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Eutrophication science: where do we go from here?

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Cultural eutrophication has become the primary water quality issue for most of the freshwater and coastal marine ecosystems in the world. However, despite extensive research during the past four to five decades, many key questions in eutrophication science remain unanswered. Much is yet to be understood concerning the interactions that can occur between nutrients and ecosystem stability: whether they are stable or not, alternate states pose important complexities for the management of aquatic resources. Evidence is also mounting rapidly that nutrients strongly influence the fate and effects of other non-nutrient contaminants, including pathogens. In addition, it will be important to resolve ongoing debates about the optimal design of nutrient loading controls as a water quality management strategy for estuarine and coastal marine ecosystems.

Introduction

Cultural eutrophication (excessive plant growth resulting from nutrient enrichment by human activity) is the primary problem facing most surface waters today. It is one of the most visible examples of human changes to the biosphere ([1,2]; Figure 1), affecting aquatic ecosystems from the Arctic to the Antarctic [3]. Eutrophication has many undesirable side effects (Table 1), major economic costs and transnational implications [4,5]. Many studies have concluded that managing phosphorus and, in coastal waters, managing nitrogen inputs is critical to maintaining desirable water quality and ecosystem integrity [6,7]. Evidence has also accumulated to favor nutrient restriction as a means of restoring eutrophic waters [2,6]. However, nutrient enrichment interacts with many site-specific conditions, especially the ecological stability of the system, and the presence of other contaminants, including infectious disease agents. Moreover, a consensus has yet to be reached concerning optimal nutrient loading controls in coastal zone eutrophication management. Our review addresses these knowledge gaps.

Nutrient loading and ecosystem stability

Interactions between nutrients, producers and their consumers remain poorly understood for most aquatic ecosystems. Major food web disturbances (e.g. winter fish kills [8], or the addition or deletion of piscivorous predators [9,10]) can cause shifts in ecosystem structure and function that persist over extended periods of time. Two strikingly different alternative states are frequently observed in shallow, nutrient-enriched aquatic systems: the first is a clear water state dominated by benthic macro-vegetation, and the second is a more turbid state dominated by algae. Many freshwater studies [11,12] show that these regime shifts can be abrupt and sometimes catastrophic [13]. Similar regime changes have been observed in shallow marine ecosystems [14]. Alternative system states have, for example, been observed in coastal soft sediment communities, which dominate the shallow (0–1 m depth) zone along the Swedish west coast [15]. Previously unvegetated shallow sediment areas now appear to be locked into a state of recurring green algal mat development that is resistant to restoration efforts. The cause of this shift could be related to an anoxia-driven 'vicious cycle' that enhances algal growth by efficiently recycling phosphorus from bottom sediments [16].

Regime shifts can also result from anthropogenic changes in the catchments and airsheds of aquatic ecosystems. For example, clearing forested catchments causes long-term increases in the loss of nutrients [17]. Applications of manure or commercial fertilizer further increase terrestrial nutrient exports: fertilized soils can become nutrient saturated, leaking nutrients into receiving waters for decades after external nutrient additions are reduced or discontinued [18]. Gaseous nitrogen emissions can occur hundreds of kilometers upwind of affected ecosystems, yet their subsequent atmospheric deposition can constitute the predominant anthropogenic nitrogen source in downwind regions [19,20].

There is recent evidence that not all regime shifts are stable, and that some alternative states are not mutually exclusive. Bayley *et al.* [21] found that alternative states in shallow lakes of the Boreal Plain in Canada were unstable. Over 70% of studied lakes shifted alternative states from two to nine times in a 6 year period. At very high nutrient concentrations, both submersed aquatic vegetation and high algal turbidity occurred. They hypothesized that due to harsh winter conditions (ice thickness, winterkill caused by anoxia) these ecosystems were strongly abiotically regulated, and lacked the biological mechanisms that maintain stable states in more temperate climates.

Whether stable or not, alternate states pose important complexities for the management of aquatic resources, and could be one of the most important issues facing aquatic ecologists today. Regime shifts need extensive further study in eutrophic lakes, estuaries and coastal

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