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Tidal marsh restoration on Sapelo Island: A legacy of R.J. Reynolds, Jr., Eugene Odum and the University of Georgia Marine Institute

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ABSTRACT

Restoration of tidal marshes throughout the 20th century have attempted to bring back important functions of natural tidal systems. In this study, vertical accretion, organic carbon (C) sequestration, and nitrogen burial were compared between a natural, never diked tidal salt marsh and a hydrologically restored tidal salt marsh on Sapelo Island, Georgia to examine the impacts of restoration years later. 64 years after hydrologic restoration in 1956, the restored marsh studied had higher rates of accretion based on ^{137}Cs and ^{210}Pb (4.8–5.1 mm/yr), C sequestration (118–125 g C/m^2/yr) and N burial (8.3–8.8.g N/m^2/yr) than the never diked marsh (2.9–3.4 mm/yr, 75–85 g C/m^2/yr, 4.8–5.6 g N/m^2/yr).

Since maximum ^{137}Cs deposition in 1964, approximately 30 cm of accretion has occurred in the restored marsh while the never diked marsh had approximately 10–30 cm of new soil deposited. The accumulated soil in the restored marsh was comparable to the natural marsh soil in terms of bulk density, percent C and N. However, below this depth, legacy effects from diking could be found through the higher soil bulk density and lower percent organic C and N relative to soils of the natural marsh.

Vertical accretion in the natural marsh appears to be keeping pace with the current rate of sea level rise (SLR) (3.4 mm/yr) while accretion in the restored marsh exceeds SLR as the marsh compensates for subsidence that occurred when it was diked. Under current SLR and accretion rates, ecosystem functions of continual sequestration of C and burial of N will be supported. However, as SLR accelerates, the ability of both marshes to sequester C and bury N will depend on their ability to keep pace. If not, the marshes will eventually convert to mudflats or open water with a concurrent loss of these and other ecosystem services.

1. Introduction

Wetland restoration involves re-establishing hydrology, the depth, duration, and frequency of inundation, anaerobic soils, and plant and animal communities characteristic of similar, yet undisturbed or minimally disturbed habitats (Craft, 2022). In tidal salt marshes, reintroduction of tidal inundation is often sufficient to re-establish anaerobic conditions and characteristic plant and animal communities (Brockmeyer et al., 1997; Craft, 2001; Frenkel and Morlan, 1989; Karberg et al., 2018; Niering, 1997; Orr et al., 2003; Smith et al., 2009; Turner et al., 1994; Warren et al., 2002; Williams and Orr, 2002; Woo et al., 2018). Over time, hydrologic restoration also leads to re-establishment of ecological functions including sediment deposition, soil accretion, carbon (C) sequestration, and nitrogen (N) and phosphorus (P) retention (Craft, 2022).

Many tidal marsh restoration projects involve restoring hydrology by breaching dikes, levees or spoil banks, re-aligning levees (e.g. managed realignment), removing tide gates, plugging mosquito ditches, or removing fill to re-introduce tides (Brockmeyer et al., 1997, Craft, 2001, Esteves and Williams, 2017, Frenkel and Morlan, 1989, Konisky et al., 2006, Niering, 1997, Orr et al., 2003, Roman et al., 1995, Smith et al., 2009, Turner et al., 1994, Warren et al., 2002, Williams and Orr, 2002). Other efforts to restore tidal marshes include planting vegetation to stabilize dredge material and eroding shorelines (Bolam et al., 2006; Broome et al., 1986, 1988b, 1992; Cornwell et al., 2020; LaSalle et al., 1991; Perry et al., 2001; Seneca et al., 1985; Staver et al., 2020; Streever,

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2000; Yozzo et al., 2004). Still, others involve placing a thin layer of dredge material onto subsiding marshes (Croft et al., 2006; DeLaune et al., 1990; Schrift et al., 2008) or creating tidal marshes by grading soils to intertidal elevation (Broome et al., 1988a). This particular practice is rarely used nowadays as hydrologic restoration is much less expensive, the likelihood of success is greater, and the historical impoundment of many tidal marshes provide more opportunities to apply hydrologic restoration.

While there are many examples of successful tidal marsh restoration by re-introducing tidal inundation (see Craft, 2022 for a review), there are few long-term studies that have monitored tidal marsh or other wetland restoration projects. Most studies periodically monitor over a period of several years to several decades (Craft et al., 2003) which may be insufficient to gauge their persistence in an era of accelerating sea level rise. In the longest-term study that could be found, Noll et al. (2019) used time series data (1984, 1995, 1998, 2017) to measure the increase in soil organic C and N of a dredge spoil island that was planted with *S. alterniflora* in 1970. Forty-seven years after planting, soil C and N pools (0–30 cm) increased from 1770 g/m^2 to 4537 g/m^2. During the same period, N pools increased from 75 g/m^2 to 264 g/m^2. Over the 47-year period, the annual rate of C sequestration and N burial was 62–66 g C/m^2/yr and 3.7–4.6 g/m^2/yr, respectively. In this paper, the authors cautioned that the long-term persistence of the marsh will depend on its vulnerability to periodic dredging of the adjacent navigation channel that threatens to erode the marsh edge.

This present study looks to address this issue by providing insight into the characteristics and functions of a decades-old restored tidal marsh. Measurements of vertical accretion, sedimentation, nitrogen (N) burial and C sequestration 64 years following hydrologic restoration of a tidal salt marsh were compared to an adjacent natural marsh that was never diked. The purpose is to evaluate the ability of the restored marsh to keep pace with sea level rise while also providing key ecosystem services, including C sequestration and N removal.

2. Methods

2.1. Site description

Soil cores were collected from a 64-year-old restored tidal salt marsh and a nearby natural tidal salt marsh adjacent to the University of Georgia Marine Institute on Sapelo Island, GA (Fig. 1). The Marine Institute was established in 1953 largely through the efforts of Professor Eugene Odum and colleagues at the University of Georgia who convinced R.J. Reynolds, Jr., the island's owner at the time, to create a world class Marine Institute there. Today Sapelo Island and the University of Georgia Marine Institute have a rich history of pioneering ecological research on tidal salt marshes and estuaries.

The restored tidal marsh was diked in 1948 by the island's owner, R. J. Reynolds, Jr., with help from the U.S. Soil Conservation Service (Craft, 2001). The site quickly converted to an unvegetated salt pan rather than the agricultural land or pastureland that Reynolds envisioned. In 1956, the dike was breached, allowing reintroduction of tidal inundation. Over an 8-year period, *Spartina alterniflora*, the foundation species of tidal salt marshes, re-established and the marsh was re-vegetated (Craft, 2001). The natural marsh—known as Teal Marsh after one of the first PhD students at the Marine Institute, John Teal, (Teal, 1958)—is located below the Institute as shown in Fig. 1a and c. The remaining dike around the restored marsh is clearly evident in Fig. 1a and b.

The restored and never diked natural marsh are part of the Lighthouse Creek drainage and are 28.9 ha and 40.6 ha in size, respectively.

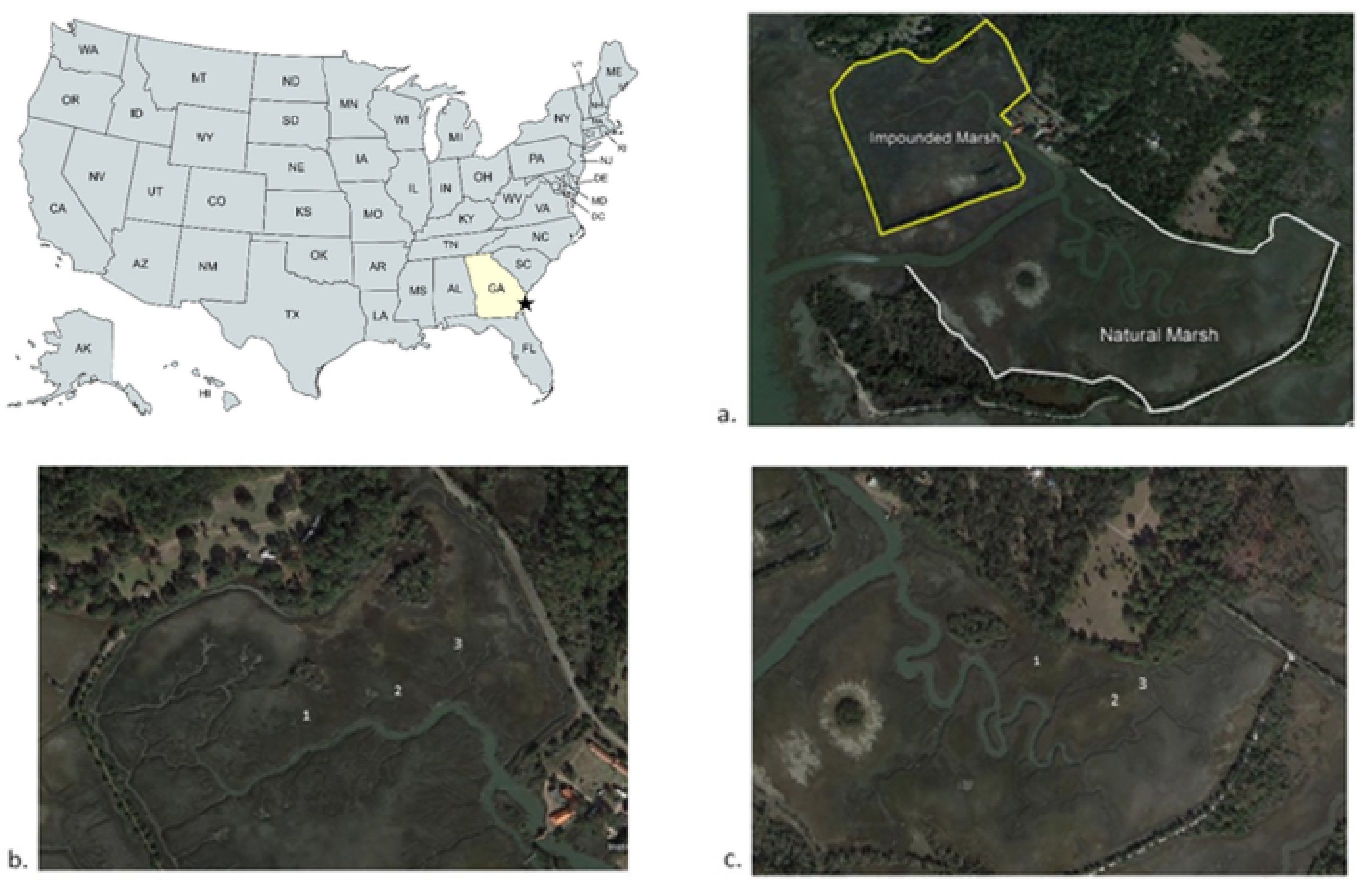

Fig. 1. Map of the US highlights the location of Sapleo Island off the coast of Georgia. Images a-c depict locations of (a) the restored and natural marsh with University of Georgia Marine Institute (center) and sampling locations of the (b) restored and (c) natural marsh, with core sample locations labeled 1–3.

Both are flooded twice daily by astronomical tides of 2.3 m on average and are dominated by a monoculture of *Spartina alterniflora* Loisel. Flooding of the marshes is almost exclusively by tidal inundation as there are no streams or ditches entering from the uplands. Marsh elevations are similar between sites, ranging from 0.82 to 0.91 m NAVD88 in the restored marsh and 0.79–0.93 m NAVD88 in the natural marsh. Annual measurements in medium height *Spartina* marshes of adjacent Dean Creek taken by the Georgia Coastal Ecosystems' Long Term Ecological Research program since 2000 were used to estimate aboveground biomass of our marshes. These values ranged from 262 g/m^2 to 348 g/m^2 (https://gce-lter.marsci.uga.edu/public/app/dataset_details.asp?accession=PLT-GCES-1609).

2.2. Soil sampling and lab analysis

Three soil cores 8.5 cm in diameter by 60 cm deep were collected from each marsh. Cores were collected at mid-marsh locations where medium height *Spartina* grows. Cores were sectioned into 2 cm increments in the field, then transported to the lab where they were air dried and weighed for bulk density. Once dried, increments were ground, passed through a 2 mm mesh sieve, and analyzed for ^{137}Cs, ^{210}Pb, organic C and total N.

Prior to C analysis, subsamples were tested for the presence of carbonates by adding one drop of 0.1 mol L^{-1} HCl and observing whether effervescence occurred. Samples containing carbonates were treated with 0.1 mol L^{-1} HCl prior to C and N analysis. Carbon and N were analyzed using a Perkin-Elmer 2400 CHN analyzer (Perkin-Elmer, Waltham MA USA). Recovery of NIST standard 1632b (bituminous coal, 76.9% C, 1.56% N) yielded 92% for C and 94% for N ($n = 10$). Analysis of in-house soil standard (6.1% C, 0.37% N) recovered 101% for C and 102% for N (n = 10). Bulk density of each depth increment was calculated from the dry weight per unit volume (Blake and Hartje, 1986). All analyses were expressed on a dry weight basis by correcting for the moisture content of the soil, determined by weighing 1 g of subsoil before and after drying at 70 °C for 24 h.

For radiometric analyses, ground soils were packed into 50 mm diameter by 9 mm petri dishes and analyzed by gamma spectrometry for ^{137}Cs using the 661.6 keV photopeak and ^{210}Pb using the 46.5 keV photopeak. Cesium-137 (half-life of 30 years) is an impulse marker produced as fallout by aboveground nuclear bomb blast testing (Ritchie and McHenry, 1990). It is typically used to measure soil accretion and accumulation. We used the increment with maximum ^{137}Cs activity to represent the year 1964, the year of greatest atmospheric fallout. Lead-210 (half-life of 22 years) is a naturally occurring radioisotope produced by decay of ^{235}Uranium and is used to estimate soil accretion during the past 100 to 150 years. We used the constant activity (CA) model to calculate accretion utilizing the exponential decrease of excess ^{210}Pb across depth as it undergoes radioactive decay (Oldfield and Appleby, 1984). Excess ^{210}Pb was calculated by subtracting background ^{210}Pb, which was determined from uniform low level ^{210}Pb activity that occurred at depth in each core.

Rates of C sequestration and N burial were calculated using ^{137}Cs and ^{210}Pb-derived accretion rates, bulk density, and C and N concentration in depth increments from the ^{137}Cs maxima and above as well as within increments containing excess ^{210}Pb. The accretion rate is calculated as the slope of the least squares regression of excess ^{210}Pb versus depth (Oldfield and Appleby, 1984). The data, however, are typically plotted with depth on the y axis (see Figs. 3 and 4) in order to visually observe whether there is an exponential decrease in ^{210}Pb with soil depth—an assumption of the constant activity model.

3. Results

3.1. Bulk density, soil organic C and N

Soil bulk density and percent organic C and N in surface soil (0–30 cm) was similar among restored and natural marshes (Table 1). However, at deeper depths (30–50 cm), bulk density was considerably greater in the restored marsh (1.19 g/cm^3) than in the natural marsh (0.56 g/cm^3). Soil organic C (1.6%) and N (0.12%) were also much lower in the 30–50 cm depth of the restored marsh than in the natural marsh (4.9% C, 0.31% N).

Carbon and nitrogen pools within the top 50 cm of soil cores were greater in the natural marsh (13,710 ± 380 g C /m^2, 723 ± 66 g N/m^2) than in the restored marsh (10,070 ± 380 g C/m^2, 547 ± 63 g N/m^2) (Table 1). There was no apparent difference in C and N pools in the top 0–10 cm but C and N pools in the natural marsh progressively increased with depth relative to the restored marsh (Table 1). Nitrogen pools were also much greater in the 30–50 cm depth of the natural marsh (190 ± 27 g/m^2) relative to the restored marsh (44 ± 27 g/m^2).

3.2. Soil accretion

^{137}Cs exhibited a well-defined maxima at depth in the six cores with maxima occurring at depths from 12 to 34 cm in the natural marsh to 32–34 cm in the restored marsh (Fig. 2). Accretion rates in the restored marsh ranged from 4.6 to 5.9 mm/yr. Overall ^{137}Cs accretion in the natural marsh was lower, but more variable, ranging from 2.0 to 5.9 mm/yr. The mean rate of accretion in the restored and natural marsh based on ^{137}Cs was 5.11 ± 0.36 and 3.39 ± 1.25 mm/yr, respectively.

^{210}Pb exhibited an exponential decrease with depth in restored and natural marsh cores (Figs. 3–4). However, the background concentration depths in the restored marsh differed from the natural marsh. The restored marsh background levels occurred at 30–40 cm versus the natural marsh at 20–40 cm, indicating a higher rate of accretion in the restored marsh. Regressions of ^{210}Pb versus depth in the restored marsh produced r^2's ranging from 0.71 to 0.90 and yielded accretion rates ranging from 4.6 to 5.0 mm/yr (Fig. 3) (Mean = 4.66 ± 0.12 mm/yr). The goodness of fit (r^2) for the regression of excess ^{210}Pb versus depth in the natural marsh were stronger than that of the restored marsh, being 0.87 to 0.94 respectively (Fig. 4). Accretion rates in the natural marsh were lower, ranging from 1.8 to 4.5 mm/yr (Mean = 2.92 ± 1.02 mm/yr).

3.3. Carbon sequestration and N burial

Carbon sequestration and N burial were greater in the restored marsh than in the natural marsh. In the restored marsh, measurements of C sequestration were similar based on ^{137}Cs and

Table 1
Soil bulk density, percent C and N, and C and N pools in the restored and natural marsh.

Depth (cm)	Bulk density (g/cm^3)	Organic C (%)	Total N (%)	Organic C (g/m^2)	Total N (g/m^2)
Restored Marsh					
0–10 cm	0.43 ± 0.01	5.6 ± 0.2	0.45 ± 0.02	2380 ± 230	211 ± 21
10–30 cm	0.42 ± 0.02	5.7 ± 0.3	0.38 ± 0.01	4590 ± 300	292 ± 34
30–50 cm	1.19 ± 0.07	1.6 ± 0.3	0.12 ± 0.02	3100 ± 680	44 ± 27
0–50 cm				10,070 ± 380	550 ± 63
Natural Marsh					
0–10 cm	0.39 ± 0.02	6.6 ± 0.2	0.45 ± 0.01	2520 ± 110	201 ± 8
10–30 cm	0.43 ± 0.01	6.9 ± 0.3	0.40 ± 0.01	5830 ± 700	331 ± 32
30–50 cm	0.56 ± 0.02	4.9 ± 0.2	0.31 ± 0.01	5340 ± 240	190 ± 27
0–50 cm				13,710 ± 1020	720 ± 66

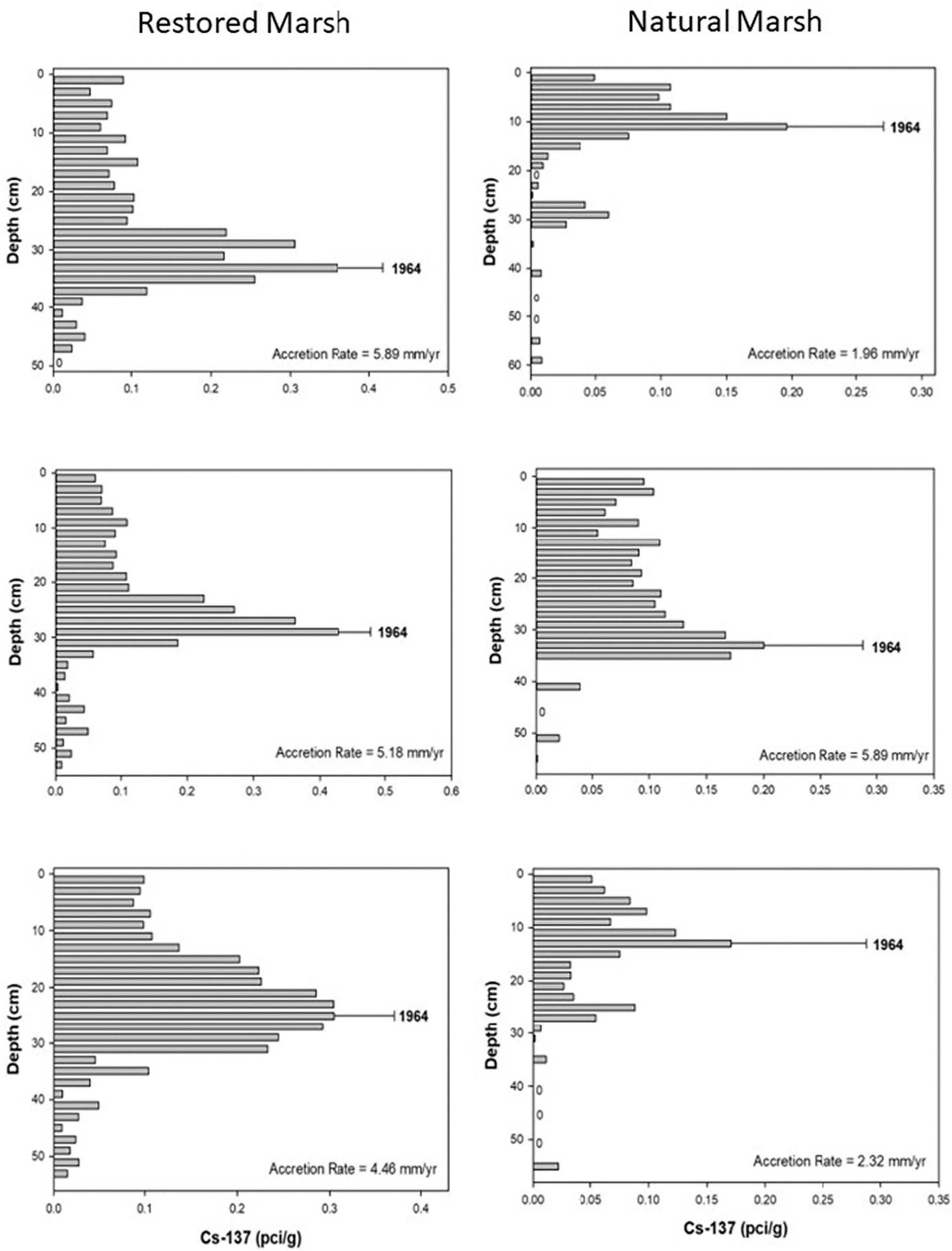

Fig. 2. ^{137}Cs activity as a function of depth in the three soil cores of the restored marsh and the three soil cores of the natural marsh.

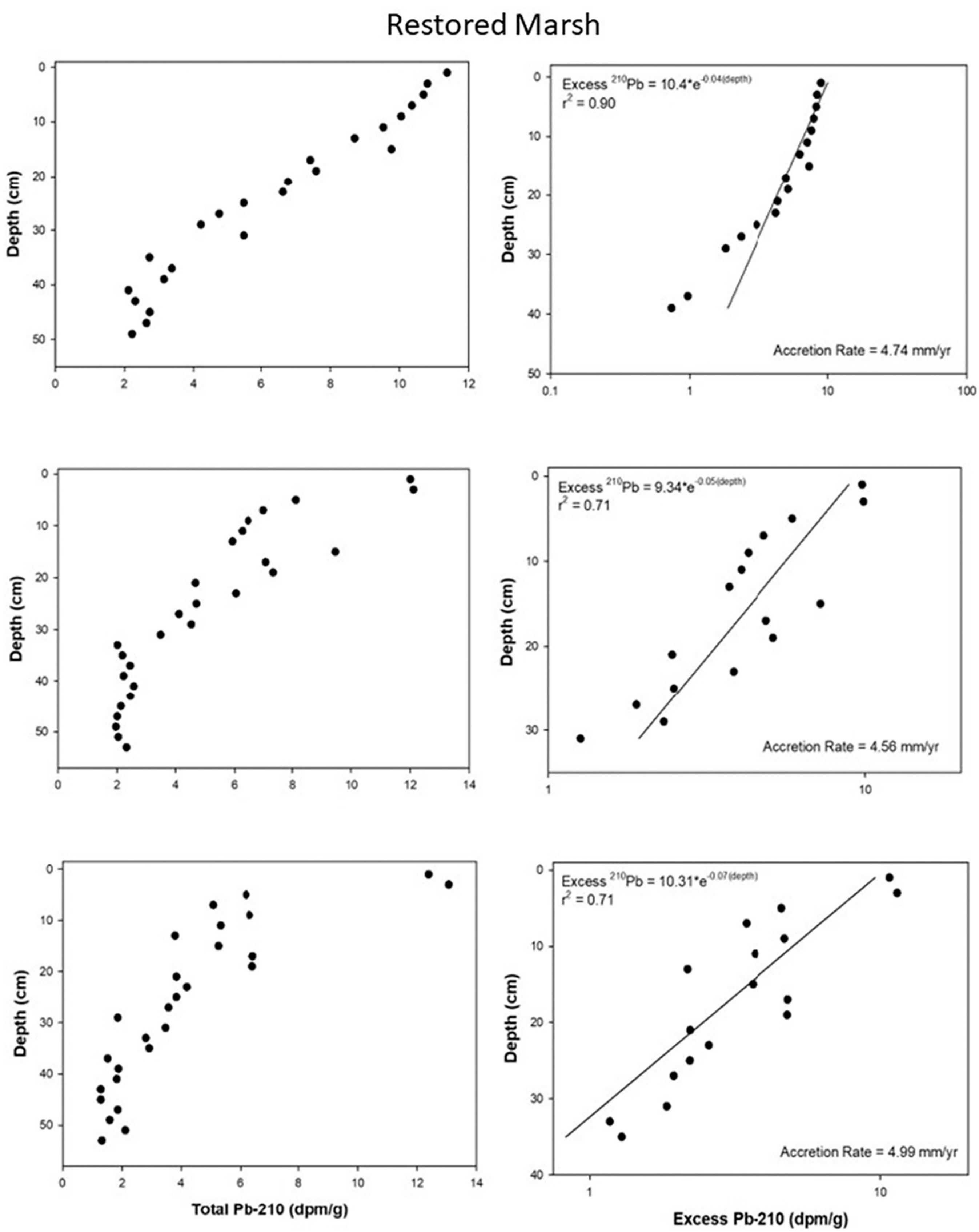

Fig. 3. Total and excess ^{210}Pb as a function of depth in soil cores of the restored marsh.

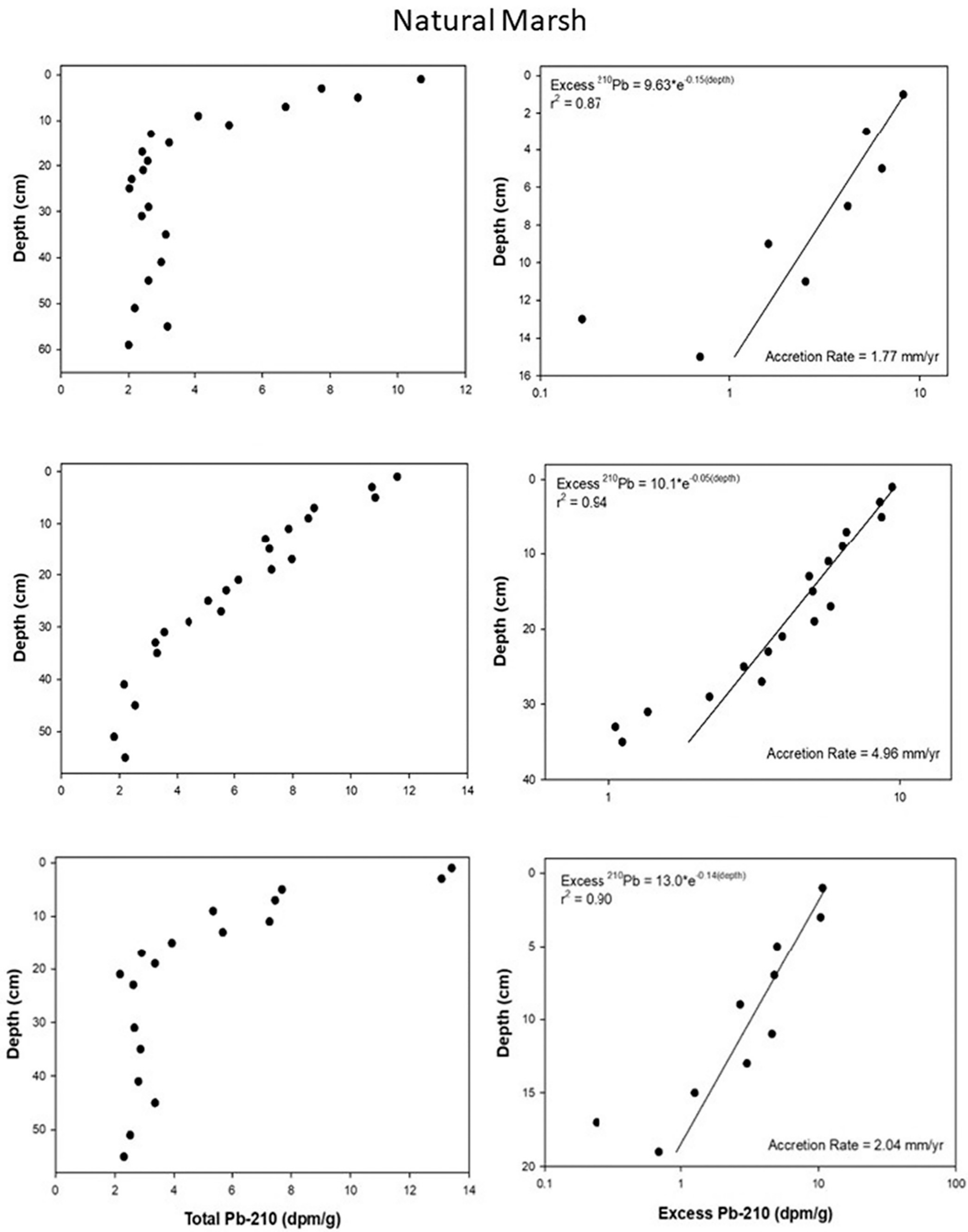

Fig. 4. Total and excess ^{210}Pb as a function of depth in soil cores of the natural marsh.

^{210}Pb and ranged from 118 ± 7.4 to 125 ± 5.2 g/m^2/yr (Table 2). Carbon sequestration in the natural marsh also was similar based on ^{137}Cs and ^{210}Pb, but was about 60% of the restored marsh (75 ± 19.8 to 85 ± 26.0 g/m^2/yr). Nitrogen accumulation in the natural marsh also was about 60% of the restored marsh, ranging from 4.8 ± 1.4 to 5.6 ± 1.7 g/m^2/yr versus 8.3 ± 0.4 to 8.8 ± 0.3 g/m^2/yr.

4. Discussion

4.1. Discussion

Diking and draining of tidal marshes affects a number of soil processes essential for maintaining elevation as sea level rises. Of immediate concern is the loss of wetland vegetation and its root mat which greatly contributes to soil elevation reduction. Blum et al. (2021) reported that root zone expansion in healthy, undrained tidal salt marshes accounted for 37% or more of the increase in marsh surface elevation over time. In the longer term, drainage leads to oxidation and soil subsidence, increasing bulk density and decreasing organic C and N (Frenkel and Morlan, 1989; Portnoy, 1999; Turner, 2004; Miller et al., 2008; Anisfeld, 2012) as was seen in this study's restored site.

The effects of drainage are especially pernicious to elevation gain. Portnoy and Giblin (1997b) reported that the elevation of a drained tidal salt marsh in Massachusetts was 90 cm below that of an undrained marsh due to reduced oxidation and sedimentation during tidal flooding plus the compaction of soil organic matter. In a microcosm experiment using freshwater marsh soil (peat) cores, Portnoy and Giblin (1997a) observed subsidence of 6–8 cm in less than two years when saltwater was introduced. The long-term effects of drainage on elevation persist over time albeit at a slower rate. In a review of drained tidal marsh wetlands, initial rapid subsidence was observed which then slowed with time. However, even after 100 years of drainage, subsidence was still occurring, especially on soils that were organic in composition (Turner, 2004).

I speculate that, in the restored marsh, loss of the root mat and soil subsidence following drainage led to a decrease in elevation relative to sea level that, once tidal inundation was re-established and vegetation re-colonized the site, the restored marsh began to re-gain elevation by building organic matter and trapping sediment. This speculation is supported by observations of higher accretion in the restored marsh based on both ^{137}Cs and ^{210}Pb measurements (Table 2). A comparison of accretion between the restored marsh and the natural marsh twenty years earlier in 1998 also indicated higher accretion in the restored marsh (5.0 mm/yr) versus the natural marsh (3.8 mm/yr) (Craft, 2001). These rates are comparable to what was estimated from this study's ^{137}Cs measurements, with 5.1 mm/yr measured in the restored marsh and 3.4 mm/yr measured in the natural marsh (Table 2).

Variation in elevation among the two marshes does not explain the observed difference in accretion since soil cores were collected from similar elevations, with 0.82–0.91 m NAVD88 in the restored marsh and 0.79–0.93 m NAVD88 in the natural marsh. Nor do differences in aboveground biomass, which facilitates sediment deposition (Morris et al., 2002), account for the increase in accretion observed in the restored marsh. While we did not measure aboveground biomass at our sampling sites, we collected cores from adjacent locations where medium height *Spartina* grows and where stem density is comparable (C. Craft, Pers. Obs.).

Table 2
Vertical accretion, C sequestration, and N burial determined by ^{137}Cs and ^{210}Pb.

	Accretion (mm/yr)		C Sequestration (g/m^2/yr)		Nitrogen Burial (g/m^2/yr)	
	Restored	*Natural*	*Restored*	*Natural*	*Restored*	*Natural*
^{137}Cs	5.11 ± 0.36	3.39 ± 1.25	118 ± 7.4	85 ± 26.0	8.3 ± 0.4	5.6 ± 1.7
^{210}Pb	4.76 ± 0.12	2.92 ± 1.02	125 ± 5.2	75 ± 19.8	8.8 ± 0.3	4.8 ± 1.4
^{137}Cs [1]	5.0	3.8	80	71	6.3	5.5

[1] One core each was collected from the same marshes in 1998 (from Craft, 2001).

Many studies, outlined in Anisfeld (2012), support the idea that once tidal inundation is re-introduced to drained marshes, vertical accretion rapidly increases as the marsh re-adjusts to the higher water levels by trapping sediment and building organic matter. Frenkel and Morlan, 1989 observed that tidal marsh restored by breaching a dike in Oregon gained approximately 10 cm of elevation during the first ten years. They suggested that it would take about 5 decades before the restored marsh gained the 35 cm of elevation that was lost after it was diked. In this study, nearly seven decades after hydrology was re-introduced, soil surface elevations were similar between restored and natural marsh, indicating that the elevation lost following drainage has recovered.

The restored marsh on Sapelo Island exhibits legacies of drainage observed in other tidal marshes that were drained then restored by dike removal and hydrologic restoration. For example, based on the location of the ^{137}Cs maxima, soil elevation levels around 1964 in the restored marsh were 30 cm below current levels compared to the natural marsh that was 10 cm lower (Fig. 2). Comparison of soil properties, bulk density and C, within the soil accreted after 1964 was roughly similar (Table 1). However, below 30 cm, bulk density of the restored marsh was double (1.19 g/cm^3) that of the natural marsh (0.56 g/cm^3) and percent organic C and N were one third that of the natural marsh (Table 1). Organic C and N pools were also considerably lower in the 30–50 cm depth of the restored marsh. Collectively, these differences in properties of soil material deposited before 1964 in the restored marsh are indicative of drainage, soil oxidation, and subsidence that occurred when the marsh was impounded from 1948 to 1956.

Accretion was consistently high in the restored marsh, but it was more variable in the natural marsh. Two of the three natural marsh cores exhibited low rates of accretion based on ^{137}Cs and ^{210}Pb measurements (1.8–2.3 mm/yr). However, core 2 exhibited accretion rates (5.2–5.9 mm/yr) that were similar to the 3 cores collected from the restored marsh (4.6–5.9 mm/yr). It is not clear why this core exhibited a high rate of accretion compared to the other two collected from natural marsh. Proximity to the upland (Fig. 1c) could cause different accretion rates as it provides a potential source of sediment. However, this does not explain the discrepancy found in this study since other core locations were equidistant (or closer) to the upland area and there is no evidence that fill was placed in the marsh. Regardless, accretion rates and soil properties examined in both marshes have important implications for ecosystem functioning.

Greater accretion in the restored marsh has led to rates of C sequestration that are 50% greater (118–125 g C/m^2/yr) than in the natural marsh (75–85 g/m^2/yr). Nitrogen burial in soil is also 50% to 75% greater in the restored marsh (Table 2). These rates are greater than those observed by Noll et al. (2019) on a 47 year-old tidal salt marsh where *S. alterniflora* was planted to stabilize a dredge spoil island and where long term C sequestration was 62–66 g/m*2*/yr and N burial was 3.7–4.8 g/m^2/yr. The lower rates likely reflect a lower tidal range (1.2 m) and hence a lower rate of accretion compared to the restored (and natural) marsh on Sapelo Island where the tide range is nearly double at 2.3 m.

The higher rate of C sequestration and N burial in the restored marsh mostly reflects the higher rate of accretion as bulk density and percent C and N in the top 30 cm converged to similar levels of the natural marsh. Other studies of tidal marshes along the Atlantic U.S coast have shown that accretion drives C sequestration in these wetlands (Craft et al., 1993, Weston et al., n.d. in press). Furthermore, in these marshes, vertical accretion is driven primarily by deposition of mineral sediment during tidal inundation. This sediment arrives from the nearby Altamaha River, the third largest river on the U.S. east coast, and the redistribution of sediment from mudflats and tidal marshes in the estuary. Accumulation of soil organic matter is non-negligible and contributes to vertical accretion as well. Soil organic C content in the restored and natural marsh is 5–6% and 6–7%, respectively (Table 1). With concentrations of this magnitude (i.e., 10–14% organic matter), the organic fraction contributes up to 20% of vertical accretion with the mineral fraction contributing the remaining 80% (Craft et al., 1993).

4.2. Conclusion

After nearly seven decades, the restored tidal salt marsh continues to sequester C and bury N at rates that exceed those of a nearby natural marsh that was never diked and drained. The higher rates are driven by accelerated accretion as the marsh builds elevation capital to compensate for subsidence that occurred when it was drained. Going forward, both the restored and natural marsh will continue to offer ecosystem services, such as C sequestration and N burial, unless accelerated sea level rise driven by global change overwhelms them.

Author credits

As sole author, CC conceived, carried out, and wrote the paper.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Christopher Craft reports financial support was provided by National Science Foundation.

Data availability

Data will be made available on request.

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