

# 渔业环境评价与 生态修复

Fishery Environmental Evaluation and  
Ecological Rehabilitation

主 编：刘 晴 徐 跑



海洋出版社

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主 编:刘 晴 徐 跑

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

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**Abstract:** The proliferation of bloom-forming, harmful (toxic, food web altering) cyanobacteria (CyanoHABs) is attributable to human nutrient over-enrichment. Phosphorus (P) input reductions have been prescribed to control CyanoHABs, because P limitation is widespread and some CyanoHABs can fix atmospheric nitrogen ( $N_2$ ), thereby satisfying 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. Many of these systems are experiencing accelerating N loads, often exceeding rates of P loading. 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. This has complicated management strategies for control because CyanoHABs are capable of taking advantage of unprecedented levels of nutrient enrichment and regional and global climatic change, including warming and altered hydrology. Future climatic change scenarios, especially temperature increases and their physical-chemical-biological effects, will likely promote CyanoHABs. Management strategies should therefore incorporate climate change scenarios in the development of predictive bloom thresholds based on the interactions of nutrient enrichment, altered thermal and hydrologic properties of aquatic ecosystems.

**Key words:** cyanobacterial bloom; nutrient enrichment; climatic change; control

## Introduction

One of the most troublesome symptoms of nutrient-over-enrichment is the proliferation of toxic, food-web altering and hypoxia-generating harmful cyanobacterial blooms, or CyanoHABs (Chorus and Bartram, 1999; Huisman et al., 2005; Paerl and Fulton, 2006) (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; Taihu, China; Kasimagaura, Japan; the Baltic Sea in Northern Europe; and the Caspian Sea in west Asia (Larsson et al., 1985; Havens et al., 2001; Elmgren and Larsson, 2001; Qin et al., 2009). Identifying environmental factors driving the rapid rise in CyanoHABs is paramount to developing management strategies aimed at ensuring sustainability of a significant fraction of the world's water resources.

When devising long-term, effective CyanoHAB management strategies, ecologists and managers face two set of "moving targets"; (1) nutrient over-enrichment in human-dominated watersheds (Vitousek et al., 1997; Conley et al., 2009), and (2) changing climatic conditions, including global warming, altered rainfall patterns and droughts, additionally modulate CyanoHABs (Paerl and Huisman, 2008). Understanding and (when possible) manipulating the interactive, and in many instances synergistic, impacts of anthropogenic and climatic drivers of CyanoHABs is a major challenge for ensuring protection and sustainability of affected waters.

Here, we synthesize established and emerging information on environmental factors influencing CyanoHAB growth and bloom potentials, in order to provide an integrative and effective approach to their management in a world experiencing contemporaneous anthropogenic and climatically-induced environmental change.

## The Players

Cyanobacteria were the first oxygenic phototrophs on Earth. They are responsible for the formation of an oxygen-rich biosphere in which they have thrived and profoundly affected biogeochemical cycling (Schopf and Walter, 1982). Their long evolutionary history has provided them with many eco-physiological adaptations and mechanism enabling them to take advantage of environmental changes and extremes. They possess high affinity uptake and intracellular storage capabilities for N and P (Syrett 1980; Healy 1982; Padisak 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 biologically-usable ammonia, via nitrogen fixation (Fogg, 1969); ensuring access to biologically-available N. In addition, CyanoHABs produce secondary metabolites potentially toxic to higher-ranked organisms, including consumers of algae (zooplankton, fish), and mammals (including man) that use affected waters as a habitat, for drinking and recreational purposes (Carmichael, 1997; Chorus and Bertram, 1999).

## Nutrient controls: Both N and P are important

CyanoHABs are stimulated by excessive anthropogenic nutrient loading (Fogg 1969; Reynolds, 1987; Paerl, 1988). In freshwater ecosystems, phosphorus (P) availability has traditionally been viewed as a key factor limiting CyanoHAB proliferation (Likens, 1972; Schindler et al.,

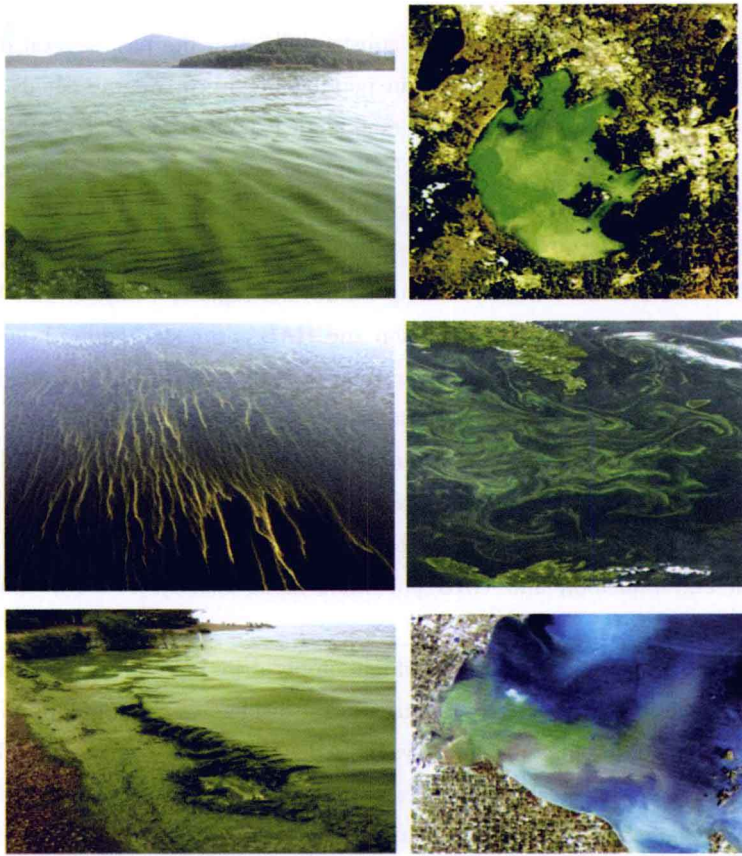


Fig. 1 Examples of large water bodies that have experienced increases in frequencies, magnitudes, and duration of CyanoHABs. Shown (on the left) are photographs of the blooms and (on the right) remote sensing images of each system. Top: Lake Taihu, China (photograph by H. Paerl), and MODIS remote sensing 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 LANDSAT image of a bloom in the Western region of the lake, near Maumee Bay during summer 2003 (Courtesy LANDSAT).

2008). Accordingly, controlling P inputs has been the “holy grail” for resource managers. Indeed, controlling P availability has reduced CyanoHAB bloom potentials in numerous freshwater lakes (Schindler, 1977). The emphasis on P reductions for CyanoHAB control is based on knowledge that some CyanoHAB genera conduct  $N_2$  fixation, which can help satisfy cellular N-requirements under P-limited conditions (Paerl and Fulton, 2006). However, at the ecosystem-level, only a fraction, usually far less than 50% of primary and secondary production demands are met by  $N_2$  fixation, even when P supplies are sufficient (Howarth et al., 1988; Paerl, 1990; Lewis and Wurtsbaugh, 2008). This indicates that  $N_2$  fixation is controlled by factors in addition to P availa-



bility.

Nutrient loading dynamics have changed substantially over the past several decades. While P reductions have been actively pursued, human population growth in watersheds has been paralleled by increased N loading, often at higher rates than P (Vitousek et al., 1997; Galloway and Cowling, 2002; Rabalais, 2002). Excessive N loads are now as large a concern as P loads as stimulants of freshwater, estuarine and marine eutrophication and harmful algal (including cyanobacterial) blooms (Nixon 1995; Havens et al., 2001; Boesch et al., 2001; Conley et al., 2009; Paerl, 2009; Hai et al., 2010). In the Baltic Sea region, Elmgren and Larsson (2001) concluded that effective control of eutrophication and HAB outbreaks required considering total amounts and ratios of N and P discharged to nutrient-sensitive river-fjord-sea continuum. Similarly, Paerl et al. (2004) showed that single nutrient input reductions, including a P-detergent ban and improved wastewater treatment for P during the 1980's in North Carolina's (USA) Neuse River System, helped solve one problem (arrest freshwater blooms), but exacerbated blooms in downstream N-sensitive estuarine waters. In both cases, parallel N and P input reductions were required to stem eutrophication and HAB potentials along the freshwater to marine continuum (Paerl, 2009).

In Florida's (USA) freshwater lakes, which supply drinking and irrigation water, excessive N loading, from expanding wastewater and agricultural discharges, was identified (in addition to P) as a key culprit in eutrophication and CyanoHAB expansion (Kratzer and Brezonik, 1981; Havens et al. 2001). In some cases (e.g. Lake Okeechobee), dominance by  $N_2$  fixing CyanoHABs (which were largely controlled by P input reductions) is now shared with non  $N_2$  fixing genera (e.g. *Microcystis*), as well as "switch hitter" CyanoHAB genera (e.g. *Cylindrospermopsis*, *Lyngbya*) that effectively compete for reactive N when it is available and then fix  $N_2$  when N is depleted. In these cases, both N and P reductions are needed to control CyanoHABs (Havens et al., 2001; Piehler et al., 2009).

In Lake Erie (USA-Canada), the current CyanoHAB problem is a resurgence of non- $N_2$  fixing *Microcystis* populations. Since 1995, blooms of *Microcystis* have annually reoccurred throughout Lake Erie (Fig. 1), a lake thought "recovered" from eutrophication due to well-managed P (but not N)-abatement programs. By what means and mechanisms have CyanoHABs re-emerged, despite concerted efforts to control P? Large lakes like Okeechobee, Taihu, Kasumigaura, Japan, deeper systems like Lake Erie and very deep systems like Lake Tahoe, CA - NV, USA tend to be co-limited by N and P (Havens et al., 2001, North et al., 2007; Elser et al., 2007; Hai et al., 2010); largely because previously-loaded P and N are effectively retained and recycled. While N can be "lost" via denitrification, this process does not appear to keep up with "new" N inputs, especially in systems heavily impacted by N over-enrichment (Seitzinger 1988; Havens et al., 2001). Overall, N and P co-limitation appears most common in eutrophic systems (Elser et al., 2007; Sterner, 2008), which are highly susceptible to CyanoHAB outbreaks (Huisman et al., 2005).

## The integral role of climate change

In addition to evolving nutrient over-enrichment issues, other environmental changes play integral roles in the recent upsurge of CyanoHABs. Climate change, specifically global warming, favors CyanoHABs in several ways. As a group, cyanobacteria exhibit optimal growth rates at relatively high temperatures, usually in excess of 25°C (Robarts and Zohary, 1987; Paerl and Huisman, 2008). At these elevated temperatures, CyanoHABs compete most effectively with eukaryotic algae (Fig. 2).

Warming of surface waters also intensifies vertical density stratification and thus suppresses vertical mixing. Furthermore, warming lengthens the period of stratification. Some CyanoHABs form gas vesicles, which provide buoyancy (Reynolds, 1987). Under strong and persistent vertically stratified conditions, positively buoyant cyanobacteria can form dense surface blooms which shade deeper non-buoyant eukaryotic phytoplankton, enhancing the CyanoHABs' competitive advantage (Huisman et al., 2004; Jöhnk et al., 2008) (Fig. 3). Increased water temperatures also decrease the viscosity of water and therefore the water's resistance to vertical migration of phytoplankton; facilitating upward (optimizing photosynthetic production) and downward (optimizing nutrient acquisition) migration by CyanoHABs. This further enhances their competitive advantages in stratified waters (Reynolds, 1987).

Dense surface blooms of cyanobacteria may locally increase water temperatures, through the intense absorption of light by their photosynthetic and photoprotective pigments. In the Baltic Sea and in Lake IJsselmeer (Netherlands), surface blooms tend to be warmer than ambient waters (Kahru et al., 1993; Ibelings et al., 2003). This represents a potential positive feedback mechanism, whereby CyanoHABs favor their own competitive dominance over eukaryotic phytoplankton (Hense et al., 2007).

A key driver of global warming is the rising level of the atmospheric greenhouse gases, most notably carbon dioxide ( $\text{CO}_2$ ). In nutrient-enriched waters, algal blooms exhibit a strong demand for  $\text{CO}_2$  to support photosynthetic growth; to the extent that the rate of  $\text{CO}_2$  supply can at times control the rate of algal biomass production (Shapiro, 1990). High rates of photosynthesis and hence high demand for  $\text{CO}_2$  will also increase the pH of affected waters, thereby restricting availability of free  $\text{CO}_2$  (Ibelings and Maberly, 1998). Under these conditions, buoyant CyanoHABs have a distinct advantage over sub-surface phytoplankton populations, since surface-dwelling taxa can directly intercept  $\text{CO}_2$  from the atmosphere, thus minimizing dissolved inorganic carbon (DIC) limitation of photosynthetic growth (Paerl and Ustach, 1982), while subsurface eukaryotic algal populations would be highly dependent on relatively slow diffusion to supply new  $\text{CO}_2$ , putting them at a disadvantage.

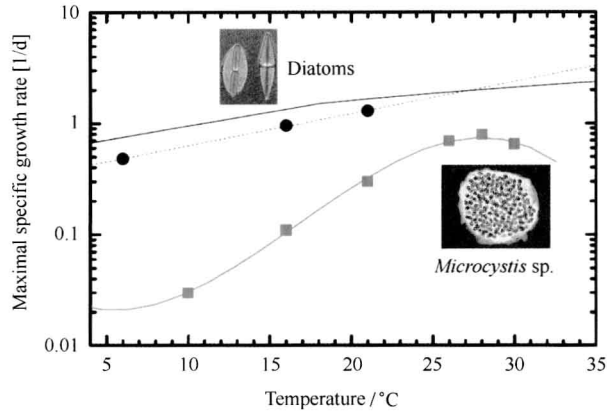


Fig. 2 Temperature dependence of the specific growth rates, a eukaryote (diatom) (Butterwick et al. 2005), and a bloom-forming cyanobacterium *Microcystis* sp. The data are from controlled laboratory experiments using light-saturated and nutrient-saturated conditions.

Summer droughts appear to be increasing in intensity and duration, possibly another symptom of global warming (IPCC, 2007). This, combined with increased use of freshwater for irrigation, has led to rising salinities worldwide. Increased salination is a serious threat to freshwater supplies; it also has major impacts on freshwater plankton composition and possibly CyanoHAB potentials. One impact of salination is increased vertical density stratification, which would benefit buoyant, scum-forming CyanoHABs (Fig. 3). In addition, some species of common CyanoHAB genera such as *Anabaena*, *Microcystis* and *Nodularia* are more salt tolerant than their eukaryotic freshwater algal counterparts (Horne and Galat, 1985; Moisander et al., 2002). Strains of *Microcystis aeruginosa* can tolerate salinities ranging up to  $10 \text{ g} \cdot \text{L}^{-1}$ , which is 30% of the salinity of seawater (Tonk et al., 2006). Likewise, *Anabaena aphanizominoidea* can withstand salt levels up to  $15 \text{ g} \cdot \text{L}^{-1}$ , while *Anabaenopsis* spp. and toxic *Nodularia spumigena* tolerate salinities ranging from  $0 \text{ g} \cdot \text{L}^{-1}$  to more than  $20 \text{ g} \cdot \text{L}^{-1}$  (Horne and Galat, 1985; Moisander et al., 2002; Mazur-Marzec et al., 2005). The high salt tolerance of these CyanoHABs allows for expanding blooms in brackish waters, including the Baltic Sea, the Caspian Sea, Patos Lagoon Estuary, Brazil, the Swan River Estuary, Australia, San Francisco Bay Delta, California and Lake Ponchartrain, Louisiana.

Global warming and associated changes in climatic oscillations affect patterns, intensities and duration of precipitation and droughts which may promote CyanoHAB dominance. For example, larger and more intense precipitation events will increase enrichment of water bodies with land-derived nutrients through enhanced erosion, surface runoff and groundwater discharge. Freshwater discharge would also increase, which in the short-term may prevent blooms by promoting flushing. However, as the discharge subsides and water residence time increases, its nutrient load will be captured and cycled by receiving water bodies, promoting bloom potentials. This scenario can be



observed in geographically-distinct places including the Swan River, Australia, Hartbeespoortdam, South Africa, the Neuse River Estuary, NC, USA, and the Potomac Estuary, MD, USA. In addition, attempts to control fluctuations in the discharge of rivers and lakes by dams and sluices increases residence time, aggravating CyanoHAB problems (Burch et al. , 1994).

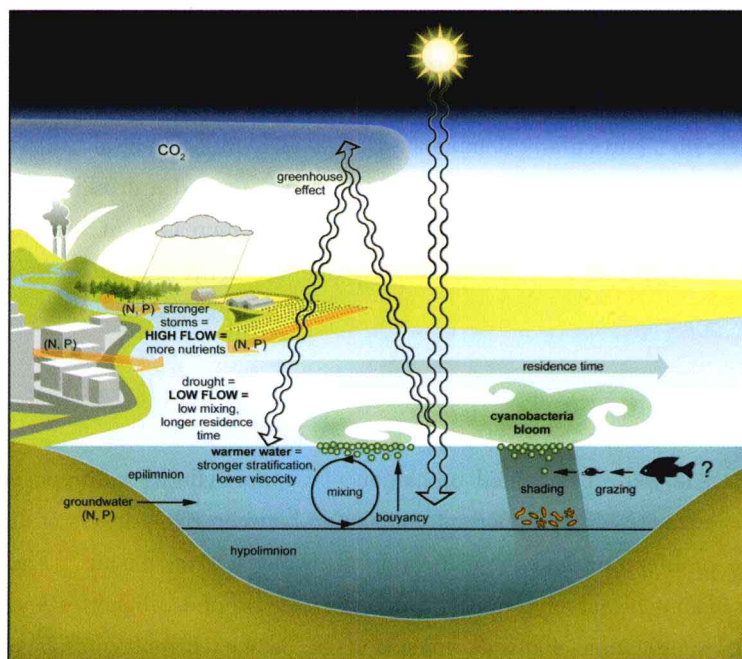


Fig. 3 Conceptual figure, illustrating the environmental processes that control cyanobacterial blooms, including impacts of climate change. Adapted from Paerl and Huisman (2009).

Overall, it appears that increases in hydrologic variability and “extremeness” such as protracted droughts benefit CyanoHABs. If conditions get so extreme as to dry up lakes and reservoirs, most CyanoHAB species can survive such extremeness for long periods (up to many years) as dormant cysts in sediments, soils, or desiccated mats (Potts, 1994).

Some toxin-producing CyanoHABs appear to be particularly successful at exploiting climatic change. The planktonic/benthic filamentous N<sub>2</sub>-fixing genus *Lyngbya* and the planktonic N<sub>2</sub> fixer *Cylindrospermopsis raciborskii* have shown remarkable expansion of their geographical ranges, possibly linked to warming and associated hydrodynamic changes. *Cylindrospermopsis* was originally described as a tropical and subtropical species. However, *C. raciborskii* appeared in southern Europe during the 1930s, and has shown a progressive increase in colonization from Greece and Hungary up to the Netherlands and northern Germany near the end of the 20th century (Padisák, 1997; Wiedner et al. , 2007). *C. raciborskii* was first identified in United States Midwest lakes in the 1950s. It probably existed in Florida inland waters for many years, but it wasn't until the 1980s that it began to aggressively proliferate in lake and river systems throughout central Florida (Chapman and Schelske, 1997). More recently, this CyanoHAB has spread throughout US