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Ecological Engineering 26 (2006) 40–54
ECOLOGICAL ENGINEERING
www.elsevier.com/locate/ecoleng

Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters: Interactive effects of human and climatic perturbations

Hans W. Paerl

University of North Carolina at Chapel Hill, Institute of Marine Sciences, 3431 Arendell Street, Morehead City, NC 28557, USA

Received 30 September 2003; received in revised form 8 December 2004; accepted 26 September 2005

Abstract

Estuaries are among the most productive, resourceful, and dynamic aquatic ecosystems on Earth. Their productive nature is linked to the fact that they process much of the world's riverine and coastal watershed discharge. These watersheds support more than 75% of the human population and are sites of large increases in nutrient loading associated with urban and agricultural expansion. Increased nutrient loading has led to accelerated primary production, or eutrophication; symptoms include increased algal bloom activity (including harmful taxa), accumulation of organic matter, and excessive oxygen consumption (hypoxia and anoxia). While nutrient-enhanced eutrophication is a "driver" of hypoxia and anoxia, physical–chemical alterations due to climatic events, such as stormwater discharge, flooding, droughts, stagnancy, and elevated temperatures are also involved. The complex interactions of anthropogenic and climatic factors determine the magnitude, duration, and aerial extent of productivity, algal booms, hypoxia, and anoxia. Using the eutrophic Neuse River Estuary (NRE), North Carolina, USA, as a case study, the physical–chemical mechanisms controlling algal bloom and hypoxia dynamics were examined. Because primary production in the NRE and many other estuaries is largely nitrogen (N) limited, emphasis has been placed on reducing N inputs. Both the amounts and chemical forms of N play roles in determining the composition and extent of phytoplankton blooms that supply the bulk of the organic carbon fueling hypoxia. Biomass from bloom organisms that are readily grazed will be readily transferred up the planktonic and benthic food chain, while toxic or inedible blooms frequently promote sedimentary C flux, microbial mineralization, and hence may exacerbate hypoxia potential. From a watershed perspective, nutrient input reductions are the main options for reducing eutrophication. Being able to distinguish the individual and cumulative effects of physical, chemical and biotic controls of phytoplankton productivity and composition is key to understanding, predicting, and ultimately managing eutrophication. Long-term collaborative (University, State, Federal) monitoring, experimental assessments, and modeling of eutrophication dynamics over appropriate spatial and temporal scales is essential for developing realistic, ecologically sound, and cost-effective nutrient management strategies for estuarine and coastal ecosystems impacted by both anthropogenic and climatic perturbations.

Keywords: Algal blooms; Climate; Estuaries; Eutrophication; Hypoxia; Management; Nitrogen; Nutrients; Phytoplankton; Water quality

E-mail address: hpaerl@email.unc.edu.

0925-8574/$ – see front matter
doi:10.1016/j.ecoleng.2005.09.006

1. Introduction

1.1. Eutrophication, hypoxia and anoxia dynamics in hydrologically variable estuaries

Estuaries are among the most productive, diverse, economically important, and hydrologically variable ecosystems on Earth (Neilson and Cronin, 1981; Hobbie, 2000). A bulk of the world's commercial and recreational fish stocks depend on estuaries as nurseries, refuges, and feeding grounds. Estuarine and coastal watersheds support approximately 75% of the world's human population and the number of coastal residents continues to rise (Vitousek et al., 1997). As such, they receive and process a large share of land-based nutrients and other pollutants entering via surface runoff, atmospheric deposition, and groundwater discharge, much of it delivered via rivers draining urban centers and agricultural watersheds (Howarth et al., 1996; Paerl, 1997; Jaworski et al., 1997; Paerl et al., 2002). The productive nature and resourcefulness of estuaries depend to a large extent on externally supplied or "new" nutrient inputs. Anthropogenic new nutrient inputs have increased dramatically; it is estimated that nitrogen (N) inputs alone have increased 10-fold in the past century (Howarth et al., 1996). Current nutrient loading rates often exceed those needed to sustain desirable production (Vollenweider et al., 1992; Jørgensen and Richardson, 1996; Boesch et al., 2001). Many estuaries are now facing nutrient-over-enrichment, or "too much of a good thing", in the form of nutrient-enhanced primary production (D'Elia, 1987; NRC, 2000). This condition, which often leads to excessive production of organic matter in the form of algal blooms (Fig. 1), is referred to as eutrophication (Nixon, 1995). Unused or partially degraded organic matter settles to the sediments, where it serves as "fuel" for microbial decomposition, converting organic matter to CO_2 and inorganic nutrients (Fig. 2).

Decomposition is an oxygen (O_2)-demanding process. Therefore, waters enriched with readily degraded or "reactive" organic matter tend to consume large amounts of O_2. If the affected waters are vertically stratified, slowly flushed, and/or stagnant, consumption of O_2 may exceed its re-supply from either atmospheric or in-stream photosynthetic (i.e., O_2 evolution) sources. The imbalance between relatively high rates of O_2 consumption and low rates of O_2 re-supply causes dissolved oxygen (DO) content to drop to levels that are low enough to adversely affect oxygen-requiring animal and plant life. DO concentrations of less than $4\,mg\,O_2\,L^{-1}$ are commonly referred to as hypoxic and are frequently stressful to higher life forms, while no detectable O_2 concentrations are termed anoxic and potentially fatal to finfish, shellfish and invertebrate species (Renaud, 1986; Pihl et al., 1991; Diaz and Rosenberg, 1995).

In addition to experiencing man-made nutrient enrichment (i.e. cultural eutrophication), estuarine and coastal ecosystems are also under the influence of natural (climatic) perturbations such as droughts, hurricanes, and flooding. Distinguishing and integrating the effects of natural and anthropogenic stressors is a difficult but essential challenge for understanding and managing coastal biotic resources.

The effects and manifestations of human and natural perturbations are readily detected and consequential at the microbial level, where a bulk of ecosystem energy and nutrient flow is mediated. Microbes have rapid growth rates, and respond to low levels of pollutants and environmental perturbations. These features make them sensitive, meaningful, and useful indicators of ecological change. In this paper, the response of suspended microalgae or phytoplankton, the dominant primary producers in many estuaries, to nutrient and climatic perturbations will be examined. The focus will be on how anthropogenic stressors interact with natural forcing features to determine the composition, distribution, and activities of phytoplankton communities.

The linkage between nutrient loading, eutrophication, and hypoxia/anoxia dynamics is often non-linear and complex in estuarine and coastal systems (Cloern, 2001). This is because these systems are hydrodynamically and biogeochemically distinct and highly variable. Climatic and physiographic differences between these systems profoundly affect physical–chemical and biological processes mediating organic matter production and accumulation, oxygen dynamics, and nutrient cycling. The complex interplay between hydrologic discharge (i.e., flushing, residence time), vertical and horizontal thermal and salinity stratification, wind and tidal mixing, frontal passage (e.g., "nor-easters"), and even larger storm events (i.e., hurricanes), determines the frequency, spatial, and temporal extent of hypoxia events in estuaries. Here we will explore the interplay of anthropogenic (nutrient) and natural (climatic) forc-