Fifteen Years of Vegetation and Soil Development after Brackish-Water Marsh Creation

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Abstract

Aboveground biomass, macro-organic matter (MOM), and wetland soil characteristics were measured periodically between 1983 and 1998 in a created brackish-water marsh and a nearby natural marsh along the Pamlico River estuary, North Carolina to evaluate the development of wetland vegetation and soil dependent functions after marsh creation. Development of aboveground biomass and MOM was dependent on elevation and frequency of tidal inundation. Aboveground biomass of *Spartina alterniflora*, which occupied low elevations along tidal creeks and was inundated frequently, developed to levels similar to the natural marsh (750 to 1,300 g/m^2) within three years after creation. *Spartina cynosuroides*, which dominated interior areas of the marsh and was flooded less frequently, required 9 years to consistently achieve aboveground biomass equivalent to the natural marsh (600 to 1,560 g/m^2). Aboveground biomass of *Spartina patens*, which was planted at the highest elevations along the terrestrial margin and seldom flooded, never consistently developed aboveground biomass comparable with the natural marsh during the 15 years after marsh creation. MOM (0 to 10 cm) generally developed at the same rate as aboveground biomass. Between 1988 and 1998, soil bulk density decreased and porosity and organic C and N pools increased in the created marsh. Like vegetation, wetland soil development proceeded faster in response to increased inundation, especially in the streamside zone dominated by *S. alterniflora.* We estimated that in the streamside and interior zones, an additional 30 years (nitrogen) to 90 years (organic C, porosity) are needed for the upper 30 cm of created marsh soil to become equivalent to the natural marsh. Wetland soil characteristics of the *S. patens* community along upland fringe will take longer to develop, more than 200 years. Development of the benthic invertebrate-based food web, which depends on organic matter enrichment of the upper 5 to 10 cm of soil, is expected to take less time. Wetland soil characteristics and functions of created irregularly flooded brackish marshes require longer to develop compared with regularly flooded salt marshes because reduced tidal inundation slows wetland vegetation and soil development. The hydrologic regime (regularly vs. irregularly flooded) of the "target" wetland should be considered when setting realistic expectations for success criteria of created and restored wetlands.

Key words: ***Juncus roemerianus*, nitrogen, organic carbon, restoration, *Spartina*, wetland creation, wetland pedogenesis.**

Introduction

Created and restored wetlands are frequently used to replace ecological functions and values lost when natural wetlands are degraded or destroyed (National Research Council 1992; Thayer 1992). In many cases, wetlands are created by grading the site to re-create or restore wetland hydrology and by planting to facilitate establishment of hydrophytic vegetation (Kusler & Kentula 1989). Studies of estuarine and freshwater created wetlands indicate that hydrophytic vegetation becomes established within 3 to 5 years (Erwin & Best 1985, Erwin et al. 1985; Seneca et al. 1985; Broome et al. 1986; Mitsch et al. 1998), but other ecological functions (e.g., habitat, food webs, nutrient cycles, soils) take longer to develop (Zedler 1993; Broome & Craft 2000; Craft et al. 1999; Nair et al. 2001). In most situations, it is unclear how long some ecological functions take to develop because of the young age of most created wetlands (<10 years) and because ecological parameters other than vegetation are not measured on a consistent basis, if at all, after creation.

Studies evaluating the long-term development of created coastal wetlands are limited mostly to salt marsh wetlands dominated by a single plant species, *Spartina alterniflora* along the Atlantic coast (Broome et al. 1986; Craft et al. 1999) and *Spartina foliosa* along the Pacific coast (Zedler 1993). These studies indicate that emergent vegetation is established within 3 to 5 years

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whereas wetland soil characteristics and associated detritus feeding organisms take longer to develop (Craft et al. 1999). In created salt marshes of North Carolina, 10 to 15 years elapsed before the benthic invertebrate community was equivalent to nearby natural marshes (Craft et al. 1999). In southern California, a salt marsh created in 1985 to provide habitat for an endangered species (Light-footed Clapper Rail, *Rallus longirostris levipes*) was declared a failure after 13 years because few rails established nests in the stunted *S. foliosa* canopy (Malakoff 1998). *Spartina foliosa* in the created marsh was not tall enough to prevent nests from being inundated by high tides. Development of wetland nutrient cycles and soils may require even longer. Nearly 30 years after marsh creation, soil characteristics such as organic C and N reservoirs are often lower in created salt marshes as compared with natural marshes (Craft et al. 1999).

We present 15 years of data describing wetland vegetation and soil development after creation of a brackish-water estuarine marsh in 1983. The marsh was created by grading an upland site to intertidal elevations, planting with *Spartina* spp. and *Juncus roemerianus*, and then introducing tidal inundation. Aboveground biomass and macro-organic matter (MOM) were measured periodically between 1983 and 1998 to evaluate the development of plant biomass stocks. MOM is defined as living and dead roots and rhizomes more than 2 mm diameter (Gallagher & Plumley 1979). Soil characteristics (0 to 30 cm) were measured in 1988 and 1998 to document rates of wetland soil development after conversion of an oxidized terrestrial soil to a chemically reduced wetland soil.

Methods

Site Description

Vegetation and soils were sampled in a 2.15-ha brackish-water marsh on the Pamlico River estuary, near Aurora, North Carolina (35°25′N, 76°75′W) that was created in 1983 as mitigation of brackish-water marsh impacts associated with surface mining of rock phosphate. A nearby natural marsh also was sampled. The created and natural marshes had similar tidal inundation (irregularly flooded by wind-driven tides), depth of flooding (<10 cm), and salinity (0 to 15 ppt) but differed in age and soil development. The created marsh was established by grading a terrestrial pine (*Pinus taeda*) forest to intertidal elevations, +15 to +43 cm mean sea level. The nearby natural marsh had more than 2 to 3 m of peat and was more than 2000 years old based on ^{14}C dating (Bellis & Gaither 1985). The natural marsh soil was classified as an organic soil (Lafitte series, Typic Medisaprist), whereas the created marsh was classified as a mineral soil with high sand and low silt, clay, and organic matter (Typic Psammaquent, Carteret series) (Craft et al. 1988) (Fig. 1).

Grading the site removed the upper 2 m of soil so that the planting substrate consisted of the "C" horizon. Three species of greenhouse-grown seedlings of *Spartina* were planted in three inundation zones. *S. alterniflora* Loisel (smooth cordgrass) was planted at the lowest elevations, +15 to +21 cm MSL, along the tidal creek. *Spartina cynosuroides* (L.) (giant cordgrass) was planted at mid-elevations (+21 to +37 cm) of the marsh interior. *S. patens* (Ait. Muhl.) (salt meadow cordgrass) was planted along the upland margin at the highest elevations, from +37 to +43 cm. In addition, greenhouse-grown *Juncus roemerianus* (Scheele) (black needlerush) was planted in low-lying areas of the marsh interior (+21 to +37 cm). At the time of planting, the created marsh was fertilized with N (224 kg/ha) and P (98 kg/ha) to facilitate establishment of emergent vegetation (Broome et al. 1988).

The natural marsh contained the same species as the created marsh but in somewhat different distribution. *Spartina cynosuroides* dominated levees along the tidal creek (33 to 46 cm MSL). *Juncus roemerianus* was common in the marsh interior at elevations below 37 cm MSL. A mixture of *S. patens* and *Distichlis spicata* (L.) (salt grass) was present in the marsh interior at elevations greater than 37 cm MSL, the same elevation as *S. patens* in the created marsh. In the natural marsh, *S. alterniflora* was found only in a few locations along the creek banks.

Vegetation Sampling

Between 1983 and 1998, emergent vegetation was sampled mostly annually in the created and the natural marsh. Aboveground biomass was measured by clipping 0.25-m^2 quadrats from each of the four vegetation zones, *S. alterniflora*, ($n = 10$ to 20 samples per year), *S. cynosuroides* ($n = 15$ to 30), *S. patens* ($n = 5$ to 20), and *J. roemerianus* ($n = 5$ to 10), of the created marsh at the end of the growing season. In the natural marsh, 0.25-m^2 quadrats were clipped from each of the four dominant vegetation zones, *S. alterniflora* ($n = 3$), *S. cynosuroides* ($n = 15$), *J. roemerianus* ($n = 10$ to 15), and *S. patens–D. spicata* ($n = 8$ to 15). The patchy distribution of *S. alterniflora* in the natural marsh, especially during the early years of the study, limited the number of samples taken each year. Within each vegetation zone, clip plots were randomly selected. Aboveground material was dried at 70°C and weighed to estimate standing crop biomass. MOM, the living and dead root and rhizome mat (Gallagher & Plumley 1979), was measured most years between 1983 and 1995 by collecting one 8.5-cm diameter by 10-cm deep soil core from each quadrat. Cores were washed on a 2-mm mesh diameter screen to separate soil from roots and rhizomes. MOM was dried at 70°C and weighed.

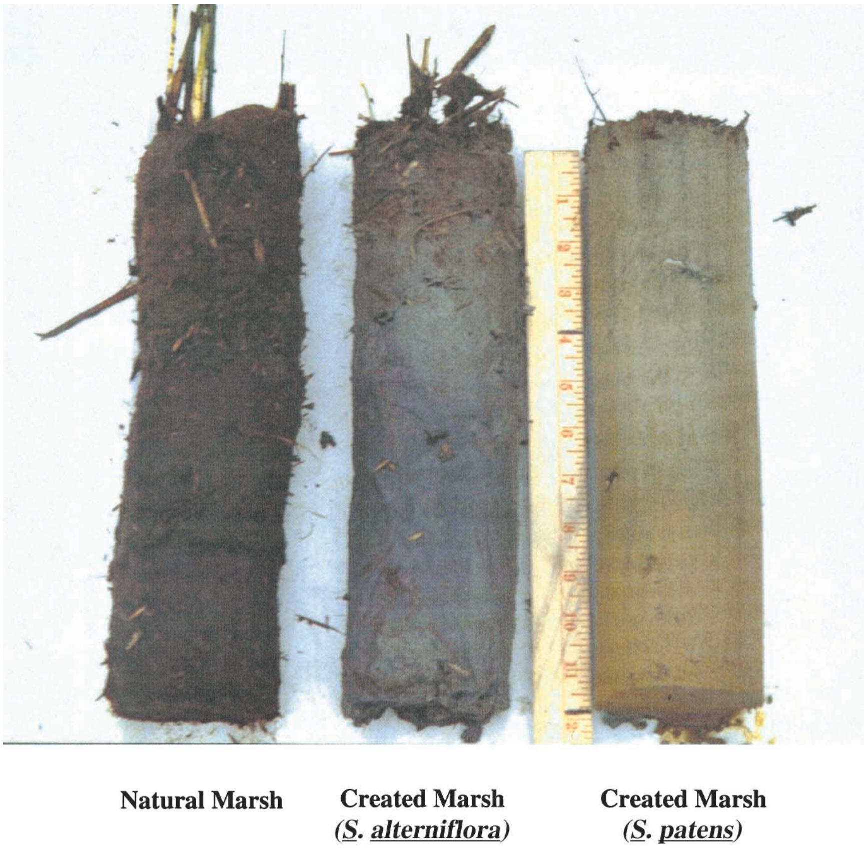


Figure 1. Soil cores (0- to 30-cm deep) collected from the natural marsh (left), *Spartina alterniflora* zone of the created marsh (middle), and *Spartina patens* zone of the created marsh (right). Note the dark color of the organic soil from the natural marsh (left) and the gray color of the chemically reduced *S. alterniflora* soil of the created marsh (middle). Also note that even after 15 years, soil from the *S. patens* zone of the created marsh (right) is not fully chemically reduced, as evidenced by the orange color characteristic of oxidized iron, in the lower portion of the core. Ruler scale in "inches."

Soil Sampling and Analysis

In October 1998, 10 soil cores (8.5-cm diameter by 30-cm deep) were collected from the created and 10 from the natural marsh. In the created marsh, three cores each were collected from the low (*S. alterniflora*) and high (*S. patens*) elevation zones. Four cores were collected from the mid-elevation zone (*S. cynosuroides*). In the natural marsh, three cores were collected from the *S. cynosuroides* zone, four from *J. roemerianus*, and three from the *S. patens–D. spicata* zone. Within each vegetation type, soil cores were taken from the clip plots, which were randomly selected. Soils were air dried, weighed, and ground to pass a 2-mm mesh diameter sieve.

Soils were analyzed for physical (bulk density, porosity) and chemical characteristics (pH, acidity, Fe, Mn), organic C, and nutrients (N, P). We used the same sampling and analytical methods as those used when the marsh was sampled in 1988 (see Craft et al. 1991) to evaluate the rate of wetland soil development after marsh creation. Bulk density was calculated using the air-dried weight of the soil after correcting for the moisture content. Porosity was calculated as 1 − (bulk density/particle density) using a particle density of 2.64 g/cm^3 for the created marsh and 1.49 g/cm^3 for the natural marsh (Craft et al. 1991).

Total N and organic C were measured with a Perkin-Elmer 2400 CHN analyzer (Perkin-Elmer, Norwalk, CT, U.S.A.). Recovery of C and N in a reference standard (Montana Soil, NIST no. 2710; C = 3%, no N value) yielded values of 2.93 ± 0.04% C and 0.29 ± 0.01 %N ($n = 3$ replicates), respectively. Total P was measured in perchloric-nitric acid digests (Sommers & Nelson 1972) using the method of Murphy and Riley (1962). Recovery of P in a reference standard (Estuarine Sediment, NIST no. 1646a; 270 µg P/g soil) yielded values of 260 ± 11 µg/g ($n = 3$).

Soil pH was measured in a 1:1 soil-to-water volume ratio. $BaCl_2$ titratable acidity and KCl exchangeable acidity (H^+, Al) were determined following the methods described by Thomas (1982). "Free" (reduced and reducible) Fe and Mn oxides were extracted with sodium dithionite and sodium citrate and analyzed by atomic absorption spectrometry (Olsen & Ellis 1982).

Statistical Analyses

One-way analysis of variance was used to detect differences in above- and belowground biomass and soil characteristics (by year) of the created versus natural marsh. Analysis of variance also was used to test for differences in soil characteristics of created (*S. alterniflora*, *S. cynosuroides*, *S. patens*) and natural marsh (*S. cynosuroides*, *J. roemerianus*, *S. patens–D. spicata*) plant communities. Mean values of marsh soil characteristics were separated using the Ryan-Einot-Gabriel-Welsch Multiple F test (SAS 1990). Regression analysis was used to test for relationships between species-specific biomass and created marsh age. All tests of significance were made at $\alpha = 0.05$.

Results and Discussion

Vegetation

Aboveground Biomass. In the created marsh, development of aboveground biomass varied according to species. *Spartina alterniflora* biomass developed quickly, achieving levels comparable with the natural marsh 3 years after marsh creation (Fig. 2a). Other published studies indicate that *S. alterniflora* biomass achieves levels similar to natural marshes within 3 to 5 years after salt marsh creation (Seneca et al. 1985; Broome et al. 1986). Aboveground biomass of *Spartina cynosuroides* consistently achieved equivalence to the natural marsh after 9 years (Fig. 2b). Aboveground biomass of *Spartina patens* never consistently achieved equivalence to the natural marsh during the 15-year period (Fig. 2c). Like *S. cynosuroides*, aboveground biomass of *Juncus roemerianus* required 9 years to consistently achieve equivalence to the natural marsh (Fig. 2d).

For *Spartina* spp., development and maintenance of aboveground biomass stocks was related to the frequency of inundation. *Spartina alterniflora*, which grew along the tidal creeks at an elevation of +15 to +21 cm MSL and was inundated the longest, developed biomass stocks similar to the natural marsh within 3 years after creation and maintained comparable levels of biomass for the 15-year period of record (Fig. 2a). *Spartina cynosuroides*, which occupied interior areas that were inundated less frequently (+21 to +37 cm), required longer to develop than *S. alterniflora*, that is, 9 years (Fig. 2b). The highest elevations within the created marsh, dominated by *S. patens* at elevations above +37 cm MSL, were inundated only during spring tides and storm tides. Although aboveground biomass of *S. patens* was similar to the natural marsh during the first 2 years after creation, these levels were not sustained. During the 15-year period of

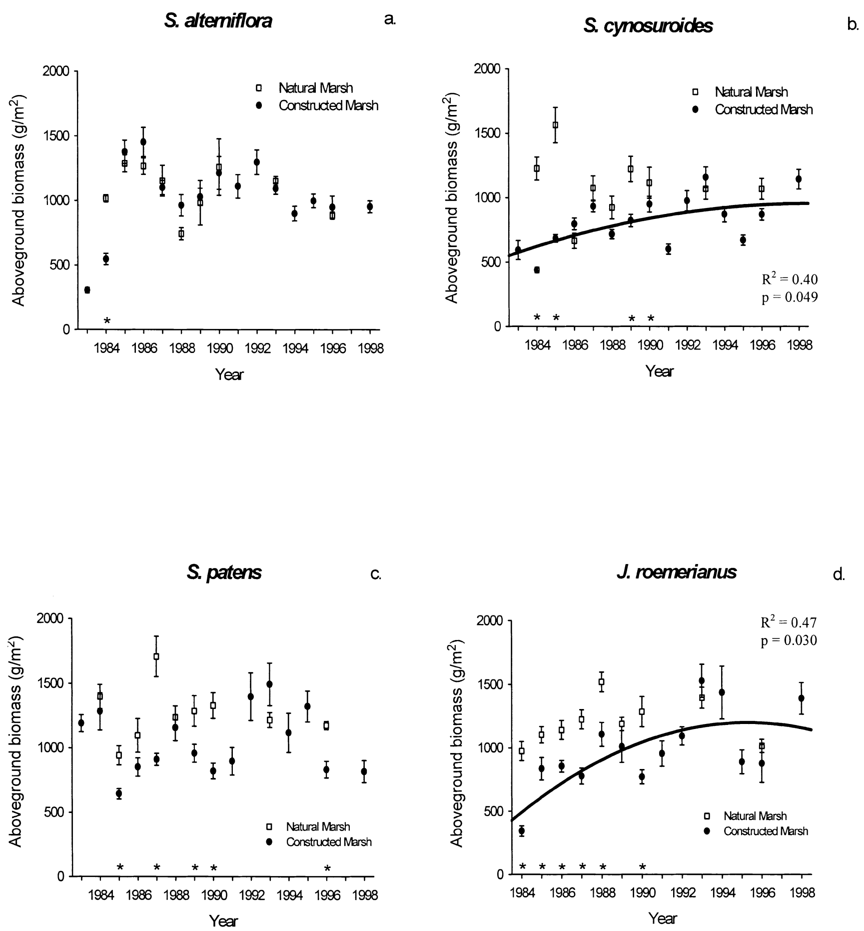


Figure 2. End of season aboveground biomass (1983–1998) of (a) *Spartina alterniflora*, (b) *Spartina cynosuroides*, (c) *Spartina patens*, and (d) *Juncus roemerianus* in a created and a natural brackish-water marsh. Values (in g/m^2) are means ± standard error. Asterisks denote that the created marsh is significantly different ($\alpha = 0.05$) from the natural marsh according to analysis of variance.

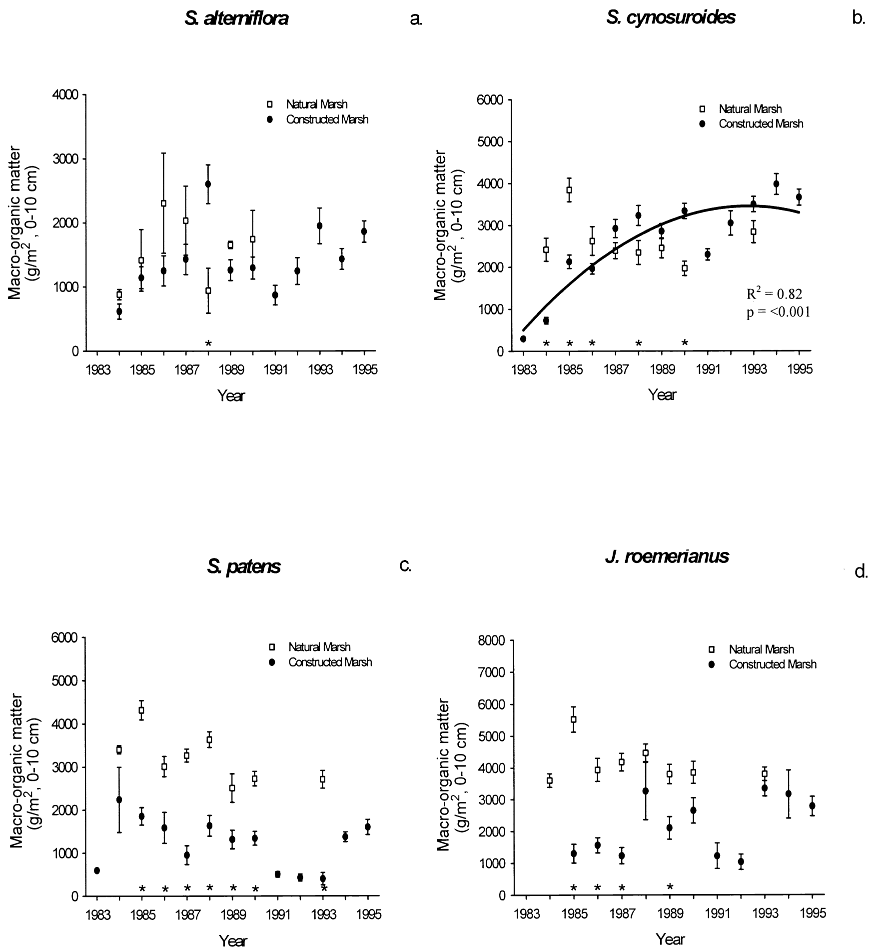


Figure 3. End of season belowground biomass (1983–1995) in the 0- to 10-cm depth of (a) *Spartina alterniflora*, (b) *Spartina cynosuroides*, (c) *Spartina patens*, and (d) *Juncus roemerianus* in a created and a natural brackish-water marsh. Values (in g/m^2) are means ± standard error. Asterisks denote that the created marsh is significantly different (α = 0.05) from the natural marsh according to analysis of variance.

record, *S. patens* biomass was consistently lower than in the natural marsh (Fig. 2c).

Other studies of created salt marshes suggest that increased duration of inundation accelerates marsh ecosystem development. For example, in a created *S. alterniflora* marsh in North Carolina, above- and belowground biomass developed more rapidly at lower elevations (11 hr inundation/day) of the marsh as compared with higher elevations (4 to 9 hr inundation/day) (Seneca et al. 1985). Conversely, reduced duration of inundation slows marsh ecosystem development. In created salt marshes of southern California, it was more difficult and took longer to successfully establish emergent vegetation, and regular N additions are needed to maintain "tall" stands of *S. foliosa* (Zedler 1996a). Tidal inundation of southern California salt marshes occurs infrequently by storm tides and infrequent episodic rainfall events (Zedler 1996b), much like the upland fringe (*S. patens* zone) of our created brackish-water marsh where vegetation development was slowest.

Aboveground biomass of *S. cynosuroides* and *Juncus* exhibited a significant relationship with created marsh age (Fig. 2, b and d). Aboveground biomass of both species increased with time before leveling off after about 10 years. In contrast, aboveground biomass of *S. alterniflora* and *S. patens* did not change in a predictable manner over time (Fig. 2, a and c). Aboveground biomass of *S. alterniflora* quickly developed to levels measured in the natural marsh, whereas biomass of *S. patens* never consistently developed to levels measured in natural *S. patens* stands.

MOM. MOM developed at about the same rate as aboveground biomass after marsh creation. In *S. alterniflora* stands, MOM (0 to 10 cm) consistently achieved equivalence to the natural marsh within 2 years after marsh creation (Fig. 3a). MOM of *S. cynosuroides* developed to levels similar to the natural marsh after 5 years (Fig. 3b), and 8 years elapsed before *Juncus* MOM achieved equivalence to the natural marsh (Fig. 3d). During the 12 years after creation, MOM of *S. patens* was consistently less than in the natural marsh (Fig. 3c). The inability of *S. patens* to establish above- and belowground biomass stocks probably reflects reduced and infrequent tidal inundation that slows wetland soil development and N accumulation at high elevations in the marsh. Only *S. cyno-*

suroides exhibited a significant relationship with created marsh age as MOM increased over time before leveling off after 10 years (Fig. 3b).

In the created marsh, MOM was much lower in the 10- to 30-cm rooting depth than in the 0- to 10-cm depth (data not shown). MOM stocks in the 10- to 30-cm depth increased over time but never approached levels found in the natural marsh. Maximum MOM (10 to 30 cm) in the created marsh ranged from 345 g/m^2 for *S. patens* to 621 g/m^2 for *S. cynosuroides.* In contrast, in the natural marsh, MOM stocks (10 to 30 cm) ranged from a low of 1,600 g/m^2 (*J. roemerianus*, 1985) to a maximum of 7,200 g/m^2 (*J. roemerianus*, 1987).

Soil

Development of Wetland Soil Characteristics. Fifteen years after creation, many soil characteristics of the created marsh (0 to 30 cm) were different from the natural marsh. Bulk density was significantly higher in the created marsh, whereas porosity, organic C, and N were lower than in the natural marsh (Table 1). Soil acidity and extractable Fe and Mn also were much higher in the created marsh (Table 1). There was no difference in soil P, C:N ratio, or pH between the created and the natural marsh (Table 1). The planting substrate of the created marsh initially consisted of "C" horizon material with high bulk density, acidity and metals (Fe, Mn), and low organic matter and N. Even after 15 years, the created marsh soil still retained many of these attributes.

Comparison of created marsh soil characteristics in 1988 and 1998 revealed significant changes during the 10-year period. Bulk density decreased and porosity, organic C, and N increased over time (Table 1). Titratable acidity also decreased during the 10-year period, whereas pH, "free" Fe, and Mn increased (Table 1). There was no significant change in exchangeable acidity (H^+, Al) in the created marsh between 1988 and 1998. The observed change in soil physical and chemical characteristics between 1988 and 1998 reflects pedogenic (soil forming) processes that dominate when soil is flooded. Under conditions of flooding or saturation, anaerobic conditions slow decomposition so that organic matter accumulates in the soil. Increased soil organic matter results in alteration of soil physical and chemical characteristics, including decreased bulk density and increased porosity, organic C, and N. Another response to flooding is the observed decrease in soil acidity between 1988 and 1998. Under anaerobic conditions, reduction of oxidized Fe and Mn to Fe^{2+} and Mn^{2+} consumes hydrogen ions, decreasing soil acidity (and increasing pH). Soil C:N decreased from 20 to 11 between 1988 and 1998, even though both organic C and N increased (Table 1).

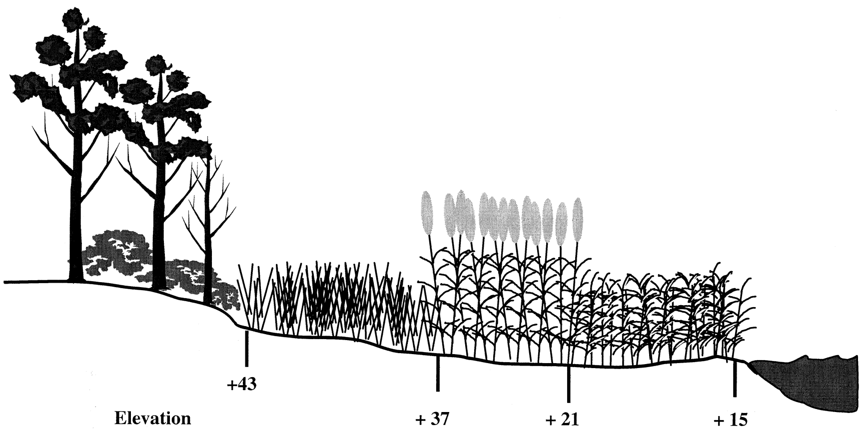
In the created marsh, development of wetland soil characteristics was positively related to marsh elevation. For example, bulk density was lower and organic C was significantly higher ($p \leq 0.05$) in the streamside (*S. alterniflora*) zone as compared with the upland margin occupied by *S. patens* (Fig. 4). Similarly, porosity was lower and N was higher ($p \leq 0.10$) in the streamside zone as compared with the upland margin. Lindau and Hossner (1981) observed a similar response in a 2-year-old created Texas salt marsh as soil organic matter, and N concentrations were highest at low elevations of the marsh and decreased with elevation. Nair et al. (2001) reported similar trends in surface soil bulk density, organic C, and N along transects from uplands into the interior of freshwater wetlands in Florida.

In contrast to C and N, "free" Fe, a relic characteristic of terrestrial soils, was significantly higher near the upland margin in the *S. patens* zone (Fig. 4). Abundant

Table 1. Soil physicochemical characteristics in the 0- to 30-cm depth of created (1988 and 1998) and natural brackish-water marshes (1998).

	Created Marsh		*Natural Marsh*
Soil Characteristic	*1988*	*1998*	*1998*
Bulk density (g/cm^3)	1.35 ± 0.03 **a**	1.21 ± 0.03 **b**	0.13 ± 0.01 **c**
Porosity (%)	48.8 ± 0.01 **a**	54.1 ± 1.2 **b**	91.3 ± 0.3 **c**
Organic C (kmol/ha)	886 ± 100 **a**	1866 ± 103 **b**	10270 ± 800 **c**
Total N (kmol/ha)	41 ± 6 **a**	165 ± 11 **b**	542 ± 33 **c**
C:N (wt:wt)	20.1 ± 3.2 **a**	11.1 ± 0.5 **b**	18.7 ± 0.4 **a**
Total P (kmol/ha)	14.7 ± 1.5 **ns**	10.8 ± 1.3 **ns**	12.0 ± 0.5 **ns**
pH	4.2 ± 0.1 **a**	5.4 ± 0.3 **b**	4.8 ± 0.1 **a,b**
Titratable acidity (kmol/ha)	417 ± 51 **a**	181 ± 55 **b**	63 ± 11 **c**
Exchangeable H^+ (kmol/ha)	0.3 ± 0.2 **a,b**	3.7 ± 1.6 **a**	0.1 ± 0.1 **b**
Exchangeable Al (kmol/ha)	4.4 ± 1.4 **a**	11.3 ± 3.9 **a**	0.6 ± 0.1 **b**
"Free" Fe (kmol/ha)	34 ± 5.9 **a**	251 ± 112 **a**	13 ± 1.3 **b**
"Free" Mn (kmol/ha)	0.1 ± 0.0 **b**	0.9 ± 0.1 **a**	0.3 ± 0.1 **b**

Values are means ± SE (n = 10). Means within each row separated by different letters are significantly different (α = 0.05) according to the Ryan-Einot-Gabriel-Welsch Multiple F test. ns, not significantly different.



Vegetation	*S. patens*	*S. cynosuroides*	*S. alterniflora*
Inundation/ Soil saturation	Infrequent	Frequent	Continuous
Bulk Density (g/cm^3)	1.30 ± 0.06 **a**	1.20 ± 0.02 **a.b**	1.13 ± 0.05 **b**
Porosity (%)	50 ± 2.0 **ns**	54 ± 1.0 **ns**	57 ± 2.0 **ns**
Organic C (kmol/ha)	1380 ± 173 **a**	1831 ± 380 **a,b**	2308 ± 333 **b**
Total N (kmol/ha)	141 ± 9.0 **ns**	170 ± 8.0 **ns**	178 ± 23 **ns**
"Free" Fe (kmol/ha)	748 ± 411 **a**	64 ± 10 **a,b**	53 ± 12 **b**

Figure 4. Effect of continuous (*Spartina alterniflora*), frequent (*Spartina cynosuroides*), and infrequent (*Spartina patens*) inundation/soil saturation on the development of wetland soil characteristics in a created brackish-water marsh. Values are means (n = 3 or 4) ± standard error. Means within each row separated by different letters are significantly different (α = 0.05) according to the Ryan-Einot-Gabriel-Welsch Multiple F test. ns, not significantly different.

"free" Fe oxides in the *S. patens* zone suggest that Fe reduction is the dominant reducing process at higher elevations in the marsh. At lower elevations dominated by *S. alterniflora* and *S. cynosuroides*, increased hydrologic exchange accelerated Fe reduction and leaching as compared with higher elevations dominated by *S. patens.* A visual representation of these differences is depicted in Figure 1. The soil core collected from the *S. alterniflora* zone of the created marsh is uniformly gray in color, indicating complete reduction of Fe^{3+} to Fe^{2+}. Also, there is evidence of organic matter accumulation in the surface 10 cm (Fig. 1). The soil core collected from the created marsh *S. patens* zone is orange in color in the lower portion. This color reflects the presence of oxidized iron that has not been reduced by iron reducing bacteria. It is likely in soils of the *S. patens* zone that iron reduction is slowed by infrequent tidal inundation and low soil organic matter, especially in the subsurface soil.

Unlike the created marsh, strong gradients in wetland soil characteristics were not observed across the natural marsh. Much of the uniformity in wetland soil characteristics is due to the fact that the natural marsh is underlain by 2 to 3 m of peat (Craft et al. 1993). In the natural marsh, soil bulk density and porosity did not differ appreciably between levees dominated by *S. cynosuroides* (bulk density = 0.14 g/cm^3, porosity = 91%) and interior areas dominated by *Juncus* and *Distichlis–S. patens* (bulk density = 0.12 to 0.13 g/cm^3, porosity = 91 to 92%). Soil organic C and N was lower and "free" Fe was higher at levee (7,520 kmol C/ha, 443 kmol N/ha, 2,360 kmol Fe/ha, respectively) versus interior (10,700 to 11,900 kmol C/ha, 550 to 610 kmol N/ha, 1,350 to 1,850 kmol Fe/ha, respectively) marsh locations. Low soil organic C and N and high free Fe beneath *S. cynosuroides* probably reflects greater deposition of terrestrial mineral sediment along the streamside levee as compared with interior areas of the marsh that are farther removed from tidal inundation (Craft et al. 1993). Created marshes typically lack a levee or berm. Marshes typically are constructed with a gradual slope from upland to tidal creek (Fig. 4) to facilitate drainage and prevent accumulation of salts and sulfides that would harm transplanted vegetation. In the created marsh, development of a levee comparable with the *S. cynosuroides* dominated levee in the natural marsh likely will take hundreds of years.

Our findings indicate that within the created marsh, wetland soil development proceeds at different rates, with reducing conditions and wetland soil characteristics developing more rapidly at low elevations that are inundated longer than at high elevations that are inundated less frequently and for shorter periods. Similar to our study, reducing conditions and wetland soil characteristics (depleted matrix) developed more rapidly in the interior of a created freshwater marsh as compared with the marsh-upland transition zone (Vepraskas et al. 1999). Five years after creation, the interior of the freshwater marsh contained depleted soil matrix, evidence of Fe reduction and leaching, and as development of an organic soil layer (Vepraskas et al. 1999).

Rate of Wetland Soil Development. Using soils data from 1988 (Craft et al. 1991) and 1998 (this study), we calculated the rate of development of various wetland soil characteristics (Table 2). Bulk density decreased at an annual rate of 0.01 g cm^3 yr^{-1} and porosity increased at 0.5%/yr. Craft et al. (1999) reported a similar decrease in bulk density (0.010 to 0.015 g cm^{-3} yr^{-1}) and increase in porosity (0.05%/yr in two 20- to 25-year-old *S. alterniflora* marshes created on dredge material (C. B. Craft, unpublished data). Organic C (118 g m^{-2} yr^{-1}) and N (17.4 g/m^{-2} yr^{-1}) also accumulated in the soil during the 10-year period. In the created marsh, organic C accumulation was similar to the nearby natural marsh (125 g C m^{-2} yr^{-1}) (Craft et al. 1993) and to other natural salt marshes in North Carolina (91 to 159 g C m^{-2} yr^{-1}) (Craft et al. 1999). Organic C accumulation in the created marsh also was comparable with *S. alterniflora* marshes created on dredge material (99 to 125 g C m^{-2} yr^{-1}) (Craft et al. 1999). The percentage of net primary production buried annually in the created marsh was 13%, which is within the range reported for other created *S. alterniflora* marshes (11 to 20%) (Craft et al. 1988) and for the natural brackish-water marsh sampled during this study (11%) (Table 2, footnote c). In contrast to organic C, nitrogen accumulation in the created marsh (17.4 g N m^{-2} yr^{-1}) was much higher than in the natural marsh (8.5 g N m^{-2} yr^{-1}) (Craft et al. 1993). Other created salt marshes in North Carolina also exhibit higher N accumulation than comparable natural marshes, which may be a response to N limitation (Craft et al. 1999).

Increased inundation and soil saturation accelerated development of properties characteristic of wetland soils. In the streamside zone (*S. alterniflora*), bulk density decreased and porosity and organic C accumulation increased at a faster rate than in the interior (*S. cynosuroides*) or upland border (*S. patens*) of the marsh where wetland soil development proceeded slowly (Table 2). In the streamside zone, bulk density decreased at a rate that was four times faster as compared with marsh soil adjacent to the upland border (Table 2). Likewise, organic C accumulation in the streamside zone (142 g m^{-2} yr^{-1}) was two times higher than along the upland border (59 g m^{-2} yr^{-1}). Nitrogen accumulation also was higher in the *S. alterniflora* zone (19.2 g m^{-2} yr^{-1}) than in the *S. patens* dominated upland border (14 g m^{-2} yr^{-1}). The proportion of net primary production buried annually also was greater in streamside and interior zones as

Table 2. Rate of change of wetland soil characteristics (soil bulk density, porosity, organic C, and total N) in the 0- to 30-cm depth of a created brackish-water marsh between 1988 and 1998.

	Rate of Change			
Soil Characteristic	*Streamside* Spartina alterniflora	*Interior* Spartina cynosuroides	*Upland* Spartina patens	*Marsh Mean*
Bulk density (g cm^{-3} yr^{-1})	−0.022 (49)	−0.015 (72)	−0.005 (234)	−0.014 (77 yr)
Porosity[b] (%/yr)	0.82	0.52	0.12	0.53
Organic C (g m^{-2} yr^{-1})	142 (71)	113 (89)	59 (151)	118 (86 yr)
Nitrogen (g m^{-2} yr^{-1})	19.2 (27)	18.1 (29)	14 (40)	17.4 (30 yr)
Percent of NPP buried[c]	14	14	6	13

Positive numbers indicate a net increase over time. Negative numbers indicate a decrease over the 10-year period. Numbers in parentheses are the number of years required for created marsh soil characteristics (0–30 cm) to become equivalent to the upper 30 cm of the natural marsh soil. Percent of net primary production (NPP) buried annually in each zone also is presented. Rate of change of terrestrial soil characteristics (e.g., soil acidity, free Fe) was not calculated.

[a]For bulk density, years until equivalence were calculated as 1998 created marsh value minus 1998 natural marsh value divided by the rate of change. For C and N, years until equivalence were calculated as 1998 natural marsh value minus 1998 created marsh value divided by the rate of change.

[b]Porosity is calculated from bulk density and so will change over time at the same rate.

[c]Percent of NPP buried annually between 1988 and 1998 was calculated from NPP of *S. alterniflora* (994 g/m^2 yr), *S. cynosuroides* (830 g/m^2 yr), and *S. patens* (1,020 g/m^2 yr) based on the method of Broome et al. (1986). Biomass was converted to organic C by multiplying by 0.45. Eleven percent of the NPP (1,126 g/m^2 yr) is buried annually in the natural marsh. Net primary production (1984–1998) was calculated as described above. Organic C accumulation (1964–1988) (125 g/m^2 yr) is from Craft et al. (1993).

compared with the *S. patens* dominated upland fringe (Table 2).

Using the rate of change data in Table 2, we calculated the amount of time needed for the created marsh soil (0 to 30 cm) to achieve equivalence with the top 30 cm of natural marsh soil. Our calculations were based on the assumption that wetland soil characteristics will change at a constant rate based on changes measured between 1988 and 1998. Of course, alteration of wetland hydrology, changes in surrounding land use (e.g., land clearing), and accelerated sea level rise caused by climate change in the future likely will affect the rate of soil change. Assuming a constant rate of change, in the *S. alterniflora* zone bulk density, organic C, and N will achieve equivalence within about 70 years after marsh creation. The *S. patens* dominated upland border of the created marsh is developing slowly and will not achieve equivalence to the natural marsh for more than 200 years. In all zones, development of soil N pools is occurring more rapidly than organic C pools. We estimate that soil N pools in all zones will require about 30 to 40 years to achieve equivalence to the natural marsh, whereas C pools will require 70 to 150 years.

We expect the marsh food web to develop in less time than the 30 to 150 years needed for the upper 30 cm of soil to form. Benthic invertebrates, an important component of the food web, are concentrated in the upper 5 cm of the soil, where C and N accumulation is greater and wetland soil formation proceeds faster (Craft 2000). In a constructed *S. alterniflora* marshes, surface soil (0 to 10 cm) C, N, and benthic invertebrate communities achieved equivalence to a nearby natural marsh within 15 to 25 years (Craft et al. 1999).

Trajectories Describing Created Marsh Ecosystem Development

There is much interest in determining whether ecological attributes follow a specific path or trajectory after wetland creation and restoration. Knowledge of such trajectories can be used to predict if or when a wetland will achieve equivalence with respect to a given ecological attribute, enabling resource managers to set "performance criteria" for wetland creation and restoration projects. Studies of created estuarine marshes along the west coast (U.S.A.) cast doubt on the applicability of trajectories to predict ecosystem development after wetland creation and restoration. Simenstad and Thom (1996) tracked ecosystem development for 7 years after restoration of a brackish-water estuarine marsh in Washington and found that only a few of 16 ecological attributes measured exhibited trajectories toward equivalency to the natural marsh. Epibenthic invertebrate, fish, and bird usage exhibited trajectories that approached asymptotic levels during the 7-year study. Biomass of the dominant macrophyte, *Carex lyngbyei*, soil organic matter, sediment chlorophyll, and benthic invertebrates increased slowly during the 3- to 5-year monitoring period without reaching an asymptote (Simenstad & Thom 1996). Zedler and Callaway (1999) measured a suite of ecological attributes for 12 years after creation of an *S. foliosa* marsh in southern California. In the southern California marsh, soil organic matter and N were weakly related to marsh age. Nitrogen content increased slowly over time, whereas soil organic increased for 5 years after marsh creation before reaching a plateau. In contrast, density of tall (>90 cm) stems and total stem length, an estimate of aboveground biomass, were unrelated to marsh age. According to Zedler and Callaway (1999), high interannual variability and lack of directional change indicate little chance that equivalence (to the natural marsh) will be achieved anytime soon.

Studies tracking ecosystem development of created marshes along the southeastern U.S. coast, on the other hand, suggest that some ecological attributes do exhibit predictable trajectories over time and structural and functional equivalence is achieved within the foreseeable future. Craft et al. (1999) periodically measured ecological attributes of vegetation, soils, and benthic invertebrates on two 20- to 25-year-old constructed *S. alterniflora* marshes in North Carolina. In this study, aboveground biomass and MOM of *Spartina* increased predictably over time before achieving equivalence to paired natural "reference" marshes. Aboveground biomass and MOM exhibited non-linear trajectories, but each was represented by a different-shaped trajectory (see Fig. 5 of Craft et al. 1999). In the two marshes, aboveground biomass increased to levels exceeding biomass stocks in the natural marsh before declining equivalence. For MOM, the trajectory increased gradually before converging to equivalence. Zedler and Callaway (1999) and Zedler and Lindig-Cisneros (2000) supported the idea that trajectories describing marsh ecosystem development, if they exist, are better represented by non-linear rather than linear curves. At the North Carolina sites, soil organic C and N and invertebrate density also increased over time after marsh creation. But, because soils and invertebrates were sampled only two times during the 25-year period, it was impossible to determine whether the trajectories were linear (or not) for these ecological attributes.

Fifteen years of data from our created brackish-water marsh support the idea that trajectories exist for some ecological attributes and that, for attributes of biomass, the trajectories are non-linear. *Spartina cynosuroides* (aboveground biomass, MOM) and *J. roemerianus* (aboveground biomass) both exhibited non-linear trajectories that increased with marsh age before converging to equivalence (Figs. 2, b and d, and 3b). However, neither *S. alterniflora* nor *S. patens* exhibited predictable trajectories over time.

Like biomass and MOM, wetland soil characteristics also exhibited measurable trends over time (Table 1).

Soil organic C increased over time in our created brackish-water marsh, a result consistent with long-term repeated measurements from created estuarine marshes in southern California (Zedler & Callaway 1999) and North Carolina (Craft et al. 1999). However, with only two measurements during our study (1988, 1998), we were unable to determine whether the trends were linear or non-linear.

Conclusions

Vegetation and soil development of created brackish-water marshes were related to tidal inundation/soil saturation. Biomass of *Spartina alterniflora*, which grew at the lowest elevations along tidal creeks and was inundated much of the time, developed to levels similar to the natural marsh within 3 years after creation. *Spartina cynosuroides* and *Juncus roemerianus*, which grew in the marsh interior and were inundated less frequently, required 9 years to achieve equivalence to the natural marsh. *Spartina patens* biomass, which grew at the highest elevations along the upland border and was inundated infrequently, never consistently achieved equivalence to the natural marsh throughout the 15-year period of record.

Wetland soil formation was slower to develop as compared with the plant community. Like vegetation, development of wetland soil characteristics such as low bulk density and high organic C and N proceeded faster at low elevations dominated by *S. alterniflora* than at higher elevations in the marsh. Calculated rates of wetland soil development calculated based on 1988 and 1998 data indicate that the streamside and interior areas of the created marsh soil (0- to 30-cm depth) will become equivalent to the natural marsh after 70 to 90 years. Wetland soil characteristics of the *S. patens* dominated upland border will require longer to develop, more than 200 years.

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