

water was significantly greater in the salt-water treatments than in the fresh-water treatments ($P < .05$, t -test) (data not shown). Also, the ratio of free to exchangeable ammonium at the end of the study was significantly greater in the salt-water treatments ($P < .01$, t -test) (data not shown). This suggests that salt intrusion significantly affects nitrogen cycling in estuarine sediments and that differences between the fresh-water treatments and salt-water treatments in Figure 1c, d, and e are real.

There was no notable difference in the amount of total inorganic nitrogen between the fresh-water oxic treatments and the fresh-water anoxic treatments (Fig. 1e). There was a difference between the salt-water treatments: a net inorganic nitrogen gain in the anoxic sediments and a net loss in the oxic sediments (Fig. 1e). Although this difference could not be statistically evaluated, it appears that denitrification was more important in the salt-water treatments than in the fresh-water treatments. These results are contrary to those of Seitzinger *et al.* (5), who suggested that denitrification is greater in fresh water. Future study should include direct, repeated measurements of denitrification, to better understand differences in the effects of the variation of salinity on denitrification.

The results of this study suggest that salinity had a major influence on the distribution and fate of nitrogen remineralized in benthic sediments. The "salt effect" that we observed appeared to be an increase in the ratio of free to exchangeable

ammonium, which supports observations of Gardner *et al.* (3). In addition, a subsequent effect of increased salinity appeared to be an increased DIN flux to the overlying water. This result is consistent with previous observations in the Parker River Estuary where ammonium fluxes were unusually high (relative to sediment remineralization) when porewater experienced large increases in salinity during the summer. Therefore, it appears that this high ammonium flux represented not only current remineralization, but also ammonium originally stored on the sediment exchange complex.

This research was partially supported by grants from WHOI Sea Grant, the Plum Island Sound LMER, the Sweetwater Trust, and the NSF-REU Boston University Marine Program.

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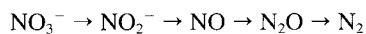
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Release of N₂ and N₂O from Salt-Marsh Sediments Subject to Different Land-Derived Nitrogen Loads

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Coastal systems receive the highest loading of anthropogenic nutrients in the world (1, 2). Denitrification (DNF), the microbial respiration of nitrate (NO₃⁻) to gaseous end products, occurs in sediments of salt marshes fringing estuaries, and provides a nitrogen sink that reduces land-derived N loading to estuarine waters. The reduction process



can result in the release of nitrous oxide (N₂O), as well as nitrogen gas. This so-called incomplete DNF has global implications, because N₂O is a trace greenhouse gas that can consume stratospheric ozone.

We used the acetylene inhibition technique (3) to measure rates of DNF in three estuaries —Childs River (CR), Quashnet River (QR), and Sage Lot Pond (SLP)—in the Waquoit Bay, Massachusetts, watershed. The estuaries receive N loads of 624,

520, and 64 kg N ha⁻¹y⁻¹, respectively, and hence provide the opportunity to see if DNF varies in salt marshes exposed to different regional-scale regimes of land-derived N inputs.

To assess whether the local availability of NO₃⁻ altered potential rates of DNF, different concentrations of NO₃⁻ (ranging from 0–5 mM) were added to three replicate bottles containing 2 ml of a slurry of sieved marsh sediment collected from the top 5 cm at each of three sites in each estuary, and 2 mM glucose amended site-specific water. The headspace was purged with helium, and each NO₃⁻ treatment was run in triplicate with and without acetylene (C₂H₂), which blocks the enzyme that reduces N₂O to N₂. The N₂O produced in the presence of C₂H₂ represents the total potential DNF. The N₂ produced was calculated as the difference between total potential DNF and N₂O production in the absence of C₂H₂. After a 5–6 h incubation, N₂O production was quantified using a Shimadzu gas chromatograph with an electron capture detector.

Rates of total potential DNF and N₂O production exhibited Michaelis-Menten saturation kinetics with increased NO₃⁻ additions (data not shown). The saturation rates (V_{max}) of both total potential DNF and N₂O production increased as the land-derived

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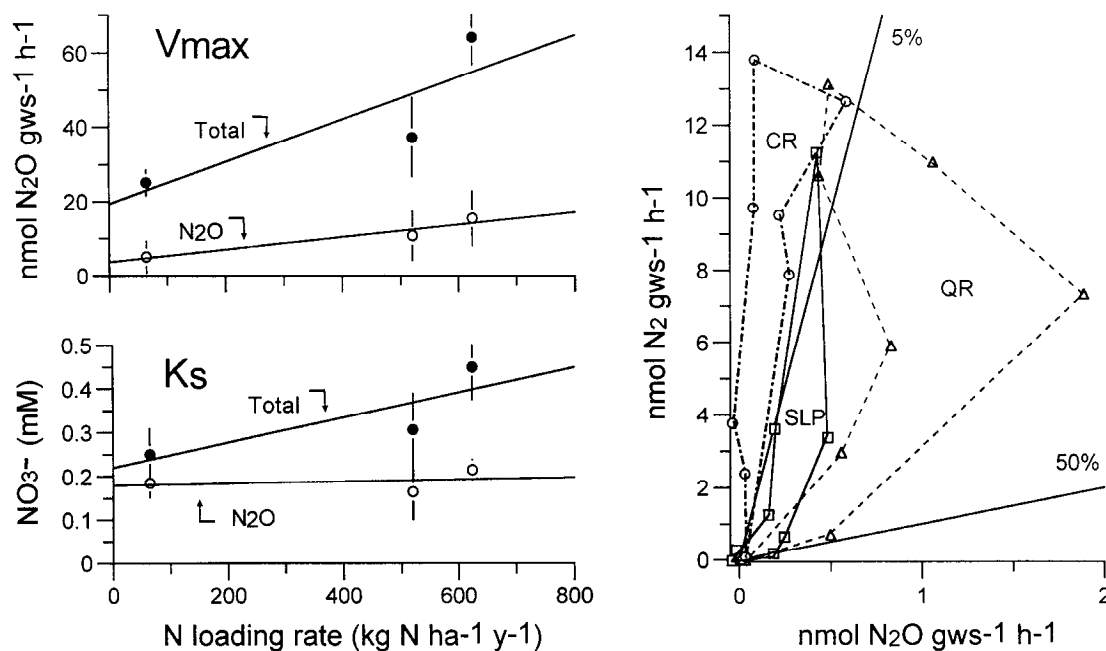


Figure 1. Top left: Relationship of saturation rates (V_{max}) of total potential DNF ($y = 0.057x + 19.299$, $r^2 = 0.715$) and N_2O production ($y = 0.017x + 3.669$, $r^2 = 0.915$) in fringing salt-marsh sediments, relative to N load. Bottom left: Relationship of half saturation constants (K_s) of total potential DNF ($y = 0.000x + 0.220$) and N_2O production ($y = 0.000x + 0.179$) to N load. Right: N_2 vs. N_2O production in Waquoit Bay estuaries—CR: Childs River, QR: Quashnet River, and SLP: Sage Lot Pond. Data includes only additions of 0–1 mM NO_3^- . Whole lines show where values might fall if ratios of N_2 to N_2O are 5% and 50%. Dashed lines circumscribe values for the three estuaries.

N load increased (Fig. 1, top left). The half saturation constant (K_s) from total potential DNF also increased with loading, whereas the K_s of N_2O production did not change (Fig. 1, bottom left).

The relative release of N_2 and N_2O from these salt marsh sediments changed with the amount of experimentally added NO_3^- and with the load of land-derived N (Fig. 1, right). We plotted N_2 and N_2O production only for measurements done at lower NO_3^- additions (<0.1 mM NO_3^-), emulating *in situ* concentrations (4). Previously reported measurements of $N_2O:N_2$ in marine and freshwater sediments are usually <5% (4). The N_2O and N_2 released from Waquoit salt-marsh sediments spanned a wide range. All the N_2O to N_2 ratios for CR (the most highly loaded estuary) were consistent with literature values, and fell below the 5% $N_2O:N_2$ line. Our ratios for the less loaded estuaries, QR and SLP, fell between 5% and 50%, indicating greater release of N_2O *in situ* relative to N_2 at lower N loads. This might mean that salt-marsh sediments exhibit greater variability in $N_2O:N_2$ released than do lake, river, and other coastal marine sediments (4). When inputs of groundwater increase NO_3^- supply and saturate rates of production (Fig. 1, top left), greater amounts of N_2O are released in estuaries with higher N loads, which agrees with other reports (5). The rate

of release of N_2O relative to N_2 may decrease as loading increases; the ratio in CR sediments is less than that of the other estuaries (Fig. 1, right). As loading increases, any local increases in NO_3^- concentrations could release more N_2O into the atmosphere, while supply of NO_3^- determined by regional loading regimes will lower N_2O produced by denitrification compared to N_2 release.

This research was supported by the Research Experiences for Undergraduates program of the National Science Foundation, and a Marine Biological Laboratory Fellowship awarded to SBJ. Thanks also to Anne Giblin, Jane Tucker, and Lori A. Soucy for help in different stages of the work.

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