

(Valiela *et al.*, unpub. data) and possess different amounts of surrounding salt marsh. Ten sites at each estuary were sampled with an Eckman dredge (0.15 m<sup>2</sup>) at the beginning of each month in all estuaries and at intervening 2-week intervals in Jehu and Hamblin Ponds. Samples were sorted by species, dried, and weighed. Nitrogen loading and salt marsh area showed no relationship ( $P$  for regression  $>0.05$ ). We therefore regressed nutrient loading versus biomass, and salt marsh area versus biomass.

Eelgrass biomass was inversely related to nitrogen loading (Fig. 1, top left;  $P = 0.0001$ ), in contrast to macroalgal biomass, which increased with nutrient loading (top right;  $P = 0.0041$ ). The shapes of the best-fit curves suggest that eelgrass is particularly sensitive to even low rates of additional nutrient loading (Fig. 1, top left), but macroalgae respond linearly over a broader range of nutrient loadings. The correlations (Fig. 1, top), however, have considerable variation; for instance, Jehu Pond has substantially more eelgrass and less algae than would be expected based on nutrient loadings alone. Part of this variability may be associated with the amount of salt marsh in the estuaries. As salt marsh area increases, eelgrass biomass increases (Fig. 1, bottom left;  $P = 0.0001$ ) and macroalgal biomass decreases (Fig. 1, bottom right;  $P = 0.0011$ ). Correlation coefficients for best-fit lines improved for both eelgrass and macroalgal biomass when plotted against salt marsh area (compare  $r^2$  values in top and bottom panels, Fig. 1). This result could be caused by lowered nitrogen loading owing to denitrification in salt marshes.

Seagrass growth is inhibited under increased nitrogen loading and macroalgal growth is enhanced. Eelgrass apparently undergoes rapid, near-exponential reduction in biomass over a narrow range of nutrient loadings, whereas macroalgae respond in a linear fashion over a broader range. The relationship between nutrient loading to coastal watersheds and estuarine macrophytes may, however, be strongly influenced by salt marsh fringing the estuaries. Fringing salt marsh might act as a buffer against nutrient loading, and thus might allow eelgrass beds to be maintained even when they are surrounded by relatively urbanized watersheds.

This work was supported by REU-NSF (OCE 9300490), NOAA (NA170R21101), and The Waquoit Bay Fellowship awarded to J. McClelland.

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## Effects of Land Use on the Degradability of Dissolved Organic Matter in Three Watersheds of the Plum Island Sound Estuary

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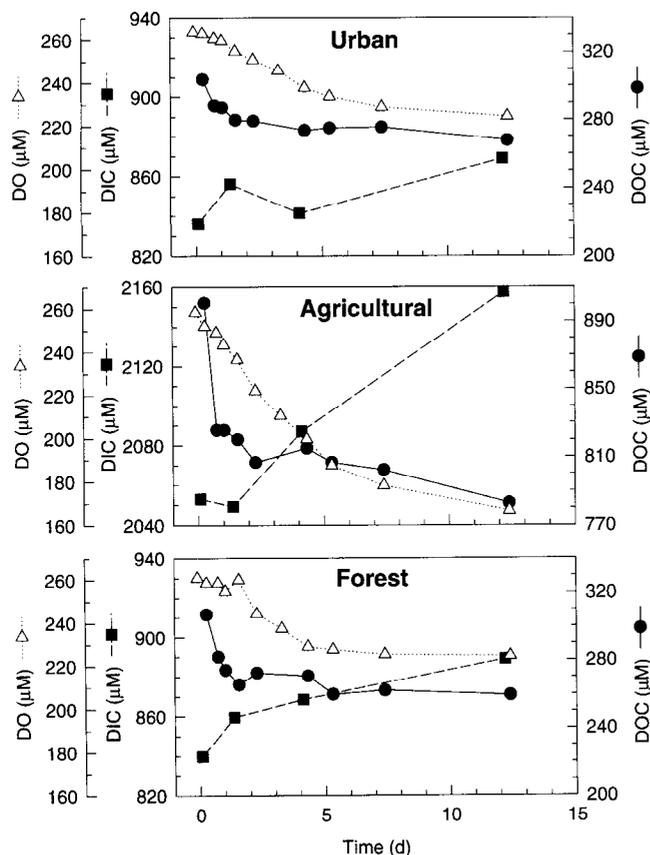
Different types of land use influence many of the fundamental processes of terrestrial ecosystems and affect the materials moving from land to estuaries and coastal marine systems. One input to estuaries is dissolved organic carbon (DOC); changes in watershed land use have increased the levels of total organic carbon transported to the ocean by 3–5 times those of natural levels (1). Yet it is not clear how much of the DOC entering estuaries is actually used by microbes and contributes to the food web and how much is resistant to degradation and moves out to the oceans. In our experiment, we determined the concentration and degradability of the DOC entering a northern Massachusetts estuary from three areas with different land uses: agriculture, forest, and urban.

Stream water collected 9 August 1994 from agricultural, urbanized, and forested watersheds was filtered (0.2  $\mu\text{m}$ ) to remove most of the bacteria and reinoculated with estuarine bacteria (20:1 dilution) from the oligohaline portion of the Parker River in the Plum Island Sound estuary. Inoculated water samples were incubated in 15-l Mylar bags, and changes in bacterial

numbers, dissolved organic and inorganic carbon (DOC, DIC), and dissolved oxygen (DO) were analyzed at several time points over a 2-week period.

Bacteria in the agricultural samples consumed a greater amount of oxygen, and did so at a faster rate, than bacteria growing in the urban or forest samples (Fig. 1). The greatest total change of oxygen occurred in the agricultural water samples, a 90.8  $\mu\text{M}$  ( $\pm 0.8 \mu\text{M}$ ) decrease. Total changes in the urban and forest bags were, respectively, 41.2  $\mu\text{M}$  ( $\pm 1.5 \mu\text{M}$ ) and 34.5  $\mu\text{M}$  ( $\pm 6.8 \mu\text{M}$ ). The DOC in the agricultural samples showed a 90.3  $\mu\text{M}$  ( $\pm 6.3 \mu\text{M}$ ) decrease; the largest decrease of the three samples (Fig. 1). There was a 48.2  $\mu\text{M}$  ( $\pm 5.1 \mu\text{M}$ ) decrease of DOC in the forest samples, and a 33.5  $\mu\text{M}$  ( $\pm 4.3 \mu\text{M}$ ) decrease in the urban samples. Most of the DOC consumed was completely oxidized, as DIC concentrations increased by 104  $\mu\text{M}$ , 49  $\mu\text{M}$ , and 33  $\mu\text{M}$  in the agricultural, forest, and urban samples, respectively (Fig. 1).

The actual concentrations of DOC were more than twice as high in the agricultural samples as in either the forest or urban



samples. The percentage of the total DOC pool utilized was similar among all three water samples: 15.7% in the forest, 10.3% in the agricultural, and 11.0% in the urban samples.

The organic matter from the agricultural watershed clearly had the greatest potential impact on the estuary. The unexpected conclusion from the experiment, however, is that the total quantity of organic matter is most important; the usable DOC made up a similar percentage of the total in water from all three watersheds.

The research was supported by an LMER grant (NSF-OCE-9214461). We thank Ishi Buffam, David Giebtbrock, Charles Hopkinson, and Eileen Monaghan for advice and assistance with sample analysis.

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**Figure 1.** The average concentrations ( $\mu\text{M}$ ) of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and dissolved oxygen (DO) in replicate 15-l Mylar bags during a 13-day incubation. DIC was measured by high-temperature catalytic oxidation, DO by automated Winkler titration, and DIC by precision coulometric  $\text{CO}_2$  analyzer.

Reference: *Biol. Bull.* **189**: 257-258. (October/November, 1995)

## Nutrient Limitation of Phytoplankton Growth in Waquoit Bay, Massachusetts

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Studies of nutrient limitation in fresh water and seawater (1, 2, 3, 4, 5, 6) show that phosphorus limits phytoplankton growth in fresh water and nitrogen does in saline water. Estuaries are situated between a fresh-water source and the sea and are characterized by a gradient of salinities; hence, each estuary must have a point at which the limiting nutrient switches from phosphorus to nitrogen. In this study we asked whether the effect of N or P varies along a fresh to salty gradient within the Childs River estuary of Waquoit Bay, Massachusetts, and whether the limiting roles of N and P vary seasonally.

Bottle enrichment experiments were carried out using water from sites of low (0-9‰), intermediate (10-19‰), and high (20-28‰) salinities. Water was filtered through a 253- $\mu\text{m}$ -mesh net to remove large zooplankton. Enrichment treatments consisted of additions that furnished 100  $\mu\text{M}$  of  $\text{NO}_3^-$  or  $\text{PO}_4^{3-}$ ; controls received no additions. The treatments were applied to two replicate bottles. All bottles were incubated near the surface in the Bay, and then collected at 1- or 2-day intervals to furnish a time sequence of phytoplankton growth, as measured by chlorophyll concentration. The shallow incubation reduced the probability

of light limitation. The containers were incubated in the Bay by attaching them to a floating rack that was anchored to the bottom of the estuary.

Phytoplankton grew in virtually all of the containers over the incubation periods. We calculated chlorophyll-specific growth rates for each month by normalizing growth rates, relative to controls, to compensate for the marked seasonal change in chlorophyll standing crop in Childs River. We calculated the normalized growth rate as  $G = (P_e - I_e)/d - (P_c - I_c)/d$ , where  $P_e$  and  $I_e$  are the peak and initial concentrations in the enriched treatments,  $P_c$  and  $I_c$  are the peak and initial chlorophyll concentrations in the control treatment, and  $d$  is the number of days of the incubation.

The normalized phytoplankton growth rates peaked in July-August in all treatments (Fig. 1). The magnitude of the peak depended on the supply of nitrogen or phosphorus and the provenance of the water. In water from the upper reaches of the river, with salinity <10‰, phosphate enrichment prompted a modest increase in phytoplankton growth during summer (Fig. 1, top); note that the standard error of means do not overlap