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PERSPECTIVE

TACKLING HARMFUL CYANOBACTERIAL BLOOMS WITH CHINESE COLLEAGUES: WE'RE ALL IN THE SAME BOAT[1]

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Harmful cyanobacterial blooms (CyanoHABs) are a rapidly proliferating global problem, threatening the use and sustainability of our freshwater resources. In recent decades, the United States, China, and other developed and developing countries threatened by CyanoHAB expansion have established collaborative efforts aimed at mitigating and managing this environmental and human health problem. However, an escalating negative political climate and restrictive policies on scientific exchange threaten these efforts. In this Perspective, I point to progress that has been made to counter the CyanoHAB problem on U.S.–Chinese fronts through our collaborations, which have been mutually beneficial from research and academic perspectives. Much like global efforts now needed to control pandemics, we are all "in the same boat" when to comes to countering the threat CyanoHABs pose for drinkable, swimmable, and fishable freshwater supplies and human health.

Key index words: **cyanobacteria; eutrophication; mitigating blooms; U.S.–China collaborations**

***Abbreviations*:** **CyanoHAB, harmful cyanobacterial bloom; GLEON, Global Lake Ecological Observatory Network; NIGLAS, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences; NSF, National Science Foundation; NSFC, National Natural Science Foundation of China; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2**

The purpose of this Perspective is to underscore the mutual benefit of U.S.–China collaborations aimed at mitigating eutrophication and tackling proliferating harmful cyanobacterial blooms (CyanoHABs) in our respective countries and on a global scale. I felt compelled to write this article in light of the increasingly restrictive policy being applied to scientific collaborations between our countries, and the counterproductive impacts that restrictions will have to all scientific research; in the current case, I am specifically addressing the global threat of CyanoHABs to drinkable, swimmable, and fishable freshwater supplies and human health.

My interest in collaborative U.S.–Chinese research on CyanoHABs started at an unlikely moment; while visiting the University of Texas at Austin Marine Science Institute as an invited speaker in 2006. There, Director at the time, Wayne Gardner, showed me a photograph of a spectacular cyanobacterial bloom in Lake Taihu (pronounced *Tai-hu*, meaning large lake in Mandarin), China. The bloom spanned the entire width of the lake, some 60 km (Fig. 1). As I recall, Wayne noted "I know how much you like working on algal blooms. . ..well here's a challenge that I know you can't resist." Wayne was right—I was fascinated by the immensity of the bloom in these photos. In spring 2007, Taihu was engulfed in a "green monster" bloom (Guo 2007), which overwhelmed the drinking water supply for over 10 million local inhabitants, leading to a crisis that cut off all drinking water supplies for over 2 weeks (Qin et al. 2010). This green monster forced the Chinese Government to truck in water potable supplies in an operation that dwarfs the more recent (2014) drinking water shutdown in Toledo, Ohio, similarly caused by bloom-related cyanotoxin production (Bullerjahn et al. 2016).

Thanks to US National Science Foundation (NSF) International Programs funding, Wayne and his technician, Mark McCarthy established a collaborative relationship in the early 2000s with researchers at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, NIGLAS to begin to address the CyanoHAB problem in Taihu by examining the potential role of sediments as nutrient storage reservoirs to support and maintain the monster blooms.

Hypereutrophic Taihu had been subjected to untreated wastewater and agricultural nutrient overenrichment over several decades of rapid urban and industrial expansion, as well as unchecked agricultural and aquaculture growth (Qin et al. 2010). We decided that the time was right to invite Wayne's Chinese colleagues and other Chinese experts to the United States to discuss a collaborative research strategy aimed at expeditiously identifying the

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FIG. 1. Cyanobacterial bloom (*Microcystis* spp.) during 2007 at Lake Taihu, China. Photocredit: Hans Paerl.

causes for the rapid proliferation of blooms in both China and the United States. With the help of an US Environmental Protection Agency planning grant, we convened an international meeting in early 2007 on cyanobacterial blooms and related nutrient dynamics at the University of North Carolina-Chapel Hill Institute of Marine Sciences in Morehead City, NC. Invited experts from China, the United States, and Europe participated. The timing of this meeting proved prophetic, as it preceded the 2007 "green monster" bloom in Taihu by only a couple of months (Guo 2007). Following the meeting, I was invited to see first-hand the magnitude and severity of the problem, and within a matter of weeks, fellow CyanoHAB researchers Steven Wilhelm, Gregory Boyer, the late Karl Havens, and our Chinese colleagues, headed up by Professors Boqiang Qin and Guangwei Zhu, wrote companion US-NSF (Engineering Directorate) and National Natural Science Foundation of China (NSFC) proposals to urgently address the causes and potential solutions to this problem. Both proposals were funded, and we quickly embarked on a joint effort to: (i) identify the causative agents of the bloom, including nutrient inputs, hydrologic, and climatic factors as possible interactive drivers; (ii) characterize the internal nutrient cycling dynamics involved in maintaining blooms, and perhaps most urgently; (iii) identify the initial steps needed to prioritize nutrient input reductions aimed at mitigating the blooms; and (iv) exploring whether Taihu was a "looking glass" for the global expansion of CyanoHABs.

Together with our Chinese colleagues, a cadre of researchers and students was mobilized to tackle this complex problem (Fig. 2). Our specific goals involved understanding nutrient-bloom interactions with dominant cyanobacterial bloom taxa and their microbiomes; we explored interactions between various loads of nitrogen and phosphorus, freshwater residence time, temperature effects, vertical mixing characteristics, and sediment-water column exchange. This long-term effort included dynamic space–time monitoring of relevant parameters, in situ nutrient manipulation bioassays, extensive characterization of nutrient forms, nutrient transformation rates, and finally a molecular analyses of the CyanoHAB "players" and their consorts (i.e., the cyanobacterial community members).

Taihu was not the only hypereutrophic lake in China exhibiting CyanoHAB proliferation. Many lakes and reservoirs in China's coastal plain and upstream regions suffered from similar problems. Managers at the Chinese provincial Environmental Protection Agency, the Ministry of Ecology and the Environment, and other agencies anticipated that

Fig. 2. (A) Hans Paerl collecting surface algal bloom sample at Lake Taihu, China. (B) Prof. Guangwei Xu and Hans Paerl collecting plankton samples at Lake Erhai, Yunnan Province, China. (C) Prof. Guangwei Xu and Hans Paerl, preparing nutrient addition bioassays near Lake Taihu. (D) Chinese Graduate Students and Hans Paerl filling bioassays with lake Taihu water. (E and F) U.S. and Chinese students working at the experimental mesocosm site located on the shore of Lake Taihu. (G) Hans Paerl and collaborators at the International Society of Limnology (SIL) meetings, held in Nanjing, China, August, 2018. (H) Prof, Yiping Li and Hans Paerl at a Graduate Student Symposium, Hohai University, Nanjing.

results from Taihu's maladies could be transferrable to their other aquatic ecosystems. On our (United States) end, understanding factors driving these systems into hypereutrophy provided key insights into understanding how some of our own most resourceful yet ailing large U.S. lakes and impoundments (e.g., Lakes Erie, Okeechobee, Klamath, Lake Pontchartrain, and numerous reservoirs and smaller lakes) were impacted by similar drivers and cyanobacterial "players," persistent across physio- and geographic boundaries. We also examined whether information about Taihu would be of multinational, if not global, relevance (e.g., Lake Winnipeg, Canada; Lake Maracaibo, Venezuela; Lake Victoria, Africa; Lake Kasumigaura, Japan; the Baltic Sea in northern Europe; the Caspian Sea in West Asia; Lake Maracaibo, Venezuela, and the Rio Negro; Uruguay). Indeed, we now recognize that proliferating CyanoHAB problems are a global phenomenon. It is thought that microbiome-scale commonalities and differences among these global blooms (Hooker et al. 2019) will aid substantially in our understanding of these blooms and help to uncover novel, effective mitigation strategies.

Our Chinese colleagues have reciprocally contributed to parallel CyanoHAB studies, symposia and collaborative working groups involved in studies on the U.S./Canadian Great Lakes (Lake Erie), Florida's Lake Okeechobee, North Carolina's coastal rivers, and numerous Midwest, West coast, and Southeast lakes and reservoirs. In addition, by virtue of sharing data on myriad Chinese lakes, these colleagues are valuable contributors to the Global Lake Ecological Observatory Network (GLEON), a "network conducting innovative science by sharing and interpreting high-resolution sensor data to understand, predict and communicate the role and response of lakes in a changing global environment." Their increasingly significant contributions to global aquatic phycological research are evident in the rapidly growing numbers of publications in premier journals; a large proportion of which are co-authored by researchers from around the globe.

To date, our collaborative efforts have yielded numerous, mutually valuable results that can best be summed up as a win–win in U.S.–China collaborative efforts aimed at reversing eutrophication of large lake ecosystems. First and foremost was the identification of nutrients that were limiting and controlling CyanoHABs on a year-round basis. Traditionally, phosphorus (P) was considered the nutrient most limiting for CyanoHABs and hence the most important to control (c.f., Schindler et al. 2008), and prior to our collaborative efforts, that assumption was also widely held by our Chinese colleagues. However, nutrient addition bioassays, as well as stoichiometric and enzymatic assays, indicated that while P proved limiting in the spring phase of bloom development, the buildup of bloom biomass during the critical summer period was controlled by *both* N and P supplies, while the magnitude and duration of blooms in summer and fall were largely controlled by N supply (Xu et al. 2010, Paerl et al. 2011, 2014a). Furthermore, the assumption that N_2 fixation by diazotrophic cyanobacterial taxa would supply the N needed to sustain blooms (Schindler et al. 2008) did not hold true for Taihu (Paerl et al. 2014b), a finding that is now translatable to many eutrophic lakes globally (Lewis et al. 2011, Paerl et al. 2016, Chaffin et al. 2018, Scott et al. 2019, Wurtsbaugh et al. 2019). These results, combined with the finding that denitrification can remove at least 30% of new N inputs annually (Paerl et al. 2011), has formed the rationale for taking a more aggressive approach to reducing external N inputs: to "de-eutrophy" Taihu far more rapidly than reducing P inputs alone. Excessive P inputs over more than three decades has led to a large legacy of P that is readily available for internal cycling in this as well as other hypertrophic large lakes in China and worldwide (e.g., Lakes Okeechobee and Erie, USA; Lake Lake Maracaibo, South America; Lake Victoria, Africa; Lakes Balaton and Maggiore, Europe; Lakes Rotorua and Rotoiti, New Zealand; Aumen and Havens 1998, Elser et al. 2007, Conley et al. 2009, Paerl and Otten 2013, Hamilton et al. 2016, Paerl et al. 2016, 2019, Qin et al. 2019).

One indication of excessive N inputs is the dominance, persistence, and geographic expansion of the non-N_2 fixing CyanoHAB genus *Microcystis*, which requires fixed N to sustain its growth and dominance (Harke et al. 2016, Hooker et al. 2019, Paerl et al. 2019). Interestingly, N_2 fixing genera, including *Anabaena* (recently renamed *Dolichospermum*), and *Aphanizomenon*, while accompanying *Microcystis* in blooms, have become subdominant over more recent decades in Taihu, as well as elsewhere in eutrophic large lakes (L. Erie, L. Okeechobee; Havens 1995). This information suggests that excessive N loading is a major factor in the eutrophication and bloom dynamics of these lakes, underscoring the need for dual N and P reductions as a CyanoHAB mitigation strategy. These far-reaching implications of these findings simply would not have been possible without our sustained and productive U.S.–China partnerships.

Collaborative research at Taihu has also provided testimony that hydrologic manipulations, such as the diversion of the Yangtze River through the lake to enhance flushing and reduce water residence time may be counter-productive as a CyanoHAB mitigation strategy in large, shallow eutrophic lakes (Paerl et al. 2019, Qin et al. 2019). Long-term water quality monitoring combined with experimental bioassay work in Taihu indicates that diverting nutrient rich water from the heavily polluted Yangtze through the lake actually increases the nutrient load (Qin et al. 2010, Li et al. 2020). Furthermore, it exacerbates the CyanoHAB problem because water residence time cannot be sufficiently reduced to flush algae out of the lake fast enough to overcome algal growth rates. Taihu has provided the wake-up call that we cannot solely engineer our way out of freshwater ecosystem degradation via eutrophication and episodic CyanoHABs without a scientific understanding of the controlling processes and causes. Parallel U.S. examples include engineering shortcomings at Lakes Okeechobee and Erie (Havens 1997, Bullerjahn et al. 2016). In summary, lessons learned from Taihu concerning nutrient dynamics, including seasonal shifts in nutrient limitation (Xu et al. 2010, Paerl et al. 2014) and the importance of "legacy" N and P supporting continued CyanoHAB production even after reduction of external nutrients (Hampel et al. 2019) have proven useful in developing long-term management strategies for other large, eutrophying lakes globally (Paerl et al. 2019).

Our collaborative research at large lakes Taihu, Erie, and Okeechobee has shown that climatic changes further impact CyanoHAB development and proliferation (Paerl et al. 2019). For example, increasing atmospheric CO_2 levels and warming, more extreme precipitation events, altered wind speeds, and more protracted droughts all play strong interactive roles in modulating eutrophication and CyanoHAB potentials (Paerl and Huisman 2008, 2009, Deng et al. 2014, 2018, Paerl et al. 2016, Ma et al. 2019). Taihu has served as an excellent testbed for evaluating these interactions and their ramifications for adaptive management of eutrophication, as bloom thresholds are shifting in light of the climatic changes taking place.

Technology transfer plays a vital role in addressing the above water quality and sustainability issues. The advent of solid state, unattended monitoring sensors and platforms, real time monitoring, and internet-based communication capabilities has expedited and streamlined our ability to rapidly assess water quality conditions. Likewise, the ever-evolving suite of molecular microbial identification and quantification techniques offers high-resolution tools to ascertain the role of CyanoHABs in ecological and environmental health issues. Now, more effectively than ever, we can evaluate CyanoHAB toxicity, as well as impacts on aquatic biodiversity, biogeochemical cycling, odor and taste of drinking water supplies, and recreational and fishery resources (c.f., Tang et al. 2018). Such novel technology and instrumentation has been developed, adapted, and used internationally to study these issues, which is necessary to ensure scientific technique development and economic competition. All of the society benefits from broad applications of such technology and idea-sharing. Research in developing regions requires the active and cooperative participation of U.S., Chinese, and other international researchers, stakeholders, and managers to yield mutual benefits and ensure sustainability of our inland waters.

Finally, there are striking parallels and obvious benefits in working collaboratively on a global scale to mitigate a range of expansive, biotic pandemics impacting human health, as illustrated by the SARS-CoV-2 crisis we are currently facing. Their causes and controls cross geographic boundaries and should be addressed on that scale. Training the next generation of partnerships between interdisciplinary scientists from the United States, China, and beyond is critically important to preserve environmental and public health. Exchanges in students and staff that have lasted from months to years—in both directions—has not only improved our understanding of systems and brought new techniques to bear on these problems, but has more importantly let us clearly understand the costs in quality of life that everyone is facing due to these blooms. Water quality problems do not stop at international boundaries. Improved educational and interactive programs are necessary to ensure that appropriate expertise is available to tackle complex, regional, and global freshwater and CyanoHAB problems worldwide. Developing and exchanging expertise around the globe is needed to address the challenge of ensuring safe, drinkable, swimmable, and fishable waters. This effort will require open academic and governmental efforts at all levels, something akin to *Doctors Without Borders*. Water is humanity's ultimate resource—without it, little else matters as far as our ability to coexist and benefit from the gift of having a water planet to share and treasure.

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H.P., investigation-lead, project administration-lead, writing-original draft-lead.

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