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Porewater chemistry of natural and created marsh soils

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Abstract: Chemistry of porewaters and soils were compared in a low organic matter (1%) created marsh established on an upland site in 1983 and a high organic matter ($\approx 50\%$) natural marsh nearby to characterize the role of created wetlands in estuarine nutrient cycles. Porewater physico-chemical properties (water level, temperature, salinity, dissolved O_2 , pH, redox potential (Eh), Fe, Mn) and nutrient (organic C, N, P, NH_4 , NO_3 , PO_4) concentrations were monitored monthly for 1 yr in the two marshes. Soil nutrients (organic C, N, P), physical properties (bulk density, texture, porosity, hydraulic conductivity) and chemical characteristics (Eh , pH, Fe, Mn, Al) also were measured at the end of the study. 5 yr after emergent vegetation was established, the conversion from upland porewater and soil properties to typical wetland characteristics was incomplete. Dissolved O_2 , Eh , Fe, Mn and NO_3 -N were significantly higher in created marsh porewaters as compared to porewaters collected from the natural marsh. The created marsh also contained lower porewater dissolved organic C and N, NH_4 -N and PO_4 -P and had lower pH. Soil bulk density and extractable Fe were significantly higher, and porosity, hydraulic conductivity, pH, total organic C and N, and exchangeable NH_4 -N and NO_3 -N were lower in the created marsh than in the natural marsh soil. These results imply that mitigation of wetland disturbance by creating wetlands on graded upland sites, initially, may not duplicate the hydrologic and nutrient cycling functions associated with natural wetlands that have developed over many years.

Key words: Estuary; Mitigation; Nutrient cycling; Wetland

INTRODUCTION

Creation of wetland habitat has been used to mitigate damage to natural wetlands caused by surface-mining and development activities (Knutson et al., 1981; Lewis, 1982; Wolf et al., 1986; Zelazny & Feierabend, 1988). Emergent vegetation has been successfully established in salt-, brackish- and freshwater environments to create or restore wetland habitat (Knutson et al., 1981; Wolf et al., 1986). In some instances, upland areas have been converted to wetlands by grading the site, flooding it and planting emergent vegetation (Broome et al., 1982, 1988a,b). Occasionally, grading upland sites exposes sulfidic materials which, upon contact with air, are oxidized to acid

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sulfates such as jarosite (Broome et al., 1988a). These acid sulfate soils require extensive liming to raise the pH to levels (> 4) capable of supporting plant growth (Broome et al., 1988a). The inherent low nutrient status of subsurface upland soils also may adversely affect the success of wetland establishment on these sites. However, this problem can be remediated by application of N and P fertilizers at the time of planting (Woodhouse et al., 1974; Broome et al., 1988a,b).

Even when low soil pH and nutrient availability are successfully overcome, newly created wetlands established on upland sites may retain substratum properties typical of terrestrial soils. Upland soils are characterized by low soil organic matter content and substantial amounts of weatherable minerals such as Fe and Mn (Daniels et al., 1984). In contrast, many wetland soils contain large amounts of soil organic matter which provide a reservoir of nutrients for the wetland community (Friedman & DeWitt, 1978; Craft et al., 1988). Created wetlands established on intertidal and upland soils accumulate soil organic matter at rates comparable to natural wetlands (Craft et al., 1988). However, because of their age, these created wetlands generally do not contain as much soil organic matter and nutrients as natural wetlands (Craft et al., 1988). The large reservoir of organic matter in wetland soils also may be a source of nutrients for adjacent aquatic communities via exchange with surface waters (Nixon, 1980; Nixon & Lee, 1985; Craft et al., 1989) and porewaters within the soils (Jordan & Correll, 1985; Craft et al., 1987). The intimate relationship between soils and porewaters in wetlands suggests that the size of the soil organic matter reservoir may be an important determinant of wetland porewater nutrient chemistry.

Upland soils, particularly subsurface soils, frequently contain little or no soil organic matter and may require periodic additions of fertilizers or substantial inputs of nutrients from floodwaters to maintain the long-term viability of the created wetland. In addition, flooding upland soils may release reduced Fe and Mn into the soil solution at levels ($> 100 \text{ mg} \cdot \text{l}^{-1}$) that may be toxic to newly planted wetland vegetation (Spratt & Wieder, 1988).

As natural wetlands continue to be lost to development, uplands will increasingly be used as sites for wetland creation. The large differences in soil organic matter and Fe and Mn content between upland and wetland soils suggest that upland soils will not provide the same nutrient cycling capabilities as natural wetland soils. For this reason, we compared soil and porewater nutrient chemistry of a created marsh established on an upland site and a nearby natural marsh. Porewaters were sampled monthly for 1 yr and analysed for selected nutrients (C, N, P), metals (Fe, Mn) and physico-chemical properties to characterize the role of created wetlands in estuarine nutrient cycles.

METHODS

SITE DESCRIPTION

Porewaters and soils were sampled in a created and a nearby natural marsh on the Pamlico River estuary, near Aurora, North Carolina. The transplanted marsh was

established in 1983 by planting greenhouse-grown seedlings of *Spartina* on a 2.15-ha upland site graded to create an intertidal zone favorable for wetland vegetation (Broome et al., 1988a,b).

Three species of greenhouse-grown seedlings were transplanted in three zones; *S. alterniflora* Loisel along the stream margin, *S. cynosuroides* (L.) in the marsh interior and *S. patens* (Ait.) Muhl. along the upland margin. The natural marsh, Jacob's Creek, was characterized by distinct zones of *S. cynosuroides* (L.) along levees, a mixture of *S. patens* (Ait.) Muhl. and *Distichlis spicata* (L.) in the marsh interior and *Juncus roemerianus* Scheele in low-lying areas along the stream and in the marsh interior. The natural and created marshes had similar hydrologic and salinity regimes but differed in age and soil development (Craft et al., 1988). The created marsh soil contained $\approx 1\%$ organic matter (top 30 cm) and was classified as a Typic Psammaquent (USDA, 1975). The natural marsh soil contained $\approx 50\%$ organic matter in the top 30 cm and was classified as a Typic Medisaprism (USDA, 1975).

POREWATER COLLECTION AND ANALYSES

In 1985, 10 wells were installed in each of the natural and created marshes by excavating 7-cm diameter by 30-cm deep holes using a soil auger. A 60-cm section of PVC pipe (7 cm o.d.), with the bottom end wrapped with glass fiber cloth, was placed in each hole. The wells were capped with a PVC end fitting containing a capillary hole to allow porewaters to respond to changes in hydrostatic pressure. The soil around each well was tamped down to inhibit seepage from the surface.

Porewaters were sampled monthly for 1 yr after pumping out each well and collecting the water that moved from the soil into the well. Water level, dissolved O_2 , salinity, redox potential (Eh) and pH were measured in each well prior to sample collection. Interstitial waters were filtered through precombusted (4 h at 450 °C) Gelman type A/E glass fiber filters, acidified with 10% H_2SO_4 and analysed for dissolved organic C, dissolved N and P, NH_4 , NO_3 , PO_4 , Fe and Mn.

Temperature and dissolved O_2 were measured with a YSI model 51A dissolved O_2 meter and probe (model 5740) (Yellow Springs Instrument, Yellow Springs, Ohio). Redox potential and pH were determined with a Fisher model 640 Accumet mini pH/mV meter (Fisher Scientific, Pittsburg, Pennsylvania). Prior to the study, the Pt redox probes were calibrated in pH 4 and 7 buffers containing a small amount of quinhydrone (Bohn, 1971). Redox potential was determined by averaging readings from three probes and correcting for the potential of the calomel reference electrode. The measured Eh values were corrected for temperature but not pH. Salinity was measured using a refractometer (American Optical, Keene, New Hampshire).

Dissolved organic C was measured with a Beckman 915-B total organic C analyser after sparging the sample with N_2 to remove inorganic C. Ammonium and NO_3 were determined by the methods of Cataldo et al. (1974) and Lowe & Hamilton (1967), respectively. Phosphate was measured according to Murphy & Riley (1962). Dissolved

N and P were determined by Kjeldahl and persulfate digestion methods, respectively (APHA, 1985). Dissolved organic N and P were calculated by the difference between the total and inorganic fractions. Fe and Mn were measured by flame atomic absorption spectrometry (APHA, 1985).

SOIL SAMPLING AND ANALYSES

10 soil cores (8.5-cm diameter by 30-cm deep) were collected from each of the natural and the created marshes. Soils were air-dried, weighed, ground, passed through a 2-mm mesh diameter screen and analysed for nutrients (C, N, P), metals (Fe, Mn, Al) and other physico-chemical properties. Air-drying the soils probably altered the recovery of exchangeable nutrients and metals but not the total and extractable elements. Organic C and total N were measured with a Perkin-Elmer 2400 CHN analyser (Perkin-Elmer, Norwalk, Connecticut). Soil organic matter was calculated from the organic C data according to Craft et al. (1991). Exchangeable $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ were measured in 1 N KCl extracts (Keeney & Nelson, 1982) using the methods of Cataldo et al. (1974) and Lowe & Hamilton (1967), respectively. Total P was estimated by analysing for $\text{PO}_4\text{-P}$ in Kjeldahl digests according to Murphy & Riley (1962). This method recovered 85% ($460 \mu\text{g} \cdot \text{g}^{-1}$) of the P in NBS reference material 1646 (estuarine sediment, $540 \mu\text{g} \cdot \text{g}^{-1}$). Extractable P was determined by the double-acid ($\text{HCl-H}_2\text{SO}_4$) method (Olsen & Sommers, 1982).

Fe, Mn and Al were extracted with sodium dithionite and sodium citrate (Olsen & Ellis, 1982) and analysed by atomic absorption spectrometry. The pH was measured in a 1 : 1 soil : water volume ratio. $\text{BaCl}_2\text{-TEA}$ titrateable acidity and KCl exchangeable Al and H^+ were determined by the methods described by Thomas (1982).

Bulk density was calculated using the dry weight and volume of the soil cores. Particle density was determined by the pycnometer method (Blake, 1965). Sand, silt and clay fractions of created marsh soils were measured by the hydrometer method (Day, 1965). Lateral hydraulic conductivity was determined by placing five piezometers each in the natural and created marshes. The tips of the piezometers were milled with 1.2-cm diameter holes throughout the bottom 10 cm and capped. Hydraulic conductivity was measured quarterly for 9 months using the piezometer method (Boersma, 1965). Soil analyses, where appropriate, were expressed on a dry weight (105°C) basis. Soil redox potentials (Eh) were measured once in July 1988. Three Pt electrodes were placed 10 and 30 cm below the soil surface adjacent to each porewater sampling well. mV readings were corrected for temperature but not for pH.

RESULTS AND DISCUSSION

POREWATER CHEMISTRY

Porewaters collected from the created marsh contained significantly higher dissolved O_2 concentrations, redox potentials and lower pH than natural marsh porewaters

(Fig. 1). Porewater redox potentials were nearly 200 mV higher in the created marsh ($\bar{x} = +335$ mV) than in the natural marsh ($\bar{x} = +141$ mV). Fe and Mn concentrations were also significantly higher in porewaters of the created marsh (Fig. 2), due to formation of soluble Fe^{2+} and Mn^{2+} by submergence of this upland subsoil. The moderately reduced created marsh porewaters also had significantly higher $\text{NO}_3\text{-N}$ concentrations than the reduced soils of the natural marsh (Fig. 3). It is likely that the higher dissolved O_2 concentrations and redox potentials in created marsh porewaters contributed to higher rates of nitrification and/or lower rates of denitrification compared to the natural marsh.

With the exception of $\text{NO}_3\text{-N}$, natural marsh porewaters generally contained higher concentrations of nutrients (C, N, P) than created marsh porewaters. Dissolved organic C and N, $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ were significantly higher in porewaters of the natural marsh (Figs. 3, 4). The high concentrations of DOC, DON, $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ in natural marsh porewaters probably resulted from lower redox potentials and larger amounts of mineralizable organic C, N and P (Table I) in this reduced, organic soil. According to DeLaune et al. (1981), under oxidizing conditions, a larger fraction of the dissolved organic C in marsh porewaters is degraded to CO_2 . As redox potentials decrease, intermediate decomposition products such as organic acids are produced, resulting in an increase in the amount of DOC in porewaters. Higher redox potentials also decrease the amount of $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ in porewaters by nitrification and formation of Fe phosphates, respectively (DeLaune et al., 1981).

There was no significant difference in dissolved organic P (natural marsh = $5.0 \pm 1.2 \mu\text{mol} \cdot \text{l}^{-1}$, created marsh = $3.0 \pm 0.7 \mu\text{mol} \cdot \text{l}^{-1}$) in porewaters collected from the natural and the created marsh. Likewise, water depth (natural marsh = -1.6 ± 2.1 cm (relative to the water level in the adjacent tidal creek) created marsh = -5.5 ± 1.6 cm), temperature (natural marsh = $15.4 \pm 0.7^\circ\text{C}$, created marsh = $15.0 \pm 0.7^\circ\text{C}$) and salinity (natural marsh = $12.1 \pm 0.4\text{‰}$, created marsh = $11.8 \pm 0.4\text{‰}$) of porewaters were not significantly different in the two marshes.

Limited information is available on porewater nutrient chemistry of created wetlands. Reimold et al. (1978) monitored interstitial water nutrients in a regularly flooded marsh transplanted with *S. alterniflora* Loisel in Georgia. Concentrations of $\text{NH}_4\text{-N}$ ($5.7\text{--}22.1 \mu\text{M} \cdot \text{l}^{-1}$) and $\text{PO}_4\text{-P}$ ($1.0\text{--}13.9 \mu\text{M} \cdot \text{l}^{-1}$) were higher in this low (1%) soil organic matter marsh compared to $\text{NH}_4\text{-N}$ ($2.0\text{--}13.5 \mu\text{M} \cdot \text{l}^{-1}$) and $\text{PO}_4\text{-P}$ ($0.3\text{--}1.2 \mu\text{M} \cdot \text{l}^{-1}$) concentrations in our created marsh (soil organic matter = 1%). The low porewater $\text{PO}_4\text{-P}$ concentrations in our marsh (compared to the regularly flooded marsh studied by Reimold et al., 1978) probably is due to removal of porewater PO_4 via formation of Fe phosphates.

More information is available concerning the porewater chemistry of natural marshes (Boulegue et al., 1982; Lord & Church, 1983; Bowden, 1984; Giblin & Howarth, 1984; Jordan & Correll, 1985; Luther et al., 1986; Feijtel et al., 1988). Jordan & Correll (1985) measured concentrations of DON ($43\text{--}64 \mu\text{M} \cdot \text{l}^{-1}$) and $\text{NH}_4\text{-N}$ ($14\text{--}19 \mu\text{M} \cdot \text{l}^{-1}$) in a tidal brackish-water marsh that were comparable to concentrations

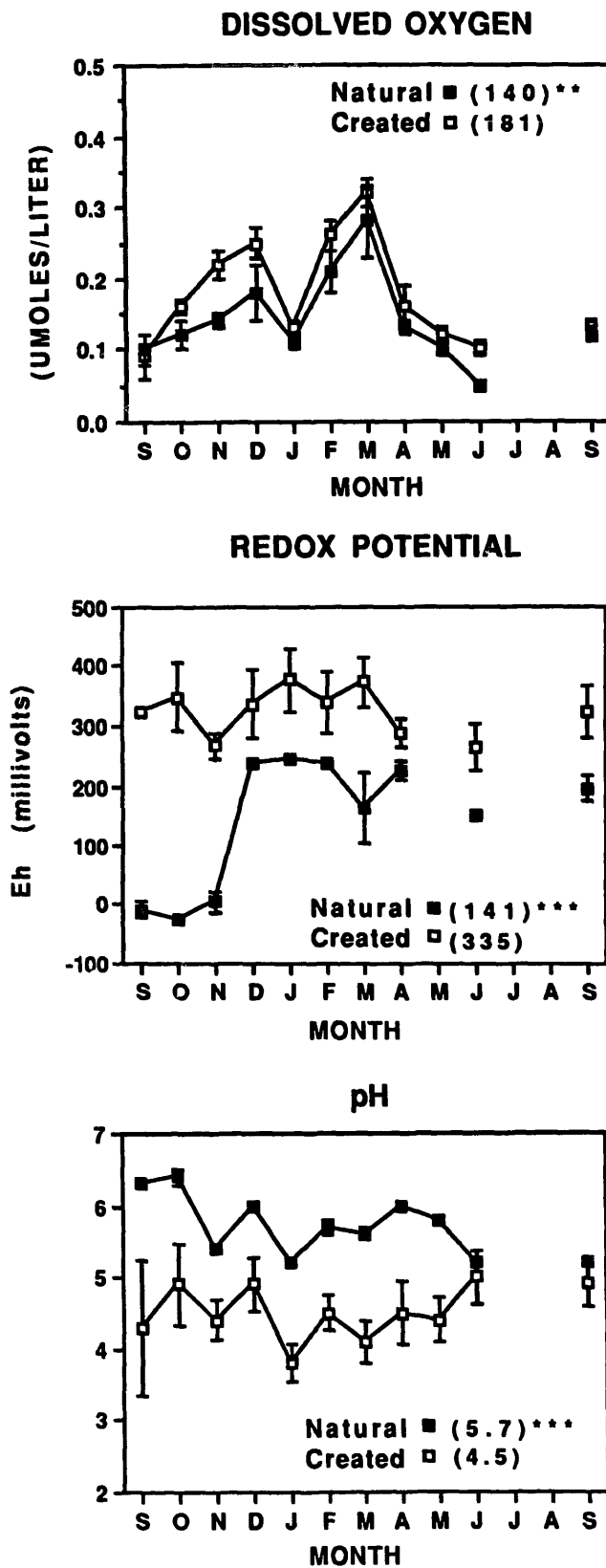


Fig. 1. Mean monthly dissolved O_2 , redox potential and pH of natural and created marsh porewaters. Mean values are in parentheses (***, **, significant according to Student's *t* test at 0.001 and 0.01 levels, respectively; NS, nonsignificant). I, SE of monthly \bar{x} value.

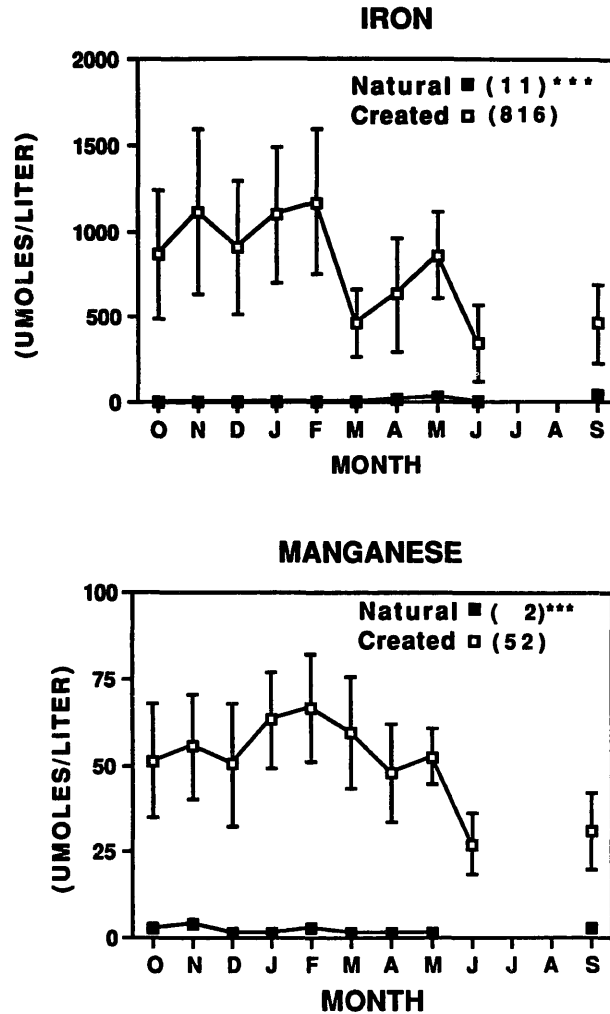


Fig. 2. Mean monthly Fe and Mn of natural and created marsh porewaters. Mean values are in parentheses. See Fig. 1 for an explanation of ***, **, NS and I.

(DON = 53–130 $\mu\text{M} \cdot \text{l}^{-1}$, $\text{NH}_4\text{-N}$ = 8–63 $\mu\text{M} \cdot \text{l}^{-1}$) found in this study. However, $\text{PO}_4\text{-P}$ concentrations (11.9–24.9 $\mu\text{M} \cdot \text{l}^{-1}$) were higher than those reported here ($\text{PO}_4\text{-P}$ = 1.3–9.1 $\mu\text{M} \cdot \text{l}^{-1}$). Phosphate-P concentrations (1–90 $\mu\text{M} \cdot \text{l}^{-1}$) also were higher in regularly flooded marsh porewaters compared to our irregularly flooded marsh while $\text{NH}_4\text{-N}$ (7–80 $\mu\text{M} \cdot \text{l}^{-1}$) concentrations were similar (Bowden, 1984; Giblin & Howarth, 1984; Lord & Church, 1983). In contrast, concentrations of DOC were much lower in a regularly flooded *S. alterniflora* Loisel marsh (3–14% soil organic matter) in southeastern North Carolina (0.14–0.31 $\text{mM} \cdot \text{l}^{-1}$; Yelverton & Hackney, 1986) compared to our natural marsh (0.86–2.06 $\text{mM} \cdot \text{l}^{-1}$). The low porewater DOC concentrations in the regularly flooded marsh probably are a result of increased tidal flushing and lower amounts of mineralizable soil organic matter.

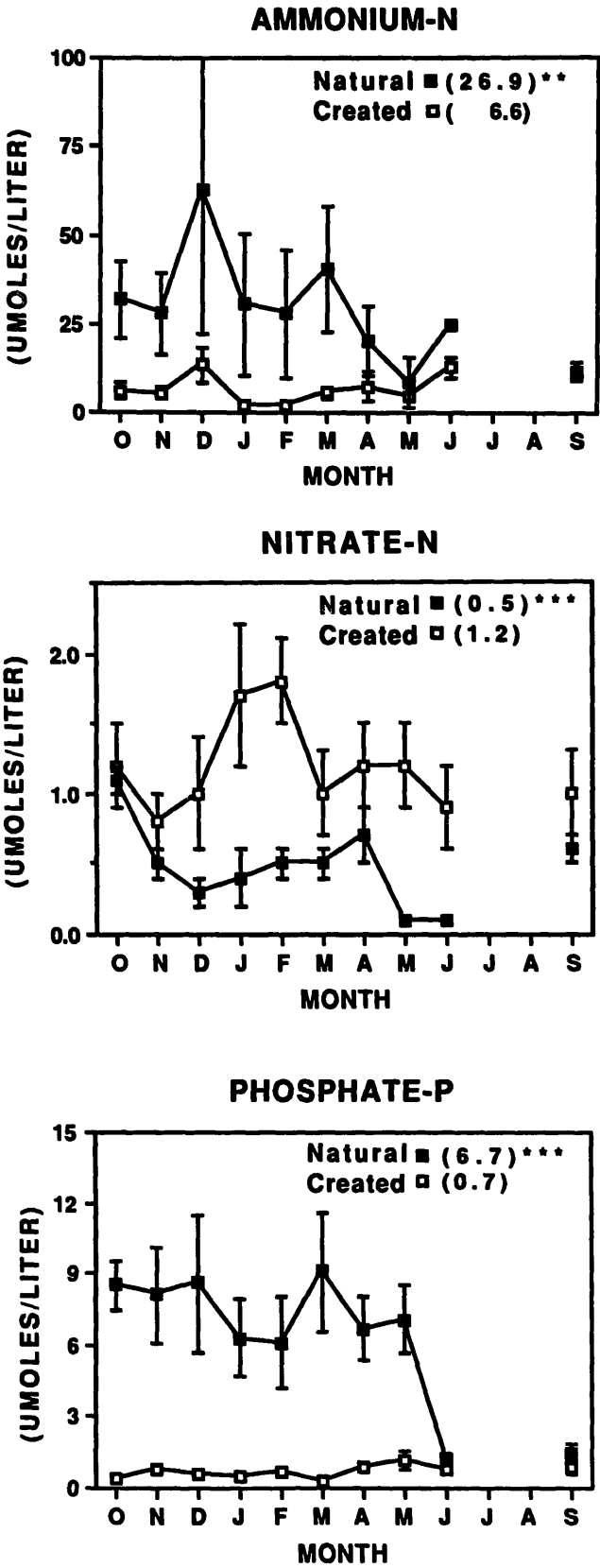


Fig. 3. Mean monthly ammonium-N, nitrate-N and phosphate-P of natural and created marsh porewaters. Mean values are in parentheses. See Fig. 1 for an explanation of ***, **, NS and I.

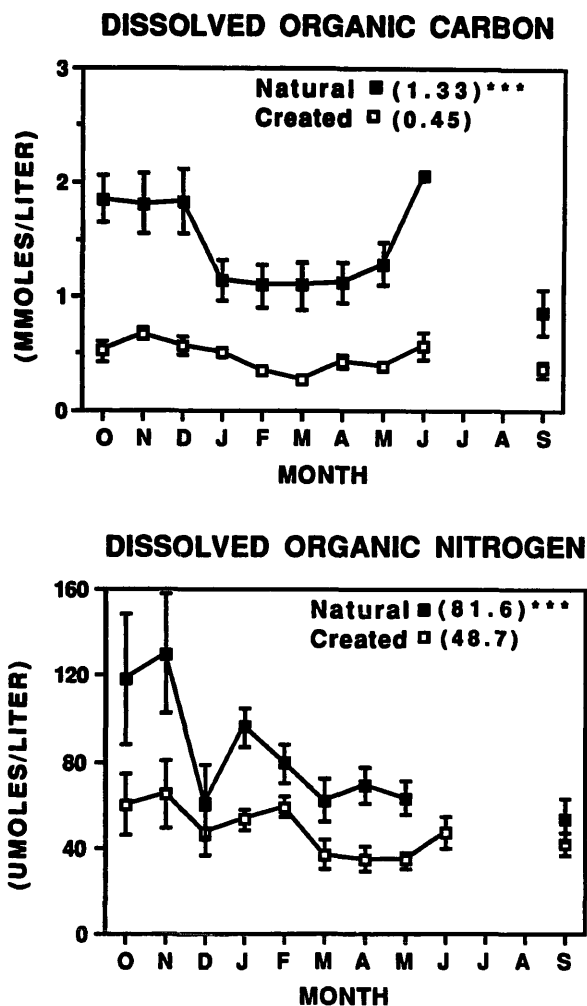


Fig. 4. Mean monthly dissolved organic C and N of natural and created marsh porewaters. Mean values are in parentheses. See Fig. 1 for an explanation of ***, **, NS and I.

SOIL CHARACTERIZATION

Porewater nutrient concentrations reflected the amount of organic matter in the natural and created marsh soils. The high organic matter content (45.5%) natural marsh soils contained high concentrations of porewater C, N and P while Fe was the major constituent in porewaters of the low organic matter (0.6%) created marsh soils (Figs. 2–4). Soil organic C and N and exchangeable $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ pools were significantly larger in the natural marsh (Table I). The natural marsh also had significantly lower bulk and particle densities than the created marsh, resulting in higher porosity and lateral hydraulic conductivity.

There was a gradient of decreasing hydraulic conductivity from the creek bank towards the interior of the natural marsh. Conductivities were highest along the marsh edge ($22.46 \pm 6.14 \text{ cm} \cdot \text{h}^{-1}$) and lowest in the *Juncus* dominated interior ($0.75 \pm 0.52 \text{ cm} \cdot \text{h}^{-1}$). Although there was no clear gradient in the created marsh, the

TABLE I

Mean physico-chemical properties (± 1 SE) of a natural and a created marsh soil ($n = 10$).

| | Natural | Created |
|--|------------------|----------------|
| Bulk density ($\text{g} \cdot \text{cm}^{-3}$) | 0.20 (<0.01) | 1.35 (0.03)*** |
| Particle density ($\text{g} \cdot \text{cm}^{-3}$) | 1.49 (0.06) | 2.64 (0.02)*** |
| Porosity (%) | 86.7 (<0.01) | 48.8 (0.01)*** |
| Hydraulic conductivity ($\text{cm} \cdot \text{h}^{-1}$) | 15.1 (3.88) | 1.0 (0.20)** |
| Texture | | |
| Organic matter (%) | 45.5 | 0.6 – |
| Sand (%) | – ¹ | 84.5 – |
| Silt (%) | – | 9.1 – |
| Clay (%) | – | 6.4 – |
| Organic C ($\text{kmol} \cdot \text{ha}^{-1}$) | 11678 (601) | 886 (100)*** |
| Organic N ($\text{kmol} \cdot \text{ha}^{-1}$) | 656 (25) | 41 (6)*** |
| Atomic C:N (wt:wt) | 15.1 (0.4) | 20.1 (3.2) NS |
| Exchangeable $\text{NH}_4\text{-N}$ ($\text{kmol} \cdot \text{ha}^{-1}$) | 3.17 (0.12) | 1.76 (0.17)*** |
| Exchangeable $\text{NO}_3\text{-N}$ ($\text{kmol} \cdot \text{ha}^{-1}$) | 0.20 (0.03) | 0.07 (0.01)** |
| Total P ($\text{kmol} \cdot \text{ha}^{-1}$) | 17.6 (1.1) | 14.7 (1.5) NS |
| Extractable P ($\text{kmol} \cdot \text{ha}^{-1}$) | 0.5 (0.05) | 0.6 (0.05) NS |
| <i>Eh</i> (10 cm) | 268 (20) | 238 (72) NS |
| <i>Eh</i> (30 cm) | – 68 (41) | 154 (67) NS |
| pH | 4.5 (<0.1) | 4.2 (0.1)* |
| Titrateable acidity ($\text{kmol} \cdot \text{ha}^{-1}$) | 248 (16) | 417 (51)** |
| Exchangeable H ($\text{kmol} \cdot \text{ha}^{-1}$) | 0.07 (0.03) | 0.29 (0.21) NS |
| Exchangeable Al ($\text{kmol} \cdot \text{ha}^{-1}$) | 2.6 (0.3) | 4.4 (1.4) NS |
| Extractable Al ($\text{kmol} \cdot \text{ha}^{-1}$) | 0.5 (0.02) | 0.6 (0.07) NS |
| Extractable Fe ($\text{kmol} \cdot \text{ha}^{-1}$) | 14.0 (0.9) | 33.8 (5.9)** |
| Extractable Mn ($\text{kmol} \cdot \text{ha}^{-1}$) | 0.4 (0.2) | 0.1 (0.02) NS |

***, **, * Significant according to Student's *t* test at 0.001, 0.01 and 0.05 levels, respectively; NS, non-significant. ¹ Organic soil. Texture was not measured.

marsh interior (also dominated by *Juncus*) had the lowest hydraulic conductivity ($0.35 \pm 0.15 \text{ cm} \cdot \text{h}^{-1}$).

The hydraulic conductivity of the natural marsh soil ($15.09 \text{ cm} \cdot \text{h}^{-1}$) was relatively higher compared to the conductivity of a marsh peat on the Chesapeake Bay ($3.53 \text{ cm} \cdot \text{h}^{-1}$; Harvey et al., 1986). However, the created marsh soil had conductivities ($0.99 \text{ cm} \cdot \text{h}^{-1}$) similar to the values reported by Harvey et al. (1986) in mineral material underlying the peat ($0.19\text{--}0.31 \text{ cm} \cdot \text{h}^{-1}$) and by Yelverton & Hackney (1986) in a low soil organic matter marsh in North Carolina ($1.08 \text{ cm} \cdot \text{h}^{-1}$). The large volume of pores (87%) in the natural marsh probably accounted for the high lateral conductivity in this soil.

Because of its young age and the manner in which it was created (excavation into the subsoil), the created marsh soil was dominated by mineral material, primarily sand sized particles (Table I). Soil organic C and N pools in the created marsh were only 6–8% of those in the natural marsh pools. Soil pH was significantly lower and titrateable

acidity and extractable Fe were higher in the created marsh compared to the natural marsh. The differences in pH, titrateable acidity and extractable Fe between the two marshes reflect the different origins and ages of the two marshes. The created marsh was established in 1983 on an upland site. Upland soils in eastern North Carolina contain larger amounts of weatherable minerals (Fe, Mn) and acidity than estuarine wetland soils (Daniels et al., 1984). Because the created marsh has been flooded only recently (compared to the natural marsh), leaching processes as influenced by soil reduction are incomplete so the soil still retains some of its upland characteristics. In contrast, the natural marsh is several thousand years old (a nearby natural marsh (Jack's creek) was dated at 2670 ± 105 yr; Bellis & Gaither, 1985) and, 2–3 m of organic soil now overlies the sandy coastal plain sediments. During the past 2000–3000 yr, the natural marsh has evolved from an upland forest, through a succession of plant communities, to a brackish-water marsh dominated by *Juncus*, *Distichlis* and *Spartina* sp. In effect, creating a wetland by grading an upland site to intertidal elevation represents a quantum jump in sea level which short circuits the evolutionary development of coastal marshes. For this reason, it is likely to take many years before the created marsh soil resembles the natural marsh soil.

Although not significantly different, redox potential (10–30 cm depth), exchangeable H and Al and extractable Al were higher in the mineral soils of the created marsh (Table I). Again, the higher *Eh*, Al and H probably reflect the upland origins of the created marsh soil. There also was no difference in total and extractable P pools in the created and natural marsh soils. Presumably, most of the P in the natural marsh is organically bound while soil P in the created marsh is associated with low solubility Fe-P compounds.

In conclusion, the created marsh established on a graded upland site retained soil physico-chemical properties characteristic of terrestrial soils. 5 yr after creation of the brackish-water marsh, the underlying soils had significantly higher bulk and particle densities, titrateable acidity and extractable Fe compared to a nearby natural marsh. Porosity, hydraulic conductivity, pH and soil organic C and N were significantly lower in the created wetland soil compared to the organic natural marsh soil. The high mineral content of the created marsh soil resulted in significantly higher porewater Fe, Mn and $\text{PO}_4\text{-P}$ and lower dissolved organic C and N, and $\text{NH}_4\text{-N}$. Redox potentials, dissolved O_2 , $\text{NO}_3\text{-N}$ also were higher in created marsh porewaters and pH was lower as a result of the young age and history of the site as an upland soil.

Wetlands created on upland sites possess soil properties that are different from natural marshes during the early years after creation. Many substratum properties characteristic of wetland soils (reducing conditions, high soil organic matter and nutrient content, increased porosity and hydraulic conductivity) may be absent initially. Furthermore, terrestrial soil properties (low soil organic matter, high bulk density, Fe, Mn) associated with graded upland sites may adversely affect the successful establishment of emergent vegetation and the ability of these systems to provide hydrologic and nutrient cycling functions characteristic of wetland ecosystems. It is likely to take many

years before the created wetland soils become reduced and, soil and porewater nutrient reservoirs develop to produce hydrologic and nutrient cycling attributes comparable to natural wetlands.

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