SPECIAL ISSUE

CSIRO PUBLISHING

Marine and Freshwater Research, 2020, **71**, i–iv
https://doi.org/10.1071/MFv71n5_ED

Editorial

Cyanobacteria in inland waters: new monitoring, reporting, modelling and ecological research

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Additional keywords: blooms, cyanotoxins, management, toxins.

Introduction to special issue

Cyanobacteria in freshwater environments are a natural part of the phytoplankton community but can cause human health and ecosystem issues through the production of toxins (Paerl *et al.* 2001). The toxins produced by cyanobacteria (cyanotoxins) are varied, and include hepatotoxins, neurotoxins, cytotoxins and skin irritants (Bartram and Chorus 1999; Wiegand and Pflugmacher 2005). Cyanotoxins can have adverse effects on human health, particularly by exposure through drinking water (Carmichael *et al.* 2001) or recreation (such as swimming; Pilotto *et al.* 1997). Cyanotoxins are also known to affect livestock and native animals drinking contaminated water (Stewart *et al.* 2008) and aquatic organisms such as fish (Drobac *et al.* 2016), zooplankton (Bownik 2016) and aquatic macrophytes (Mitrovic *et al.* 2004, 2005). The risks from cyanotoxins increase with the density of cyanobacterial blooms, so understanding the drivers of cyanobacterial growth and dominance, as well as the risks of cyanotoxins, is important for management.

Cyanobacterial blooms are anticipated to expand and change their distribution, frequency and intensity in inland waters with increasing global warming and climate change (Paerl and Huisman 2009). This is concerning due to the potential impact of blooms in new locations and increased bloom intensity in previously affected areas. This special issue of the Journal brings together papers that use new and diverse scientific tools available for monitoring, reporting and modelling cyanobacterial growth, as well as ecological research on cyanobacteria and their toxins that can help expand our research and management capabilities. These approaches to the monitoring of cyanobacteria within waterways may give further insights into risks and management approaches.

New ways of monitoring for cyanobacteria

Remote sensing technology and algorithms continue to mature, enabling more accurate monitoring of cyanobacteria over large spatial scales with higher-frequency observations (e.g. Ogashawara *et al.* 2013; Kudela *et al.* 2015; Cicerelli *et al.* 2017). Semi-analytical modelling techniques, where water-leaving radiance is linked to inherent optical properties and in-water photopigment concentrations, have also been developed (Mishra *et al.* 2013; Li *et al.* 2015). In this special issue, Borges *et al.* (2020) explore the performance of different semi-analytical algorithms for chlorophyll (Chl)-*a*. Using Sentinel-2 Multispectral Instrument imagery and its atmospheric correction algorithms, Borges *et al.* (2020) found that phycocyanin concentration is strongly correlated to Chl-*a* concentration and that the Inversion Model of Inland Waters semi-analytical algorithm was the best performing. Interestingly, Borges *et al.* (2020) found that an algorithm using top-of-atmosphere reflectance performs better than an algorithm using atmospheric correction, showing that even without an adequate atmospheric correction, monitoring of cyanobacteria can be achieved using semi-analytical bio-optical models.

Cyanobacterial blooms are changing in relation to climate change (Paerl *et al.* 2020). By using new and diverse scientific tools, various temporal and spatial scales of monitoring and detection of cyanobacterial blooms will be important to water resource managers. In this special issue, Drozd *et al.* (2020) provide a novel analysis of hyperspectral remote sensing data, resulting in semi-empirical models for large spatial- and temporal-scale monitoring of cyanobacteria. Their results show the importance of the red and near-infrared spectral region for identifying cyanobacteria in hypereutrophic waters. In a more targeted approach, Stoyneva-Gärtner *et al.* (2020) report a valuable case study of cyanobacterial blooms using a drone as a remote observational tool to choose sampling points, together with the laboratory analysis of marker algal pigments by HPLC. Although the use of drones is weather dependent, the monitoring approach of Stoyneva-Gärtner *et al.* (2020) shows considerable potential for speedy and efficient data acquisition. In a rare study of soil microbial distribution in semi-arid floodplain wetlands, Kobayashi *et al.* (2020) examined the relationship between historical inundation frequency and cyanobacteria in soils based on high-throughput sequencing, targeting the bacterial *16S* rRNA gene. Kobayashi *et al.* (2020) report no significant effect of historical inundation frequency on the proportional abundance of cyanobacteria and suggest that cyanobacteria occupy a different hydrological niche from the other microbes, such as Proteobacteria and Actinobacteria, in those environments.

Understanding what drives cyanobacterial blooms

Understanding the drivers of cyanobacterial blooms can be useful in determining appropriate management actions. For example, if thermal stratification is important in bloom development, artificial mixing may be a useful tool in a reservoir or lake to mitigate blooms (Visser *et al.* 2016). Similarly, nutrient management of waterways also benefits from an understanding of which nutrient, or combination of nutrients, is limiting growth (Paerl *et al.* 2014; Müller and Mitrovic 2015). Cyanobacterial blooms are a major issue in China, with some lakes showing extreme eutrophication. For example, Lake Taihu, China's third largest freshwater lake, has experienced massive cyanobacterial blooms dominated by *Microcystis* spp. (Chen *et al.* 2003) and it has been suggested that both N and P reductions are required to reduce biomass (Paerl *et al.* 2014). In another area of China, namely Jinan City, Zhao *et al.* (2020) examined the drivers of cyanobacterial blooms in lakes and reservoirs and found that nutrients (both P and N) and water temperature were important predictors of cyanobacterial growth. In the areas where human populations were greater, P and N had a greater effect on the cyanobacterial community. Nutrient management may be a potential management tool for this area of China.

Wilk-Wozniak (2020) reviews the factors involved in the development of blooms with a focus on the often-overlooked interactions between cyanobacteria and zooplankton, ciliates, heterotrophic bacteria, viruses and fungi. The review shows a complex food web and suggests that cyanobacterial blooms are not an ecological endpoint, but rather the mid-point. In another study challenging our understanding of cyanobacteria blooms, Grover *et al.* (2020) explored eco-evolutionary trade-offs between the costs of heterocyst formation and the production of cyanotoxins. Through numerical modelling, Grover *et al.* (2020) suggest that major taxa of cyanobacteria are differentially adapted to varying N and P supplies, and that biomass stoichiometry is related to toxin production. They note that this modelling approach can be extended into models of community and ecosystem dynamics to explore implications of N fixation for cyanobacterial biomass and toxin production.

Cyanobacterial toxins

Toxin production by cyanobacteria is a primary concern for water resource management. Understanding the concentrations of cyanotoxins in waters is important for risk management and adherence to various guideline recommendations, such as the World Health Organization (WHO) guidelines for drinking water (Bartram and Chorus 1999). Porojan *et al.* (2020) examined microcystin concentrations across 17 reservoirs in Singapore for a 12-month period. Tropical areas are less studied for cyanobacterial research and more knowledge on cyanobacterial blooms and toxin production is needed for these areas (Mowe *et al.* 2015). Porojan *et al.* (2020) found that cyanotoxins were usually low but, on one occasion at one reservoir, were close to the WHO guideline of 1.0 $\mu g\ L^{-1}$, whereas four reservoirs had concentrations above 0.3 $\mu g\ L^{-1}$. Porojan *et al.* (2020) also examined the factors affecting microcystin concentrations at these four reservoirs and found total monthly rainfall and total N were most important.

The concentrations of cylindrospermopsins (CYNs) and anatoxins was also examined in Singapore by Abbas *et al.* (2020) after developing a method using liquid chromatography–tandem mass spectrometry (LC-MS/MS) using a triple-stage quadrupole mass spectrometer with a turbo-assisted ion spray source. Abbas *et al.* (2020) found that cylindrospermopsin was more prevalent than anatoxin-a and that intracellular cylindrospermopsin concentrations exceeded 0.4 $\mu g\ L^{-1}$ in six reservoirs surveyed, and slightly exceeded the provisional CYN drinking water guidelines on one occasion in one reservoir. These authors found the most important environmental factors affecting CYN concentrations were total N, nitrate and total P concentrations. Anatoxin-a concentrations were low ($<0.1\ \mu g\ L^{-1}$) for all reservoirs (Abbas *et al.* 2020).

Lovin and Brooks (2020) focused on anatoxin-a and its analogues and examined published data from around the world to identify exceedances of guideline values. These authors found that when blooms occurred, recreational and potable source waters exceeded guidelines of 0.1, 1 and 300 $\mu g\ L^{-1}$ for 79.62, 48.37 and 1.42% of the time respectively. Of the occurrences, 66% were from lacustrine ecosystems compared with reservoir, river, coastal and other systems, with almost all data from Asia–Pacific, Europe and North America (Lovin and Brooks 2020). This latter point underscores the need for more monitoring efforts in diverse systems and in developing regions.

In addition to hepatotoxic microcystins, *Microcystis aeruginosa* is known to produce a variety of other secondary metabolites (SMs), which may have adverse effects on aquatic ecosystems (Janssen 2019). Pearson *et al.* (2020) characterised the distribution, composition and conservation of the 9 different SM biosynthesis gene clusters by analysing the 27 *M. aeruginosa* genomes derived from different climate zones. Their results highlight the potential chemical diversity inherent within this species and multiple factors for shaping the evolution of such pathways. The only cyanotoxin biosynthesis gene cluster identified in their screening study was the *mcy* cluster, suggesting that the production of non-microcystin cyanotoxins by this taxon is either absent or rare (Pearson *et al.* 2020).

Management and mitigation of blooms

Management and mitigation of blooms requires sound knowledge of the factors driving bloom formation and toxin production. Approaches to manage blooms have included reductions in nutrients to inland and coastal waters to limit the biomass of cyanobacteria (Willén 2001; Jeppesen *et al.* 2005); artificial mixing to prevent thermal stratification in lakes and reservoirs (Visser *et al.* 2016); flow management to reduce thermal stratification in rivers (Mitrovic *et al.* 2003, 2011); food web manipulation to increase the grazing of cyanobacteria (Mehner *et al.* 2002) and macrophyte recovery to promote clear water states through allelopathy (Song *et al.* 2019), among other techniques. Paerl *et al.* (2020) discuss the confounding effects and challenges posed by climate change on toxic cyanobacterial blooms. Paerl *et al.* (2020) suggest that rising temperatures and the increasing frequencies and magnitudes of extreme weather events will promote cyanobacterial blooms and affect the efficacy of remedial measures, and suggest the setting of stricter nutrient reduction targets for bloom control. Further, Paerl *et al.* (2020) suggest the efficacy of current methods for control will need to be re-evaluated considering climate change effects.

Guidelines and approaches to the management of cyanobacteria also need to be regularly reviewed for best practice, and ideally using the most up-to-date information. Moustaka-Gouni *et al.* (2020) discuss some of the potential issues with sampling, estimation of biomass and the use of cyanobacteria when calculating phytoplankton indices to assess water quality. They discuss some of these issues from the viewpoint of Greece and using the Water Framework Directive as an example, considered the most innovative European environmental legislation. Problems discussed concern the exclusion of most chroococcalean taxa from cyanobacterial biovolume estimations in lakes and reservoirs of the Mediterranean region, treatment of the mucilage of colonial chroococcalean taxa in biovolume estimations and the overlooking of deep-water cyanobacterial blooms due to sampling depth (Moustaka-Gouni *et al.* 2020). This highlights the need for regular review and discussion of the current state of knowledge in cyanobacterial research and the improvement and better application of guidelines.

Collectively, the papers in this special issue provide an interesting range of new information and perspectives on cyanobacteria in inland waters, focussing on new monitoring, modelling and ecological research. These papers contribute to further our knowledge about freshwater cyanobacterial blooms, which will help manage their ongoing issues for water management. With climate change predicted to increase the number and intensity of blooms in the future (Paerl and Huisman 2009), new knowledge and approaches are required to best manage the human and ecological risks of cyanobacterial blooms and associated toxins.

Conflicts of interest

Simon M. Mitrovic, Tsuyoshi Kobayashi and Daniel L. Roelke are guest editors of the Cyanobacteria special issue and are Associate Editors for *Marine and Freshwater Research*. Despite these relationships, they took no part in the review and acceptance of this or any other manuscript in this issue that they authored. The authors declare that they have no further conflicts of interest.

Acknowledgements

The editors of this special issue acknowledge the Association for Scientists in Limnology and Oceanography (ASLO) for supporting our Session 087 ‘Cyanobacteria in Inland Waters: New Monitoring, Reporting, Modelling and Ecological Research’ at the 2018 Summer Meeting in Victoria, British Columbia, Canada, that launched this special issue.

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