Soil Organic Carbon, Nitrogen, and Phosphorus as Indicators of Recovery in Restored *Spartina* Marshes

by Christopher B. Craft

Carbon:Nitrogen ratio indicates complete recovery of water-quality improvement functions in a Georgia marsh after 42 years.

Scientists frequently measure soil properties, such as organic matter, nutrient content and particle size (sand, silt, clay), to gauge the development of functional equivalence in terrestrial and wetland restoration projects (Dancer and others, 1977; Marrs and others, 1981; Craft and others, 1988, 1999; Langis and others, 1991; Li and Daniels, 1994; Daniels and Zipper, 1995; Bishel-Machung and others, 1996; Piehler and others, 1998). Organic matter and nitrogen content are especially useful because they serve as indicators of energy flow (carbon) and nutrient (nitrogen) cycles. Because many ecosystems are nitrogen limited, ecosystem development during primary succession or succession on created, restored, or rehabilitated sites depends on accumulation of nitrogen in the soil and plant biomass (Marrs and others, 1981). In detritus-based ecosystems, such as forests and wetlands, soil organic matter supports secondary production by contributing detritus to heterotrophic organisms (Craft and others, 1999) and labile carbon (C) to fuel microbial processes like denitrification (Thompson and others, 1995) and nitrogen (N) fixation (Piehler and others, 1998).

Ecologists who have compared soil characteristics in created and restored wetlands typically report that these new communities have lower levels of organic matter, N and fine particles (silt, clay) and higher C:N ratios and levels of coarse particles (sand) than natural wetlands (Lindau and Hosner, 1981; Craft and others, 1988, 1991, 1999; Langis and others, 1991; Bishel-Machung and others, 1996). However, wetlands are sinks for organic C and nutrients (Schlesinger, 1997, Mitsch and Gosselink, 1993), and quickly begin to sequester these materials. For example, in two constructed saltwater cordgrass (*Spartina alterniflora*) marshes in North Carolina, the soil C and N levels (0-10 cm depth) increased over time and, after 20 to 25 years, were equivalent to those in natural marshes (Craft, 2000). Soil C:N ratios decreased over time and, after 25 years, were similar to those of natural marshes. After 25 years, organic C and phosphorus (P) accumulation were similar in constructed and natural marshes, whereas N accumulation was much higher in the constructed marshes (7-12 g N/m^2/yr compared to 2-5 g N/m^2/yr in natural marshes) (Craft and others, 1999). Because organic C and N are critical for the development of ecosystem processes, soil-based metrics (for example, organic C and N pools, C:N, C and N accumulation) that describe biogeochemical cycling of these elements may be powerful indicators of ecosystem development in the course of wetland creation or restoration.

In this article, I discuss a study where I measured soil nutrient (organic C, N, and P) concentrations, pools and ratios (0-10 cm depth) in a 42-year-old restored saltwater cordgrass marsh and a natural saltwater cordgrass marsh on Sapelo Island, Georgia to evaluate the development of biogeochemical cycles following restoration. Soil C:N ratios may be especially useful for evaluating the availability of nitrogen to wetland biota in these N-limited ecosystems. I also compared sediment and organic C, N, and P accumulations as a way of evaluating the capacity of the restored marsh to improve the quality of the water moving through it.

Methods

The restored and natural salt marshes I studied are adjacent to the University of Georgia Marine Institute, on Sapelo Island, Georgia. In 1948, the landowner, aided by the U.S. Soil Conservation Service, built a dike that converted about 20 acres of saltwater cordgrass marsh into pasture for a dairy herd. Diking eliminated tidal inundation and wetland hydrology, but had the unintended effect of creating an acid, sulfate-rich soil known as "cat clay" (E.P. Odum, personal communication) that was unable to support vegetation of any kind (Figure 1a). Although there are no historical data concerning soil C, N and P prior to diking, the salt-encrusted, barren landscape with bleached mussel shells shown in Figure 1a clearly demonstrates that the diked area was not functioning as a salt marsh during this time. Eight years later the dike was breached by the state of Georgia, which acquired the property as part of the Marine Institute, and tidal inundation was restored to the marsh. The marsh gradually restored itself (Figure 1b) over a period of five years (E.P. Odum, personal communication) and has persisted since that time (Figure 1c). Except for the remnants of the breached dike that surround it, the restored marsh today resembles the naturally occurring saltwater cordgrass marshes around Sapelo Island.

The natural saltwater cordgrass marsh used as a reference in this study is adjacent to the restored marsh, just outside the old dike. Both marshes are inundated twice daily with a tidal amplitude of 2-3 meters. The salinity of surface water in the marshes ranges from 25 to 35 ppt. Unlike salt marsh soils along the northeastern coast of the United States, which often are organic soils, marshes at Sapelo Island are underlain by mineral soils low in organic matter (less than 10 percent) and with high clay content.

Soils were sampled by collecting 10 cores (8.5 cm in diameter and 10 cm

A.

B.

C.

Figure 1. Time-lapse record of 40 years in the life of a recovering salt marsh at Sapelo Island, Georgia: (a) Expanse of toxic "cat clay" substrate in 1955, seven years after this part of the marsh was separated from the Atlantic Ocean by a dike. (b) The same site three years later and two years after breaching of the dike. Note the recovery of saltwater cordgrass following re-establishment of tidal flow and subsequent reducing soil conditions. *Photos by E.P Odum* **(c) Forty years later. Note the lush growth throughout the marsh and surrounding area.** *Photo by Chris Craft*

deep) from each marsh in August 1998. I stratified the samples by collecting three cores each from tall (streamside) and short cordgrass zones, and four cores from medium-height stands of cordgrass. I prepared these samples and analyzed them for bulk density, organic C, and total N and P as described by Craft and others (1988). I calculated soil organic C, N, and P pools using mean measurements of bulk density and nutrient concentrations (Table 1).

I determined vertical accretion in the marsh by collecting one core (30 cm deep) from the medium height saltwater cordgrass stand in each marsh. I sectioned soil cores into 2-cm depth increments and analyzed each increment for Cesium-137 by measuring the photopeak at 661.62 keV using gamma spectrometry (Craft and Richardson, 1998). Cesium-137 is an impulse marker produced by fallout from aboveground thermonuclear weapons testing in the 1950s and 1960s. The ^{137}Cs peak in the soil corresponds to 1964, the period of maximum fallout from aboveground nuclear testing by the United States and the former Soviet Union (Ritchie and McHenry, 1990). Cesium-137 is useful for measuring post-restoration C, N, and P accumulation in our marshes because it integrates accumulation during the time since the tidal inundation was reintroduced in 1956. Rates of accumulation of sediment, organic C, N, and P were calculated using bulk density and nutrient concentrations were measured in 2-cm depth increments of the ^{137}Cs cores down to, and including the ^{137}Cs peak. In the natural marsh, the Cesium-137 peak was located 14 cm below the soil surface whereas, in the restored marsh, the peak was found 18 cm below the soil surface (Figure 2).

Results and Discussion

There was no difference (Student's t-test, p=0.05) in soil C, N, P, C:N, and N:P (0-10 cm) between samples from the restored marsh taken 42 years after re-introduction of tidal inundation, and samples from the natural marsh (Table 1). Soil nutrients, C:N and N:P in the two marshes were within the range reported for natural saltwater cordgrass marshes along the Atlantic and Gulf coasts of the United States. Soil

Table 1. Comparison of soil nutrient concentrations, ratios and pools (0-10 cm) and rates of nutrient and sediment accumulation in a 42-year-old restored marsh and a natural saltwater cordgrass marsh on Sapelo Island, Georgia. Nutrient concentration and pool data are expressed as means ±1 standard error (n=10).

	Restored Georgia	Georgia	Natural Atlantic	Gulf
Concentrations:[1]				
Organic C (%)	4.68±0.20	3 81±0 39	0.2-28	1 2-16.4
Nitrogen (%)	0 41±0.02	0 34±0 04	0 04-0 65	0.46-1.17
Phosphorus (Mg/g)	520±32	468±48	128-786	500-833
C.N (per g)	13 6±0.5	13.7±0.6	18-20	12-20
N:P (per g)	17 6±1 1	17 0±2.4	3-17	27-34
Pools:[2]				
Organic C (g/m²)	1264±54	1372±140	620-4160	2780-6970
Nitrogen (g/m²)	111±5	122±14	38-270	165-185
Phosphorus (g/m²)	14±0.9	17±1 7	12-88	12-13
Accumulation:[3]				
Sediment (g/m²/yr)[4]	1600	1380	160-2670	1740-2700
Organic C (g/m²/yr)	80	71	21-215	183-393
Nitrogen (g/m²/yr)	6 3	5.5	1.3-11	11-23
Phosphorus (g/m²/yr)	0 60	0.35	0-0 4	0.7-2 3

1 Data from Atlantic and Gulf coast natural marshes are from Craft and others (1999)

2 Sapelo Island pools were calculated from the C N, and P concentration data and mean (n=10) bulk density of 0 36 g/cm3 and 0 27 g/cm3 (0-10 cm) in the natural and restored marshes, respectively Other marsh data are from Coultas and Calhoun (1976), Darmody and Foss (1978), DeLaune and others 1981), Hatton and others (1983), Griffin and Rabennorst (1989), Craft and Reader (1997), Craft and others, (1988, 1999)

3 Accumulation rates of Sapelo Island marshes were calculated using the accretion rates and bulk densities in Figure 2 and C, N, and P in 2 cm increments above, and including, the ^{137}Cs peak of the ^{137}Cs dated cores Accumulation data from other natural marshes are from Craft and others (1999) and Anisfeld and others (1999)

4 Sedimentation rates of other natural marshes are from DeLaune and others (1981), Hatton and others (1983), Craft and Reader (1997), Craft and others (1993) and Anisfeld and others (1999)

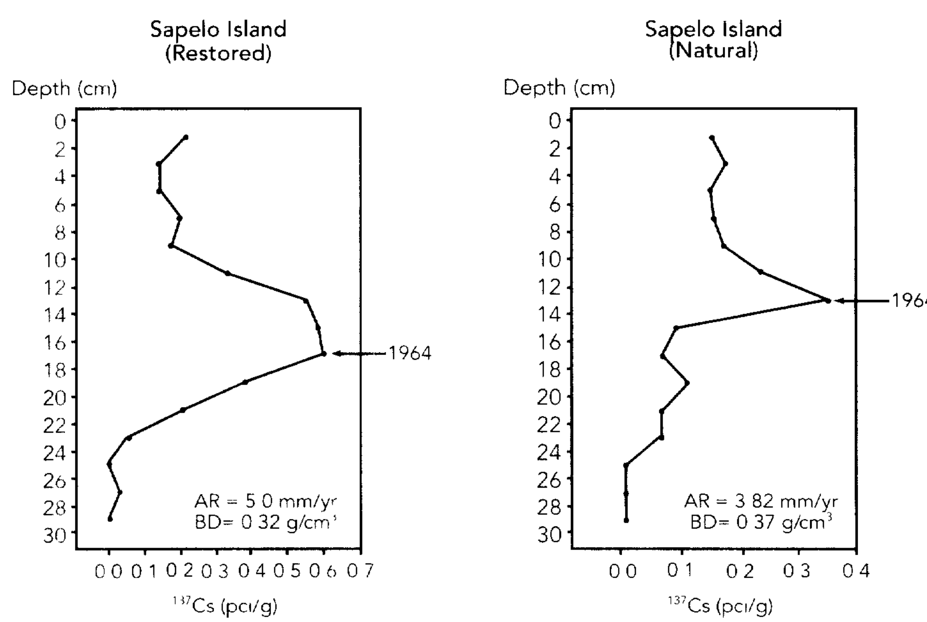

Figure 2. Depth distribution of ^{137}Cs in a natural and a 42-year-old restored saltwater cordgrass marsh at Sapelo Island, Georgia.

C:N ratios in our Sapelo Island marshes were substantially less than 20:1, suggesting that sufficient N is available to satisfy microbial N needs (Tisdale and others, 1985). I also found no difference in soil-nutrient pools (0-10 cm) between the natural marsh and the restored marsh (Table 1). Carbon, N and P pools in the Georgia marshes were within the range reported for natural saltwater cordgrass marshes along the Atlantic Coast, but were smaller than those in Gulf Coast marshes where tidal amplitude is much lower.

Vertical accretion was higher in the restored marsh (5.0 mm/yr) than in the natural marsh (3.82 mm/yr). The pronounced peak in ^{137}Cs in both cores suggests that the ^{137}Cs method is effective for estimating vertical accretion in our Sapelo Island marshes (Figure 2). In the restored marsh, increased vertical accretion resulted from higher rates of sediment deposition and organic C, N and P accumulation (Table 1), which may be a response to renewed tidal inundation following breaching of the dike surrounding the marsh. Anisfeld and colleagues (1999) reported that restoration of tidal inundation to flow-restricted marshes along Long Island Sound resulted in increased vertical accretion and sedimentation. In the restored marshes Anisfeld's group studied, 150 years of tidal restriction by tide gates led to oxidation of organic matter and soil subsidence, effectively lowering the elevation of the marsh. In the 1970s, reintroduction of tidal inundation increased water levels in the marshes, leading to accelerated sedimentation and vertical accretion. At Sapelo Island, the short duration of diking (eight years) and limited sample size (one core per marsh) makes it difficult to determine whether the observed increase in vertical accretion and sedimentation was due to re-introduction of tidal inundation.

In the restored marsh, P accumulation (0.60 g/m²/yr) was 71 percent higher than in the natural marsh (0.35 g/m²/yr). The large difference in P accumulation between the two marshes was the result of higher soil P concentrations in the restored marsh core (378 µg P/g soil versus 251 µg P/g). Using the mean P concentration of the bulk cores (0-10 cm) yielded a

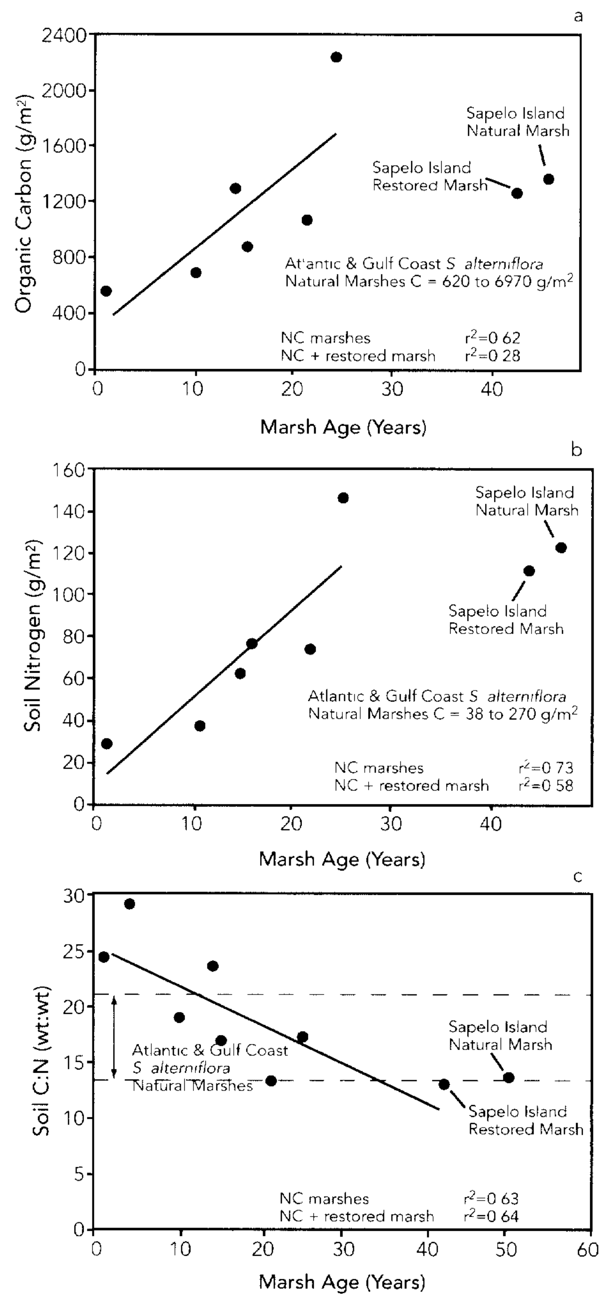

Figure 3. The relationship between the age of saltwater cordgrass marshes in North Carolina (constructed) and Georgia (restored) and the following soil metrics: (a) organic carbon, (b) soil nitrogen, and (c) soil carbon:nitrogen ratio.

rate of P accumulation that was 26 percent higher in the restored marsh (0.83 compared to 0.66 g P/m²/yr). Accumulations of sediment, C, N, and P in the Sapelo Island marshes were within the range reported for other saltwater cordgrass marshes along the Atlantic Coast but lower than those reported for Gulf Coast marshes, where subsidence and sediment deposition from the Mississippi River accelerated rates of vertical accretion, sedimentation and nutrient accumulation (Table 1).

I compared soil organic C and N pools and C:N (0-10 cm) in our 42-year-old restored marsh with a chronosequence (1-24 years old) of constructed saltwater cordgrass marshes in North Carolina to determine whether these metrics are robust enough to be applied across different geographic regions (Figure 3).

Regressions using only the North Carolina data revealed strong relationships between soil metrics and marsh age ($p < 0.06$; $r^2 = 0.62$-0.73) (C and N pool data not shown; C.B. Craft, unpublished data). When the 42-year-old restored marsh was included, the "goodness of fit" of the regressions for N ($r^2 = 0.58$, and especially C ($r^2 = 0.28$) decreased, suggesting that the predictive power of these equations is not generally applicable across different geographic regions. Soil C:N ratios, however, exhibited a strong relationship with marsh age when both North Carolina and Georgia marshes were included ($p<0.02$). Soil C:N ratios decreased with the age of the constructed/restored marshes ($r^2=0.64$) (Figure 3) and, after 20 years, were comparable to those of natural saltwater cordgrass marshes along the Atlantic and Gulf coasts. This finding suggests that the soil C:N ratio may be robust enough to serve as a good indicator of N bioavailability in created and restored salt marshes across different geographic regions.

The similarity in soil-nutrient concentrations, ratios, pools, and accumulation in our Sapelo Island marshes suggests that the 42-year-old restored marsh provides the same level of biogeochemical and water quality improvement functions as the natural marsh. Soil-based metrics, especially C:N ratios, should be considered when evaluating attempts to restore or create salt marshes or other ecosystems in which nitrogen is limiting.

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