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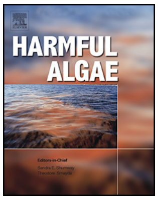

Review

Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients

Hans W. Paerl[a,*], Wayne S. Gardner[b], Karl E. Havens[c], Alan R. Joyner[a], Mark J. McCarthy[d], Silvia E. Newell[d], Boqiang Qin[e], J. Thad Scott[f]

[a] The University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, NC 28557, USA
[b] The University of Texas, Marine Science Institute, Port Aransas, TX 78373, USA
[c] University of Florida Institute of Food and Agricultural Sciences and Florida Sea Grant College Program, Gainesville, FL 32611, USA
[d] Wright State University, College of Science and Mathematics, Dayton, OH 45435, USA
[e] Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, PR China
[f] University of Arkansas, Department of Crop, Soil and Environmental Sciences, Fayetteville, AR 72701, USA

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ABSTRACT

Mitigating the global expansion of cyanobacterial harmful blooms (CyanoHABs) is a major challenge facing researchers and resource managers. A variety of traditional (e.g., nutrient load reduction) and experimental (e.g., artificial mixing and flushing, omnivorous fish removal) approaches have been used to reduce bloom occurrences. Managers now face the additional effects of climate change on watershed hydrologic and nutrient loading dynamics, lake and estuary temperature, mixing regime, internal nutrient dynamics, and other factors. Those changes favor CyanoHABs over other phytoplankton and could influence the efficacy of control measures. Virtually all mitigation strategies are influenced by climate changes, which may require setting new nutrient input reduction targets and establishing nutrient-bloom thresholds for impacted waters. Physical-forcing mitigation techniques, such as flushing and artificial mixing, will need adjustments to deal with the ramifications of climate change. Here, we examine the suite of current mitigation strategies and the potential options for adapting and optimizing them in a world facing increasing human population pressure and climate change.

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1. Introduction

The global expansion of cyanobacterial harmful algal blooms (CyanoHABs) is a serious threat to the ecological integrity, ecosystem services, safe use, and sustainability of inland and coastal waters (Carmichael, 2001; Huisman et al., 2005; Paerl and Fulton, 2006; Paul, 2008; Paerl et al., 2011; Paerl and Otten, 2013; O'Neil et al., 2012). CyanoHABs often are toxic, disrupt food webs, can lead to hypoxia, and result from high anthropogenic nutrient inputs to impacted ecosystems (Fogg, 1969; Reynolds and Walsby, 1975; Paerl, 1988). Some ecosystems are more susceptible to CyanoHABs than others due to varying morphometry, hydrology,

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[*] Corresponding author. Tel.: +1 252 726 6841x133; fax: +1 252 726 2426.
E-mail address: hpaerl@email.unc.edu (H.W. Paerl).

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geography, and the relative size and influence of watersheds (Fee, 1978; Wetzel, 2001; Huisman et al., 2005; Paerl and Otten, 2013). Differences in human activities in water- and airsheds influence the hydrology, qualitative and quantitative loads of nutrients, sediments, and other pollutants, which lead to differential responses by cyanobacteria vs. eukaryotic algae (Smith, 1983, 1990; Paerl and Otten, 2013).

Climate change, including global warming, is causing changes to regional rainfall and hydrology, which will have cumulative effects with nutrient-over-enrichment in modulating CyanoHABs (Paerl and Scott, 2010; Moss et al., 2011). Regional and global warming enhances the initiation, magnitude, duration, and distribution of CyanoHABs (Peeters et al., 2007; Jöhnk et al., 2008; Paul, 2008; Paerl and Huisman, 2008; Paerl et al., 2011; Kosten et al., 2012). Furthermore, increasing variability in rainfall patterns impacts nutrient and sediment delivery, sediment-water exchange and metabolism, flushing and water residence time, and vertical stratification, which, in turn, may affect CyanoHAB dominance and persistence (Mitrovic et al., 2003; Scott et al., 2008; Paerl and Huisman, 2008; Elliott, 2010; Paerl, 2014; Zhu et al., 2014). For example, changes in rainfall patterns, including more intense rainfall events followed by extensive summer droughts, result in episodic nutrient inputs, followed by strengthened and prolonged stratification, favoring CyanoHAB development and persistence (Paerl and Huisman, 2008, 2009; Winston et al., 2014). Forecasting these events is preempted by the inability to downscale climate predictions, both temporally and spatially (Hall, 2014).

Controlling CyanoHABs may be more challenging in the future than now due to warming effects. Examination of 143 lakes along a climate gradient in Europe and South America (Kosten et al., 2012) indicated that increased water temperature led to a gradual rise in the frequency of occurrence of cyanobacteria, up to a maximum of 60% at a total nitrogen (TN) concentration of 2 mg L^{-1}. However, cyanobacterial dominance increased stepwise along the temperature gradient when TN concentrations were increased to 4 mg L^{-1}, and the frequency of occurrence of cyanobacteria reached 80% at the highest temperatures (near 30 °C). Non-linear state changes in lake ecosystems are difficult to predict and extremely difficult to reverse after they occur (Scheffer et al., 2001). If the same kind of response trajectories occur for harmful cyanobacterial blooms, nutrient controls become much more crucial as increasing atmospheric temperatures approach these critical thresholds.

While forecasting the effects of climate change is a challenge, especially on local and regional scales, the high probability that future climatic conditions will favor bloom formation poses an added challenge to developing effective mitigation strategies that consider both nutrient and climate drivers (Figs. 1 and 2). Interactions between warming, changing hydrology, agricultural and industrial expansion, and nutrient delivery to aquatic ecosystems will require new approaches to managing CyanoHABs. Nutrient-growth threshold responses for CyanoHAB taxa likely will be altered as physical (e.g., temperature) and geochemical (e.g., nutrient fluxes) controls on these thresholds also change, resulting in moving targets in our quest for long-term CyanoHAB control.

In this contribution, we consider the impacts of current and anticipated climate changes, specifically warming and increased hydrologic variability and extremes, on CyanoHAB mitigation strategies. We evaluate these strategies for a range of impacted aquatic ecosystems and identify research priorities when there is insufficient information to reach conclusions about how climate change will influence the efficacy of a particular treatment.

2. Influence of climate change and human activities on CyanoHAB mitigation strategies

CyanoHAB mitigation strategies can be categorized as: (1) within water- and airsheds and (2) within waterbodies.

2.1. Watersheds and Airsheds

Extensive literature links macronutrient supply rates with the distribution and abundance of cyanobacteria (c.f., Likens, 1972; Vincent, 1987; Potts and Whitton, 2000; Huisman et al., 2005; Paerl and Fulton, 2006). Therefore, control of anthropogenic

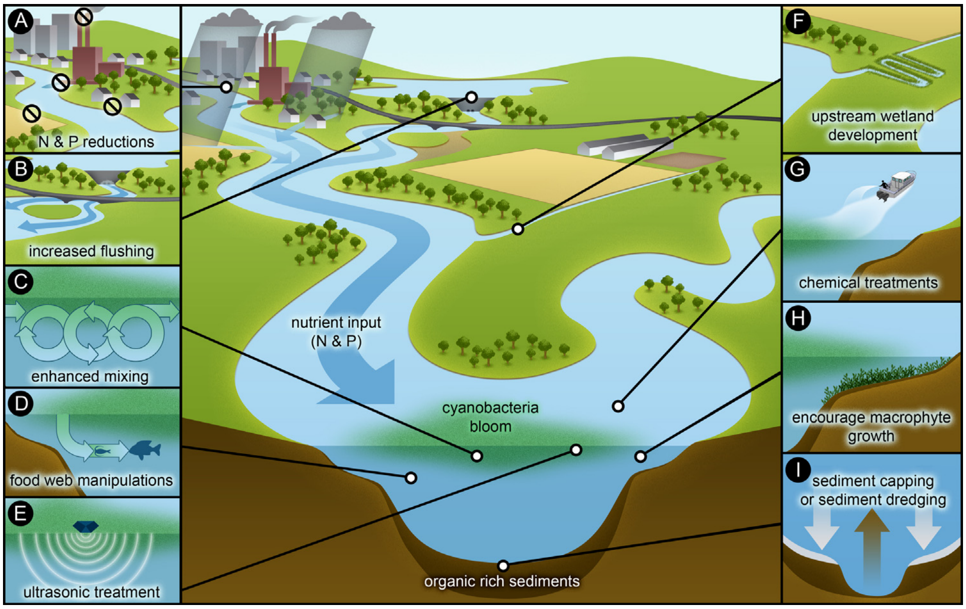

Fig. 1. Conceptual illustration of various approaches currently in use to control CyanoHABs, including control measures in the watershed and within the ecosystem. A. Point and non-point source nutrient (in most cases, both N and P) input reductions. B. Increasing flushing rates (decreasing water residence times). C. Mechanically-enhanced vertical mixing. D. Manipulating food webs to encourage filtering and consumption of CyanoHABs. E. Utilizing ultrasound waves to control algal growth. F. Nutrient attenuation/removal through upstream wetland development. G. Application of algaecides, including copper salts, hydrogen peroxide. H. Encourage growth of submersed and emergent aquatic vegetation for nutrient attenuation and removal. I. Dredging and capping of bottom sediments to reduce sediment-water column nutrient regeneration.