

Tropical cyanobacterial blooms: a review of prevalence, problem taxa, toxins and influencing environmental factors

Maxine A.D. MOWE,^{1*} Simon M. MITROVIC,² Richard P. LIM,² Ambrose FUREY,³ Darren C.J. YEO¹

¹Freshwater & Invasion Biology Laboratory, Department of Biological Sciences, National University of Singapore, 14 Science Drive 4, Singapore 117543; ²Centre for Environmental Sustainability, School of the Environment, University of Technology, Sydney, PO Box 123, Broadway NSW 2007, Australia; ³Mass Spectrometry Research Centre (MSRC), Department of Physical Sciences, Cork Institute of Technology, Bishopstown, Cork, Ireland

*Corresponding author: maxinemowe@gmail.com

ABSTRACT

Toxic cyanobacterial blooms are a major issue in freshwater systems in many countries. The potentially toxic species and their ecological causes are likely to be different in tropical zones from those in temperate water bodies; however, studies on tropical toxic cyanobacterial blooms are sporadic and currently there is no global synthesis. In this review, we examined published information on tropical cyanobacterial bloom occurrence and toxin production to investigate patterns in their growth and distribution. Microcystis was the most frequently occurring bloom genus throughout tropical Asia, Africa and Central America, while *Cylindrospermopsis* and *Anabaena* blooms occurred in various locations in tropical Australia, America and Africa. Microcystis blooms were more prevalent during the wet season while *Cylindrospermopsis* blooms were more prevalent during the dry period. Microcystin was the most encountered toxin throughout the tropics. A meta-analysis of tropical cyanobacterial blooms showed that Microcystis blooms were more associated with higher total nitrogen concentrations, while *Cylindrospermopsis* blooms were more associated with higher maximum temperatures. Meta-analysis also showed a positive linear relationship between levels of microcystin and N:P (nitrate:phosphate) ratio. Tropical African Microcystis blooms were found to have the lowest microcystin levels in relation to biomass and N:P (nitrate:phosphate) compared to tropical Asian, Australian and American blooms. There was also no significant correlation between microcystin concentration and cell concentration for tropical African blooms as opposed to tropical Asian and American blooms. Our review illustrates that some cyanobacteria and toxins are more prevalent in tropical areas. While some tropical countries have considerable information regarding toxic blooms, others have few or no reported studies.

Key words: Cyanobacterial blooms, tropical areas, toxin production, Microcystis, *Cylindrospermopsis*, N:P.

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INTRODUCTION

Cyanobacterial blooms have been recognised as a health issue in freshwater systems in many countries (Briand *et al.*, 2003; Falconer, 2008) mainly because some species are capable of producing potent toxins that are harmful to humans and animals. Currently there are two types of cyanotoxins that are particularly problematic to humans: hepatotoxins (cyclic peptides) and neurotoxins (alkaloids) (Sivonen, 1999; Stewart *et al.*, 2008; Wiegand and Pflugmacher, 2005; Zurawell *et al.*, 2005; Chen *et al.*, 2009). Toxin-producing cyanobacteria have been responsible for serious cases of human and livestock poisoning and deaths in a number of countries worldwide (e.g., in Brazil, Australia and North America) (Francis, 1878; Beasley *et al.*, 1989; Azevedo *et al.*, 2002; Cox *et al.*, 2005; Sotero-Santos *et al.*, 2006).

In one of the most serious incidents in the tropics, 116 kidney dialysis patients in Northeast Brazil suffered from liver failure, resulting in 52 fatalities, due to dialysis water that was sourced from a nearby reservoir contaminated

with microcystins in 1996 (Carmichael, 1996; Joachimsen *et al.*, 1998; Carmichael *et al.*, 2001; Komarek *et al.*, 2001; Azevedo *et al.*, 2002). Since that incident some studies have been carried out on several reservoirs in South and Central America documenting blooms and progenitor species (Díaz-Pardo *et al.*, 1998; Carmichael *et al.*, 2001; Lind and Davalos-Lind, 2002; Ramirez *et al.*, 2002; Bittencourt-Oliveira *et al.*, 2005; Frias *et al.*, 2006; Merino-Ibarra *et al.*, 2007; Berry and Lind, 2010; Vasconcelos *et al.*, 2010; Rejmánková *et al.*, 2011). A review by Dorr *et al.* (2010) revealed that there has been increased cyanobacterial bloom occurrence in water bodies in South America requiring better methods for screening and testing of cyanobacterial toxins.

Another case of human hepatoenteritis caused by cyanobacterial toxin poisoning in a tropical area occurred on Palm Island, Australia, in 1979, where 148 adults and children were affected by the toxin in their drinking water taken from a lake with high levels of the cyanobacterial species *Cylindrospermopsis raciborskii*, which is known to produce cylindrospermopsin, a newly identified hepa-

toxin at that time (Hawkins *et al.*, 1985). These cases illustrate the importance and need to understand the toxin producing cyanobacterial species, their prevalence and causes of blooms.

Although cyanobacterial blooms are a worldwide phenomenon, there are differences in the typical species and toxins found in temperate and tropical areas (Bartram *et al.*, 1999). However, most published studies focus on cyanobacterial toxins and blooms in temperate regions with considerably less work reported from tropical areas. Nevertheless, as demonstrated by the cyanotoxin cases in Brazil and Australia, toxic cyanobacterial blooms in tropical countries can occur with considerable harmful effect. Within the tropics, cyanobacterial toxins and blooms have been more intensively studied in certain countries such as Brazil, Australia and Thailand, but an overall global review of blooms in the tropics is lacking. This review aims to address this gap by highlighting cyanobacterial bloom studies undertaken in tropical areas. In this review, data on the i) prevalence, problem taxa, toxin production and ii) influencing environmental factors for toxic cyanobacterial blooms is assessed for tropical countries across four continents. This information is synthesised and evaluated to reveal trends across tropical countries, which may be different from those in sub-tropical and temperate locations.

METHODS

The literature was located using Web of Science and Google Scholar using the keywords: *cyanobacteria*, *blooms*, *tropics* and *tropical countries*, with specific country searches for the period between 1970 and 2013. For the purpose of this review, the word *bloom* was defined as Alert Level 1 by the World Health Organization (Bartram *et al.*, 1999), which denotes high biomass (cell counts of 2000 cells mL⁻¹ or 0.2 mm³ L⁻¹ biovolume or 1 µg L⁻¹ chlorophyll *a*) of cyanobacterial species in a water body. In total, 142 papers covering 186 water bodies were obtained from regional and international journals for the qualitative discussion of overall trends in cyanobacterial blooms. Percentages of dominant cyanobacterial bloom genera were calculated for all the tropical blooms reported. A subset of 66 papers covering 91 water bodies was chosen based on information on cyanobacteria toxins found, for example, microcystins (MC-RR & MC-LR) were found via LC-MS testing. These papers were used to calculate percentage of different cyanobacterial toxins detected for the toxic tropical cyanobacterial blooms reported.

A subset of 33 papers covering 48 water bodies was selected for a meta-analysis of environmental factors influencing bloom formation. The criterion for choosing these 33 studies was availability of data on the identification of the bloom species, highest total nitrogen concentration (TN, mg L⁻¹), highest total phosphorus

concentration (TP, mg L⁻¹), and minimum and maximum temperatures. In order to ascertain which factors were more important for tropical bloom formation, metadata on environmental variables and genera of cyanobacteria were examined for relationships using non-metric multidimensional scaling (NMDS) (R, Vegan package, Oksanen *et al.*, 2013). Blooms were arranged by presence or absence of dominant genera (*Microcystis*, *Cylindrospermopsis*, *Anabaena*, and *Planktothrix*). An NMDS was run on the genera data, which contained 48 data points from tropical Asia, America, Australia and Africa. As cyanobacterial biomass was not recorded by all of the 33 studies it was not used as a criterion for the meta-analysis. The environmental variables (highest total nitrogen concentration, highest total phosphorus concentration, total nitrogen to total phosphorus ratio based on molar ratios, minimum and maximum temperatures) were then fitted onto the NMDS using envfit (R, Vegan package, Oksanen *et al.*, 2013). To analyse the effect of types of water bodies on cyanobacterial bloom genera present, the meta-data created above was analysed using NMDS and Adonis (Permutational Multivariate Analysis of Variance using Distance Matrices) and plotted using ordiellipse (R, Vegan package, Oksanen *et al.*, 2013).

In order to analyse the relationship between nutrient levels and microcystin levels, eight papers covering 14 water bodies were selected based on the availability of information for i) maximum total microcystin concentration (µg L⁻¹); ii) nitrate (mg L⁻¹) in the water body at the time of the maximum microcystin concentration; iii) phosphate (orthophosphate/soluble reactive phosphorus, PO₄) (mg L⁻¹) in the water body at the time of the maximum microcystin concentration. A regression analysis on nitrate, phosphate, N:P (nitrate: phosphate), and maximum total microcystin concentration was then carried out using Spearman's correlation coefficient (rho). For the analysis of maximum temperatures and microcystin concentration, 11 papers covering 17 water bodies were selected based on the availability of information on i) maximum (highest) temperatures of water body during sampling and ii) maximum total microcystin concentration (µg L⁻¹). A regression analysis on the maximum temperature of the water body and the maximum total microcystin concentration was carried out using Spearman's correlation coefficient (rho). For the analysis of *Microcystis* biomass and microcystin concentration, eight papers covering 27 water bodies were selected based on availability of information: i) total microcystin concentration (µg L⁻¹); ii) cell count of *Microcystis* from the same water body. A regression analysis on the *Microcystis* cell count and microcystin concentration was then carried out using Spearman's correlation coefficient (rho).

RESULTS AND DISCUSSION

Prevalence, problem taxa, toxin production

General patterns of cyanobacteria and cyanotoxins across tropical areas

Microcystis was the most prevalent bloom-causing genus in tropical Africa and Asia, while *Cylindrospermopsis* was the most common in tropical Australia and the second most prevalent genus in tropical Asia (Fig. 1). *Microcystis* and *Cylindrospermopsis* blooms have occurred in similar frequency in tropical America. *Anabaena* blooms were the second most frequently occurring genus in tropical Africa. As expected, the frequency of cyanobacterial bloom occurrence in tropical Australia was much lower compared to that of other tropical countries, due to the relatively smaller land area of tropical northern Australia.

The most frequently encountered toxin throughout the tropics was microcystin except for tropical Australia where cylindrospermopsin was more frequently encountered (Fig. 2). The frequent occurrence of cylindrospermopsin in Australia was expected given the higher frequency of recorded *Cylindrospermopsis* blooms (Griffiths and Saker, 2003). The second most encountered toxin in Africa was anatoxin, produced by blooms of *Anabaenopsis*, *Arthrospira* and *Anabaena* species (Ballot *et al.*, 2005; Odokuma and Isirima, 2007). Despite the presence of *Anabaena* in tropical Asia, anatoxin was not detected, with the only two toxins detected being microcystin and cylindrospermopsin. The lack of expertise required for testing for neurotoxins may partly account for the lack of documented occurrences (Jewel *et al.*, 2003).

Saxitoxin was detected in tropical American and tropical African blooms by HPLC and various other detection

methods (ESI, LC-MS, FLD). This toxin was produced by blooms of *Cylindrospermopsis* and *Lyngbya* in Brazil, Mexico, Guatemala and Nigeria (Lagos *et al.*, 1999; Bouvy *et al.*, 1999; Molica *et al.*, 2005; dos Anjos *et al.*, 2006; Berry and Lind, 2010; Rejmánková *et al.*, 2011; Sant'Anna *et al.*, 2011). Comparisons of the neurotoxic *Cylindrospermopsis* strains from Brazil and Mexico revealed the Brazilian strain to have acute neurotoxicity from the presence of saxitoxin, neosaxitoxin and decarbamoylsaxitoxin and the Mexican strains isolated were found to be non-toxic (Bernard *et al.*, 2003).

Patterns in toxin testing across the tropics

The percentage of cyanobacterial blooms that undergo toxin testing has increased in tropical Africa and America and remained relatively constant in tropical Australia from the 1990s to the present, but decreased in tropical Asia. Many blooms that occur in tropical Asia are not tested for toxins despite reports of fish kills or harm to livestock (Tab. 1); this could be due to a lack of expertise and cyanotoxin testing equipment (Jewel *et al.*, 2003). Another reason could be a greater focus on the general limnology of lake ecosystems rather than cyanobacterial bloom formation or its management (Mizuno and Mori, 1970; Lewis 1973, 1978; Green *et al.*, 1976, 1978). Toxin testing in India, Bangladesh, Philippines, Singapore, Sri Lanka, Thailand, and Vietnam have been carried out using HPLC (high performance liquid chromatography) and various detection methods from UV (ultraviolet) to MALDI-TOF (matrix assisted laser desorption time of flight mass spectrometry) (Tab. 1). Blooms in Australian water bodies were tested using mouse bioassays in the 1990s, and later by HPLC for more detailed toxin results (Saker and Griffiths, 2001; Griffiths and Saker, 2003; White *et al.*, 2003; Bor-

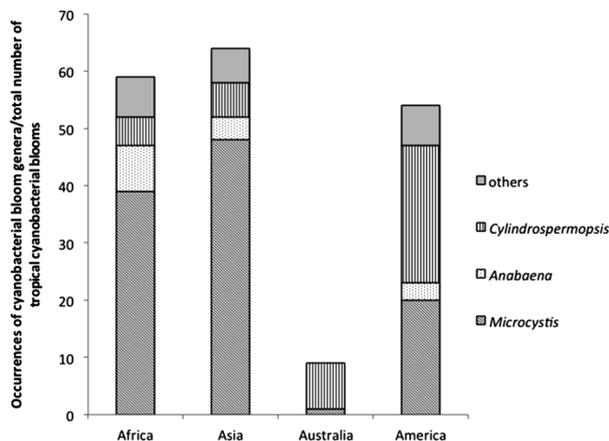


Fig. 1. Proportion of tropical cyanobacterial genera, out of total number of tropical cyanobacterial blooms.

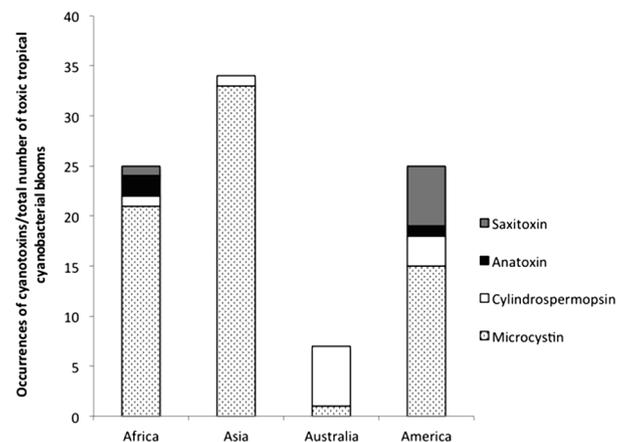


Fig. 2. Proportion of different cyanobacterial toxins, out of total number of toxic tropical cyanobacterial blooms.

mans *et al.*, 2004). In the case of tropical Africa, many of the blooms were detected in reservoirs and lakes used for drinking water, highlighting a need for toxicity testing in these countries (Akin-Oriola *et al.*, 2006). Past studies of bloom occurrence and toxin testing via ELISA test kits/HPLC and MALDI-TOF MS have been carried out in

Ethiopia, Ghana, Nigeria, Uganda, Kenya, Tanzania and Zimbabwe but few or no studies in other central African countries, such as The Democratic Republic of Congo, Central African Republic and South Sudan (Tab. 2, Fig. 3).

An increase in toxin testing in tropical America was most prominently seen in Brazil, Mexico and Guatemala

Tab. 1. Summary of cyanobacterial blooms, prevalence and toxins recorded in tropical Asia and Australia.

Country	Potential toxic species found	Toxin test	Toxins found	Amount of toxins	References
Australia	<i>Cylindrospermopsis raciborskii</i> *, <i>Aphanizomenon</i> sp., <i>Anabaena</i> sp., <i>Anabaena tenericaulis</i> & <i>Microcystis panniformis</i> *	Mouse bioassay & HPLC/MS	CYN & MC	CYN: 1.0-20 µg/L, MC: 1000-2500 µg/L	Hawkins <i>et al.</i> , 1985; Hawkins and Griffiths, 1993; McGregor and Fabbro, 2000; Saker and Griffiths, 2001; Griffiths and Saker, 2003; White <i>et al.</i> , 2003; Bormans <i>et al.</i> , 2004
Bangladesh	<i>Microcystis aeruginosa</i> *, <i>Microcystis</i> sp.*, <i>Anabaena flos-aquae</i> & <i>Planktothrix</i> sp.	RP-HPLC & HPLC/LCMS & HPLC/UV	MC-LR,-RR,-YR	0.14-1360 µg/L	Welker <i>et al.</i> , 2004; Ahmed <i>et al.</i> , 2008; Ahmed and Luckas, 2008; Jahan <i>et al.</i> , 2010
Cambodia	<i>Microcystis aeruginosa</i>	Not tested	Not tested	Not tested	Campbell <i>et al.</i> , 2006
Hong Kong	<i>Microcystis aeruginosa</i> , <i>M. Incerta</i> & <i>Anabaena flos-aquae</i>	Not tested	Not tested	Not tested	Hodgkiss, 1974
India	<i>Microcystis aeruginosa</i> *, <i>M. novacekii</i> , <i>M. viridis</i> *, <i>M. wesenbergii</i> & <i>M. icthyoblabe</i>	RP-HPLC/ MALDI-TOF & RP-HPLC/ LC/ESI/MS	MC-LR,-RR	280-1540 µg/g	Agrawal <i>et al.</i> , 2006; Tyagi <i>et al.</i> , 2006; Prakash <i>et al.</i> , 2009; Sangolkar <i>et al.</i> , 2009
Indonesia	<i>Microcystis aeruginosa</i> , <i>Cylindrospermopsis raciborskii</i> & <i>Planktothrix agardhii</i>	Not tested	Not tested	Not tested	Padisak, 1997; Prihantini <i>et al.</i> , 2008; Retnaningdyah <i>et al.</i> , 2010
Malaysia	<i>Microcystis</i> spp., <i>Cylindrospermopsis raciborskii</i> & <i>Planktothrix agardhii</i>	Not tested	Not tested	Not tested	Rouf <i>et al.</i> , 2008; Harith and Hassan, 2011; Mansoor <i>et al.</i> , 2011
Myanmar	<i>Microcystis</i> spp.	Not tested	Not tested	Not tested	Green, 2010
Philippines	<i>Microcystis aeruginosa</i> *, <i>Cylindrospermopsis raciborskii</i>	HPLC/ MALDI-TOF	MC-LR	11472-12158 µg/g	Cuvin-Aralar <i>et al.</i> , 2002; Baldia <i>et al.</i> , 2003; Baldia <i>et al.</i> , 2007
Singapore	<i>Microcystis</i> spp.*, <i>Cylindrospermopsis raciborskii</i> , <i>Planktothrix</i> sp. <i>Anabaena</i> sp. & <i>Aphanizomenon</i> sp.	HPLC/LC-MS	MC-LR	2660-2800 µg/L	Yang and Chiam-Tai, 1991; Sim, 2009; Te and Gin, 2011
Sri Lanka	<i>Microcystis aeruginosa</i> *, <i>M. incerta</i> *, <i>Anabaena</i> sp. & <i>Planktothrix</i> sp.	HPLC/ET-MS	MC-LR,-RR	0.8-81 µg/L	Jayatissa <i>et al.</i> , 2006
Thailand	<i>Microcystis aeruginosa</i> *, <i>M. wesenbergii</i> & <i>Cylindrospermopsis raciborskii</i> *	ELISA/HPLC-MS	MC-LR,-RR,-YR, CYN	MC: 2.2±3.0 µg/L and 9.4±2.0 µg/L CYN: 1020 µg/g	Mahakhant <i>et al.</i> , 1998; Li <i>et al.</i> , 2001; Wang <i>et al.</i> , 2002; Prommana <i>et al.</i> , 2006; Khuantrairong <i>et al.</i> , 2008
Vietnam	<i>Microcystis</i> spp.*, <i>Jaaginema</i> sp., <i>Arthrospira masartii</i> , <i>Oscillatoria perornata</i> , <i>Planktothrix zahidii</i> & <i>Pseudanabaena cf. moniliformis</i> *	ELISA/HPLC-UV	MC-LR,-RR	2.94 µg/L and 18.94 µg/L	Nguyen <i>et al.</i> , 2007a; Nguyen <i>et al.</i> , 2007b; Dao <i>et al.</i> , 2010

MC, Microcystin; CYN, *Cylindrospermopsis*; *species tested for toxins.

with testing carried out via mouse and fish bioassay, ELISA & HPLC/PDA, MALDI-TOF (Tab. 3). This increase was probably motivated by the two incidents that led to human fatalities in 1988 and 1996 (Teixeira *et al.*, 1993; Domingos *et al.*, 1999; Carmichael *et al.*, 2001; Azevedo *et al.*, 2002; Molica 2002). Few studies have been conducted in other countries such as Panama and Colombia (Bartram *et al.*, 1999; Dorr *et al.*, 2010).

Problem taxa - Prevalence in tropical water bodies and toxins produced

Microcystis

Tropical Asia and Australia

The majority of blooms (77%) in tropical Asia were caused by *Microcystis* spp., usually *Microcystis aeruginosa* (Fig. 1; Tab. 1). Several species (*M. aeruginosa*, *M. no-*

Tab. 2. Summary of cyanobacterial blooms, prevalence and toxins recorded in tropical Africa.

Country	Potential toxic species found	Toxin test	Toxins found	Amount of toxins	References
Cameroon	<i>Planktothrix mougeotii</i> , <i>Oscillatoria putrida</i> & <i>Microcystis</i> spp. (<i>M. aeruginosa</i> , <i>M. wesenbergii</i>)	Not tested	Not tested	Not tested	Kemka <i>et al.</i> , 2003; Green, 2010
Cote d'Ivoire	Unknown bloom-forming species	Not tested	Not tested	Not tested	Bouvy <i>et al.</i> , 1998; Arfi <i>et al.</i> , 2001
Ethiopia	<i>Microcystis</i> sp.*	ELISA	No MC found	No MC found	Gremberghe <i>et al.</i> , 2011
Ghana	<i>Microcystis aeruginosa</i> * & <i>Anabaena flos-aquae</i>	HPLC	MC-RR	0.03-3.21 µg/L	Addico <i>et al.</i> , 2006
Kenya	<i>Microcystis aeruginosa</i> *, <i>Arthrospira fusiformis</i> * & <i>Anabaenopsis abijatae</i> *	ELISA/HPLC- MALDI-TOF	MS MC-LR & Anatoxin-a	MC: 1.6-39.0 µg/g Anatoxin: 0.5-2.0 µg/g	Ballot <i>et al.</i> , 2005; Haande <i>et al.</i> , 2007; Kotut <i>et al.</i> , 2010
Malawi	<i>Anabaena</i> sp.	Not tested	Not tested	Not tested	Gondwe <i>et al.</i> , 2007
Nigeria	<i>Cylindrospermopsis</i> sp*. <i>Anabaena</i> sp.*, <i>Microcystis</i> sp.* (<i>Microcystis aeruginosa</i> , <i>M. flos-aquae</i> , <i>M. wesenbergii</i>), <i>Lyngbya</i> sp.*, <i>Aphanizomenon flos-aquae</i> , <i>Oscillatoria limnetica</i> & <i>Anabaena spiroides</i>	ELISA/ HPLC-MALDI- TOF	MC, CYN, Anatoxin-a, Anatoxin-a(s), STX	MC: 1.4-3.8 µg/L	Anadu <i>et al.</i> , 1990; Kemdirim, 2000; Ezra and Nwankwo, 2001; Akin-Oriola, 2003; Akin-Oriola <i>et al.</i> , 2006; Odokuma and Isirima, 2007; Chia <i>et al.</i> , 2009; Okechukwu and Ugwumba, 2009; Onyema, 2010; Ajuzie, 2012
Senegal	<i>Microcystis aeruginosa</i> & <i>Cylindrospermopsis raciborskii</i>	Mouse bioassay	No CYN/STX found	No CYN/STX found	Berger <i>et al.</i> , 2006; Bouvy <i>et al.</i> , 2006; Dufour <i>et al.</i> , 2006
Tanzania	<i>Anabaena</i> sp., <i>Microcystis</i> sp.*	HPLC-DAD/ MALDI-TOF	MC-RR	0-1.0 µg/L	Sekadende <i>et al.</i> , 2005
Uganda	<i>Microcystis aeruginosa</i> , <i>M. flos-aquae</i> , <i>Anabaenopsis</i> spp., <i>Aphanizomenon</i> sp., <i>Anabaena</i> sp. & <i>Cylindrospermopsis raciborskii</i>	ELISA, HPLC/MALDI- TOF & LC- MS/MS	MC-RR, (Asp3) MC-RR, MC-YR, (Asp3) MC-YR, MC-LR, MC-RY, (Asp3) MC-RY	0.2-61.2 µg/L	Ganf, 1974; Komarek and Kling, 1991; Oliver and Ganf, 2000; Haande <i>et al.</i> , 2007; Haande <i>et al.</i> , 2008; Green, 2010; Okello <i>et al.</i> , 2010; Okello & Kurmayer, 2011; Poste <i>et al.</i> , 2013
Zimbabwe	<i>Microcystis aeruginosa</i> *, <i>M. wesenbergii</i> , <i>M. novacekii</i> , <i>C. raciborskii</i> , <i>Lyngbya</i> sp., <i>Anabaena</i> sp., <i>Aphanizomenon</i> sp. & <i>Oscillatoria</i> sp.	ELISA	MC-LR	0.2-22.48 µg/L	Ramberg, 1987; Magadza, 2006; Mhlanga <i>et al.</i> , 2006a; Mhlanga <i>et al.</i> , 2006b; Magadza, 2008-2009; Kunz, 2011; Tendaupenyu, 2012; Mhlanga, n.d.

MC, Microcystin; CYN, Cylindrospermopsin; *species tested for toxins.

vacekii, *M. viridis*, *M. wesenbergii* and *M. ichthyoblabe*) occurred as blooms in different countries and samples containing *M. aeruginosa*, *M. viridis* and *M. incerta* (now *Aphanocapsa incerta*) produced microcystins (microcystin LR, RR and YR) (Tab. 1). In Asia, 66% of *Microcystis* blooms produced microcystins; the remaining blooms in Myanmar and Indonesia were not tested for toxins (Fig. 4, Tab. 1). Evidence from Myanmar and Indonesia were based on papers that lacked taxonomic detail and toxin analysis (Tab.1). Therefore, the cyanobacterial bloom occurrences from these countries are likely to be an underestimate of actual cyanobacterial bloom occurrences.

Microcystis blooms in Bangladesh, Sri Lanka, Vietnam, Thailand, Singapore and the Philippines have recorded microcystin levels above the WHO drinking

water guideline level of $1 \mu\text{g L}^{-1}$ (Cuvin-Aralar *et al.*, 2002; Wang *et al.*, 2002; Baldia *et al.*, 2003; Welker *et al.*, 2004; Jayatissa *et al.*, 2006; Prommana *et al.*, 2006; Nguyen *et al.*, 2007b). In India, livestock poisoning as well as skin lesions in children were reported from the shores of lakes and reservoirs (Agrawal *et al.*, 2006). A bloom in Bangladesh may have resulted in massive fish kills and reduction in livelihood of the communities that depend on fishing for subsistence (Jewel *et al.*, 2003); however, no toxin analysis was carried out on the bloom and fish samples (Jewel *et al.*, 2003). Other studies on *Microcystis* blooms in Bangladesh by the World Health Organization (Welker *et al.*, 2004) confirm the presence of microcystins in the drinking water bodies.

There was only one notable *Microcystis* bloom in trop-

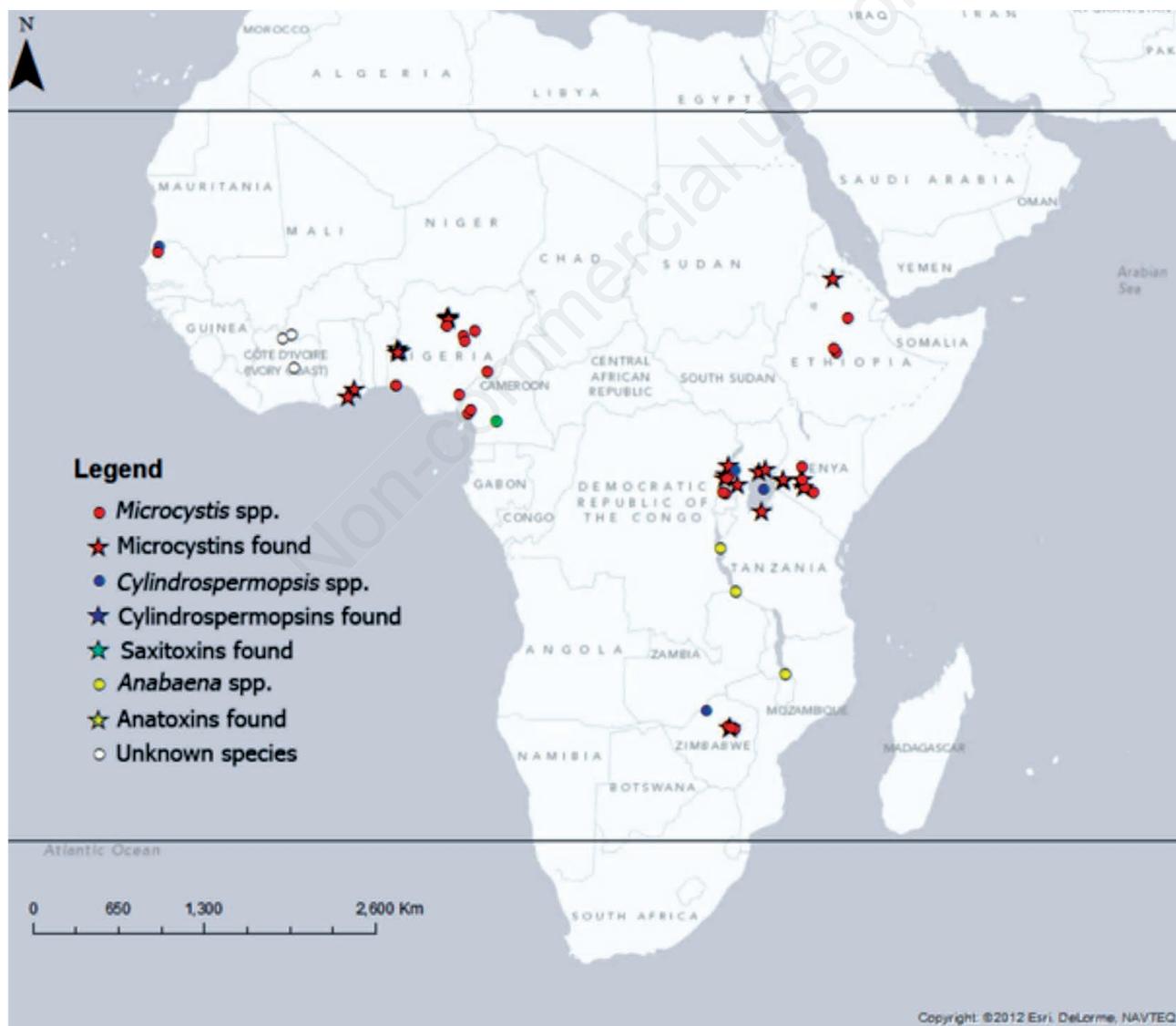


Fig. 3. Map of tropical Africa showing locations of cyanobacterial blooms, horizontal lines enclose the tropical region around the equator.

ical Australia, recorded from Lake Elphinstone, caused by *Microcystis panniformis*, with a very high microcystin level of 2500 µg L⁻¹ (White *et al.*, 2003). It is notable that *M. panniformis* was not found to produce high levels of toxins in tropical Asia (Tab. 1) although it formed a bloom with extremely high toxin levels in tropical Australia.

Tropical Africa

Microcystis was the bloom-causing genus in 66% of blooms in tropical African countries (Figs. 1 and 3; Tab. 2). The main species responsible were *M. aeruginosa*, *M. flos-aquae* and *M. wesenbergii*, which produced microcystins (MC-RR, (Asp3) MC-RR, MC-YR, (Asp3) MC-YR, MC-LR, MC-RY, (Asp3) MC-RY) in Ethiopia, Ghana, Tanzania, Nigeria, Uganda and Zimbabwe (Tab. 2). Of

these countries, microcystin levels higher than 1 µg L⁻¹ were recorded from water bodies in Ghana, Nigeria, Uganda and Zimbabwe (Ndebele and Mhlanga, 2006; Chia *et al.*, 2009; Kotut *et al.*, 2010; Sitoki *et al.*, 2012). The highest microcystin level of 61.2 µg L⁻¹ was detected in a cyanobacterial bloom in Lake Saka, Uganda (Okello *et al.*, 2010; Okello and Kurmayer, 2011, Poste *et al.*, 2013). Little is known about toxin production by *Microcystis* blooms in Cameroon and Senegal as they have not been tested (Tab. 2).

Tropical America

In tropical America, 35% of total blooms were caused by species of *Microcystis*, namely *M. aeruginosa*, *M. panniformis*, *M. protocystis*, *M. novacekii* and *M. viridis* (Figs. 1 and 5; Tab. 3), with concentrations of microcystins above

Tab. 3. Summary of cyanobacterial blooms, prevalence and toxins recorded in tropical America.

Country	Potential toxic species found	Toxin test	Toxins found	Amount of toxins	References
Brazil	<i>Cylindrospermopsis raciborskii</i> *, <i>Microcystis aeruginosa</i> *, <i>M. novacekii</i> *, <i>M. panniformis</i> *, <i>M. protocystis</i> *, <i>M. viridis</i> *, <i>Planktothrix agardhii</i> *, <i>Aphanizomenon</i> sp., <i>Oscillatoria</i> sp., <i>Anabaena oumiana</i> , <i>A. crassa</i> ; <i>Dolichospermum circinalis</i> (formerly <i>Anabaena circinalis</i>) & <i>Radiocystis fernandoi</i> *	Mouse and fish bioassay, ELISA & HPLC/PDA, MALDI-TOF MC-RR, MC-hRhR,	MC-LR,MC-YR, CYN, STX, NEO, GTX1,GTX2, GTX3, GTX4, Anatoxin-a(s)	MC-LR: 19.5 µg/L STX: 9.3 MU/mg dry cells	Branco and Senna, 1994; Bouvy <i>et al.</i> , 1999; Domingos <i>et al.</i> , 1999; Bouvy <i>et al.</i> , 2000; Huszar <i>et al.</i> , 2000; Carmichael <i>et al.</i> , 2001; Azevedo <i>et al.</i> , 2002; Molica, 2002; Bittencourt-Oliveira, 2003; Vieira <i>et al.</i> , 2003; Vieira <i>et al.</i> , 2005; dos Anjos <i>et al.</i> , 2006; Frias <i>et al.</i> , 2006; Sotero-Santos <i>et al.</i> , 2006; Sant'Anna <i>et al.</i> , 2007; Sant'Anna <i>et al.</i> , 2008; Figueredo and Giani, 2009; Werner and Laughinghouse IV, 2009; Molica <i>et al.</i> , 2005; Bouvy <i>et al.</i> , 2003; Bittencourt-Oliveira <i>et al.</i> , 2011; Moura <i>et al.</i> , 2007; Ferrão-Filho <i>et al.</i> , 2007; Piccin-Santos & Bittencourt, 2012; Soares <i>et al.</i> , 2012
Guatemala	<i>Lyngbya hieronymusii</i> *, <i>L. birgei</i> *, & <i>L. robusta</i> *	LC-MS/MS	CYN & STX	CYN: 0.6-1.2 ng/L, STX: 2.9-5.8 ng/L	Rejmánková <i>et al.</i> , 2011
Mexico	<i>Microcystis aeruginosa</i> *, <i>M. panniformis</i> *, <i>M. protocystis</i> *, <i>Planktothrix agardhii</i> *, <i>Cylindrospermopsis catemaco</i> *, <i>C. philippinensis</i> *, <i>Pseudanabaena</i> <i>mucicola</i> , <i>Anabaena</i> sp., <i>Nostoc</i> sp. & <i>Oscillatoria</i> sp.	ELISA/HPLC/ LC-MS/MALDI- TOF	MC-LR,-FR, HYR, YR, HtYR, CYN & STX	MC: 4.9 µg/L-78 µg/L, CYN: 21.34±2.00 ng/L, STX: 5.30±2.56 ng/L	Díaz-Pardo <i>et al.</i> , 1998; Lind and Davalos-Lind, 2002; Ramirez <i>et al.</i> , 2002; Romero, 2002 Merino-Ibarra <i>et al.</i> , 2007; Berry and Lind, 2010; Vasconcelos <i>et al.</i> , 2010
Venezuela	<i>Microcystis aeruginosa</i> , <i>Anabaena volzii</i> , <i>A. spiroides</i> & <i>Anabaenopsis</i> sp.	Not tested	Not tested	Not tested	Lewis, 1986

MC, Microcystin; CYN, *Cylindrospermopsis*; *species tested for toxins.

1 $\mu\text{g L}^{-1}$ recorded from lake and reservoir water in Mexico and Brazil (Tab. 3). Microcystins were also detected from *Radiocystis fernandoi* in Brazil (Vieira *et al.*, 2003), a species that did not produce toxins in tropical Asia, Australia or Africa. The greatest number of microcystin variants (MC-LR, FR, HYR, YR, HtYR) was detected from water bodies in Mexico (Tab. 3). Although *Microcystis aeruginosa* was detected in Venezuela, it was not tested for toxins and thus, little is known about occurrences of microcystins in this country (Tab. 3). A study in Sao Paulo, Brazil, found that *Microcystis* strains could produce paralytic shellfish poisons or PSPs, namely GTX4 (47.6%), GTX2 (29.5%), GTX1 (21.9%), GTX3 (1.0%) as well as a microcystin (MC-RR) (Sant-Anna *et al.*, 2011). The production of neu-

rotoxins by *Microcystis* has never been recorded in any of the other tropical blooms.

Cylindrospermopsis

Tropical Asia and Australia

The second most prevalent genus in tropical Asia was *Cylindrospermopsis* (Figs. 1 and 4). This genus was encountered in six out of thirteen countries in tropical Asia (Tab. 1). The genus was bloom-forming in Singapore and potentially so in Thailand and Vietnam (Khoo *et al.*, 1977; Li *et al.*, 2001; Pongswat *et al.*, 2004; Meesukko *et al.*, 2007; Khuantrairong and Traichaiyaporn, 2008; Dao *et al.*, 2010). The only bloom-forming species was *Cylin-*

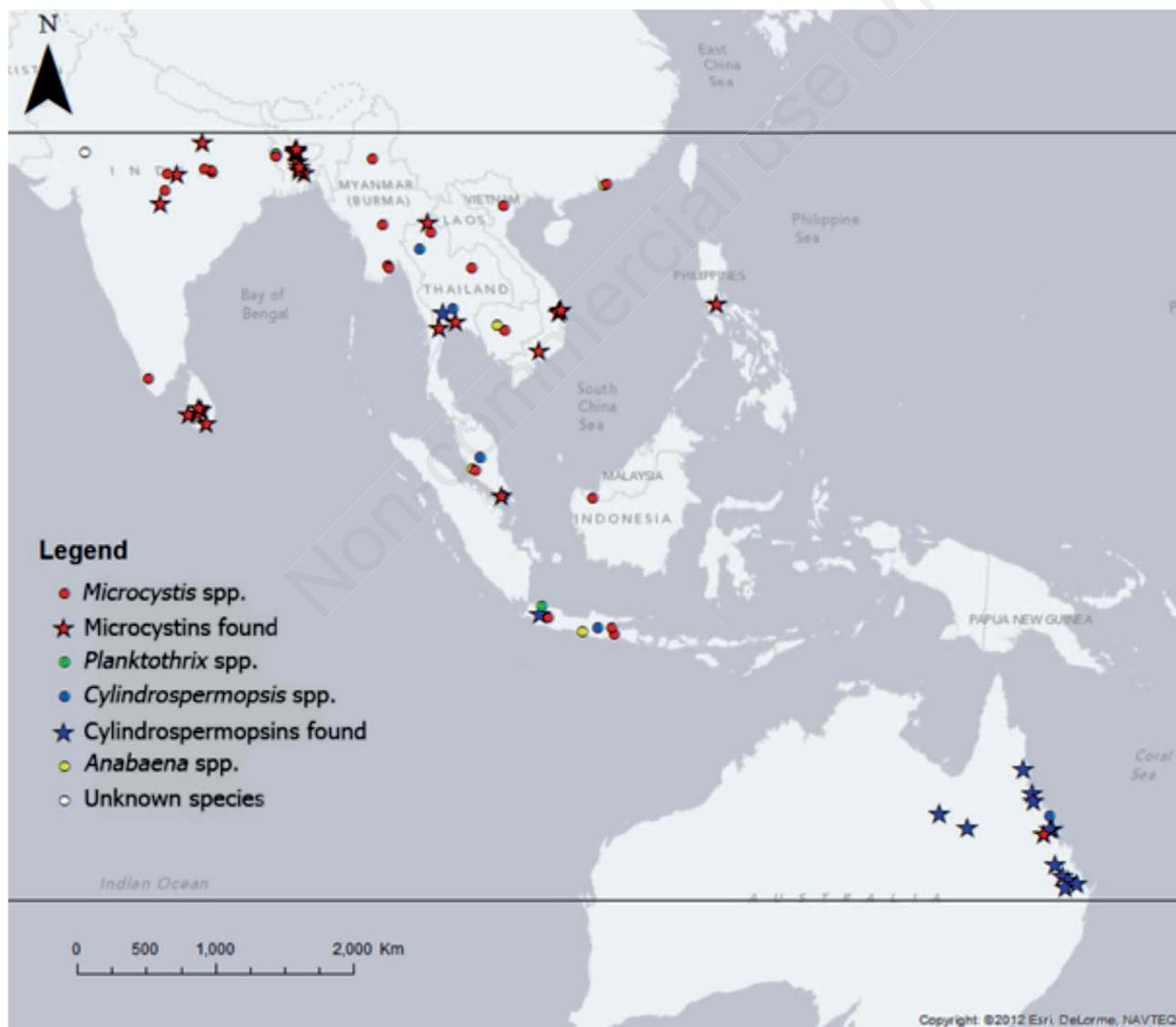


Fig. 4. Map of tropical Asia and Australia showing locations of cyanobacterial blooms, horizontal lines enclose the tropical region around the equator.

drospermopsis raciborskii, although recent taxonomic revisions now recognise more than one species, e.g., coiled morphotypes of *C. raciborskii* are now known as *C. philippinensis* (Komárek and Mareš, 2011). Even though *C. raciborskii* has been bloom-forming in one country and commonly found in two others, cylindrospermopsin production of 1.02 mg g⁻¹ was recorded from only one study in Thailand (Li *et al.*, 2001). The toxin level of this strain was much lower than an Australian strain cultured in the same conditions (1.358 mg g⁻¹) (Li *et al.*, 2001).

In contrast to tropical Asia, *Cylindrospermopsis* was the dominant bloom-forming genus in tropical Australia, accounting for seven out of eight blooms (Figs. 1 and 4; Tab. 1). *C. raciborskii* blooms from Palm Island were highly toxic with cylindrospermopsin levels of up to 20 µg L⁻¹ recorded (McGregor and Fabbro, 2000; Griffiths and Saker, 2003). Additionally, *C. raciborskii* blooms from Palm Island were strongly implicated in the severe hepatoenteritis poisoning of 149 people in 1979 (Hawkins *et al.*, 1985).

Tropical Africa

Cylindrospermopsis blooms were the second most prevalent blooms in tropical Africa (Fig. 1). It was found in four out of eleven countries including Nigeria, Senegal, Uganda and Zimbabwe (Tab. 2; Fig. 3). The only species recorded was *Cylindrospermopsis raciborskii*; however, only strains from ponds in Nigeria were found to produce cylindrospermopsin (Odokuma and Isirima, 2007). Strains from Kazinga Channel, Uganda and Lake Guiers, Senegal were isolated and tested for toxins by LC-MS and mouse bioassay respectively, but were not found to produce any cylindrospermopsin and saxitoxins (Lake Guier isolates) (Haande *et al.*, 2008; Berger *et al.*, 2006).

Tropical America

Cylindrospermopsis was the most encountered bloom genus in the tropical Americas occurring in 47% of all documented cyanobacterial blooms (Figs. 1 and 5). Three species were frequently encountered, *C. raciborskii*, *C. catemaco* and *C. philippinensis* (Tab. 3). These blooms were recorded from Brazil and Mexico (Fig. 5; Tab. 3). Saxitoxins (STX, NEO, GTX2 and GTX3) and cylindrospermopsins were produced by several strains of *Cylindrospermopsis* isolated from Brazil and Mexico (Bouvy *et al.*, 1999; Molica *et al.*, 2002; Molica *et al.*, 2005; dos Anjos *et al.*, 2006; Frias *et al.*, 2006; Ferrão-Filho *et al.*, 2007; Berry and Lind, 2010). The *Cylindrospermopsis* blooms in the tropical Americas differ from the *Cylindrospermopsis* strains isolated in Thailand and Australia, in that they produced saxitoxin in addition to cylindrospermopsins (Tabs. 1, 2 and 3).

Other problem taxa

Anabaena

Less than 7% of total blooms that occurred in tropical Asia were dominated by *Anabaena* spp. (Tab. 1, Fig. 4). These blooms were not tested for toxins, although a bloom of *Anabaena flos-aquae* in Bangladesh caused massive fish kills (Jewel *et al.*, 2003). *Anabaena* blooms also occurred in Nigeria, Tanzania, Ghana, and Malawi (Tab. 2; Fig. 3). Microcystin variants were detected in raw water in Ghana containing *A. flos-aquae* and *Microcystis aeruginosa*, thus, toxin production could not be attributed specifically to *A. flos-aquae* (Addico *et al.*, 2006). The only *Anabaena* sp. blooms that tested positive for anatoxin-a and anatoxin-a(s) occurred in Nigeria (Odokuma and Isirima 2007). In Tapacura Reservoir in Brazil, blooms of *Anabaena spiroides* co-dominated with *Cylindrospermopsis raciborskii*. *Anabaena spiroides* was found to produce anatoxin-a(s) and a mixed bloom sample of *C. raciborskii* and *A. spiroides* was found to contain saxitoxins (Stx and NeoStx) (Molica *et al.*, 2005).

Planktothrix

Planktothrix blooms were found in four out of thirteen tropical Asian countries including Malaysia, Indonesia, Vietnam, Singapore and Thailand (Li *et al.*, 2001; Merican *et al.*, 2006; Nguyen *et al.*, 2007b; Prihantini *et al.*, 2008; Pham *et al.*, 2011). *Planktothrix agardhii*, a possible toxin producing species, is currently known to form blooms in Indonesia and Brazil (Akcaalan *et al.*, 2006; Moura *et al.*, 2011). *P. agardhii* blooms in Carpina Reservoir, Brazil were found to co-dominate with *C. raciborskii*. These blooms were not tested for toxins, although some strains of *P. agardhii* can produce hepatotoxins (Janse *et al.*, 2005).

Planktothrix zahidii was bloom-forming in Vietnam (Nguyen *et al.*, 2007a). However, this species did not produce any microcystins. Toxin testing on other *Planktothrix* species in Malaysia, Indonesia, Singapore and Thailand has yet to be reported.

Pseudanabaena

While microcystins are mostly produced by *Microcystis* spp., one microcystin variant (MC-LR) was also produced by a strain of *Pseudanabaena* cf. *moniliformis* isolated in Vietnam (Tab. 1). This species was detected in lower concentrations in the reservoirs compared with *Microcystis* spp. Another species, *Pseudanabaena mucicola*, was also recorded in water bodies in Mexico and Brazil and *Pseudanabaena* sp. was recorded in Bangladesh (Welker *et al.*, 2004; Frias *et al.*, 2006; Vasconcelos *et al.*, 2010). Toxin testing was carried out on water bodies in all three countries containing *P. mucicola* and *Pseudanabaena* sp., but the microcystin level could not be attributed to either species due to the presence of *Microcystis*

spp. It is important to note that *Pseudanabaena* is similar in morphology to *Cylindrospermopsis*, thus, records of *Pseudanabaena* in Mexico, Brazil and Bangladesh (Welker *et al.*, 2004; Frias *et al.*, 2006; Vasconcelos *et al.*, 2010), which did not include pictures and formal descriptions of *Pseudanabaena* species could not be verified, and might potentially be misidentifications.

Arthrospira and Anabaenopsis

Blooms of *Arthrospira fusiformis* and *Anabaenopsis abijitae* that produced anatoxin-a were recorded in the Kenyan rift lakes (Ballot *et al.*, 2005; Odokuma and Isirima, 2007) (Tab. 2; Fig. 3). These species were otherwise not bloom-forming in any other tropical country.

Lyngbya

Lyngbya spp. blooms were recorded in Guatemala

and Nigeria, with the species from Guatemala (*L. hironymusii*, *L. birgei*, and *L. robusta*) producing saxitoxins and cylindrospermopsins and the species from Nigeria (*Lyngbya* sp.) producing only saxitoxins (Odokuma and Isirima, 2007; Rejmánková *et al.*, 2011). These bloom-forming species were rare or absent in other tropical regions. The levels of cylindrospermopsin and saxitoxin recorded from Guatemala were relatively low (CYN: 0.6 to 1.2 ng l⁻¹, STX: 2.9 to 5.8 ng L⁻¹) and thus, do not appear to pose an immediate danger in water supplies. However, these blooms should be monitored for any changes in toxin production level (Rejmánková *et al.*, 2011). The level of saxitoxins in blooms of *Lyngbya* sp. from the Sombreiro River in Nigeria was not quantified, and thus, warrants further testing to ascertain the level of saxitoxins present (Odokuma and Isirima, 2007).

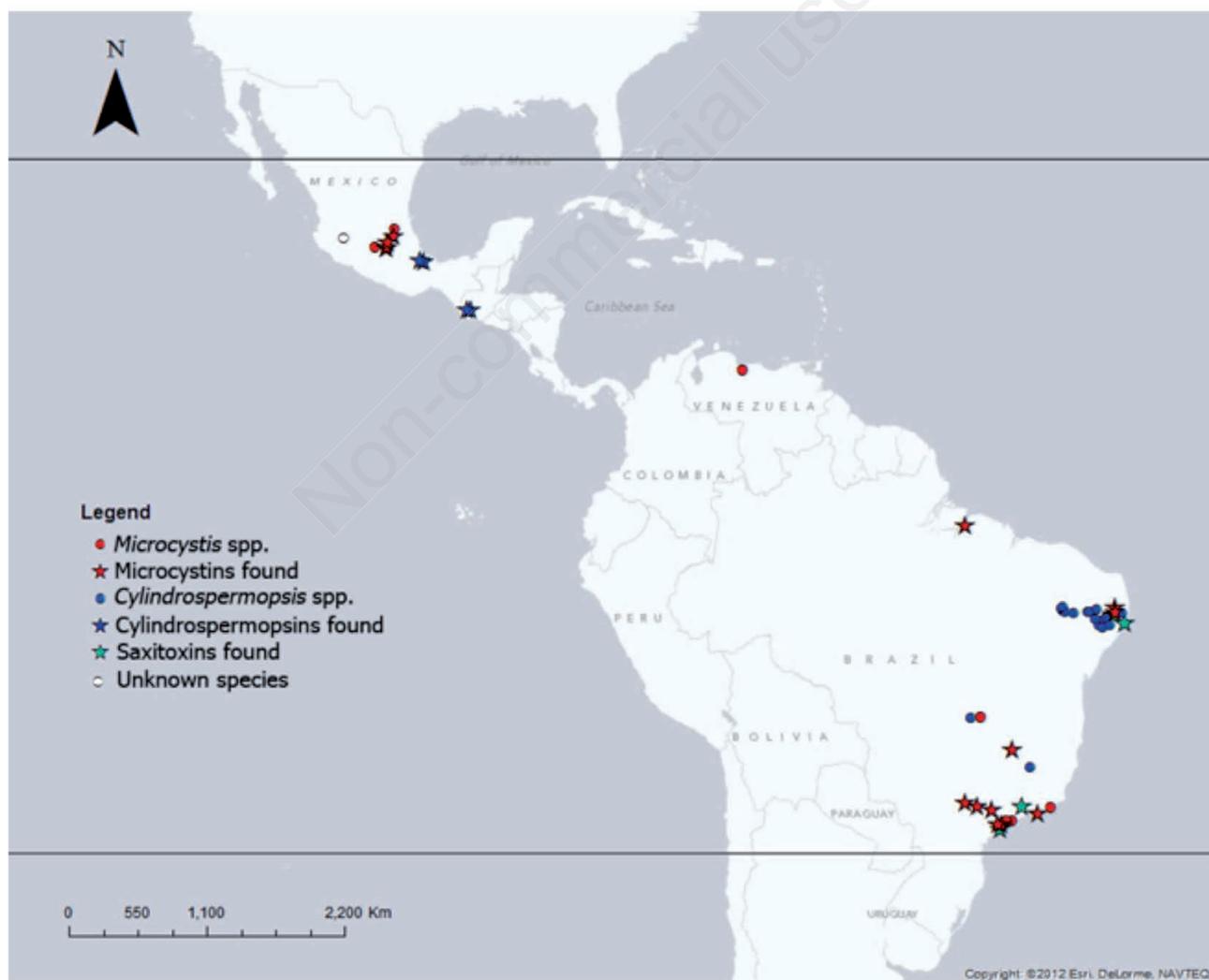


Fig. 5. Map of tropical America showing locations of cyanobacterial blooms, horizontal lines enclose the tropical region around the equator.

INFLUENCING ENVIRONMENTAL FACTORS FOR TOXIC CYANOBACTERIAL BLOOMS

Many factors contribute to the occurrence of cyanobacterial blooms. Most cyanobacterial blooms in temperate regions occur in the summer when temperature, light and nutrient conditions are suitable for cyanobacterial dominance over other species in a lake phytoplankton community (Jöhnk *et al.*, 2008; Davis *et al.*, 2009). This predictability of cyanobacterial blooms in temperate regions allows preventive measures to be implemented to reduce their occurrence in water bodies used for potable purposes (Mitrovic *et al.*, 2011). Tropical cyanobacterial blooms tend to be affected by temperature, nutrient input, and brief periods of drought and heavy rain (Bouvy *et al.*, 2000; Baldia *et al.*, 2003). Unlike temperate bloom events that occur in the warmer months and last for the entirety of the summer, tropical bloom events can occur at any time of the year and usually last for a few weeks at a time (Huszar *et al.*, 2000; Figueredo and Giani, 2009; Prakash *et al.*, 2009).

Seasonality in the tropics

Some water bodies in the tropics encounter a distinct seasonality in wet and dry periods, with some dry periods lasting several months (Figueredo and Giani, 2009). Nitrogen-fixing species were found to be bloom-forming during the dry season, due to strong thermal stratification and water column stability (Sprober *et al.*, 2003). Since nitrogen fixing genera such as *Anabaena* and *Cylindrospermopsis* are able to fix atmospheric nitrogen for growth, these genera are able to compete in conditions of lower nitrogen,

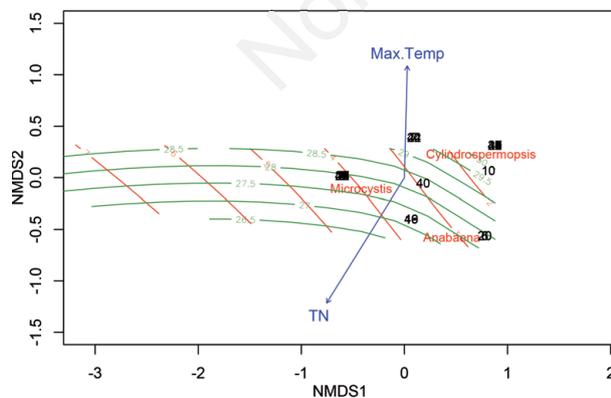


Fig. 6. Non-metric multidimensional scaling of tropical cyanobacterial blooms overlaid with maximum nitrogen levels and maximum temperatures (stress<0.01), arrows indicate nitrogen and temperature effects on bloom genera. Oblique lines represent smoothers connecting total nitrogen concentrations and intersecting lines represent smoothers connecting maximum temperature values.

for example, after a long period of stratification (Khuantairong *et al.*, 2008; Bormans *et al.*, 2004; Hawkins and Griffiths, 1993; Hawkins, 1985; Saker and Griffith, 2001; Komarek and Kling, 1991; Okechukwu and Ugwumba, 2008; Berger *et al.*, 2006; Dufour *et al.*, 2006; Gondwe *et al.*, 2007; Branco and Senna, 1994; Bouvy *et al.*, 1999; Bouvy *et al.*, 2003; Vieira *et al.*, 2005; Vieira *et al.*, 2003). Some studies documented *Microcystis* blooms in the wet season due to elevated nutrient levels in the various water bodies, occurring after periods of heavy rainfall (Ochumba and Kibaara, 1989; Makahant *et al.*, 1998; Salonen *et al.*, 1999; Arfi *et al.*, 2001; Kitaka *et al.*, 2002; Wang *et al.*, 2002; Welker *et al.*, 2004; Sekandende *et al.*, 2005; Meesuko *et al.*, 2007; Krishnan, 2008; Onyema 2010; Sitoki *et al.*, 2012). Although wet/dry seasonality in the tropics can contribute to cyanobacterial blooms, some water bodies with distinct dry and wet seasons do not show seasonality in cyanobacterial bloom occurrence (Figueredo and Giani, 2009; Werner and Laughinghouse, 2009; Frias *et al.*, 2006; dos Anjos *et al.*, 2006).

Effects of nutrients and temperature on tropical blooms

Based on the results of the NMDS, highest total nitrogen (TN) concentration was significantly related to the occurrences of specific cyanobacterial genera (Fig. 6) (P-value=0.025* < P_{critical}=0.05). Although total nitrogen was non-linearly associated with dominance of cyanobacterial genera, as seen from the surface fitting in Fig. 6, higher nitrogen levels were more associated with *Microcystis* blooms, while lower nitrogen levels were associated with *Cylindrospermopsis* blooms. Maximum temperature was also significantly related to cyanobacterial genera (Fig. 6) (P-value=0.029* < P_{critical}=0.05). Higher maximum temperature was more associated with *Cylindrospermopsis* blooms compared to *Microcystis* and *Anabaena* blooms (Fig. 6).

The results of this meta-analysis corroborates some findings from individual studies across all regions, which identify elevated total nitrogen concentrations as one of the more important factors in the development of tropical *Microcystis* blooms (Mahakhant *et al.*, 1998; Huszar *et al.*, 2000; Cuvin-Aralar *et al.*, 2002; Welker *et al.*, 2004; Jayatissa *et al.*, 2006; Magadza, 2006; Ghosh *et al.*, 2008; Chia *et al.*, 2009; Rejmánková *et al.*, 2011). Other factors such as high temperature do contribute to *Microcystis* bloom formation, however, the role of temperature was not as important as total nitrogen concentration (Fig. 6). Some studies have found that higher temperatures favour *Cylindrospermopsis* blooms (Bouvy *et al.*, 2000; Huszar *et al.*, 2000; Saker and Griffiths, 2001; Berger *et al.*, 2006; Dufour *et al.*, 2006; Ghosh *et al.*, 2008; Figueredo and Giani, 2009), while high total nitrogen concentration may not be as important for *Cylindrospermopsis* bloom occurrence, due to the fact that *Cylindrospermopsis* are nitrogen-fixing

cyanobacterial genera (Bouvy *et al.*, 1999; Rustadi *et al.*, 2002; Gondwe *et al.*, 2007; Khuantrairong and Traichaiyaporn, 2008). Comparing this outcome to temperate areas, *Cylindrospermopsis* blooms in France are similarly affected by high temperature (Briand *et al.*, 2002). Higher temperatures were found to be a key factor in germination of akinetes (Briand *et al.*, 2002). However, it is important to note that a combination of these factors, and not a single factor alone, usually leads to the development of a bloom (Paerl *et al.*, 2001; Jacoby *et al.*, 2003).

Highest total phosphorus concentration was found to be non-significant ($P\text{-value}=0.669 > P_{\text{critical}}=0.05$) in relation to the genera of bloom-forming cyanobacteria from the tropics in this meta-analysis. This could be due to the fact that TN:TP ratios were below 23:1 in most studies surveyed indicating non-limiting phosphorus conditions according to Guildford and Hecky (2000) and thus, the highest total phosphorus did not have any significant effect on the genera of bloom-forming cyanobacteria.

The ratios of total nitrogen:total phosphorous (TN:TP) were also found to be non-significant ($P\text{-value}=0.832 > P_{\text{critical}}=0.05$) in relation to genera of bloom-forming cyanobacteria. This surprising outcome may not necessarily be due to the reduced importance of TN:TP in determining cyanobacterial dominance, but in the lack of long-term data present in the papers selected for the analysis. In temperate lakes, low TN:TP and stable water conditions have been shown to lead to the dominance of both nitrogen and non-nitrogen-fixing cyanobacteria (Smith *et al.*, 1983). However, as noted by Paerl *et al.* (2001), TN:TP ratios may have less of an effect when total nitrogen and total phosphorous are not limiting, which seems to be the case for most tropical lakes and reservoirs in the analysis.

Another factor that has been known to affect the dominance of cyanobacterial bloom species is the type of water body (Dokulil and Teubner, 2000). In temperate regions, large shallow lakes such as Lake Taihu in China are conducive to *Microcystis* blooms, while deeper, well-mixed lakes in France are conducive to *Cylindrospermopsis* blooms, and deep, alpine lakes are favourable to *Planktothrix* blooms (Dokulil and Teubner, 2000). There were three main types of water bodies in the present metadata, natural lakes, artificial reservoirs, and ponds. There was a significant difference in bloom genera between lakes and reservoirs (Fig. 7, $P\text{-value}=0.001 * < 0.05$), with *Microcystis* blooms found in more natural lakes than reservoirs and *Cylindrospermopsis* blooms found in more reservoirs than natural lakes, as indicated in Fig. 7 by the clear separation between two ellipses. This could be due to the difference in structure of tropical lakes and reservoirs. Natural lakes usually discharge surface water but reservoirs can have outlets at different depths and thus, this may affect the outflow of the water body (Ji, 2008). Most reservoirs may encounter extreme fluctuations in

water level depending on water usage, while natural lakes tend to have less extreme fluctuations in water level and very little control of discharge depth (Ji, 2008). Greater mixing and higher turbidity of the mixed layer in reservoirs and could lead to more *Cylindrospermopsis* blooms, especially in times of drought (Bouvy *et al.*, 2000). Stable water conditions and limited changes in discharge depths combined with high nutrients may lead to a higher occurrence of *Microcystis* blooms in natural lakes (Baldia *et al.*, 2003). However, it is important to note that the studies used in this meta-analysis may not be representative of all tropical lakes and reservoirs. The effect of ponds could not be discerned in this analysis, as there was only one pond out of the 48 water bodies selected. However, similar genera were present in this pond compared to the other water body types.

Other factors such as light intensity and stratification of the lakes were not taken into account for this meta-analysis due to the lack of detailed information on light and temperature profiles of the water bodies. Flushing of water bodies was not analysed in this meta-analysis due to the lack of detailed information for flushing rates of different water bodies. Poste *et al.* (2013) showed that higher flushing rates of Napoleon Gulf in Lake Victoria had led to a lower biomass of *Microcystis* compared to other less flushed sites such as Lake George and Lake Saka in Uganda. However, the rate of flushing and difference in biomass was not quantified and thus, higher flushing in combination with other factors may have caused the lower biomass of *Microcystis*. Jayatissa *et al.* (2006) did note a decrease in cyanobacterial blooms in Sri Lanka due to flushing and dilution of water after heavy rains. However, this study noted that cell density of *Micro-*

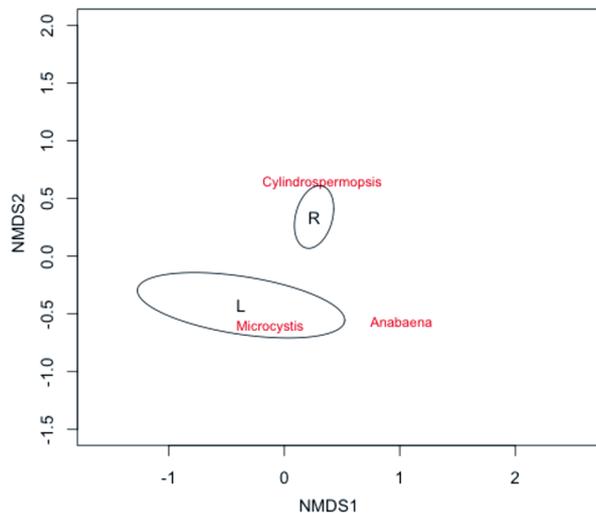


Fig. 7. Non-metric multidimensional scaling of tropical cyanobacterial blooms overlaid with ellipses indicating types of water bodies (L, lakes; R, reservoirs; $P\text{-value}=0.001 * < 0.05$).

cystis remained high even without scum formation throughout the wet and dry seasons. Retention time was indicated as an important variable in determining the biomass of cyanobacteria in Funil Reservoir in Brazil (Soares *et al.*, 2012). In Barra Bonita reservoir, cyanobacterial biomass was recorded during both short and long retention times and in highly stratified and destratified conditions, indicating that nutrient availability was more important than flushing (Dellamano-Oliveira *et al.*, 2008). Overall, flushing and retention time of a tropical reservoir may be important in determining biomass in the surface water, however, nutrients may play a larger role in determining biomass growth in the entire water body throughout the year.

Effects of nutrient levels on microcystin production

Nitrogen concentration was found to be one of the more important factors influencing tropical *Microcystis* bloom formation (Fig. 6). Cyanobacterial blooms in tropical countries occurred over a wide range of N:P ratios. The N:P values found in tropical lakes with the highest microcystin values appear to be similar to those in temperate lakes at approximately 20 (Orihel *et al.*, 2012) (Fig. 8). It was found that as N:P (nitrate:phosphate) values increased, the level of microcystins increased significantly (Spearman's rank correlation, $\rho=0.746$, $P\text{-value}=0.002 < P_{\text{crit}} 0.05$) for microcystin levels higher than $1 \mu\text{g L}^{-1}$ (R Core Team 2012) (Fig. 8). There are distinct geographical patterns present in the level of N:P (nitrate:phosphate) and microcystins encountered in the tropics, with African blooms having lower microcystin values and N:P (nitrate:phosphate) ratios recorded compared to blooms in Asia and Australia (Fig. 8). This could be due to an artefact in the timing of the data collection (snapshot data vs long term data) and not purely due

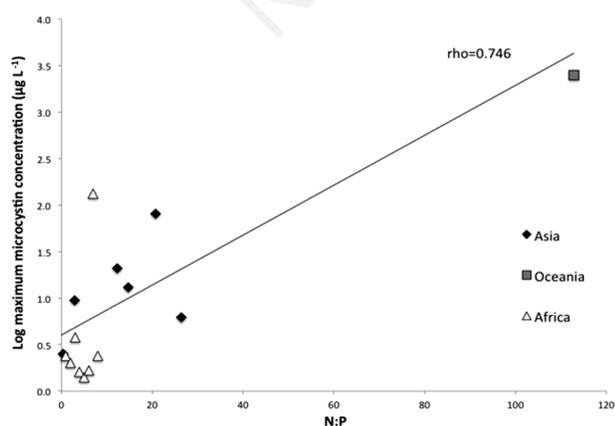


Fig. 8. Log maximum microcystin concentrations ($\mu\text{g L}^{-1}$) at different N:P values in tropical lakes and reservoirs. Cyanobacterial blooms with less than $1 \mu\text{g L}^{-1}$ of microcystin recorded were not included in this analysis.

to a lower N:P (nitrate:phosphate) ratio present in African water bodies (Chia *et al.*, 2009). However, it is important to note that the data analysed were taken from studies that documented microcystin concentration as well as nitrate and phosphate levels. Some studies that documented high microcystin concentrations ($>3 \mu\text{g L}^{-1}$; Addico *et al.*, 2006) did not document nitrate or phosphate levels and thus could not be taken into account for this analysis. Also, studies that documented the presence of microcystins without quantification could not be accounted for (Odokuma and Isirima, 2007; Haande *et al.*, 2007).

However, it is important to note that the N:P (nitrate:phosphate) ratio alone is not the only factor influencing the level of microcystin production by cyanobacteria. Different strains and species of microcystin-producing cyanobacteria respond differently to individual changes in concentrations of nitrogen and phosphorus (de Figueiredo *et al.*, 2004). The data on nutrient levels in tropical lakes and reservoirs are also sparse and thus the relationship between N:P (nitrate:phosphate) ratios and microcystin production in tropical countries cannot be fully explored. Different species and strains of cyanobacteria can also have differing levels of microcystin production based on other factors such as temperature.

Effect of temperature on microcystin concentration

Increased temperatures in temperate countries can lead to more toxic strains developing and outcompeting non-toxic strains of *Microcystis* (Briand *et al.*, 2008; Davis *et al.*, 2009). The higher gene copy of microcystin synthetase genes (McyD) in *Microcystis* species at elevated temperatures could mean increased toxicity of cyanobacterial blooms under warmer conditions (Davis *et al.*, 2009). However, this trend has yet to be found in tropical water bodies and Spearman's correlation analysis on the maximum temperatures of water bodies and total microcystin concentration based on 11 papers and 17 water bodies, did not yield significant results ($\rho=0.318$, $P\text{-value}=0.229 > P_{\text{crit}} 0.05$). Studies that did not document the maximum temperatures for individual water bodies were excluded and thus, there is a certain bias in the results that could have led to this insignificant effect of temperature. However, temperature ranges in the tropics are within $1\text{-}8^\circ\text{C}$ for each water body (Ahmed *et al.*, 2008; Wang *et al.*, 2002; White *et al.*, 2003; Kotut *et al.*, 2010) and this small increase in temperature, which was within the optimum temperature range of *Microcystis* toxin production ($25\text{-}30^\circ\text{C}$, Van der Westhuizen and Eloff, 1985; Kim *et al.*, 2005), may not significantly affect toxicity.

Effect of microcystis biomass on microcystin concentration

The concentration of cyanobacteria may also influence microcystin levels. Studies in temperate, sub-tropical as

well as tropical countries have found positive correlations between the concentration of microcystin and the concentration of cyanobacteria in blooms (Xu *et al.*, 2008; Poste *et al.*, 2013). Our analysis across tropical American and Asian regions also showed microcystins to significantly increase (Spearman's rank correlation, $\rho=0.94$, $P\text{-value}=0.017^* < P_{\text{crit}} 0.05$) with increasing concentration of *Microcystis* spp. (R Core Team, 2012) (Fig. 9). However, this trend was clear only for toxin concentrations higher than $1 \mu\text{g L}^{-1}$. Concentrations of blooms from tropical American and Asian countries containing known toxic strains of cyanobacteria can possibly be used to estimate microcystin levels in areas where regular toxin testing is unavailable or unaffordable. This correlation was not significant for tropical African blooms (Spearman's rank correlation, $\rho=0.373$, $P\text{-value}=0.153 > P_{\text{crit}} 0.05$), where tropical African blooms had lower microcystin concentration per cell concentration as compared to tropical Asian and American blooms (Fig. 9). The lower microcystin concentration per cell in African lakes was based

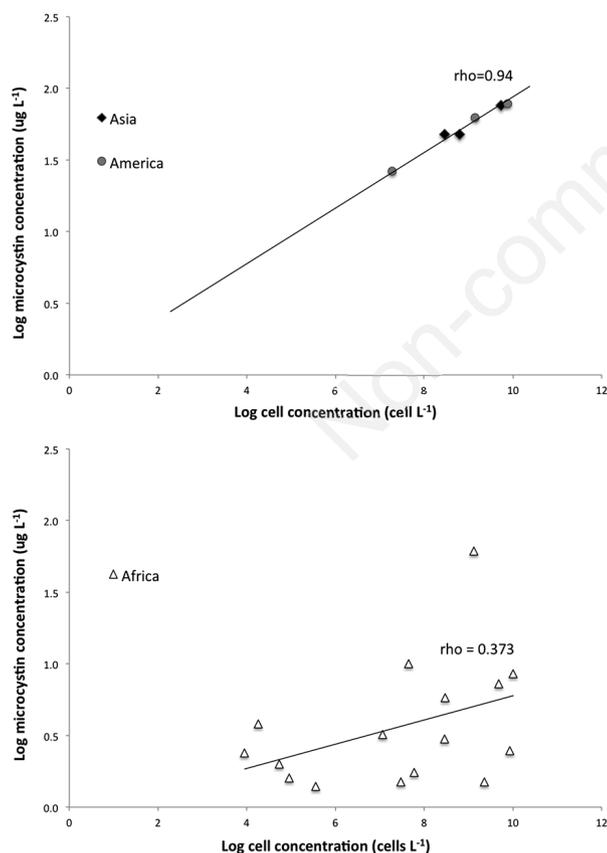


Fig. 9. Log microcystin concentrations ($\mu\text{g L}^{-1}$) plotted against log cell abundance (cells L^{-1}) for different cyanobacterial blooms in the tropics. Cyanobacterial blooms with less than $1 \mu\text{g L}^{-1}$ of microcystin recorded were not included in this analysis.

on a limited amount of studies and could be a result of the infrequent sampling and short time periods sampled (monthly for 1 year, Okello *et al.*, 2010; monthly for 6 months, Poste *et al.*, 2013). Data collected bimonthly and over a longer period of time should be more indicative of the trends. Also, Okello *et al.* (2011) found that there was significant within site variation of microcystin production per *Microcystis* cell for lakes in Uganda and that average microcystin per cell was dependent on the proportion of *mcyB* genotype of *Microcystis* more than direct cell counts. However, this trend was not clear in other tropical water bodies. Vasconcelos *et al.* (2010) indicated that even though *mcyB* was present in a Mexican lake sample, there was zero microcystins detected and similarly, another lake that had zero *mcyB* detected, had microcystins detected. Thus, there is no clear indicator of microcystin content in water bodies across the tropics but each water body should have its own guideline for either *mcyB* genotypes or *Microcystis* cells, depending on which factor has better predictive power. The variation of microcystin production by *Microcystis* has also been noted in temperate blooms where time and location were important factors in determining microcystin production within a connected freshwater ecosystem (Sabart *et al.*, 2010). Another important note about this correlation analysis is that it was based on a limited number of studies and water bodies and in order to improve its applicability and context, more studies with higher frequency of sampling over longer periods of time should be added.

CONCLUSIONS

It is important to understand the prevailing patterns or trends of toxic cyanobacterial blooms in the tropics as these may differ from the more widely studied temperate and subtropical regions. Across the tropics, the genus *Microcystis* was the most prevalent bloom-forming cyanobacteria, followed by *Cylindrospermopsis*, with fewer blooms formed by *Anabaena* and *Planktothrix*. However, different tropical regions were also characterized by different bloom-forming species such as *Cylindrospermopsis* spp. being more prevalent in tropical Australia and Brazil, and *Microcystis* spp. more so in Asia, Africa and Central America. Microcystins were the most frequently encountered toxins, while cylindrospermopsins, anatoxins and saxitoxins were detected in fewer water bodies in tropical areas.

Various studies showed that *Cylindrospermopsis* blooms were more likely to occur in the dry season as compared to the wet season in the tropics while *Microcystis* blooms were found to bloom during the wet season after heavy rain.

Based on our meta-analysis, increasing total nitrogen levels were related to more *Microcystis* blooms and higher maximum temperatures were associated with more *Cylin-*

drospermopsis blooms. Tropical lakes were significantly associated with *Microcystis* blooms while tropical reservoirs were significantly associated with *Cylindrospermopsis* blooms. Microcystin levels from *Microcystis* blooms were found to have a positive relationship with N:P (nitrate:phosphate) ratios across the tropics. Tropical African blooms were found to have no significant correlation between microcystin concentration and cell concentration as compared to Asian and American blooms, which showed significant positive correlation between microcystin concentration and cell concentration. Concentrations of blooms from tropical Asian and American countries containing known toxic strains of cyanobacteria can possibly be used to estimate microcystin levels in areas where regular toxin testing is unavailable or unaffordable. Maximum temperature of tropical water bodies did not have a significant effect on total microcystin concentrations, which may be due to the warmer temperatures experienced being within the optimum temperature range for microcystin production.

Although, the results from our meta-analysis and correlation analysis agree with the general literature on cyanobacterial blooms, it is important to note that all the analyses were based on small subsets of the total literature found on tropical countries, and that there were many water bodies without information that were not included. There could also be possible bias of data due to low frequency of sampling and short sampling duration in several studies. Thus, more information about cyanobacterial blooms in tropical countries is still needed to gain further insights into their patterns of occurrence, toxin production and causes of blooms.

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REFERENCES

- Addico G, Hardege J, Komarek J, Babica P, de Graft-Johnson KAA, 2006. Cyanobacteria species identified in the Weija and Kpong reservoirs, Ghana, and their implications for drinking water quality with respect to microcystin. *Afr. J. Mar. Sci.* 28:451-456.
- Agrawal MK, Ghosh SK, Bagchi D, Weckesser J, Erhard M, Bagchi S, 2006. Occurrence of microcystin-containing toxic water blooms in Central India. *J. Microbiol. Biotechnol.* 16:212-218.
- Ahmed MS, Hiller S, Luckas B, 2008. *Microcystis aeruginosa* bloom and the occurrence of microcystins (Heptapeptides Hepatotoxins) from an aquaculture pond in Gazipur, Bangladesh. *Turk. J. Fish. Aquat. Sc.* 8:37-41.
- Ahmed MS, Luckas B, 2008. *Microcystis aeruginosa* (Chroococcales, Cyanobacteria) bloom and the occurrence of microcystins in a freshwater pond in Bangladesh. *Journal for Centre for Development of Research* 4:135-141.
- Ajuzie CC, 2012. A first survey of phytoplankton community richness in Lamingo Reservoir, Jos, Nigeria: A wake-up call for the continuous monitoring of microalgae in surface waters serving as drinking water sources in Nigeria. *New York Sci. J.* 5:1-8.
- Akcaalan R, Young FM, Metcalf JS, Morrison LF, Albay M, Codd GA, 2006. Microcystin analysis in single filaments of *Planktothrix* spp. in laboratory cultures and environmental blooms. *Water Res.* 40:1583-1590.
- Akin-Oriola GA, 2003. On the phytoplankton of Awba reservoir, Ibadan, Nigeria. *Rev. Biol. Trop.* 51:1-6.
- Akin-Oriola GA, Anetekhai MA, Oriola A, 2006. Algal blooms in Nigerian waters: an overview. *Afr. J. Mar. Sci.* 28:219-224.
- Anadu DI, Obiaha A, Ejike C, 1990. Water quality and plankton periodicity in two contrasting mine lakes in Jos, Nigeria. *Hydrobiologia* 208:17-25.
- Arfi R, Bouvy M, Cecchi P, Pagnao M, Thomas S, 2001. Factors limiting phytoplankton productivity in 49 shallow reservoirs of North Côte d'Ivoire (West Africa). *Aquat. Ecosyst. Health* 4:123-138.
- Azevedo SMFO, Carmichael WW, Jochimsen EM, Rinehart KL, Lau S, Shaw GR, Eaglesham GK, 2002. Human intoxication by microcystins during renal dialysis treatment in Caruaru-Brazil. *Toxicology* 181:441-446.
- Baldia SF, Conaco MCG, Nishijima T, Imanishi S, Harada KI, 2003. Microcystin production during algal bloom occurrence in Laguna de Bay, the Philippines. *Fisheries Sci.* 69:110-116.
- Baldia SF, Evangelista AD, Aralar EV, Santiago AE, 2007. Nitrogen and phosphorus utilization in the cyanobacterium *Microcystis aeruginosa* isolated from Laguna de Bay, Philippines. *J. Appl. Phycol.* 19:607-613.
- Ballot A, Krienitz L, Kotut K, Wiegand C, Pflugmacher S, 2005. Cyanobacteria and cyanobacterial toxins in the alkaline crater lakes Sonachi and Simbi, Kenya. *Harmful Algae* 4:139-150.
- Bartram J, Burch M, Falconer IR, Jones G, Kuiper-Goodman T, 1999. Situation assessment, planning and management, p. 183-210. In: I. Chorus and J. Bartram (eds.), *Toxic cyanobacteria in water*. Taylor and Francis.
- Beasley VR, Dahlem AM, Cook WO, Valentine WM, Lovell RA, Hooser SB, Harada K-I, Suzuki M, Carmichael WW, 1989. Diagnostic and clinically important aspects of cyanobacterial (blue-green algae) toxicoses. *J. Vet. Diagn. Invest.* 1:359-365.
- Berger C, Ba N, Gugger M, Bouvy M, Rusconi F, Coute A, Troussellier M, Bernard C, 2006. Seasonal dynamics and toxicity of *Cylindrospermopsis raciborskii* in Lake Guiers (Senegal, West Africa). *Microb. Ecol.* 57:355-366.
- Bernard C, Harvey M, Briand JF, Biré R, Krysz S, Fontaine JJ, 2003. Toxicological comparison of diverse *Cylindrospermopsis raciborskii* strains: evidence of liver damage caused by a french *C. raciborskii* strain. *Environ. Toxicol.* 18:176-186.
- Berry JP, Lind O, 2010. First evidence of "paralytic shellfish

- toxins" and cylindrospermopsin in a Mexican freshwater system, Lago Catemaco, and apparent bioaccumulation of the toxins in "tegologo" snails (*Pomacea patula catemacensis*). *Toxicon* 55:930-938.
- Bittencourt-Oliveira MC, 2003. Detection of potential microcystin-producing cyanobacteria in Brazilian reservoirs with a *mcyB* molecular marker. *Harmful Algae* 2:51-60.
- Bittencourt-Oliveira MC, Kujbida P, Cardozo KHM, Carvalho VM, Moura AdN, Colepicolo P, Pinto E, 2005. A novel rhythm of microcystin biosynthesis is described in the cyanobacterium *Microcystis panniformis* Komárek et al. *Biochem. Bioph. Res. Co.* 326:687-694.
- Bittencourt-Oliveira MC, Oliveira MC, Pinto E, 2011. Diversity of microcystin-producing genotypes in Brazilian strains of *Microcystis* (Cyanobacteria). *Braz. J. Biol.* 71:209-216.
- Bormans M, Ford PW, Fabbro LD, 2004. Spatial and temporal variability in cyanobacterial populations controlled by physical processes. *J. Plankton Res.* 27:61-70.
- Bouvy M, Arfi R, Cecch P, Corbin D, Pagano M, Saint-Jean L, Thomas S, 1998. Trophic coupling between bacterial and phytoplanktonic compartments in shallow tropical reservoirs (Ivory Coast, West Africa). *Aquat. Microb. Ecol.* 15:25-37.
- Bouvy M, Ba N, Ka S, Sane S, Pagano M, Arfi R, 2006. Phytoplankton community structure and species assemblage succession in a shallow tropical lake (Lake Guiers, Senegal). *Aquat. Microb. Ecol.* 45:147-161.
- Bouvy M, Falcão D, Marinho M, Pagano M, Moura A, 2000. Occurrence of *Cylindrospermopsis* (Cyanobacteria) in 39 Brazilian tropical reservoirs during the 1998 drought. *Aquat. Microb. Ecol.* 23:13-27.
- Bouvy M, Molica RJR, Oliveira SD, Marinho M, Beker B, 1999. Dynamics of a toxic cyanobacterial bloom (*Cylindrospermopsis raciborskii*) in a shallow reservoir in the semi-arid region of northeast Brazil. *Aquat. Microb. Ecol.* 20:285-297.
- Bouvy M, Nascimento SM, Molica RJR, Ferreira A, Huszar V, Azevedo SMFO, 2003. Limnological features in Tapacurá reservoir (northeast Brazil) during a severe drought. *Hydrobiologia* 493:115-130.
- Branco CW, Senna PA, 1994. Factors influencing the development of *Cylindrospermopsis raciborskii* and *Microcystis aeruginosa* in the Paranoa Reservoir, Brasilia, Brazil. *Algalogical Studies* 75:85-96.
- Briand JF, Robillot C, Quiblier-Lloberas C, Humbert JF, Couté A, Bernard C, 2002. Environmental context of *Cylindrospermopsis raciborskii* (Cyanobacteria) blooms in a shallow pond in France. *Water Res.* 36:3183-3192.
- Briand JF, Jacquet S, Bernard C, Humbert JF, 2003. Health hazards for terrestrial vertebrates from toxic cyanobacteria in surface water ecosystems. *Vet. Res.* 34:361-377.
- Briand E, Yepremian C, Humbert JF, Quiblier C, 2008. Competition between microcystin- and non-microcystin-producing *Planktothrix agardhii* (cyanobacteria) strains under different environmental conditions. *Environ. Microbiol.* 10:3337-3348.
- Campbell IC, Poole C, Giesen W, Valbo-Jorgensen J, 2006. Species diversity and ecology of Tonle Sap Great Lake, Cambodia. *Aquat. Sci.* 68:355-373.
- Carmichael WW, 1996. Liver failure and human deaths at a haemodialysis centre in Brazil: microcystins as a major contributing factor. *Harmful Algae News* 15:11-12.
- Carmichael WW, Azevedo SMFO, An JS, Molica RJR, Jochimsen EM, Lau S, Rinehart KL, Shaw GR, Eaglesham GK, 2001. Human fatalities from cyanobacteria: Chemical and biological evidence for cyanotoxins. *Environ. Health Persp.* 109:663-668.
- Chen J, Xie P, Li L, Xu J, 2009. First identification of the hepatotoxic microcystins in the serum of a chronically exposed human population together with indication of hepatocellular damage. *Toxic. Sci.* 108:81-89.
- Chia AM, Abolude DS, Ladan Z, Kalaboms A, 2009. The presence of microcystins in aquatic ecosystems in Northern Nigeria: Zaria as a case study. *Res. J. Env. Toxic.* 3:170-178.
- Cox PA, Banack SA, Murch SJ, Rasmussen U, Tien G, Bidigare RR, Metcalf JS, Morrison LF, Codd GA, Bergman B, 2005. Diverse taxa of cyanobacteria produce beta-N-methylamino-L-alanine, a neurotoxic amino acid. *P. Natl. Acad. Sci. USA* 102:5074-5078.
- Cuvin-Aralar ML, Fastner J, Focken U, Becker K, Aralar EV, 2002. Microcystins in natural blooms and laboratory cultured *Microcystis aeruginosa* from Laguna de Bay, Philippines. *Syst. Appl. Microbiol.* 25:179-182.
- Dao TS, Cronberg G, Nimptsch J, Do-Hong L-C, Wiegand C, 2010. Toxic cyanobacteria from Tri An Reservoir, Vietnam. *Nova Hedwigia* 90:433-448.
- Davis TW, Berry DL, Boyer GL, Gobler CJ, 2009. The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms. *Harmful Algae* 8:715-725.
- de Figueiredo DR, Azeiteiro UM, Esteves SM, Goncalves FJ, Pereira MJ, 2004. Microcystin-producing blooms - a serious global public health issue. *Ecotox. Environ. Safe.* 59:151-163.
- Dellamano-Oliveira MJ, Vieira AAH, Rocha O, Colombo V, Sant-Anna CL, 2008. Phytoplankton taxonomic composition and temporal changes in a tropical reservoir. *Fund. Appl. Limnol.* 171:27-38.
- Díaz-Pardo E, Vazquez G, López-López E, 1998. The phytoplankton community as a bioindicator of health conditions of Atezca Lake, Mexico. *Aquat. Ecosyst. Health* 1:257-266.
- Dokulil MT, Teubner K, 2000. Cyanobacterial dominance in lakes. *Hydrobiologia* 438:1-12.
- Domingos P, Rubim TK, Molica RJR, Azevedo SMFO, Carmichael WW, 1999. First report of microcystin production by picoplanktonic cyanobacteria isolated from a Northeast Brazilian drinking water supply. *Environ. Toxicol.* 14:31-35.
- Dorr FA, Pinto E, Soares RM, Azevedo SMFO, 2010. Microcystins in South American aquatic ecosystems: Occurrence, toxicity and toxicological assays. *Toxicon* 56:1247-1256.
- dos Anjos FM, Bittencourt-Oliveira C, Zajac MP, Hiller S, Christian B, Erler K, Lucas B, Pinto E, 2006. Detection of harmful cyanobacteria and their toxins by both PCR amplification and LC-MS during a bloom event. *Toxicon* 48:239-245.
- Dufour P, Sarazin G, Quiblier C, Sane S, Leboulanger C, 2006. Cascading nutrient limitation of the cyanobacterium *Cylindrospermopsis raciborskii* in a Sahelian lake (North Senegal). *Aquat. Microb. Ecol.* 44:219-230.
- Ezra AG, Nwankwo DI, 2001. Composition of phytoplankton algae in Gubi reservoir, Bauchi, Nigeria. *J. Aquat. Sci.* 16:115-118.
- Falconer IR, 2008. Health Effects associated with controlled exposures to cyanobacterial toxins, p. 607-612 In: H. K. Hud-

- nell (ed.), Cyanobacterial harmful algal blooms. Springer.
- Ferrão-Filho A, da Costa S, Ribeiro MGL, Azevedo SMFO, 2007. Effects of a saxitoxin-producer strain of *Cylindrospermopsis raciborskii* (Cyanobacteria) on the swimming movements of cladocerans. *Environ. Toxicol.* 23:161-168.
- Figueredo CC, Giani A, 2009. Phytoplankton community in the tropical lake of Lagoa Santa (Brazil): Conditions favoring a persistent bloom of *Cylindrospermopsis raciborskii*. *Limnologia* 39:264-272.
- Francis G, 1878. Poisonous Australian lake. *Nature* 18:11-12.
- Frias HV, Mendes MA, Cardozo KH, Carvalho VM, Tomazela D, Colepicolo P, Pinto E, 2006. Use of electrospray tandem mass spectrometry for identification of microcystins during a cyanobacterial bloom event. *Biochem. Biophys. Res. Co.* 344:741-746.
- Ganf GG, 1974. Phytoplankton biomass and distribution in a shallow eutrophic lake (Lake George, Uganda). *Oecologia* 16:9-29.
- Ghosh SK, Das PK, Bagchi SN, 2008. PCR-based detection of microcystin-producing cyanobacterial blooms from Central India. *Indian J. of Experimental Biol.* 46:66-70.
- Gondwe MJ, Guildford SJ, Hecky RE, 2007. Planktonic nitrogen fixation in Lake Malawi/Nyasa. *Hydrobiologia* 596:251-267.
- Green J, Corbet SA, Watts E, Lan OB, 1976. Ecological studies on Indonesian lakes. Overturn and restratification of Ranu Lamongan. *J. Zool.* 180:315-354.
- Green J, Corbet SA, Watts E, Lan OB, 1978. Ecological studies on Indonesian lakes. The montane lakes of Bali. *J. Zool.* 186:15-38.
- Green J, 2010. Geographical variation in rotifers associated with *Microcystis* blooms. *Hydrobiologia* 662:197-204.
- Gremberghe I, Gucht K, Vanormelingen P, Asmelash T, Dejenie T, D'hondt S, Declerck S, Meester L, Vyverman W, 2011. Genetic diversity of *Microcystis* blooms (Cyanobacteria) in recently constructed reservoirs in Tigray (Northern Ethiopia) assessed by rDNA ITS. *Aquat. Ecol.* 45:289-306.
- Griffiths DJ, Saker ML, 2003. The Palm Island mystery disease 20 years on: a review of research on the cyanotoxin cylindrospermopsin. *Environ. Toxicol.* 18:78-93.
- Guildford SJ, Hecky RE, 2000. Total nitrogen, total phosphorus, and nutrient limitation in lakes and oceans: Is there a common relationship? *Limnol. Oceanogr.* 45:1213-1223.
- Haande S, Ballot A, Rohrlack T, Fastner J, Wiedner C, Edvardsen B, 2007. Diversity of *Microcystis aeruginosa* isolates (Chroococcales, Cyanobacteria) from East-African water bodies. *Arch. Mikrobiol.* 188:15-25.
- Haande S, Rohrlack T, Ballot A, Røberg K, Skulberg R, Beck M, Wiedner C, 2008. Genetic characterisation of *Cylindrospermopsis raciborskii* (Nostocales, Cyanobacteria) isolates from Africa and Europe. *Harmful Algae* 7:692-701.
- Harith M, Hassan R, 2011. Blue-green algae and nutrient concentrations in two Tor tambroides aquaculture ponds differing in construction. *J. Trop. Biol. Conserv.* 8:51-61.
- Hawkins PR, Runnegar MTC, Jackson ARB, Falconer IR, 1985. Severe hepatotoxicity caused by the tropical cyanobacterium (Blue-GreenAlga) *Cylindrospermopsis raciborskii* (Woloszynska) Seenaya and Subba Raju isolated from a domestic water supply reservoir. *Appl. Environ. Microbiol.* 50:1292-1295.
- Hawkins PR, Griffiths DJ, 1993. Artificial destratification of a small tropical reservoir: effects upon the phytoplankton. *Hydrobiologia* 254:169-181.
- Hodgkiss IJ, 1974. Studies on Plover Cove Reservoir, Hong Kong: composition and distribution of the phytoplankton and its relationship to environmental factors. *Freshwater Biol.* 4:111-126.
- Huszar VLM, Silva LHS, Marinho M, Domingos P, Sant' Anna CLS, 2000. Cyanoprokaryote assemblages in eight productive tropical Brazilian waters. *Hydrobiologia* 424:67-77.
- Jacoby JM, Collier DC, Welch EB, Hardy FJ, Crayton M, 2000. Environmental factors associated with a toxic bloom of *Microcystis aeruginosa*. *Can. J. Fish. Aquat. Sci.* 57:231-240.
- Jahan R, Khan S, Haque MM, Choi JK, 2010. Study of harmful algal blooms in a eutrophic pond, Bangladesh. *Environ. Monit. Assess.* 170:7-21.
- Janse I, Kardinaal WEA, Agterveld MK, Meima M, Visser PM, Zwart G, 2005. Contrasting microcystin production and cyanobacterial population dynamics in two *Planktothrix*-dominated freshwater lakes. *Environ. Microbiol.* 7:1514-1524.
- Jayatissa LP, Silva EI, McElhiney J, Lawton LA, 2006. Occurrence of toxigenic cyanobacterial blooms in freshwaters of Sri Lanka. *Syst. Appl. Microbiol.* 29:156-164.
- Jewel MAS, Affan MA, Khan FA, 2003. Fish mortality due to cyanobacterial bloom in an aquaculture pond in Bangladesh. *Pak. J. Biol. Sci.* 6:1046-1050.
- Ji Z-G, 2008. Lakes and reservoirs, p. 509-565. In: Z-G Ji (ed.), Hydrodynamics and water quality: modeling rivers, lakes, and estuaries. J. Wiley & Sons.
- Joachimsmen EM, Carmichael WW, An JS, Cardo DM, Coockson ST, Holmes CEM, Antunes BC, Melofilo DA, Lyra TM, Barreto VST, Azevedo SMFO, Jarvis WR, 1998. Liver failure and death after exposure to Microcystins at haemodialysis centre in Brazil. *New Engl. J. Med.* 338:873-878.
- Jöhnk KD, Huisman JEF, Sharples J, Sommeijer BEN, Visser PM, Stroom JM, 2008. Summer heatwaves promote blooms of harmful cyanobacteria. *Glob. Change Biol.* 14:495-512.
- Kemdirim EC, 2000. Diel rythim of plankton and physicochemical parameters in Kangimi reservoir, Kaduna State Nigeria. *J. Aquat. Sci.* 15:35-39.
- Kemka N, Njiné T, Zébazé Togouet SH, Niyitegeka D, Monkiedje A, Foto Menbohan S, Nola M, Compère P, 2003. Quantitative importance of cyanobacteria populations in a hypertrophic shallow lake in the subequatorial African region (Yaounde Municipal Lake, Cameroon). *Arch. Hydrobiol.* 156:495-510.
- Kitaka N, Harper DM, Mavuti KM, 2002. Phosphorus inputs to Lake Naivasha, Kenya, from its catchment and the trophic state of the lake. *Hydrobiologia* 488:73-80.
- Kim, HR, Kim CK, Ahn TS, Yoo S, Lee DH, 2005. Effects of temperature and light on microcystin synthetase gene transcription in *Microcystis aeruginosa*. *Key Eng. Mat.* 277-279:606-611.
- Khoo HW, Yang SL, Goh CJ, 1977. A preliminary limnological study of Seletar Reservoir. *J. Singapore Nat. Acad. Sci.* 6:1-12.
- Khuantrairong T, Traichaiyaporn S, 2008. Diversity and seasonal succession of the phytoplankton community in Doi Tao Lake, Chiang Mai Province, Northern Thailand. *Natural History J. Chulalongkorn Univ.* 8:143-156.
- Komarek J, Azevedo SMFO, Domingos P, Komarkova J, Tichy

- M, 2001. Background of the Caruaru tragedy: a case taxonomic study of toxic cyanobacteria. *Algological Studies* 103:9-29.
- Komarek J, Kling H, 1991. Variation in six planktonic cyanophyte genera in Lake Victoria (East Africa). *Algological Studies* 61:21-45.
- Komarek J, Mares J, 2012. An update to modern taxonomy (2011) of freshwater planktic heterocytous cyanobacteria. *Hydrobiologia* 698:327-351.
- Kotut K, Ballot A, Wiegand C, Krienitz L, 2010. Toxic cyanobacteria at Nakuru sewage oxidation ponds - A potential threat to wildlife. *Limnologia* 40:47-53.
- Krishnan JR, 2008. Investigation on hydrobiology and water quality parameters of Periyar Lake, Thekkady, Kerala. Ph.D. Thesis, Mahatma Gandhi University, Kerala.
- Kunz M, 2011. Effect of large dams in the Zambezi River basin: changes in sediment, carbon and nutrient fluxes. Ph.D. Thesis, Swiss Federal Institute of Technology, Zurich.
- Lagos N, Onodera H, Zagatto PA, Andrinolo D, Azevedo SMFO, Oshima Y, 1999. The first evidence of paralytic shellfish toxins in the freshwater cyanobacterium *Cylindrospermopsis raciborskii*, isolated from Brazil. *Toxicon* 37:1359-1373.
- Lewis WM, 1973. A limnological survey of Lake Mainit, Philippines. *Int. Rev. Hydrobiol.* 58:801-818.
- Lewis WM, 1978. Dynamics and succession of the phytoplankton in a tropical lake: Lake Lanao, Philippines. *J. Ecol.* 66:849-880.
- Lewis WM, 1986. Phytoplankton succession in Lake Valencia, Venezuela. *Hydrobiologia* 138:189-203.
- Li R, Carmichael WW, Brittain S, Eaglesham GK, Shaw GR, Mahakhant A, Noparatnaraporn N, Yongmanitchai W, Kaya K, Watanabe MM, 2001. Isolation and identification of the cyanotoxin cylindrospermopsin and deoxy-cylindrospermopsin from a Thailand strain of *Cylindrospermopsis raciborskii* (Cyanobacteria). *Toxicon* 39:973-980.
- Lind OT, Davalos-Lind LO, 2002. Interaction of water quantity with water quality: the Lake Chapala example. *Hydrobiologia* 159:159-167.
- Magadza CHD, 2006. Kariba reservoir: experience and lessons learned. *Lake Reserv. Manage.* 11:271-286.
- Magadza CHD, 2008-2009. Re-eutrophication and pathogenic contamination of Lake Chivero. In: M. Nakamura (ed.), *Integrated lake basin management*. International Lake Environment Committee.
- Mahakhant A, Sano T, Ratanachot P, Tong-a-ram T, Srivastava VC, Watanabe MM, Kaya K, 1998. Detection of microcystins from cyanobacterial water blooms in Thailand fresh water. *Phycol. Res.* 46:25-29.
- Mansoor H, Sorayya M, Aishah S, Mosleh MAA, 2011. Automatic Recognition System for some cyanobacteria using image processing Techniques and ANN approach. *Proceedings Int. Conf. on Environmental & Computer Science*, Singapore, 19:73-78.
- McGregor GB, Fabbro LD, 2000. Dominance of *Cylindrospermopsis raciborskii* (Nostocales, Cyanoprokaryota) in Queensland tropical and subtropical reservoirs: Implications for monitoring and management. *Lake Reserv. Manage.* 5:195-205.
- Meesukko C, Gajaseeni N, Peerapornpisal Y, Voinov A, 2007. Relationships between seasonal variation and phytoplankton dynamics in Kaeng Krachan Reservoir, Phetchaburi Province, Thailand. *Natural History J. Chulalongkorn Univ.* 7:131-143.
- Merican F, Wan Asmadi WA, Wan Maznah WO, Mashhor M, 2006. A note on the freshwater algae of Gunung Stong, Kelantan, Malaysia. *Trop. Life Sci. Res.* 17:65-76.
- Merino-Ibarra M, Monroy-Rios E, Vilaclara G, Castillo FS, Gallegos ME, Ramirez-Zierold J, 2007. Physical and chemical limnology of a wind-swept tropical highland reservoir. *Aquat. Ecol.* 42:335-345.
- Mhlanga L, 2011. *Limnology of lakes and rivers (Zimbabwe)*. EOLSS Publishers, Oxford, UK. Available from: <http://www.eolss.net>
- Mhlanga L, Day J, Chimbari M, Siziba N, Cronberg G, 2006a. Observations on limnological conditions associated with a fish kill of *Oreochromis niloticus* in Lake Chivero following collapse of an algal bloom. *Afr. J. Ecol.* 44:199-208.
- Mhlanga L, Day J, Cronberg G, Chimbari M, Siziba N, Annadotter H, 2006b. Cyanobacteria and cyanotoxins in the source water from Lake Chivero, Harare, Zimbabwe, and the presence of cyanotoxins in drinking water. *Afr. J. Aquat. Sci.* 31:165-173.
- Mitrovic SM, Hardwick L, Dorani F, 2011. Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. *J. Plankton Res.* 33:229-241.
- Mizuno T, Mori S, 1970. Preliminary hydrobiological survey of some Southeast Asian inland waters. *Biol. J. Lin. Soc.* 2: 77-177.
- Molica R, Oliveira EJA, Carvalho PVVC, Costac ANSF, Cunha MCC, Melo GL, Azevedo SMFO, 2005. Occurrence of saxitoxins and an anatoxin-a(s)-like anticholinesterase in a Brazilian drinking water supply. *Harmful Algae* 4:743-753.
- Molica R, Onodera H, Garcia C, Rivas M, Andrinolo D, Nascimento S, Meguro H, 2002. Toxins in the freshwater cyanobacterium *Cylindrospermopsis raciborskii* (Cyanophyceae) isolated from Tabocas reservoir in Caruaru, Brazil, including demonstration of a new saxitoxin analogue. *Phycologia* 41:606-611.
- Moura AN, Dantas EW, Oliveira HS, Bittencourt-Oliveira MC, 2011. Vertical and temporal dynamics of cyanobacteria in the Carpina potable water reservoir in northeastern Brazil. *Braz. J. Biol.* 71:451-459.
- Ndebele MR, Magadza CH, 2006. The occurrence of microcystin-LR in Lake Chivero, Zimbabwe. *Lake Reserv. Manage.* 11:57-62.
- Nguyen LTT, Cronberg G, Annadotter H, Larsen J, 2007a. Planktic cyanobacteria from freshwater localities in ThuaThien-Hue province, Vietnam. II. Algal biomass and microcystin production. *Nova Hedwigia* 85:35-49.
- Nguyen LTT, Cronberg G, Larsen J, Moestrup Ø, 2007b. Planktic cyanobacteria from freshwater localities in ThuaThien-Hue province, Vietnam. I. Morphology and distribution. *Nova Hedwigia* 85:1-34.
- Ochumba PBO, Kibaara DI, 1989. Observations on blue-green algal blooms in the open waters of Lake Victoria, Kenya. *Afr. J. Ecol.* 27:23-34.
- Odokuma LO, Isirima JC, 2007. Distribution of cyanotoxins in aquatic environments in the Niger Delta. *Afr. J. Biotech.* 6:2375-2385.
- Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR,

- O'Hara RB, Simpson, P, Solymos GL, Henry M, Stevens H, Wagner H, 2013. vegan: Community Ecology Package. R package version 2.0-7. Available from: <http://CRAN.R-project.org/package=vegan>
- Okechukwu O, Ugwumba A, 2009. Cyanobacteria abundance and its relationship to water quality in the Mid-Cross River floodplain, Nigeria. *Int. J. Trop. Biol.* 57:33-43.
- Okello W, Kurmayer R, 2011. Seasonal development of cyanobacteria and microcystin production in Ugandan freshwater lakes. *Lake Reserv. Manage.* 16:123-135.
- Okello W, Ostermaier V, Portmann C, Gademann K, Kurmayer R, 2010. Spatial isolation favours the divergence in microcystin net production by *Microcystis* in Ugandan freshwater lakes. *Water Res.* 44:2803-2814.
- Oliver RL, Ganf GG, 2000. Freshwater Blooms, p. 149-194 In: B. A. Whitton and M. Potts (eds.), *The ecology of cyanobacteria: their diversity in time and space*. Kluwer Academic Publ.
- Onyema IC, 2010. Phytoplankton diversity and succession in the Iyagbe lagoon, Lagos. *Eur. J. Sci. Res.* 43:61-74.
- Orihel DM, Bird DF, Brylinsky M, Chen H, Donald DB, Huang DY, Giani A, Kinniburgh D, Kling H, Kotak BG, Leavitt PR, Nielsen CC, Reedy S, Rooney RC, Watson SB, Zurawell RW, Vinebrooke RD, 2012. High microcystin concentrations occur only at low nitrogen-to-phosphorus ratios in nutrient-rich Canadian lakes. *Can. J. Fish. Aquat. Sci.* 69:1-6.
- Padisak J, 1997. *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya et Subba Raju, an expanding, highly adaptive cyanobacterium: worldwide distribution and review of its ecology. *Arch. Hydrobiol.* 107:563-593.
- Paerl HW, Fulton RS, Moisaner PH, Dyble J, 2001. Harmful freshwater algal blooms, with an emphasis on cyanobacteria. *TheSciWorldJo* 1:76-113.
- Pham MN, Tan HTW, Mitrovic S, Yeo HHT, 2011. A checklist of the algae of Singapore. Raffles Museum of Biodiversity Research, Singapore.
- Piccin-Santos V, Bittencourt-Oliveira MC, 2012. Toxic cyanobacteria in four Brazilian water supply reservoirs. *J. Environ. Prot. Ecol.* 3:68-73.
- Pongswat S, Thammathaworn S, Peerapornpisal Y, Thaneea N, Somsiri C, 2004. Diversity of phytoplankton in the Rama IX Lake, a man-made lake, Pathumthani Province, Thailand. *ScienceAsia* 30:261-267.
- Poste AE, Hecky RE, Guildford SJ, 2013. Phosphorus enrichment and carbon depletion contribute to high *Microcystis* biomass and microcystin concentrations in Ugandan lakes. *Limnol. Oceanogr.* 58:1075-1088.
- Prakash S, Lawton LA, Edwards C, 2009. Stability of toxigenic *Microcystis* blooms. *Harmful Algae* 8:377-384.
- Prihantini NB, Widyawan A, Rianto R, Ariyani Y, Wardhana W, Hendrayanti D, 2008. Potential toxic cyanobacteria in three lakes of Jakarta-Bogor area, Indonesia. *Mar. Res. Indonesia* 33:95-100.
- Prommana R, Peerapornpisal Y, Whangchai N, Morrison LF, Metcalf JS, Ruangyuttikarn W, Towpromma A, Codd GA, 2006. Microcystins in cyanobacterial blooms from two freshwater prawn (*Macrobrachium rosenbergii*) ponds in Northern Thailand. *ScienceAsia* 32:365-370.
- R Development Core Team, 2012. R: A language and environment for statistical computing. R Foundation for statistical computing, Vienna, Austria. Available from: <http://www.R-project.org>
- Ramberg L, 1987. Phytoplankton succession in the Sanyati basin, Lake Kariba. *Hydrobiologia* 153:193-202.
- Ramirez P, Nandini S, Sarma SSS, Valderrama ER, Cuesta I, Hurtado MD, 2002. Seasonal variations of zooplankton abundance in the freshwater reservoir Valle de Bravo (Mexico). *Hydrobiologia* 467:99-108.
- Rejmánková E, Komárek J, Dix M, Komárková J, Girón N, 2011. Cyanobacterial blooms in Lake Atitlan, Guatemala. *Limnologia* 41:296-302.
- Retnaningdyah C, Soegianto A, Irawan B, 2010. Blooming stimulation of *Microcystis* in Sutami Reservoir using nutrients nitrate and phosphate in different ratio. *J. Trop. Life Sci.* 1:42-46.
- Romero EM, 2002. [Determinación de toxinas biológicas en una fuente de abastecimiento de agua dulce]. [Article in Spanish.] *Proceedings XXVIII American Congr. of Sanitary and Environmental Engineering*, Cancun, Mexico.
- Rouf AA, Ambak MA, Shamsudin L, Phang SM, Ho SC, 2008. Temporal changes in the periphytic algal communities in a drowned tropical forest reservoir in Malaysia: Lake Kenyir. *Lake Reserv. Manage.* 13:271-287.
- Rustadi, Kuwabara R, Kamiso HN, 2002. Water quality and planktological approach to monitor eutrophication by cage-culture of red tilapia (*Oreochromis* sp.) at the Sermo Reservoir, Yogyakarta, Indonesia. *Asian Fish. Sci.* 15:135-144.
- Sabart M, Pobel D, Briand E, Combourieu B, Salencon MJ, Humbert JF, Latour D, 2010. Spatiotemporal variations in microcystin concentrations and in the proportions of microcystin-producing cells in several *Microcystis aeruginosa* populations. *Appl. Environ. Microbiol.* 76:4750-4759.
- Saker, ML and Griffiths DJ, 2001. Occurrence of blooms of the cyanobacterium *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya and Subba Raju in a north Queensland domestic water supply. *Mar. Freshwater Res.* 52:907-915.
- Salonen K, Sarvala J, Järvinen M, Langenberg V, Nuottajävi M, Vuorio K, Chitamwebwa DBR, 1999. Phytoplankton in Lake Tanganyika - vertical and horizontal distribution of in vivo fluorescence. *Hydrobiologia* 407:89-103.
- Sangolkar LN, Maske SS, Muthal PL, Kashyap SM, Chakrabarti T, 2009. Isolation and characterization of microcystin producing *Microcystis* from a Central Indian water bloom. *Harmful Algae* 8:674-684.
- Sant'Anna CL, Azevedo SMTD, Werner VR, Dogo CR, Fernanda RR, Carvalho LR, 2008. Review of toxic species of Cyanobacteria in Brazil. *Algalogical Studies* 126:251-265.
- Sant'Anna CL, de Carvalho LR, Fiore MF, Silva-Stenico ME, Lorenzi AS, Rios FR, Konno K, Garcia C, Lagos N, 2011. Highly toxic *Microcystis aeruginosa* strain, isolated from São Paulo-Brazil, produce hepatotoxins and paralytic shellfish poison neurotoxins. *Neurotoxin Res.* 19:389-402.
- Sant'Anna CL, Melcher SS, Carvalho MDC, Gemelgo MP, Azevedo MTDP, 2007. Planktic cyanobacteria from upper Tietê basin reservoirs, SP, Brazil. *Rev. Brasil Bot.* 30:1-17.
- Sekadende BC, Lyimo TJ, Kurmayer R, 2005. Microcystin production by cyanobacteria in the Mwanza Gulf (Lake Victoria, Tanzania). *Hydrobiologia* 543:299-304.
- Sim AJQ, 2009. Isolation of different cyanobacteria types from Singapore reservoirs. Nanyang Technological University.

- Sitoki L, Kurmayer R, Rott E, 2012. Spatial variation of phytoplankton composition, biovolume, and resulting microcystin concentrations in the Nyanza Gulf (Lake Victoria, Kenya). *Hydrobiologia* 691:109-122.
- Sivonen K, 1999. Cyanobacterial toxins. *Vesitalous* 5:11-18.
- Soares MCS, Marinho MM, Azevedo SMFO, Branco CWC, Huszar VLM, 2012. Eutrophication and retention time affecting spatial heterogeneity in a tropical reservoir. *Limnologica* 42:197-203.
- Sotero-Santos RB, Silva CR, Verani NF, Nonaka KO, Rocha O, 2006. Toxicity of a cyanobacteria bloom in Barra Bonita Reservoir (Middle Tiete River, Sao Paulo, Brazil). *Ecotox. Environ. Safe.* 64:163-170.
- Sprober P, Shafik HM, Presing M, Kovacs AW, Herodek S, 2003. Nitrogen uptake and fixation in the cyanobacterium *Cylindrospermopsis raciborskii* under different nitrogen conditions. *Hydrobiologia* 506-509:169-174.
- Stewart I, Seawright AA, Shaw GR, 2008. Cyanobacterial poisoning in livestock, wild mammals and birds - an overview, p. 613-637 In: H.K. Hudnell (ed.), *Cyanobacterial harmful algal blooms: state of the science and research needs*. Springer.
- Smith VH, 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. *Science* 221:669-671.
- Te SH, Gin KYH, 2011. The dynamics of cyanobacteria and microcystin production in a tropical reservoir of Singapore. *Harmful Algae* 10:319-329.
- Tendaupenyu P, 2012. Nutrient limitation of phytoplankton in five impoundments on the Manyame River, Zimbabwe. *Water SA* 38:97-104.
- Teixeira MGL, Costa MCN, Carvalho VLP, Pereira MS, Hage E, 1993. Gastroenteritis epidemic in the area of the Itaparica Dam, Bahia, Brazil. *Bull. Pan American Health Organ.* 27:244-53.
- Tyagi MB, Singh DP, Kumar A, Jha PN, Sinha RP, 2006. Hepatotoxicity of *Microcystis aeruginosa* strains growing as blooms in certain eutrophic ponds. *Exp. Clin. Sci. J.* 5:66-78.
- Van der Westhuizen AJ, Eloff JN, 1985. Effect of temperature and light on the toxicity and growth of the blue-green alga *Microcystis aeruginosa* (UV-006). *Planta* 163:55-59.
- Vasconcelos V, Martins A, Vale M, Antunes A, Azevedo J, Welker M, Lopez O, Montejano G, 2010. First report on the occurrence of microcystins in planktonic cyanobacteria from Central Mexico. *Toxicon* 56:425-431.
- Vieira JMdS, Azevedo MTP, Azevedo SMFO, Honda RY, Corrêa B, 2003. Microcystin production by *Radiocystis fernandoi* (Chroococcales, Cyanobacteria) isolated from a drinking water reservoir in the city of Belém, PA, Brazilian Amazonia region. *Toxicon* 42:709-713.
- Vieira JMdS, Azevedo MTP, Azevedo SMFO, Honda RY, Corrêa B, 2005. Toxic cyanobacteria and microcystin concentrations in a public water supply reservoir in the Brazilian Amazonia region. *Toxicon* 45:901-909.
- Wang X, Parkpian P, Fujimoto N, Ruchirawat KM, DeLaune RD, Jugsujinda A, 2002. Environmental conditions associating microcystins production to *Microcystis aeruginosa* in a reservoir of Thailand. *J. Environ. Sci. Heal. A.* 37:1181-1207.
- Welker M, Chorus I, Fastner J, 2004. Occurrence of cyanobacterial toxins (Microcystins) in surface waters of rural Bangladesh - pilot study. *Federal Government Agency Berlin, Germany*.
- Werner VR, Laughinghouse IV HD, 2009. Bloom-forming and other planktonic *Anabaena* (Cyanobacteria) morphospecies with twisted trichomes from Rio Grande do Sul State, Brazil. *Nova Hedwigia* 89:17-47.
- Wiegand, C, Pflugmacher S, 2005. Ecotoxicological effects of selected cyanobacterial secondary metabolites a short review. *Toxicol. Appl. Pharm.* 203:201-218.
- White SH, Fabbro LD, Duivenvoorden LJ, 2003. Changes in cyanoprokaryote populations, *Microcystis* morphology, and microcystin concentrations in Lake Elphinstone (Central Queensland, Australia). *Environ. Toxicol.* 18:403-412.
- Xu Q, Chen W, Gao G, 2008. Seasonal variations in microcystin concentrations in Lake Taihu, China. *Environ. Monit. Assess.* 145:75-79.
- Yang SL, Chiam-Tai YC, 1991. Algae and algal blooms in Singapore reservoirs. *Public Util. Board Res. Develop. J.* 3:17-27.
- Zurawell RW, Chen H, Burke JM, Prepas EE, 2005. Hepatotoxic cyanobacteria: A review of the biological importance of microcystins in freshwater environments. *J. Toxicol. Env. Health* 8:1-37.