

Effects of nutrient loading on the carbon balance of coastal wetland sediments

Abstract—Results of a 12-yr study in an oligotrophic South Carolina salt marsh demonstrate that soil respiration increased by $795 \text{ g C m}^{-2} \text{ yr}^{-1}$ and that carbon inventories decreased in sediments fertilized with nitrogen and phosphorus. Fertilized plots became net sources of carbon to the atmosphere, and sediment respiration continues in these plots at an accelerated pace. After 12 yr of treatment, soil macroorganic matter in the top 5 cm of sediment was 475 g C m^{-2} lower in fertilized plots than in controls, which is equivalent to a constant loss rate of $40 \text{ g C m}^{-2} \text{ yr}^{-1}$. It is not known whether soil carbon in fertilized plots has reached a new equilibrium or continues to decline. The increase in soil respiration in the fertilized plots was far greater than the loss of sediment organic matter, which indicates that the increase in soil respiration was largely due to an increase in primary production. Sediment respiration in laboratory incubations also demonstrated positive effects of nutrients. Thus, the results indicate that increased nutrient loading of oligotrophic wetlands can lead to an increased rate of sediment carbon turnover and a net loss of carbon from sediments.

Many coastal areas are vulnerable to the direct effects of global warming, depending on the ability of coastal wetlands to accumulate sediment and maintain elevation relative to rising sea level. The preservation and accumulation of organic carbon in sediments is recognized to be an important mechanism by which many coastal wetlands keep pace with rising sea level (Redfield and Rubin 1962; Hatton et al. 1983). Organic carbon in the form of peat is thought to accumulate in wetland soils because anaerobic microorganisms appear to be more limited in their ability to attack lignocelluloses than their aerobic counterparts in terrestrial environments (Young and Frazer 1987). However, as lignocelluloses are biodegradable under anoxic conditions (Benner et al. 1984), anoxia appears to be a necessary but insufficient condition for peat accumulation. Furthermore, wetlands with characteristically anoxic soils or sediments display a wide range of concentrations of soil organic matter, which suggests that control of carbon storage is far more complex than the availability of oxygen.

Low nutrient loadings are a characteristic of many peat-accumulating wetlands such as ombrotrophic bogs and pocosins (Press et al. 1986; Mitsch and Gosselink 1993), which suggests that nutrient availability may be a determinant of organic carbon preservation. Support of a connection between carbon preservation and nutrient loading is found in research that demonstrates that the initial decomposition rate of plant litter is most rapid in tissues having high nitrogen:lignin ratios (Melillo et al. 1982) and that litter decomposition rate is affected by site fertility (Fenn 1991; Royer and Minshall 1997; Thormann and Bayley 1997). Moreover, nitrogen can greatly enhance the degradation of lignin by soil microorganisms (Aumen et al. 1983; King et al. 1983; Blanchette 1991; Worrall and Wang 1991). However, the net car-

bon balance of soils is the product of a complex set of parallel processes with both positive and negative effects, and the net effect on the carbon balance of organic-rich soils is unknown. For example, increased nutrient loading decreases the proportion of production allocated to roots (Ågren and Ingestad 1987; Levin et al. 1989) and may increase the mineralization of organic carbon, but it also stimulates total primary production.

An experiment to test the effects of increased nutrient loadings on the carbon balance of sediments was begun in an oligotrophic salt marsh at North Inlet, South Carolina. North Inlet estuary is nutrient poor due to its geomorphological setting, and primary production in its salt marshes is nitrogen limited (Morris 1988). Surface-water inputs to the estuary are minimal ($\approx 3\%$ of the tidal exchange) from a forested 75-km^2 watershed. Consequently, terrigenous nutrient inputs are insignificant. Permanent experimental plots have been fertilized monthly in North Inlet during the growing season with 30 mol N and $15 \text{ mol P m}^{-2} \text{ yr}^{-1}$ since 1984.

North Inlet salt marshes are dominated by a monoculture of the grass *Spartina alterniflora*. Aboveground primary production of *S. alterniflora* has been measured on permanent control and fertilized plots using a nondestructive census technique (Morris and Haskin 1990). Mean aboveground dry matter production, based on measurements made in six plots per treatment from 1985 through 1996 ($n = 72$), increased in fertilized plots to $3,280 \pm 300 \text{ g m}^{-2} \text{ yr}^{-1}$ ($\pm 1 \text{ SE}$) from $780 \pm 50 \text{ g m}^{-2} \text{ yr}^{-1}$ in control sites.

Pore-water nutrients and chlorinity were measured monthly from December 1993 through December 1997 using diffusion samplers left in the sediment at depths of 10, 25, and 50 cm to equilibrate for a period of 1 month. Geometric mean pore-water chlorinities in control and fertilized treatments were similar (13 g liter^{-1} in control sites and 12 g liter^{-1} in fertilized sites), which indicates that the increased productivity and, by extension, evapotranspiration on fertilized sites has not dewatered the sediments.

Fertilization of experimental plots has raised the geometric mean pore-water concentrations (average of monthly samples collected at 10, 25, and 50 cm) of NH_4^+ to $120 \mu\text{M liter}^{-1}$ ($n = 430$) from $33 \mu\text{M liter}^{-1}$ ($n = 890$) and dissolved reactive phosphorus (DRP) to $35 \mu\text{M liter}^{-1}$ from $1.3 \mu\text{M liter}^{-1}$. These concentrations from fertilized plots are well within the range of nutrient concentrations seen in eutrophic estuarine surface waters (e.g., Samuels and Mason 1997) and are similar to nutrient levels we have observed in eutrophic salt marshes around Charleston Harbor, South Carolina. Salt marshes there had geometric mean pore-water NH_4^+ and DRP concentrations (average of monthly samples collected at 10, 25, and 50 cm) of $139 \mu\text{M liter}^{-1}$ ($n = 846$) and $35 \mu\text{M liter}^{-1}$ ($n = 704$), respectively. Thus, while the rates of application of N and P to fertilized plots at North Inlet are very high, the resultant pore-water concentrations of N and P are not unusual.

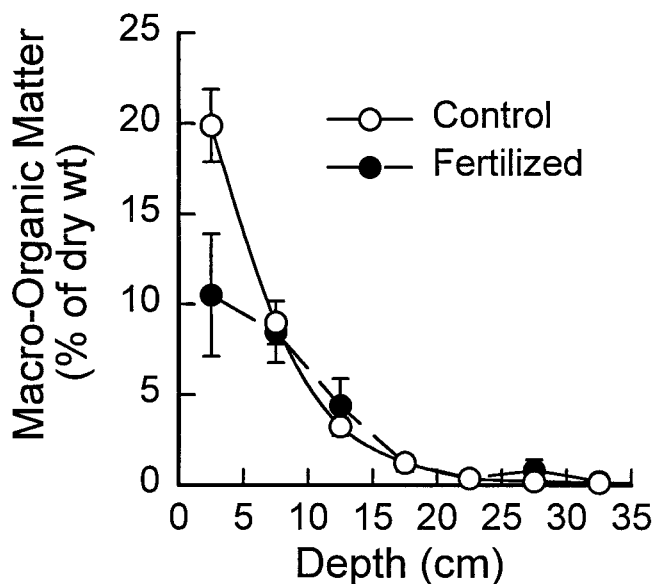


Fig. 1. Depth profiles of total macroorganic matter, as a percent of total dry sediment weight, from control ($n = 5$) and fertilized sites ($n = 5$) in a North Inlet, South Carolina, marsh. Fertilized and control sites are the same as those in Table 1. Macroorganic matter was defined as organic material retained on a 1-mm sieve and was combusted to correct for ash weight. Cores were collected during June 1996.

Soil cores taken from this experimentally fertilized site at North Inlet during 1996 showed that there has been an absolute decrease in soil carbon in the top 5 cm that is largely attributable to a decline in macroorganic matter (Fig. 1). Macroorganic matter in the top 5 cm declined from $1,201 \pm 57 \text{ g C m}^{-2}$ in control sites to $726 \pm 187 \text{ g C m}^{-2}$ in fertilized sites ($P < 0.04$). These fertilized sites have also demonstrated relatively higher rates of sediment respiration throughout the experiment (Table 1), but it is not known if soil carbon continues to decline.

Several factors could modify the profile of sediment organic matter, including a change in sedimentation rate. The surface elevation of the long-term fertilized sites has increased relative to control sites by about 1 cm due to an initial pulse in sediment accretion. Monthly measurements of the surface elevations of newly established (June 1996) fertilized and control sites indicate that their relative elevations diverged rapidly during the second year of treatment. By August 1997, the surface of fertilized plots had gained an average of 0.83 cm in elevation relative to controls, a difference that has since remained stable. The initial pulse of sediment accretion in the fertilized plots was probably due to a positive effect on sediment trapping by aboveground biomass, which increased rapidly in the second year (e.g., Morris 1988). Dilution by this small increment in sediment accretion in fertilized plots cannot account for the decline in concentration of organic carbon in sediments to the extent that has been observed. For example, a 1-cm deposit of organic-free sediment could reduce the macroorganic matter content of the top 5 cm of sediment by about one-fifth, or from 20 to 16%, but not from 20 to 10% (Fig. 1). Moreover,

Table 1. Mean sediment respiration ($\text{ml m}^{-2} \text{ h}^{-1}$ of CO_2 , $\pm 1 \text{ SE}$) in control and fertilized plots from South Carolina marsh treated with N and P since 1984. Fertilized sites differ significantly from control sites ($P < 0.03$, $n = 110$).

Date of measurement	Control sites	Fertilized sites
Aug 1985	434 ± 175	669 ± 143
Nov 1985	54 ± 5	206 ± 42
Feb 1986	63 ± 12	94 ± 18
Apr 1986	621 ± 91	925 ± 126
Jul 1992	115 ± 22	236 ± 95
Aug 1996	90 ± 13	217 ± 46

the actual reduction by this mechanism should be less than one-fifth, because belowground production would contribute organic matter to the surface sediment following the pulse.

Other factors that may modify the sediment organic matter profile are changes in the rates of production and loss of organic carbon. In situ rates of soil respiration, measured periodically as the accumulation of CO_2 into the headspace of static chambers (Morris and Whiting 1986), were consistently higher in fertilized plots than in control plots by an average of 115% (Table 1). The respiratory loss of carbon from fertilized sediments exceeded that from control plots by $795 \text{ g C m}^{-2} \text{ yr}^{-1}$. This additional respiratory loss of soil carbon from fertilized plots was far greater than the cumulative 475 g C m^{-2} decline in soil macroorganic matter that occurred over 12 yr. Thus, an increase in primary production largely accounts for elevated rates of soil respiration. Nevertheless, there has been a net decline in carbon storage in the fertilized sites.

The increase in soil respiration in the fertilized plots may reflect an increase in primary production and turnover of soil carbon, a change in the proportions of labile and refractory carbon produced, or a change in the stability of "refractory" carbon (Fig. 2). Changes in belowground production are probably more significant to soil respiration than changes in leaf production, because tidal export of surface litter removes much of the aboveground production. Fertilization has a greater effect on production of *Spartina* leaf biomass than belowground biomass, but total belowground production can still vary by a factor of ~ 3 over an extreme range of nutrient supply (Morris 1982).

Sediment respiration from control sites was also increased when sediment samples incubated in the laboratory were enriched with nutrients. Sediment taken from the top 5 cm of control plots was divided, with half serving as an unamended control, while the other half was amended with $(\text{NH}_4)_2\text{HPO}_4$ to bring the pore-water concentration to $4.8 \text{ mM liter}^{-1}$. CO_2 evolution from nutrient-amended vials ($71 \pm 25 \mu\text{l g}^{-1} \text{ d}^{-1}$ [$\pm 1 \text{ SD}$]) was significantly ($P = 0.02$) greater than from controls ($51 \pm 14 \mu\text{l g}^{-1} \text{ d}^{-1}$). This observation suggests that exogenous nutrient availability to the microbial population is a limiting factor for decomposition at this oligotrophic site and that the response does not depend exclusively on a change in the chemical quality of the organic matter that is produced (e.g., a greater nitrogen concentration in plant tissue).

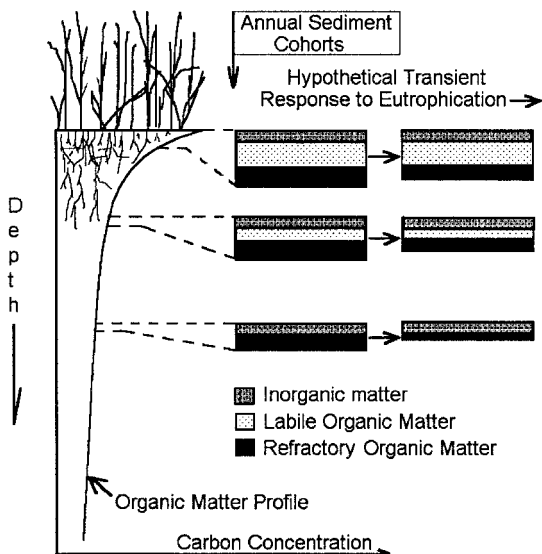


Fig. 2. Sediments can be viewed conceptually as consisting of a stack of annual cohorts that are formed at the surface and are buried over time by subsequent cohorts (Morris and Bowden 1986). The cohort at the sediment surface is formed from live roots, sedimentary inputs, and additions of labile and refractory organic carbon from root turnover and leaf litter. Over time, there are additional, but diminishing, inputs from roots, and eventually, the cohort stabilizes as a combination of inorganic matter and refractory carbon. In steady state, the profile of sediment organic matter will decline asymptotically to a minimum that is determined by the sum total of all refractory carbon inputs as the cohort passes through the root zone. A hypothetical response to an increase in nutrient loading shows a change in litter quality at the surface (an increase in the fraction of labile carbon) and a transient decrease in the quantity of "old" refractory carbon at depth, which shifts the carbon profile to a new trajectory.

Differences in sediment respiration rates between salt marshes may also be attributable to nutrient loading. For example, a Danish salt marsh had about twice the soil respiration rate of the North Inlet salt marsh (Morris and Whiting 1986; Morris and Jensen 1998), even though South Carolina experiences a warmer climate, and both marshes are dominated by *Spartina* grasses. Sediment respiration was measured in the field in both marshes using the same static chamber technique as that described above. Pore-water nutrient concentrations in the Danish marsh (Jensen et al. 1985) are typically one to two orders of magnitude greater than what we observed at North Inlet, which is consistent with the higher Danish respiration rate. The ammonium concentration in the Danish marsh exceeds even that observed in fertilized plots at North Inlet.

The differences in in situ respiration rates that were observed in Danish and North Inlet marshes were duplicated in the laboratory. Three replicate 20-g samples of wet sediment from each of these marshes were added to 200-ml sterile Erlenmeyer flasks with 100 ml of distilled H₂O and stoppered, and five headspace samples were analyzed for CO₂ by gas chromatography (thermal conductivity detector) during an 80-h incubation. Sediment samples used in these incubations contained about 3–5% carbon and had similar

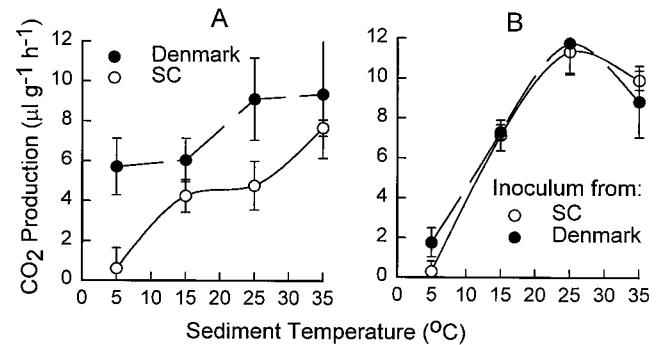


Fig. 3. Mean rates of CO₂ production (± 1 SD, $n = 3$) from sediment slurries made from samples collected from salt marshes at Skallingen, Denmark, and North Inlet, South Carolina. Slurries were incubated at the temperatures shown. The respiration rate of native sediments is shown in (A), while the respiration rate of a common, sterile substrate (autoclaved sediment from North Inlet) inoculated with sediment from Skallingen and North Inlet is shown in (B). No significant CO₂ production was observed in duplicate killed control microcosms prepared for each sediment at each incubation temperature.

bulk densities and porosities. Danish sediments had higher rates of CO₂ production at all temperatures tested (Fig. 3A). When a common, sterilized sediment (from North Inlet) was inoculated with sediment from either source, the CO₂ production was independent of the source of inoculum (Fig. 3B). This lab experiment demonstrated that the respiration rate differs between sites because of a difference in the availability of substrate, perhaps related to nutrient availability, rather than a difference in microbial community structure or effects of soil physical properties.

A large global increase in the flux of reactive forms of N and P to natural ecosystems is occurring (Vitousek et al. 1997), and this is reflected in increased nutrient concentrations in surface waters and estuaries (Smith et al. 1987). Coastal wetlands are particularly susceptible to these increased nutrient loadings, because they typically occupy the interface where surface water and groundwater discharge into the sea. Changes in the large refractory pool of carbon in wetland soils have broader significance than coastal land loss. Wetlands, including peatlands, contain a large inactive pool of soil carbon that is roughly equivalent to the carbon content of the atmosphere (Sundquist 1993). Any change in the mobility of this carbon or of the carbon balance of peat soils would have important implications for global climate.

Increased nutrient loading may change the storage of soil carbon because of effects on (1) the stability of the existing refractory carbon pool, (2) the decay rate of labile organic carbon, (3) primary production, or (4) the allocation ratio between above- and belowground plant production. From the standpoint of sediment accretion and the carbon balance of wetland soils, it is important to determine which of these responses is most sensitive to nutrients. Of the possible responses, the first is perhaps the most significant, as it can quickly reduce the existing standing stock of soil carbon. Responses 2, 3, and 4 should affect the future carbon balance of soils, but they would have the least effect on existing standing stocks. To date, our data show that fertilization of

an oligotrophic salt marsh has significantly reduced the carbon standing stock and increased the turnover rate of soil carbon, which indicates that increased nutrient loadings could result in a net transfer of soil carbon to the atmosphere from organic-rich soils. This has important implications for global climate, to the extent that eutrophication may alter the carbon balance of wetland soils generally, and for maintenance of coastal wetlands threatened by rising sea level.

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