Special Issue

Nutrient Enrichment and Estuarine Eutrophication[1]

Nutrient enrichment of estuaries has increased dramatically during the past several decades. Agricultural intensification, accelerating watershed development, escalating fossil fuel use, ongoing wastewater fluxes, and other human-mediated activities all yield elevated concentrations of nutrients (mainly nitrogen) that enter estuaries and other coastal environments. Such nutrient over-enrichment now causes the majority of U.S. estuaries to be moderately to highly eutrophic, and to display a range of ecological and biogeochemical responses that signal a shift in the balance of selective forces shaping biotic communities in the affected waters. Expressions of eutrophication include an array of cascading environmental responses such as rapid microalgal and macroalgal growth, harmful algal blooms (HABs), reduced biodiversity, imbalanced food webs, diminished harvestable fisheries, loss of essential habitat (e.g., seagrass and shellfish beds), and decreased ecosystem resilience. In severe cases, eutrophication causes hypoxia or anoxia, massive mortality of benthic organisms, and marked alteration of biotic community structure.

There is considerable variation in how estuaries respond to nutrient enrichment. Delaware Bay, for example, does not exhibit classical symptoms of eutrophication primarily due to light attenuation associated with turbid conditions and to the large horizontal transport, rapid flushing, and export of nutrients to coastal ocean waters. In contrast, the coastal bays of Maryland, Delaware, and New Jersey are generally moderately to highly eutrophic not only because of elevated nutrient inputs, but also due to their shallow depths and extreme enclosure. In general, shallow estuaries with restricted circulation and high residence times (e.g., lagoonal bays) tend to exhibit the most acute eutrophic conditions because they typically retain exogenous nutrients.

Barnegat Bay, New Jersey is one such example. It is highly eutrophied, as evidenced by both primary and secondary symptom expressions of high phytoplankton abundance, HABs, macroalgal blooms, loss of submerged aquatic vegetation, and impaired fisheries. This system is particularly susceptible to nutrient enrichment because of highly developed watershed areas, poor flushing, and restricted circulation. In addition, it receives large nutrient inputs via atmospheric deposition. However, while Barnegat Bay is among the most heavily eutrophied estuarine environments of the United States, it is by no means unique in either this designation or its characteristics.

Thus, in April 2004, a joint science and management symposium focusing on nutrient enrichment of coastal systems was held at Rutgers University in New Brunswick, New Jersey. The symposium addressed a range of ecological, health, and management issues surrounding nutrient enrichment and, in many cases, did so by concentrating on observed changes in the Barnegat Bay–Little Egg Harbor Estuary. This invited feature is an outgrowth of the Rutgers symposium, and it presents papers that examine a variety of nutrient enrichment and eutrophication problems not only in Barnegat Bay, but in shallow estuarine and coastal marine ecosystems throughout the eastern United States and other world regions.

The first paper by Kennish et al. assesses the effects of escalating nutrient loading to a shallow lagoonal estuary in New Jersey. The authors show that alteration of the structure and function of the estuary associated with progressive eutrophication is manifested by a succession of primary and secondary responses, including changes in biotic community composition and habitat conditions that signal increasing ecosystem disturbance. Bowen et al. then describe a web-based modeling tool (NLOAD) that may help coastal managers evaluate the effectiveness of a variety of options to reduce nitrogen loads. Through simulations, Bowen et al. convey how even modest cutbacks in the use of fertilizer inputs to the Barnegat Bay watershed could significantly reduce the amount of nitrogen entering the bay. The paper by Gao et al. demonstrates that nitrogen fluxes to the estuarine surface from the coastal airshed in New Jersey are a significant source of nutrient enrichment to the system, contributing to potential eutrophication problems. The final paper on northeastern U.S. estuaries is

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[1] Reprints of this 196-page Special Issue are available for $20.00 each. Prepayment is required. Order reprints from the Ecological Society of America, Attention: Reprint Department, 1707 H Street, N.W., Suite 400, Washington, DC 20006.

by Deegan et al., who discuss experimental alterations of salt marsh ecosystems by addition of nutrients in flooding waters, and by reduction of top-down control by mummichogs.

The next two papers by Wazniak et al. and Glibert et al. examine deteriorating conditions in Maryland's coastal bays. Both papers attribute much of the problem to rising nitrogen inputs. The degrading symptoms are manifested most conspicuously by repeated occurrences of brown tide blooms caused by the pelagophyte *Aureococcus anophagefferens*. The strength of the brown tide blooms has been attributed to the availability of dissolved organic nitrogen rather than inorganic nitrogen forms. Yet, inorganic loading may still be the ultimate driver; during the past decade, long-term changes in nutrient concentrations and biotic composition have led to organic nitrogen-based eutrophication.

Moving farther south, Paerl et al. investigate anthropogenic nutrient enrichment in a hydrologically complex coastal system of North Carolina. They detail how phytoplankton community biomass (chlorophyll *a*) and group-specific chemotaxonomic indicators (chlorophylls and carotenoids) can be used to effectively assess community responses to nutrient inputs and other drivers of ecological change. Natural environmental stressors are also targeted, notably, climatic perturbations (such as hurricanes) that greatly influence physical forcing factors (e.g., hydrology) shaping the expressions of eutrophication. Hsieh et al. also focus on the same Neuse River Estuary and track bacterioplankton responses to eutrophication by sampling *Vibrio* spp. and phytoplankton concentrations along the estuarine gradient. *Vibrio* cells interact with phytoplankton in surface waters of the estuary, and both components must be considered in model development of bacterial dynamics in response to eutrophication of the system.

The emphasis on phytoplankton blooms continues in the paper by Livingston, which recounts the responses of plankton assemblages and associated coastal food webs to natural and anthropogenic nutrient loading in the Perdido River–Bay system of eastern Alabama and the western Florida Panhandle. Rabalais et al. also concentrate on the Gulf region, assessing hypoxia of the coastal ecosystem in the northern Gulf of Mexico, where paleoindicators of eutrophication in bottom sediments record recent anthropogenic influence. Here, areas of chronic hypoxia are coincident with accelerating nitrogen loads from the Mississippi River system commencing in the 1950s. The temporal shifts in this coastal ecosystem parallel the time sequence of similarly eutrophied coastal waters globally.

While much of this volume addresses U.S. ecosystems, the final three papers extend its scope to other regions of the world. First, Nixon et al. highlight rapid current and future changes in tropical regions by describing nutrient concentrations and dynamics in eight coastal lagoons of Ghana. They correlate dissolved inorganic nitrogen inputs and corresponding aquatic impacts with high population densities in coastal watersheds. Next, Conley et al. analyze long-term patterns of hypoxia and anoxia in coastal marine ecosystems of Denmark. They reveal decreasing dissolved oxygen concentrations in these ecosystems, most evident during the 1980s, with the benthic communities undergoing significant alteration in response to near-bottom hypoxia. Finally, Rochelle-Newall et al. conclude the volume with a paper that presents information on the metabolic balance of the Bay of Palma (Spain), Randers Fjord (Denmark), and the Scheldt Estuary (Belgium and The Netherlands); collectively, these sites encompass significant gradients in nutrient enrichment and eutrophication. Using artificial neural networks, the authors develop a mathematical model of the gross primary production to community respiration ratio, a valuable indicator in the study of ecosystem metabolism and a potentially useful management tool.

This Special Issue of *Ecological Applications* joins a growing body of literature that highlights the problems of, and some potential solutions to, coastal eutrophication. Changes to the coastal environment have been explosive in recent decades, and for the most part are continuing at a worrisome pace. However, synthetic ecological understanding coupled to new management approaches clearly has the potential to improve conditions in the coastal waters of the United States and elsewhere. Our hope is that the papers presented here will help contribute to that larger goal.

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