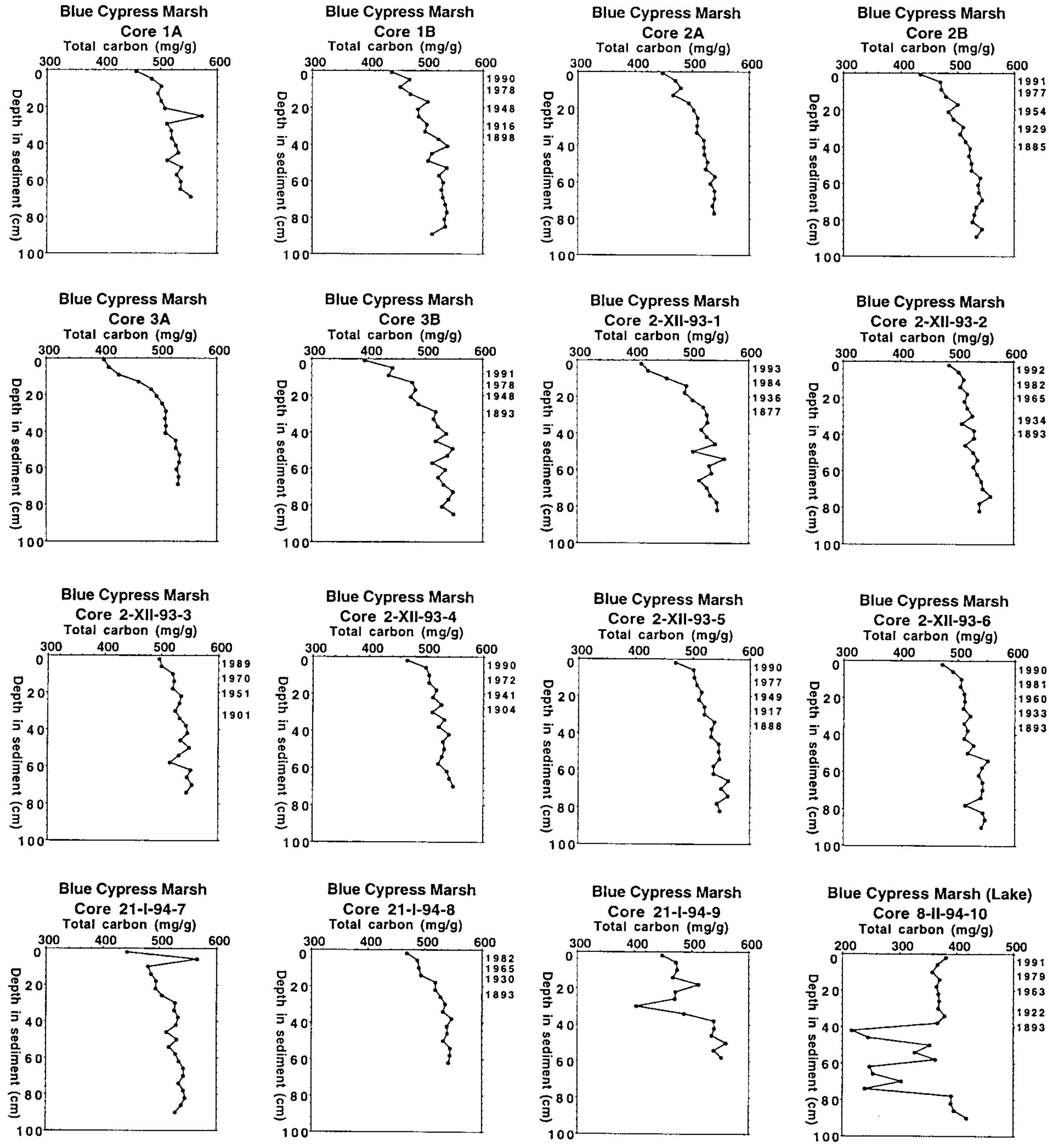

Figure 2. Total carbon concentration in sediment cores from the Upper St. Johns River Basin plotted against selected dates (in datable cores), and depth in the sediment.

Since the 1970s, values have been between 25 and 53 mg cm^{-2} yr^{-1}. Between 1920 and recent times, bulk sediment accumulation increased 1.7–3.4-fold at the eleven sites (Figure 11). Around 1920, C accumulation rates at the eleven sites ranged between 4.4 and 13.0 mg cm^{-2} yr^{-1}. Since the 1970s, C accumulation rates ranged between 11.7 and 24.4 mg cm^{-2} yr^{-1}. The eleven sites demonstrated 1.6–3.0-fold increases in C sequestering (Figure 11). Total N accumulation rate around 1920 ranged from 0.33–1.06 mg cm^{-2} yr^{-1} among the

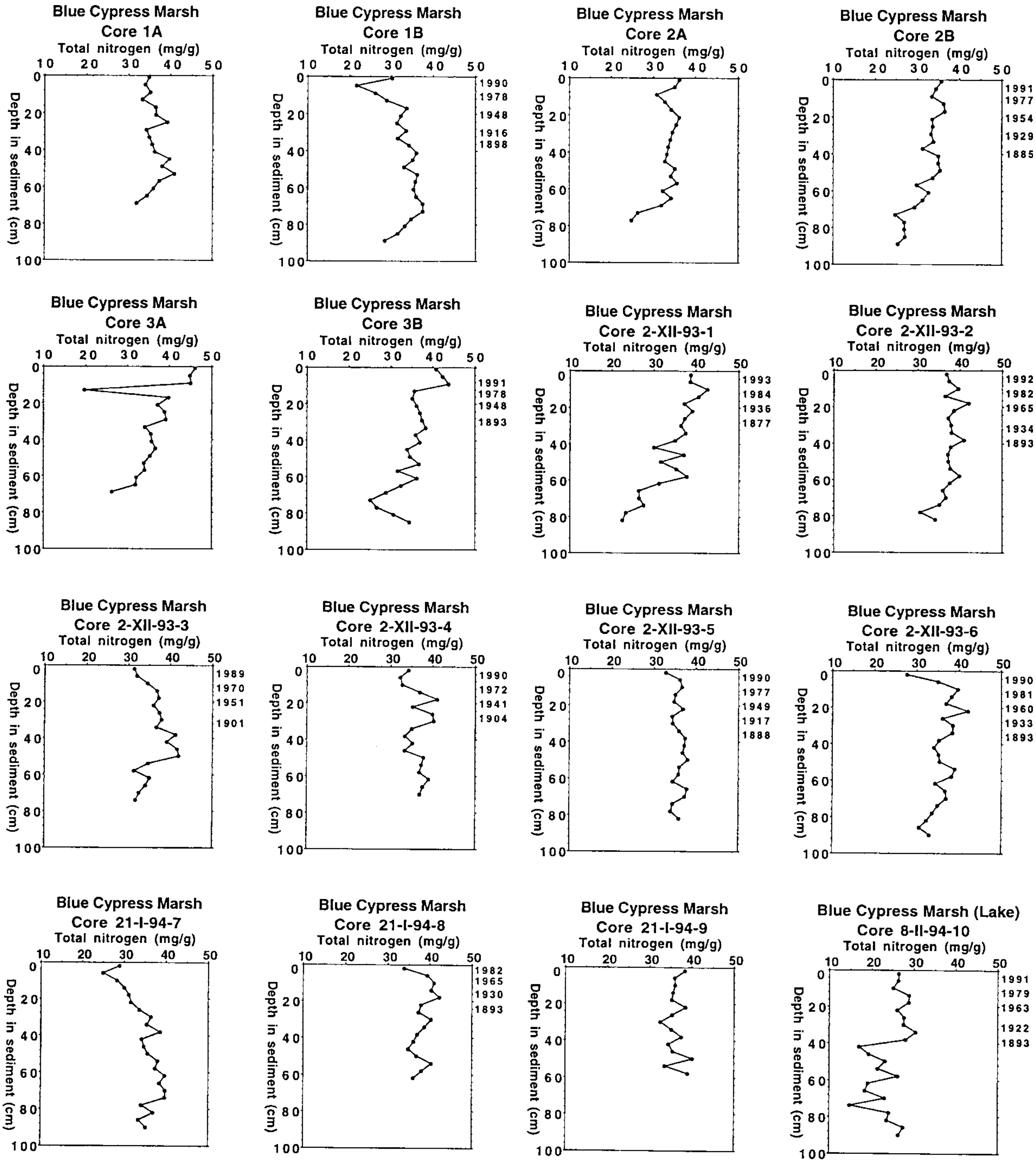

Figure 3. Total nitrogen concentration in sediment cores from the Upper St. Johns River Basin plotted against selected dates (in datable cores), and depth in the sediment.

eleven core sites. Since the 1970s, total N accumulation has ranged between 0.80–1.76 mg cm^{-2} yr^{-1}. Increases were apparent at all sites and ranged from 1.6–3.7-fold (Figure 11). In 1920, total P accumulation rate at the marsh sites was between 0.002–0.006 mg cm^{-2} yr^{-1}. Since the 1970s, P accumulation averaged between 0.008 and 0.038 mg cm^{-2} yr^{-1}. Recent rates are 2.3–17.0 times greater than rates estimated for 1920 (Figure 11).

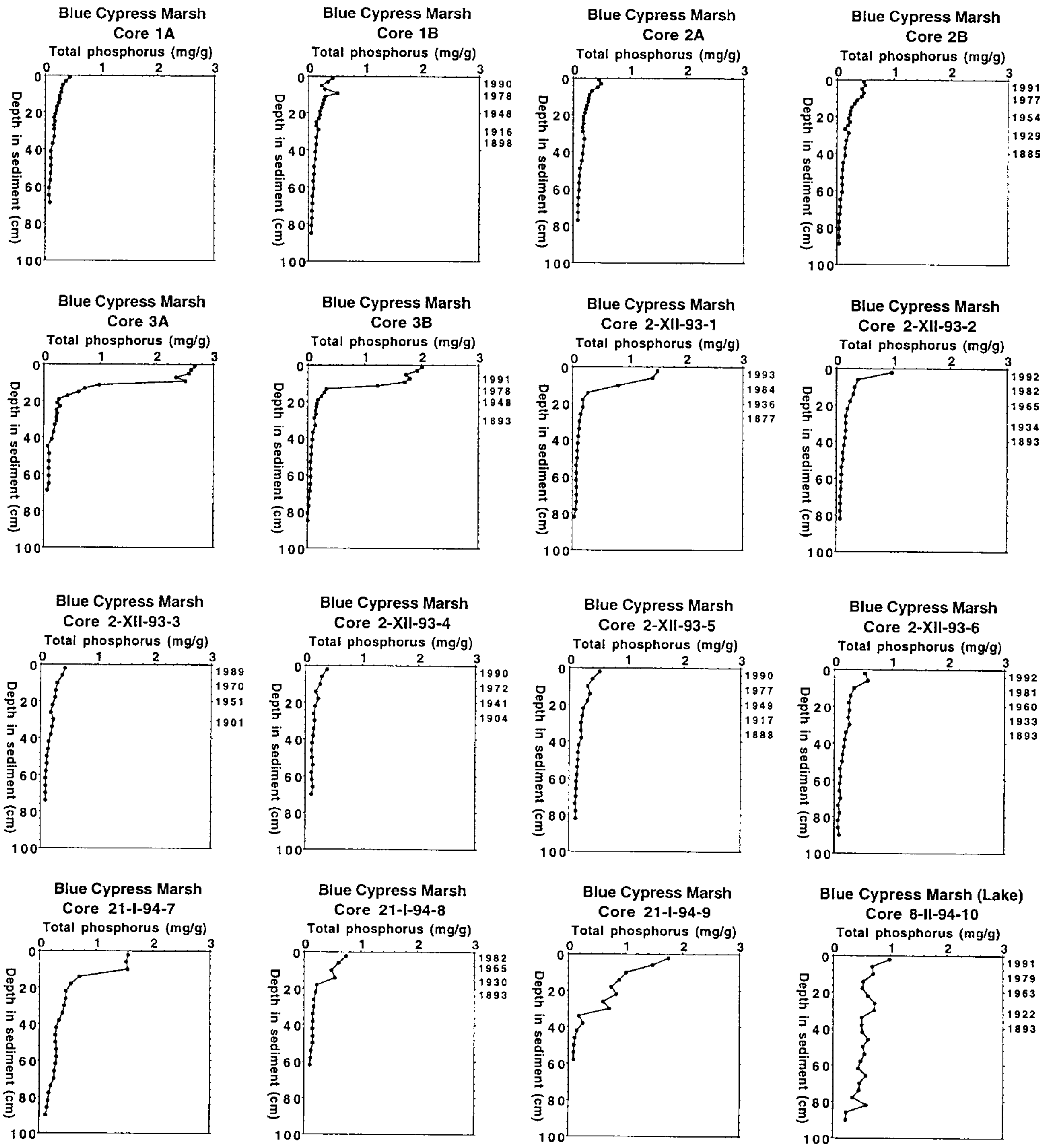

Figure 4. Total phosphorus concentration in sediment cores from the Upper St. Johns River Basin plotted against selected dates (in datable cores), and depth in the sediment.

Discussion

Physical and chemical stratigraphy

Stratigraphic distribution of total P (Figure 4) differed from that for C and N (Figures 2 & 3), in that all 16 cores showed increasing total P concentrations near the tops of profiles. Several factors may account for this trend in P concentration. First, high total P in surface deposits may reflect presence of P-rich, benthic algae. Algae possess little support tissue and have lower C:P ratios than peat-producing macrophytes. Second, high

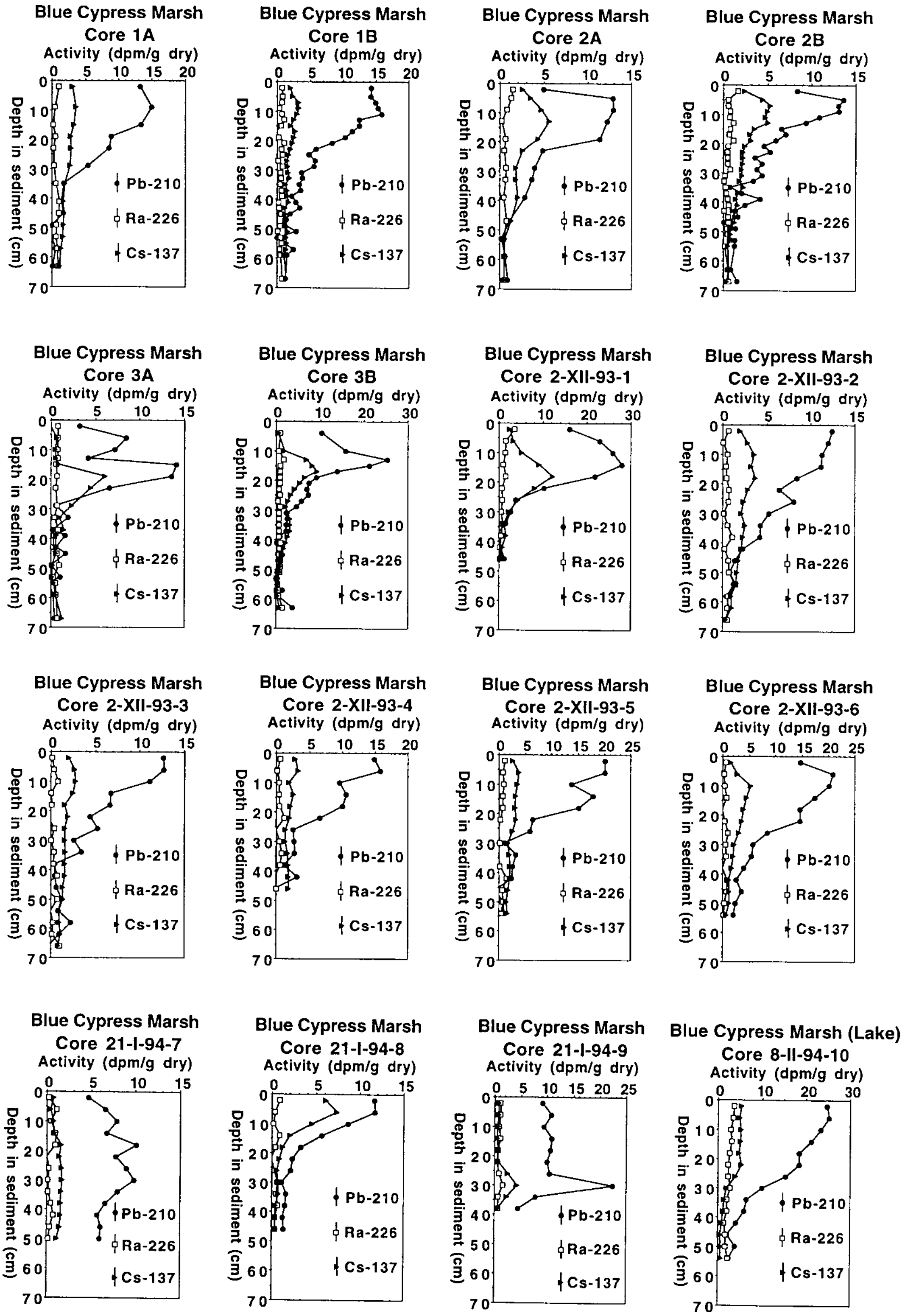

Figure 5. Radioisotope activities (dpm g^{-1}) vs. depth in cores from the Upper St. Johns River Basin. Cores 1B, 2B, and 3B were fully counted and dated using the crs ^{210}Pb dating model. Cores 1A, 2A, and 3A were collected ~ 50 m from their respective duplicates and were gamma counted at broader sampling intervals simply to assess stratigraphic replicability. Cores 21-I-94-7 and 21-I-94-9 were not dated (see text).

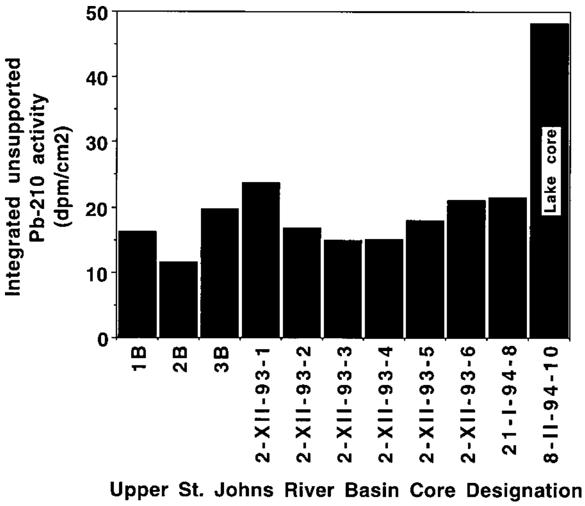

Figure 6. Integrated unsupported ^{210}Pb activity in ten dated marsh cores and the core from Blue Cypress Lake (8-II-94-10). Intersite differences in the calculated ^{210}Pb fallout rate derived from marsh cores were small, ranging from 0.36–0.74 dpm cm^{-2} yr^{-1}. Higher integrated activity in the Blue Cypress Lake core probably reflects focusing of sediment and associated ^{210}Pb to the coring site.

total P concentrations in near-surface marsh sediments may reflect post-depositional mobility of dissolved P (Carignan & Flett, 1981). Nevertheless, total P in these peaty sediments is probably bound primarily in refractory OM, so upward transport of dissolved P in interstitial water probably has little effect on total P concentration in profiles. Third, high total P in recent sediments probably reflects increasing P loading rates and assimilation in the marsh.

Core Chronologies

Most Blue Cypress Marsh cores demonstrated a general decline in total ^{210}Pb activity with increasing sediment depth, suggesting the radionuclide can be used to date recent deposits reliably (Figure 5). Duplicate cores from core sites 1, 2, and 3 display well-replicated radioisotope stratigraphies (Figure 5), indicating that single cores can be used to evaluate local, temporal changes in sedimentation. Duplicate cores also yielded similar stratigraphies for chemical variables (Figures 2–4). Two cores (21-I-94-7, 21-I-94-9) were deemed undatable because total ^{210}Pb activity varied little with depth (Figure 5). Although strong P gradients in the cores argue against sediment mixing (Figure 4), lack of ^{210}Pb stratigraphy suggested post-depositional ^{210}Pb transport, or mixing by physical or biological processes. Alternatively, the relatively 'flat' ^{210}Pb profiles in the two cores may reflect recent increases in nutrient loading, that in turn caused progressively higher bulk sediment accumulation which diluted atmospherically-derived radionuclide input.

Radium-226 (i.e. supported ^{210}Pb) activities were low and fairly constant in marsh deposits, generally < 1 dpm g^{-1}, indicating that downcore, asymptotic total ^{210}Pb values estimate supported ^{210}Pb activity accurately. Blue Cypress Lake sediments displayed higher and more variable ^{226}Ra activities (1.26–3.60 dpm g^{-1}), similar to findings in many Florida lakes (Brenner et al., 1994, 1995, 1996, 1997, 2000). Accurate dating of Florida lake cores generally requires direct measurement of supported ^{210}Pb activities on a level-by-level basis.

The mean ^{210}Pb fallout rate in marshes of the USJRB (0.56 dpm cm^{-2} yr^{-1}) is lower than the reported global average of ~ 1.1 dpm cm^{-2} yr^{-1} (Nozaki et al., 1978), and less than regional mean fallout rates (0.77–1.21 dpm cm^{-2} yr^{-1}) derived from Florida lake cores (Binford & Brenner, 1986, 1988). Relatively higher rates of unsupported ^{210}Pb accumulation in lakes reflect preferential focusing of lacustrine sediment, along with its associated ^{210}Pb, to depositional areas where cores are collected.

Cesium-137, an artificial radionuclide injected into the atmosphere by nuclear weapons testing, sometimes can be used to identify the period of maximum atmospheric fallout in the early 1960s (Krishnaswami & Lal, 1978). About half the cores from the USJRB displayed a distinct ^{137}Cs peak (Figure 5). In those cores, highest ^{137}Cs actvities generally occurred at depths corresponding to the period of maximum fallout, as determined by ^{210}Pb dating. In the other cores, ^{137}Cs activity varied little with depth, and was in some cases measured in sediments that ^{210}Pb dating indicates were deposited prior to atmospheric bomb testing, sometimes by many decades. This suggests that ^{137}Cs is mobile in some USJRB marsh and lake deposits. Post-depositional cesium mobility has been invoked to explain the lack of distinct ^{137}Cs peaks in some ^{210}Pb-dated Florida lake cores (Brenner et al., 1994), in soft-water lake deposits (Davis et al., 1984), and in ombrotrophic peats (Oldfield et al., 1979). Nevertheless, ^{137}Cs has been used successfully to date Florida Everglades peats (Craft & Richardson, 1993a, 1993b, 1998; Reddy et al., 1993), and rapidly accreting salt marsh deposits (Delaune et al., 1978), where the radionuclide was probably immobilized by adsorption to organic matter or clay particles. Some organic sediments in the USJRB may lack expanding lattice clays that would otherwise serve as binding sites for soluble ^{137}Cs, and uptake by plants may redistribute cesium in USJRB sediments.

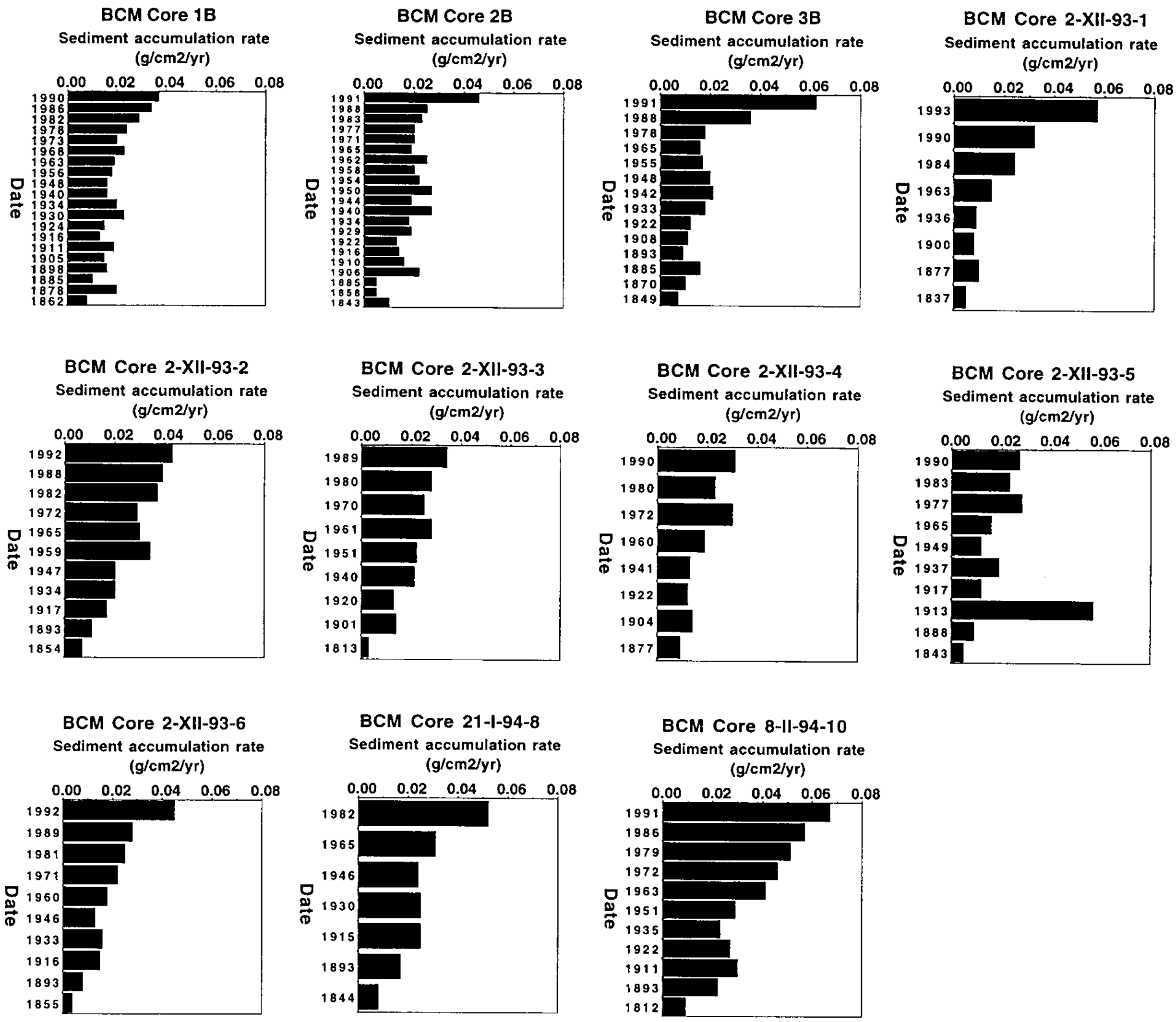

Figure 7. Bulk sediment accumulation rate plotted vs. date for ten marsh cores and the core from Blue Cypress Lake.

Because of potential problems associated with using ^{137}Cs as a datum in the marsh cores, we relied on ^{210}Pb, which is bound tightly to organic and mineral particles and capable of providing continuous age-depth relations for sediments up to about 100 years old (Craft & Richardson, 1998).

Sediment and nutrient accumulation rates

Mean sediment accretion since ~ 1900 has been fairly similar across the ten marsh sites in the USJRB (0.33 ± 0.05 cm yr^{-1}). At the Blue Cypress Lake core site, mean sediment accumulation since 1900 was 0.40 cm yr^{-1}. This value may not reflect lakewide sedimentation accurately because many shallow Florida lakes experience sediment resuspension and focusing, yielding a heterogeneous distribution of bottom deposits (Whitmore et al., 1996). The mean peat accumulation rate in the marsh since ~ 1963 (0.53 ± 0.11 cm yr^{-1}) was calculated to enable comparison with Everglades studies, some of which are based on ^{137}Cs dating. The high, recent accretion rates in the USJRB are a consequence of both a trend toward increased mass accumulation through time (Figure 7) and less compaction in uppermost deposits. Vertical accretion since ~ 1963 in the USJRB is slightly higher than accretion rates between 1964 and 1989 reported for areas of the Everglades subjected to extended hydroperiods (0.28–0.32 cm yr^{-1}) or phosphorus enrichment (0.40 cm yr^{-1}) (Craft & Richardson, 1993a, 1993b). Reddy et al.

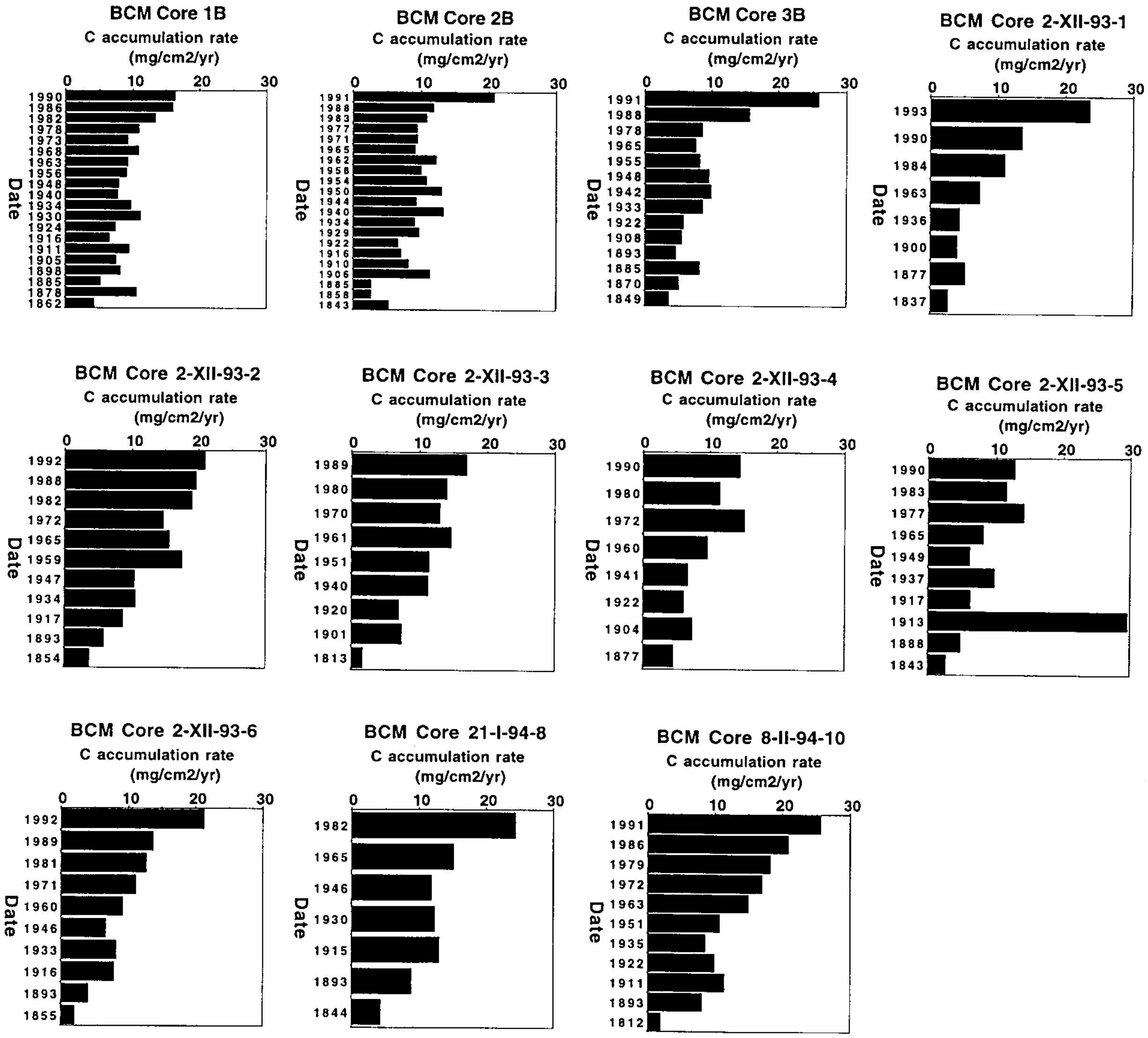

Figure 8. Total C accumulation rate plotted vs. date for ten marsh cores and the core from Blue Cypress Lake.

(1993) reported net peat accumulation rates between 1964 and 1990 for nine sites in Everglades Water Conservation Area (WCA) 2A. The mean value (0.52 ± 0.25 cm yr^{-1}) was nearly identical to the mean for the USJRB marshes, and the highest value for the Everglades (1.13 cm yr^{-1}) was measured nearest an inflow structure that carried nutrient-enriched water. More recent studies of nutrient-enriched portions of WCA 2A confirm earlier findings, indicating that peat has accreted at a rate of 0.58–0.67 cm yr^{-1} (Craft & Richardson, 1998).

We compared recent mass accumulation rates of bulk sediment, OM, and nutrients in the USJRB with values reported for 34 Florida lakes (Binford & Brenner, 1992) to evaluate whether nutrient sequestering rates in the USJRB were similar to values measured in other Florida aquatic ecosystems (Table 2). Bulk sediment accumulation rates in the lakes are higher than rates measured in the marsh, perhaps because lakes receive higher inputs of inorganic colluvium. This also may reflect the fact that cores collected from shallow Florida lakes are typically taken in depositional areas that may receive resuspended, redeposited material, thereby providing an overestimate of mean, lakewide material accumulation (Whitmore et al., 1996). Deposition throughout the marsh may be more homogenous, as reflected by the similar total integrated ^{210}Pb inventories for the ten wetland profiles (Figure 6). Recent OM,

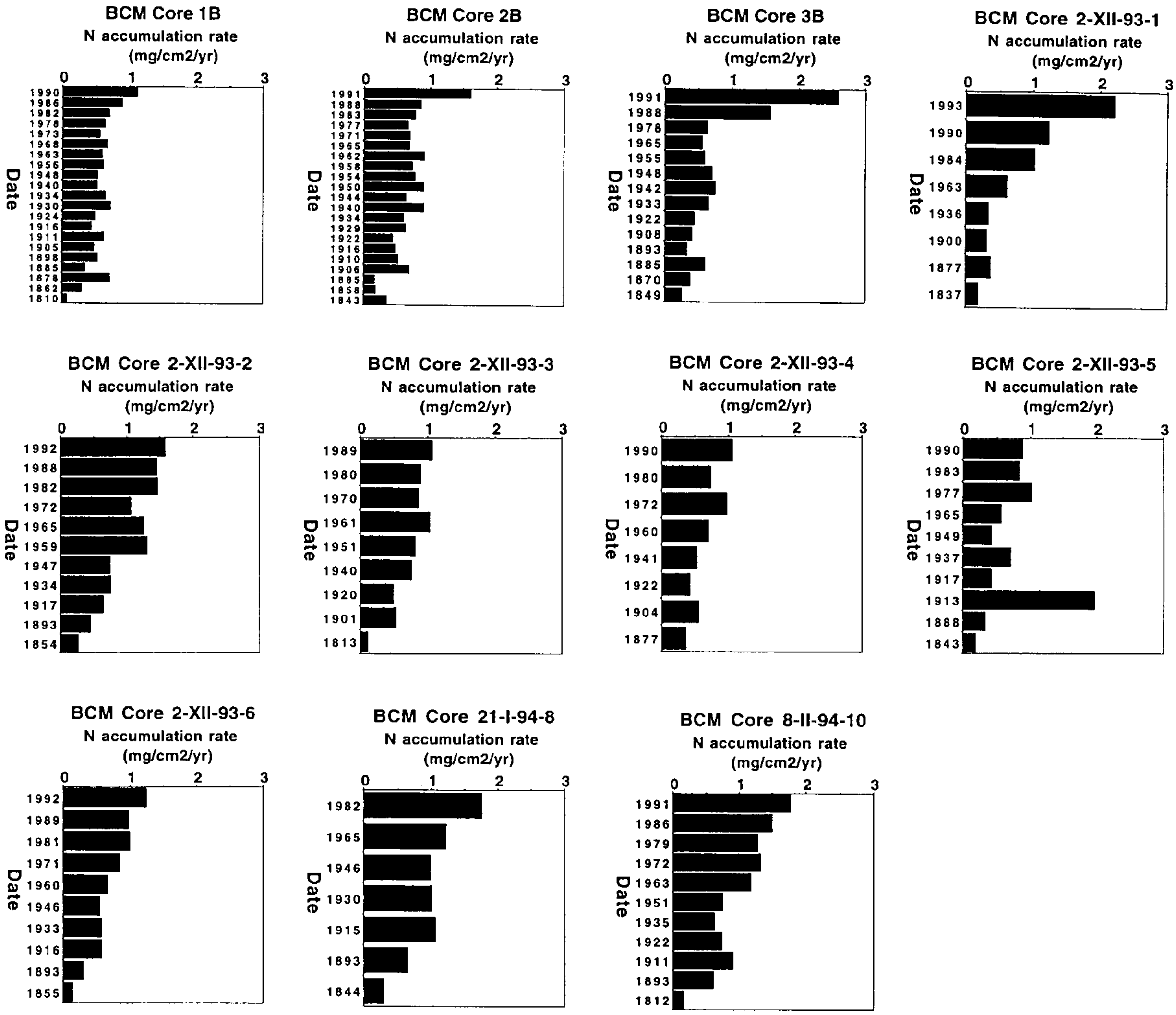

Figure 9. Total N accumulation rate plotted vs. date for ten marsh cores and the core from Blue Cypress Lake.

total C and total N accumulation rates in the USJRB are similar to corresponding mean values recorded for the 34 Florida lakes. Mean total P accumulation in the marsh is lower than the mean recorded for the lake basins. Recent P accumulation rates at several sites in the marsh are lower than the minimum value recorded in the 34-lake data set. The modern rate of P accumulation in Blue Cypress Lake is < 40% of the mean value for the 34-lake data set. This difference may be a consequence of the fact that many of the waterbodies in the 34-lake data set overlie phosphate-rich deposits, receive high P loading, and therefore accumulate P in their sediments rapidly.

We also compared recent phosphorus accumulation in marsh deposits with rates measured in eutrophic Lake Okeechobee, Florida (Brezonik & Engstrom, 1998). Prior to 1910, total P accumulation in the mud zone of the lake averaged about 0.023 mg cm^{-2} yr^{-1}. By the 1980s, the value had risen about 4-fold, to 0.085 mg cm^{-2} yr^{-1}. Both pre-disturbance and post-disturbance rates of P accumulation in the lake generally exceed those measured in the marsh. Again, this may reflect, in part, the fact that cores from the depositional zone of the lake provide overestimates of nutrient accumulation due to sediment focusing.

Despite the fact that total P accumulation rates in the marsh are low relative to those measured in Florida lakes, all sites in the marsh and the core from Blue Cypress Lake displayed marked increases in total P accumulation over time. The most recent P accumulation rates were more than ten times higher than rates calculated for the base of the sections. Both an in-

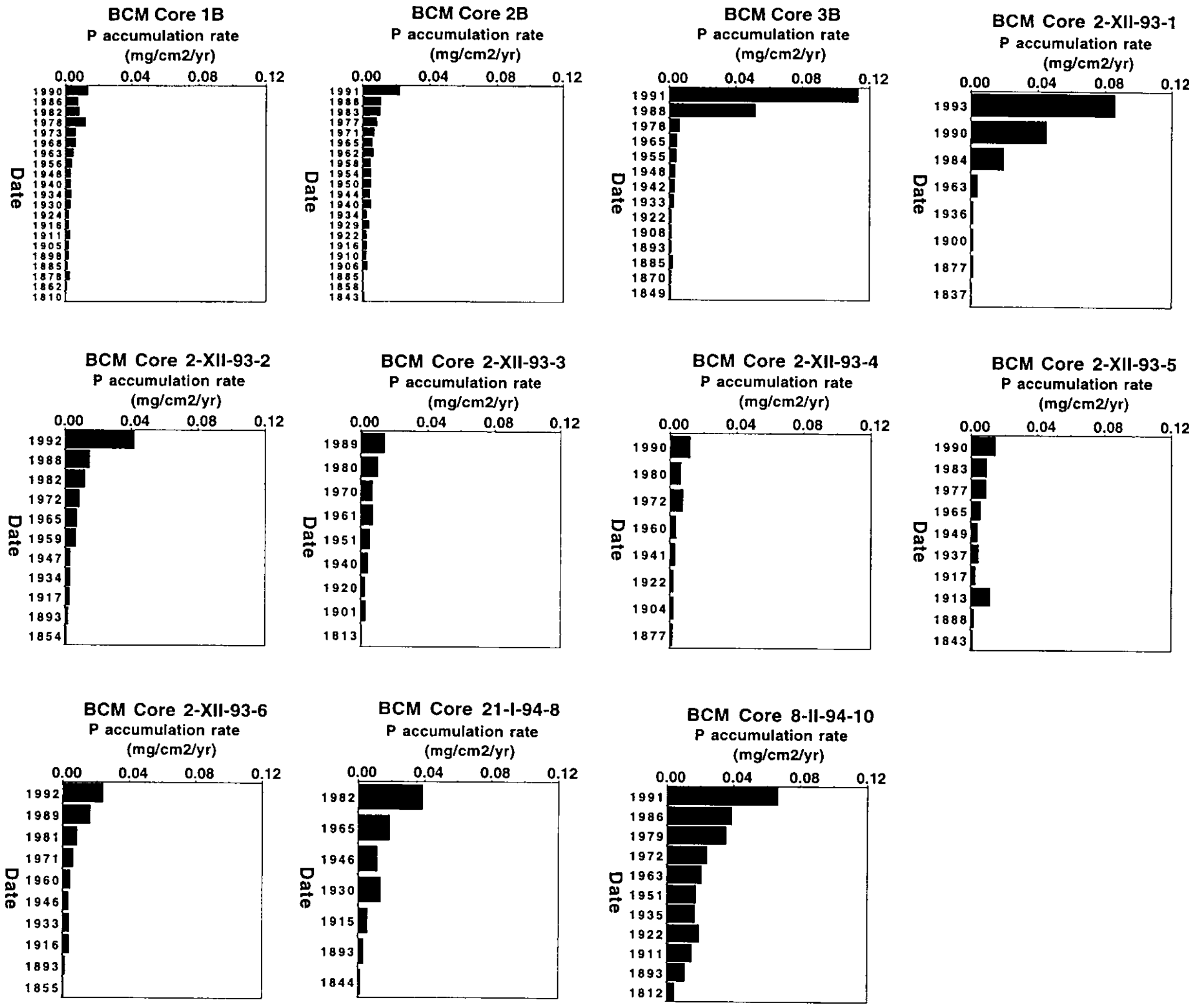

Figure 10. Total P accumulation rate plotted vs. date for ten marsh cores and the core from Blue Cypress Lake.

crease in total P content of the sediment and slight increases in bulk sediment accumulation through time account for the rise in P accumulation rate during recent times.

Phosphorus accumulation rates in the marsh since the 1970s are about 2–17 times higher than rates recorded for the period around 1920. In Blue Cypress Lake, the rate of P accumulation since the 1970s was 2.3 times higher than the rate recorded ~ 1920. Calculated historic trends in total P accumulation probably reflect past P loading and P deposition rates in the ecosystem. Although computed rates of P sequestering may be affected by post-depositional nutrient migration, most sediment P in the marsh is probably bound in refractory organic matter that is permanently buried in place. Increased rates of sediment and nutrient accumulation in the wetlands during the past century are consistent with findings in Lakes Hell 'n' Blazes, Sawgrass, and Washington (Brenner et al., 1999), which constitute the upper reaches of the St. Johns River channel (Figure 1).

Conclusions

We conclude, based on data from eleven ^{210}Pb-dated cores, that the marsh and Blue Cypress Lake experienced increased P loading over the past ~ 70 years. Increased phosphorus supply drove higher rates of primary productivity, in turn accounting for higher C and N burial rates since the 1970s than around 1920. In most cases, C and N accumulation rates since the 1970s were

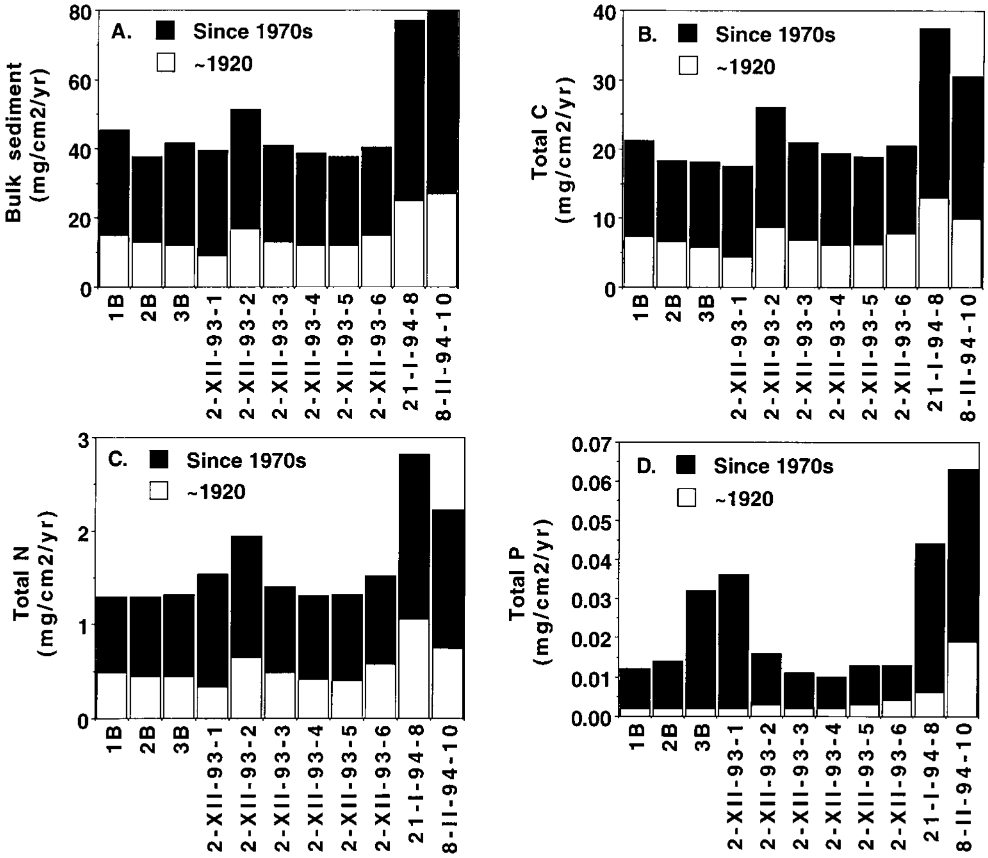

Figure 11. (A–D) Comparison of bulk sediment and nutrient (C, N, P) accumulation rates (mg cm^{-2} yr^{-1}) around 1920 with the mean rate since the 1970s for ten marsh core sites in the USJRB and in Blue Cypress Lake. The accumulation rate for 1920 reflects the rate from the sampling interval with a bottom date closest to 1920. The accumulation rate 'since 1970s' is the mean rate for the period from the most recent ^{210}Pb date in the 1970s to the core collection date in the 1990s. In core 21-I-94-8, a 1970s date was lacking, and the 'since 1970s' value represents the accumulation rate between 1982 and 1994.

1–3 times rates calculated for 1920. Higher rates probably reflect increased plant production. Increases in C and N burial between 1920 and the present are not as pronounced as changes in P accumulation over the same time period. Several factors may account for the disparity. First, some of the buried P may reach the ecosystem in a form unavailable for plant growth. Second, P may no longer limit primary productivity. Lastly, diagenetic processes may reduce C and N concentrations in sediments via respiration, methanogenesis and denitrification. Phosphorus, however, is permanently sequestered in the sediments due to its sedimentary biogeochemical cycle.

Marsh cores from the USJRB also display interesting spatial trends with respect to phosphorus accumulation rates. At core sites 1, 2, and 3, located at varying distances from the point source of nutrient loading, predisturbance (~ 1920) P accumulation rates were identical, 0.002 mg cm^{-2} yr^{-1}. Rates of P accumulation since the 1970s differ among the three sites, with greater rates of nutrient sequestering nearest the source of nutrient loading (site 3B), and progressively lower P sequestering rates measured at greater distance from the point source. P accumulation rates since the 1970s ranged from 0.008–0.012 mg cm^{-2} yr^{-1} at seven of the marsh sites. Sites 3B, 93-1, and 94-8 registered higher recent P sequestering rates, ranging from 0.030–0.038 mg cm^{-2} yr^{-1}. Inter-site differences in P accumulation rates probably indicate different histories of local nutrient loading. Data from the Blue Cypress Marsh indicate that historical rates of nutrient sequestering, ascertained using paleolimnological techniques, can be integrated into wetland management plans and used to set target nutrient loading values.

Table 2. Recent sediment accumulation rates (mg cm^{-2} yr^{-1}) in 34 Florida lakes, in marshes of the USJRB, and in Blue Cypress Lake. Florida lake data are for mid-basin surface samples and represent mean lakewide sedimentation rates for periods ranging from 2–10 years prior to the time of sample collection (see Binford & Brenner 1986, 1988). Data for the marshes and Blue Cypress Lake represent site-specific accumulation rates for the 1–12 year period prior to core collection

	Bulk	Organic matter	Carbon	Nitrogen	Phosphorus
*Florida Lakes					
Mean	234	39.8	20.0	1.83	0.171
sd	407	19.3	10.3	1.07	0.134
range	32–2080	15.3–88.9	6.9–46.7	0.56–4.42	0.024–0.586
Marsh Cores					
1B	37	33.4	16.3	1.11	0.013
2B	46	41.9	20.8	1.61	0.022
3B	62	53.7	25.9	2.58	0.113
2-XII-93-1	57	49.1	23.5	2.21	0.085
2-XII-93-2	43	39.7	20.9	1.58	0.042
2-XII-93-3	34	31.8	16.9	1.06	0.014
2-XII-93-4	31	28.9	14.5	1.06	0.012
2-XII-93-5	27	24.5	12.7	0.88	0.014
2-XII-93-6	45	42.7	21.3	1.25	0.024
2-XII-93-8	52	46.2	24.4	1.76	0.038
8-II-94-10 (Lake)	67	45.7	25.5	1.77	0.066
Mean	46	39.8	20.2	1.53	0.040
sd	13	9.1	4.5	0.53	0.034
range	27–67	24.5–53.7	12.7–25.9	0.88–2.58	0.012–0.113

*From Binford et al. (1992).

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