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Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems

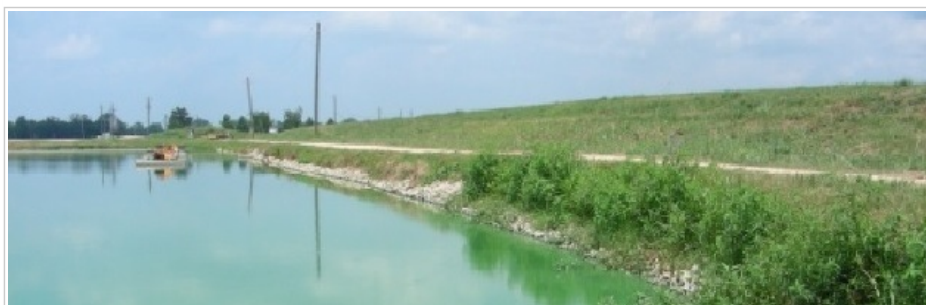
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Eutrophication is a leading cause of impairment of many freshwater and coastal marine ecosystems in the world. Why should we worry about eutrophication and how is this problem managed?

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Introduction

Eutrophication is characterized by excessive plant and algal growth due to the increased availability of one or more limiting growth factors needed for **photosynthesis** (Schindler 2006), such as sunlight, carbon dioxide, and nutrient fertilizers. Eutrophication occurs naturally over centuries as lakes age and are filled in with sediments (Carpenter 1981). However, human activities have accelerated the rate and extent of eutrophication through both point-source discharges and non-point loadings of limiting nutrients, such as nitrogen and phosphorus, into aquatic ecosystems (i.e., cultural eutrophication), with dramatic consequences for drinking water sources, fisheries, and recreational water bodies (Carpenter *et al.* 1998). For example, aquaculture scientists and pond managers often intentionally eutrophy water bodies by adding fertilizers to enhance primary productivity and increase the density and biomass of recreationally and economically important fishes (Figure 1) via bottom-up effects on higher trophic levels (Boyd & Tucker 1998). However, during the 1960s and 1970s, scientists linked algal blooms to nutrient enrichment resulting from anthropogenic activities such as agriculture, industry, and sewage disposal (Schindler 1974). The known consequences of cultural eutrophication include blooms of blue-green algae (i.e., cyanobacteria, Figure 2), tainted drinking water supplies, degradation of recreational opportunities, and **hypoxia**. The estimated cost of damage mediated by eutrophication in the U.S. alone is approximately \$2.2 billion annually (Dodds *et al.* 2009).



Figure 1

Aquaculture ponds, such as these channel catfish production ponds, typically contain high concentrations of nutrients, such as nitrogen and phosphorus, due to regular feeding of the fish. Consequently, these ponds are also plagued by recurring cyanobacterial blooms and hypoxia.

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Figure 2
Sampling Lago de Pátzcuaro during a cyanobacterial bloom with Ilyana Berry, Dr. John Berry, and Dr. Fernando Bernal-Brooks.
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Consequences

The most conspicuous effect of cultural eutrophication is the creation of dense blooms of noxious, foul-smelling phytoplankton that reduce water clarity and harm water quality (Figure 2). Algal blooms limit light penetration, reducing growth and causing die-offs of plants in littoral zones while also lowering the success of predators that need light to pursue and catch prey (Lehtiniemi *et al.* 2005). Furthermore, high rates of photosynthesis associated with eutrophication can deplete dissolved inorganic carbon and raise pH to extreme levels during the day. Elevated pH can in turn 'blind' organisms that rely on perception of dissolved chemical cues for their survival by impairing their chemosensory abilities (Figure 3) (Turner & Chislock 2010). When these dense algal blooms eventually die, microbial decomposition severely depletes dissolved oxygen, creating a hypoxic or **anoxic** 'dead zone' lacking sufficient oxygen to support most organisms. Dead zones are found in many freshwater lakes including the Laurentian Great Lakes (e.g., central basin of Lake Erie; Arend *et al.* 2011) during the summer. Furthermore, such hypoxic events are particularly common in marine coastal environments surrounding large, nutrient-rich rivers (e.g., Mississippi River and the Gulf of Mexico; Susquehanna River and the Chesapeake Bay) and have been shown to affect more than 245,000 square kilometers in over 400 near-shore systems (Diaz & Rosenberg 2008). Hypoxia and anoxia as a result of eutrophication continue to threaten lucrative commercial and recreational fisheries worldwide.



Figure 3
Helisoma trivolvis (left) and *Physa acuta* (right) are two of the most common freshwater snails in North America. Both species use chemical cues to detect predators such as molluscivorous fish and typically respond by hiding under rocks and logs or in shallow water.
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Some algal blooms pose an additional threat because they produce noxious toxins (e.g., microcystin and anatoxin-a; Chorus and Bartram 1999). Over the past century, harmful algal blooms (HABs) have been linked with (1) degradation of water quality (Francis 1878), (2) destruction of economically important fisheries (Burkholder *et al.* 1992), and (3) public health risks (Morris 1999). Within freshwater ecosystems, cyanobacteria are the most important phytoplankton associated with HABs (Paerl 1988). Toxigenic cyanobacteria, including *Anabaena*, *Cylindrospermopsis*, *Microcystis*, and *Oscillatoria* (*Planktothrix*), tend to dominate nutrient-rich, freshwater systems due to their superior competitive abilities under high nutrient concentrations, low nitrogen-to-phosphorus ratios, low light levels, reduced mixing, and high temperatures (Downing *et al.* 2001; Paerl & Huisman 2009; Paerl and Paul 2012). Poisonings of domestic animals, wildlife (Figure 4), and even humans by blooms of toxic cyanobacteria have been documented throughout the world and date back to Francis' (1878) first observation of dead livestock associated with a bloom of cyanobacteria. Furthermore, cyanobacteria are responsible for several off-flavor compounds (e.g., methylisoborneol and geosmin) found in municipal drinking water systems as well as in aquaculture-raised fishes, resulting in large financial losses for state and regional economies (Crews & Chappell 2007). In addition to posing significant public health risks, cyanobacteria have been shown to be poor quality food for most zooplankton grazers in laboratory studies (Wilson *et al.* 2006; Tillmanns *et al.* 2008), thus reducing the efficiency of energy transfer in aquatic food webs and potentially preventing zooplankton from controlling algal blooms.



Figure 4

A dead African buffalo (*Syncerus caffer*) found in a reservoir with a dense bloom of the toxic cyanobacterium *Microcystis* at the Loskop Dam Nature Reserve in South Africa.

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Eutrophication is also associated with major changes in aquatic community structure. During cyanobacterial blooms, small-bodied zooplankton tend to dominate plankton communities, and past observational studies have attributed this pattern to anti-herbivore traits of cyanobacteria (e.g., toxicity, morphology, and poor food quality) (Porter 1977). However, the biomass of planktivorous fish is often positively related to nutrient levels and ecosystem productivity. Piscivorous fishes (e.g., bass, pike) tend to dominate the fish community of nutrient-poor, oligotrophic lakes, while planktivorous fishes (e.g., shad, bream) become increasingly dominant with nutrient enrichment (Jeppesen *et al.* 1997). Thus, an alternative explanation for the lack of zooplankton control of cyanobacterial blooms could include consumption of zooplankton by planktivores.

Controls

Given the widespread extent of water quality degradation associated with nutrient enrichment, eutrophication has and continues to pose a serious threat to potable drinking water sources, fisheries, and recreational water bodies. Although many municipalities have passed legislation to regulate point-source loading of nutrients, eutrophication and cyanobacterial blooms are still prevalent in surface waters around the world (Smith & Schindler 2009). Predicted climate change and human population growth has the potential to further degrade water quality and quantity, and there is an immediate need by water resource managers to understand how to minimize the intensity and frequency of algal and cyanobacterial blooms (Paerl & Paul 2012).

Water resource managers routinely employ a variety of strategies to minimize the effects of cultural eutrophication, including (1) diversion of excess nutrients (Edmondson 1970), (2) altering nutrient ratios (Downing *et al.* 2001), (3) physical mixing (Huisman *et al.* 2004), (4) shading water bodies with opaque liners or water-based stains, and (5) application of potent algaecides and herbicides (Boyd & Tucker 1998). In general, these strategies have proven to be ineffective, costly, and/or impractical, especially for large, complex ecosystems (but see Edmondson 1970). Water quality can often be improved by reducing nitrogen and/or phosphorus inputs into aquatic systems, and there are several well-known examples where bottom-up control of nutrients has greatly improved water clarity. However, nutrient reduction can be difficult (and expensive) to control, especially in agricultural areas where the algal nutrients come from nonpoint sources. Furthermore, in lakes where external loading of nutrients has been reduced, **internal loading** of nutrients from sediments may prevent improvements in water quality (Søndergaard *et al.* 2003). The use of algaecides, such as copper sulfate, is also effective at reducing HABs temporally (Boyd & Tucker 1998). However, algaecides are expensive to apply, do not control the primary cause of the problem (i.e., abundant resources for primary producers) and pose risks to humans, livestock, and wildlife, in addition to harming a variety of non-target aquatic organisms.

Another alternative for improving water quality in nutrient-rich lakes has been **biomanipulation** - the alteration of a food web to restore ecosystem health (Shapiro *et al.* 1975). The basic premise is that secondary consumers (planktivorous fishes) are removed either through the addition of tertiary consumers (piscivorous fishes) or harvesting, which allows for the dominance of large-bodied, generalist grazers (e.g., *Daphnia*) to control phytoplankton (Figure 5). When planktivorous fishes are abundant and there is no predation refuge (e.g., oxygenated hypolimnion) for large-bodied zooplankton, less efficient small-bodied zooplankton grazers (e.g., rotifers and herbivorous copepods) typically dominate zooplankton communities, thus allowing for the overgrowth of phytoplankton (i.e., algal bloom). Many past studies have shown strong correlations between the size structure of zooplankton communities and phytoplankton abundance. These data support the notion that predatory top-down forces can have important implications for aquatic communities and ecosystems. With that said, fish-centric **biomanipulation** effects on water quality are typically short-lived (i.e., weeks to months), most obvious in small, easily-managed systems (i.e., ponds), and impacted by resource availability, namely phosphorus and nitrogen (Benndorf 1990; Carpenter *et al.* 1995).



Figure 5

Daphnia are generalist herbivores that play a powerful role in the structure and function of lake ecosystems and can have large effects on phytoplankton abundance, water clarity, and water quality when abundant.

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Conclusions

Despite dramatic improvements in water quality as a result of large-scale efforts to reduce nutrient enrichment (e.g., Clean Water and Safe Drinking Water Acts in the 1970s), cultural eutrophication and concomitant HABs continue to be the leading cause of water pollution for many freshwater and coastal marine ecosystems and are a rapidly growing problem in the developing world (Smith & Schindler 2009). Given that the demand for freshwater resources is expected to increase dramatically, protecting diminishing water resources has become one of the most pressing environmental issues and will likely become more complicated as climate change, species invasions, and pollution further degrade water quality and quantity (Schindler 2006). Control and management of cultural eutrophication is a complex issue and will require the collective efforts of scientists, policy makers, and citizens to reduce nutrient inputs, to develop effective, long-term biomanipulation techniques, and to eventually restore aquatic communities.

Glossary

anoxia: Lack of dissolved oxygen in water

biomanipulation: The alteration of a food web to restore ecosystem health Eutrophication - elevated primary production

HAB: Harmful algal bloom; abundant phytoplankton

hypoxia: Reduced dissolved oxygen concentration in water that stresses an organism

internal loading: Release of nutrients, such as phosphorus and nitrogen, from sediments during low oxygen concentration conditions

photosynthesis: Conversion of inorganic carbon (carbon dioxide) to organic carbon (glucose) by a primary producer

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