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Review

Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change

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A B S T R A C T

Harmful (toxic, food web altering, hypoxia generating) cyanobacterial algal blooms (CyanoHABs) are proliferating world-wide due to anthropogenic nutrient enrichment, and they represent a serious threat to the use and sustainability of our freshwater resources. Traditionally, phosphorus (P) input reductions have been prescribed to control CyanoHABs, because P limitation is widespread and some CyanoHABs can fix atmospheric nitrogen (N_2) to satisfy their nitrogen (N) requirements. However, eutrophying systems are increasingly plagued with non N_2 fixing CyanoHABs that are N and P co-limited or even N limited. In many of these systems N loads are increasing faster than P loads. Therefore N and P input constraints are likely needed for long-term CyanoHAB control in such systems. Climatic changes, specifically warming, increased vertical stratification, salinization, and intensification of storms and droughts play additional, interactive roles in modulating CyanoHAB frequency, intensity, geographic distribution and duration. In addition to having to consider reductions in N *and* P inputs, water quality managers are in dire need of effective tools to break the synergy between nutrient loading and hydrologic regimes made more favorable for CyanoHABs by climate change. The more promising of these tools make affected waters less hospitable for CyanoHABs by 1) altering the hydrology to enhance vertical mixing and/or flushing and 2) decreasing nutrient fluxes from organic rich sediments by physically removing the sediments or capping sediments with clay. Effective future CyanoHAB management approaches must incorporate both N and P loading dynamics within the context of altered thermal and hydrologic regimes associated with climate change.

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1. Introduction

One of the most troublesome symptoms of nutrient over-enrichment is the proliferation of toxic, food-web altering and hypoxia-generating cyanobacterial harmful blooms, or CyanoHABs (Chorus and Bartram, 1999; Huisman et al., 2005) (Fig. 1). CyanoHABs are expanding geographically and now threaten the ecological integrity and sustainability of some of the world's largest and most resourceful water bodies, including Lakes Victoria, Africa; Erie, US–Canada; Okeechobee, Florida, USA (Havens et al., 2001); Taihu, China (Qin et al., 2010); Kasumigaura, Japan (Havens et al., 2001); the Baltic Sea in Northern Europe (Conley et al., 2009a); and the Caspian Sea in West Asia (Paerl and Huisman, 2008). In addition to their negative ecological, biogeochemical and health impacts, CyanoHABs cause serious economic losses to affected waters. In the USA alone, CyanoHABs result in losses of recreational, drinking, and agricultural water resources that are worth >$2 billion annually (Dodds et al., 2009). Identifying environmental factors driving the rapid rise in CyanoHABs is paramount to developing management strategies

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Fig. 1. Examples of large water bodies that have experienced increases in frequencies, magnitudes, and duration of CyanoHABs. Shown (on the left) are photographs of the blooms and (on the right) remote sensing images of each system. Top: Lake Taihu, China (photograph by H. Paerl), and MODIS remote sensing image of the lake and nearby cities (May, 2007) (Courtesy NASA). Middle: Baltic Sea-Gulf of Finland (courtesy of Finnish Border Guard and Institute of Marine Research, Helsinki, Finland), and SeaWiFS image of the same region (June 2005) (Courtesy NASA). Bottom: Lake Erie, southern shore (photograph courtesy NOAA), and Modis satellite image of a bloom in the Western basin of the lake, near Maumee Bay during summer 2009 (Modis, NOAA Coastwatch-Great Lakes).

aimed at protecting a significant fraction of the world's fresh and brackish water resources.

When devising long-term CyanoHAB control strategies, ecologists and managers face two sets of covarying trends; 1) nutrient over-enrichment in human-dominated watersheds (Vitousek et al., 1997; Conley et al., 2009b), and 2) changing climatic conditions, including global warming and altered rainfall patterns with increased severity of droughts and floods (Paerl and Huisman, 2008). Understanding and, when possible, managing interactive impacts of anthropogenic and climatic drivers of CyanoHABs is a major challenge to ensuring protection and sustainability of affected waters. Here, we synthesize established and emerging information on environmental factors influencing CyanoHAB bloom potential and dynamics, in order to provide a perspective and integrative approach to their management in a world experiencing contemporaneous anthropogenic and climatically-induced environmental change.

2. CyanoHAB Characteristics

The 3.5+ billion year evolutionary history of cyanobacteria has provided them with numerous physiological adaptations and mechanisms, enabling them to take advantage of environmental changes and extremes. Many genera possess high affinity uptake and intracellular storage capabilities for nitrogen (N) and phosphorus (P) (Padisák, 1997; Flores and Herrero, 2005); ideal for exploiting periodic enrichment of these potentially-limiting nutrients. Some genera can convert “inert” atmospheric nitrogen (N_2) into ammonia, via nitrogen fixation (Fogg, 1969), ensuring access to biologically-available N. In addition, CyanoHABs produce secondary metabolites potentially toxic to higher-ranked consumer organisms, including zooplankton, fish, and mammals (including man) that use affected waters as a habitat, and for drinking and recreational purposes (Chorus and Bartram, 1999).