Influence of Biotope and Biotic Factors on Cyanobacteria Abundance, Genotype and Toxin Production

Maria Iasmina MOZA¹ ² ³ ⁴, Carmen POSTOLACHE ¹ ⁴ ⁵

¹Faculty of Biology, University of Bucharest, Department of Systems Ecology and Sustainable Development, Doctoral School in Ecology, 91-95 Splaiul Independenței St., district 5, 050095, Bucharest, Romania
²Foundation Conservation Carpathia, Wildlife Genetic Monitoring Laboratory, Calea Feldioarei nr. 27, 500450, Brasov, Romania
³Swiss Federal Institute for Environmental Science and Technology-Eawag, Überlandstrasse 133, P.O.Box 611, 8600, Dübendorf, Switzerland
⁴Research Institute of the University of Bucharest - ICUB, 36-46 Bd. M. Kogalniceanu St., district 5, 050107, Bucharest, Romania

Correspondence 1: Maria Iasmina Moza, Faculty of Biology, University of Bucharest, Department of Systems Ecology and Sustainable Development, Doctoral School in Ecology, Splaiul Independenței no. 91-95, district 5, 050095, Bucharest, Romania and Foundation Conservation Carpathia, Wildlife Genetic Monitoring Laboratory, Calea Feldioarei 27, 500450, Brasov, Romania
Tel.: +40 743620132
E-mail: iasmina_moza@yahoo.com

Correspondence 2: Carmen Postolache, Faculty of Biology, University of Bucharest, Department of Systems Ecology and Sustainable Development, Doctoral School in Ecology, Splaiul Independenței no. 91-95, district 5, 050095, Bucharest, Romania
E-mail: carmen_postolache83@yahoo.com
Abstract

Environmental genetics-related modern methods are shown as important indicators of various cyanotoxins syntheses, and their knowledge and use are critically analyzed. Microcystins and other cyanotoxins loads and syntheses are related to different drivers, like various chemical elements and compounds (especially nutrients, such as nitrogen and phosphorus, and their ratio), then to the light, conductivity, temperature, and other climatical and hydrological factors, to which spatial and geographical features (such as the surface of the water bodies) have to be added. The biotic relationships include different specific and supraspecific, uni- and bilateral links between the cyanobacteria, and subsequently their synthesized toxins, and protozoans (or protoctists), chromists, macrophytes, different systematical and ecological groups of zooplankton, and others. The importance of, but also the gaps in, the knowledge and the scarcity of studies involving ectocrines mediated interactions between different groups of algae and plants are highlighted. The paper ends with an interesting classification of lakes' trophicity, illustrated with conceptual diagrams, based on possible scenarios of cyanobacteria behavior.

Key words: cyanobacteria, toxic, biotic factors, abiotic factors, interactions, allelopathy
1. Introduction

In the last decades, toxic or so-called harmful algal blooms (HABs) have been increasingly reported on a global scale in frequency, distribution and impact of their effects on public health, living resources, and local economies (1-3). Such blooms occur not only in marine and estuarine environment, where there are about 150 harmful or toxic microalgal species (4), but also in the freshwater ecosystems impacted by eutrophication, where cyanobacteria represent the dominant. Mass populations of toxic cyanobacteria are a global phenomenon and the recent recognition that incidences of blooms may increase significantly under future climate change serves to reinforce further the seriousness of the potential risks to human health (1). Due to this, toxic cyanobacteria have gained in recent years increasing amounts of attention by the scientists, authorities and general public worldwide (5).

The cyanotoxins are secondary metabolites produced by about 40 species of cyanobacteria (6), that include neurotoxic, hepatotoxic, genotoxic, inflammatory and cytotoxic agents (7). The genera known for their potential ability to produce toxic substances include Anabaena, Aphanizomenon, Cylindrospermopsis, Lyngbya, Microcystis, Nodularia, Nostoc and Planktothrix (8); however, even if the species able to produce toxins are present, they may release toxins only in special circumstances, under the pressure of several anthropogenic or environmental factors. With over 90 known congeners globally, hepatotoxic microcystins (mcyE gene is involved in their synthesis) are among the most potent and commonly encountered toxins (9) and they are mainly produced by species belonging to the Microcystis, Anabaena and Planktothrix genera, although many other taxa were shown to have toxic potential (10, 11). Genetic-based methods enhanced the understanding of the natural distribution of genes that are involved in cyanotoxins production, despite only indicating potential toxin producers (12). Quantitative real-time PCR (qPCR) has been increasingly applied to monitor potentially toxic cyanobacteria population shifts in diverse aquatic ecosystems worldwide (13, 14); because is sensitive and rapid.

Although the ecology of cyanobacteria is well described, the relationship between population dynamics and environmental factors that trigger the presence of genes involved in microcystins synthesis is poorly understood (15). For example, density of the hepatotoxic cells were direct correlated with the microcystins (MCs) concentration from water (16) and in concordance, with the gene (mcyE for example) copies number inside the cells. Some strains may produce higher MC concentration than others under the same laboratory conditions, while others can be more or less toxic depending on cultivating conditions (17). In addition, the succession of cyanobacteria species and biomass is influenced by seasonal changes of several factors including nutrients, grazing, light and temperature, which affect also the concentration of MC in the field (18). In environment, different strains produce different concentrations of MCs but not all the time target genes involved in MCs synthesis are well correlate with this concentrations as a recent study demonstrate (15). The effects of
environmental factors on the abundance of MC-producing and non-toxic Microcystis genotypes have, however, been studied on a limited scale (15).

A brief overview on the influence of several physic-chemical parameters is provided in (18) and summarized below: a positive correlation between toxic genotypes (mcyA) and nitrate (NO$_3$-N) concentrations was noticed, while temperature and orthophosphate (PO$_4$-P) concentration seem not to influence mcyA abundance (19). In the same lake, a direct influence of the cyanophage assemblage in shifts of MC-producing and non-MC-producing subpopulations was suggested (20). NH$_4$ and NO$_3$ were also shown to increase toxic (mcyA), Microcystis strains abundance and MC concentrations in a hypereutrophic pond (21), without affecting the total Microcystis abundance. Total phosphorus was shown to positively correlate with both toxic (mcyD) and total Microcystis abundance in Lake Erie, USA, while mcyD genotypes correlated negatively with NO$_3$, total nitrogen, nitrogen to phosphorus ratio and pH (22). Phosphorus was also shown to correlate positively with the relative abundance of potentially hepatotoxic (mcyE/ndaF) cyanobacterial community of river Nile, Egypt, at a site showing strong phosphorus limitation (23).

In spite of the fact that both nitrogen and phosphorus influence the numbers/proportion of toxic genotypes, other factors such as low water depth, high pH, high temperature, lack of wind and water column stability, nutrient and light availability, favor cyanobacteria development (24) increasing the risk hazard.

Also, allelopathic relationships with macrophytes or other algal groups and grazing pressures of zooplankton or fish communities should be further considered as it has been noticed that competition and grazing stimulate the toxin production (25, 26). The cumulative impact of all these factors on toxin producing cyanobacteria requires more detailed investigations in order to elaborate effective management measures to prevent health hazards. Within this review we summarize the effect of biotic and abiotic factors on cyanobacteria abundance, genotype and toxicity.

2. Interaction with environmental factors

It is well known that organisms interact with their living and nonliving environment so, they are affected by abiotic (physical and chemical) and biotic (presence and activities of other organisms) factors. These adaptations are the result of evolution, the driving force of which is natural selection (27, 28). Cyanobacteria play an invaluable role in freshwater ecosystems because of their abilities to produce oxygen via oxygenic photosynthesis and convert atmospheric nitrogen to the biologically available form, ammonium (NH$_4^+$) (9, 29-31). Additionally their status as primary producers strengthens their connection to the aquatic environment, as they contribute to the foundation of the food web, especially stimulating bottom up food web shifts in shallow, eutrophic lakes (32).

2.1. Abiotic factors

2.1.1. Physical and chemical parameters
Light conditions in shallow lakes may change on a time scale of days to weeks due to changes in cloudiness or wind-induced resuspension of sediments. It was demonstrated that light intensity is a critical factor influencing the production of cyanotoxins (33). Changes in light conditions may profoundly affect the microcystin composition and thereby the toxicity of cyanobacteria (34); the transcription of two genes responsible for microcystin production was already shown to be influenced by light quality (33). For example, the harmful cyanobacterium *Planktothrix agardhii*, a species that prefers mostly shallow, turbid lakes, produces a more toxic variant during periods of sunny weather, when recreational activities in lakes are most attractive (34). It has been documented that the excessive growth of cyanobacteria can reduce water transparency with light penetration to only few centimeters, and thus having important effects on both pelagic and benthic communities (35). The reduction of the euphotic zone together with the excessive increase in the ratio between the epilimnetic mixing layer and the euphotic depth is an unfavorable factor for other organisms (35).

Another physical parameter of the water, which has exhibited a high positive correlation with MCs concentration, but not with the number of *mcyE* gene copies, was the conductivity. Conductivity is a parameter related to the ability of electric conduction of water, and can indicate the ion concentration. *Microcystis* utilize various inorganic ions such as macronutrients and trace metal for growth (36). This confirms previous studies showing that alkaline pH (7.5 - 8.5), electrical conductivity from 241 to 367 µS/cm, and temperature ranging from 24.8 to 32ºC, are promoting microcystin development (37).

The pH of water may also influence toxin production. For *M. aeruginosa*, higher MC production occurred at pH values above and below their optimum growth threshold (33).

Temperature is a crucial parameter of the environment that influences the survival, metabolism, growth and reproduction of all cyanobacteria, as well as the interactions between them and other species (38) as well a fundamental relationship with cyanotoxin production (33). For example, some cyanotoxins are often found at temperatures that would be considered sub-optimum for cell growth, with maximum reported at 20 ºC and production ceasing at temperatures exceeding 35 ºC, namely cylindrospermopsin (33). Anatoxin-a production has also been shown to be highest at 20 ºC, whereas maximum production of MC and nodularin has been reported to occur between 18 and 25 ºC (33). Other studied showed that temperature, DO and *Microcystis* biomass positively correlated with MC accumulation as well (39). Temperature alone may only partly determine bloom formation and it is accepted that a combination of factors are responsible for a bloom to develop: increasing temperatures, decreasing nutrients and increased water column stability (40); temperature has the most pronounced effect on toxicity; the highest toxicity was found at 20ºC, but reduced at temperatures in excess of 28ºC.
According to Paes and his colleagues (41), in all studied reservoirs that experienced toxic blooms water transparency was reduced. *P. rubescens* abundance appears to be strongly influenced by water transparency, at least in pre-alpine lakes (42).

A series of mild winters with earlier ice break-up can lead to an earlier stratification and a shift in the composition of the phytoplankton from diatoms to cyanobacteria (43). After some scientists the bloom of cyanobacteria is associated with thermal stratification (44). Other authors suggest that both growth and toxin production as *Anabaena* may be controlled by salinity (45).

2.1.2. Nutrients

Freshwaters enrichment with nitrogen is a dynamic process, reflecting land use, hydrologic conditions, population and economic growth (46, 47). Recent field studies have shown that bloom production by *Microcystis* sp. (a widespread cyanobacterial genus frequently producing blooms) is often associated with high levels of nitrogen (48, 49). Other experiments have demonstrated that toxic blooms are more likely to occur under elevated nitrogen concentrations (50).

Toxin production in non-nitrogen fixing cyanobacteria, such as *Microcystis* and *Planktothrix*, has been shown to peak with high concentrations of nitrogen (33). According to a recent study (51), total MC concentrations could be explained by a combination of abiotic factors like dissolved organic nitrogen (DIN), water temperature and ammonium (NH$_4^+$). In this study, however, the best overall model to predict MC concentration combined both environmental variables and species biomass (51). Total nitrogen, water temperature, ammonium and dissolved organic nitrogen influenced the cyanobacterial community structure, which in turn resulted in differences in the dominant MC congener and the overall toxicity. Ammonium (NH$_4^+$) did not emerge as a significant variable in the multivariate model although it is considered important in structuring cyanobacterial communities based on empirical studies of some lakes (51).

The presence of N can contribute to both increased and decreased MC production, depending on the genera (33). Nitrogen and phosphorus are the main elements for the matter and energy metabolism of the algae (52). Toxin production in non-nitrogen fixing cyanobacteria, such as *Microcystis* and *Planktothrix*, has been shown to peak with high concentrations of nitrogen (33). When attempting biomanipulation, the omission of nitrogen causes approximately ten fold decrease in toxicity (40). High levels of nitrogen and phosphorus in freshwaters favour the growth of toxic strains over nontoxic ones (53). Total nitrogen, pH, and the surface area of the lake predicted the occurrence probability of *mcyE* genes, whereas total phosphorus alone accounted for MC concentrations (54).

Historically, phosphorus was seen as the primary limiting nutrient in freshwaters (55), and now it is generally accepted that reduction in phosphorus input is an effective way to inhibit cyanobacterial dominance in freshwater ecosystems. Unlike nitrogen, which can exist in gaseous form, phosphorus can only be found in dissolved ionic and
particulate forms in natural waters. Cyanobacteria are able to dominate the phytoplankton communities at very low phosphorus concentrations, because they have a very high natural affinity for this element (56, 57).

The findings related to phosphorous also demonstrate the importance of this nutrient to toxin production (33). It is known that phosphorus was the limiting resource for phytoplankton biomass but the mixotroph Dinobryon biomass increased with decreasing total phosphorus concentrations (58). There are studies were the regression analysis showed that the densities of phytoplankton and total phosphorus were positively and linearly correlated ($R=0.715$) (52). In the same study the correlation between the concentration of TN and the density of phytoplankton was not remarkable ($R=0.166$). P and N sources have been considered as the main factors to affect the growth of Microcystis cells and MC levels, and such influencing process is so complicated that the different conclusions were obtained by different investigators from different lakes (59).

N:P ratio in water is an important parameter in controlling cyanobacterial blooms, with several data suggesting that total molar N:P ratios above 15 discourage the occurrence of these phenomena (60, 61). After a screening of more than 240 water bodies, scientist concluded that maximum concentrations of microcystins occurred in hypereutrophic lakes at mass ratios of N:P below 23 and that many planktonic cyanobacteria have a benthic life stage where they engage in “luxury uptake” of P from sediments, and consequently, episodes of cyanobacterial recruitment from sediments can dramatically decrease the N:P ratio in the water column (62). “TN/TP rule” hypothesis that cyanobacteria tended to dominate in the lake when TN/TP <29, while decreased when TN/TP >29 but this rule is less applicable to highly eutrophic waters when both N and P nutrients are very high. (59). It was also suggested that, at least in one highly eutrophic lake TN/TP ratio is not the factor bursting of blooms of Microcystis (59). Microcystis occurred only at higher TN, TP, temperature and pH values (63) for example. The toxicity of M. aeruginosa is known to change depending on seasons (41, 64).

2.1.3. Variation in toxin concentration

Cyanotoxin production is dependent on a number of environmental conditions. Predominantly, these could include nutrient concentration, light intensity, and temperature (33). Eutrophication increased the co-occurrence of potentially MC-producing cyanobacterial genera, raising the risk of toxic-bloom formation (54). In general, studies considering the effects of nutrients on toxin production find a positive correlation between the nutrient of interest and cellular toxin content. Research focusing on nitrogen, cyanobacterial growth, and subsequent toxin production, report that increased nitrogen corresponds to increased toxin production (65-67). Recent studies showed that physical and chemical parameters did not significantly account for both intracellular and dissolved microcystins occurrence (68).

World Health Organization setting a guideline value of 1 μg/l for microcystin-LR in drinking water (69). Is notable that typical environmental concentrations of MC are below 10 μg/L (33).
For some organisms that accumulate microcystins, total MC concentrations declined after October and began to increase in May, from the season point of view, that give us also a clue about the toxin production in the ecosystem (39). Microcystins production did not correlate with the high level of nutrients (t test, p > 0.1). In fact, microcystins were never detected in the more eutrophic reservoirs (68). The cyanobacterial biomass in water, pH, and temperature explain the variability of MC concentration in the sediment of shallow lakes also (70). MC and abundances of total Microsytis and MC-producing Microsytis (MCM) were shown to be positively correlated with pH, DO and TP (59). A significant difference was found for conductivity, phosphates and the presence of microcystins Mc-LR and Mc-Tot in the oligo- and eutrophic reservoirs (68). It is speculated that N and P nutrients and the associated genes (e.g., mcy) may jointly drive MC concentration and toxigenicity (59). Also species biomass was the best predictor of MC concentrations (51) and the highest growth rate is not correlated with highest toxicity (40) that reveal that cell density may not be the best predictor for the toxicity. *Microcystis* was often observed coexisting with *Anabaena*, *Planktothrix* and *Phormidium* (59) and therefore can bloom together.

### 2.2. Biotic factors

#### 2.2.1. Zooplankton

When the density of phytoplankton was too high it was concluded that the multiplication of zooplankton was restrained or harmed by the worse eutrophication of the system (52). Zooplankton and cyanobacteria may interact directly via the feeding and excretion of zooplankton (71) and indirectly via trophic linkage pathways and behavioral responses to physical and chemical parameters (light, temperature, turbulence, pH, and dissolved oxygen). Results of laboratory studies (72) suggest that many colonial cyanobacteria are either not eaten or are a poor food for large zooplankton, particularly *Daphnia*. Therefore, at times when these colonial forms dominate the phytoplankton, *Daphnia* populations might be expected to show decreased growth and fecundity in response to food limitation or toxicity. Is very probably that an any effect of cyanobacteria on zooplankton could be influenced by evolutionary mechanisms in natural systems with a long history of cyanobacterial blooms: zooplankton that co-occur with dense biomass of cyanobacteria have better chance to adapt than others that were not exposed to these conditions (41). It was already demonstrated that, if the proportion of any toxic cyanobacteria and any edible algae studied is in concordance with tested microorganism needs, the survival rate is growing (64, 73-76). This suggests that in nature, at least some of the total amount of *M. aeruginosa* is consumed, but only when the strain is not highly toxic. Therefore changes in the cyanobacterial abundances in nature are not only related to physical and chemical variables but are also likely due to grazing from zooplankton (64). There were species-specific differences in the filtration and feeding rates of zooplankton when offered mixed diets of green algae and toxic cyanobacteria. These probably explain the coexistence of different zooplankton species in *Microcystis*-dominant waterbodies. (76)
It has been previously shown that some rotifers like *Brachionus calyciflorus* react negatively to the presence of cyanobacteria (*Microcystis aeruginosa* and *Synechococcus elongatus*) because they lack essential compounds and not because of their cell size (77). On the other hand, when nutrient-rich green algae serve as food, the difference in the cell size matters and it is reflected directly in the lower growth rate of the rotifer population.

Among zooplankton, rotifers were shown to display a high range of tolerance to temperature. Thus, in some subtropical shallow lakes, the rotifer density increased with the increase in temperature, reaching its maximum at approximately 23°C but decreased slightly when the temperature exceeded 25°C (78). An experiment focused on the effect of *Microcystis aeruginosa* on the survival and reproduction of the rotifer *Brachionus calyciflorus* using the life table method at different temperatures showed that *M. aeruginosa* suppressed the survival and reproduction of *B. calyciflorus*, particularly at a concentration of 10^6 cells/mL according to (79).

Some laboratory experiments have shown that temperature can play an important role in modifying the effect of toxic cyanobacteria on freshwater, planktonic herbivores. Thus, in rotifers acclimated for many generations to low (12°C-14°C), intermediate (19°C), and high (25°C-26°C) temperature, susceptibility to the cyanobacterium and its toxin increased significantly with temperature. The results indicate that seasonal increases in water temperature, and climate warming, may exacerbate the impact of toxic cyanobacteria on rotifers like *Brachionus calyciflorus* and *Asplanchna girodi*, and perhaps other zooplankton taxa (80). So, is clear that a potentially modifying effect of temperature needs to be considered when investigating the effect of the dynamics of zooplankton populations on toxic cyanobacteria also. For example temperature is one of the important variables affecting the population growth and reproduction of rotifers including *B. calyciflorus*; higher temperatures (30°C) stimulate their population growth (81). Usually when two or more rotifer species compete for limited resources, one or more of them may be adversely affected by the presence of other (64) so the bad food quality is not the only limited factors for rotifers to taken into account.

Even if the cyanobacteria strain is nontoxic or toxic, at least in the case of *B. calyciflorus*, this type of diet suppresses the population growth; effects were less severe than that produced by toxic *M. aeruginosa* (73). Is was observed that in eutrophic systems higher abundance of rotifers is often observed with higher abundance of cyanobacteria, which indicates that not all cyanobacteria inhibit rotifer growth (41, 74). Additionally, rotifers are affected by three selected forms (unicellular, filamentous, and colonial) of cyanobacteria (73). *Cylindrospermopsis raciborskii* is less harmful to the rotifer *Brachionus calyciflorus* than the worldwide occurring cyanobacterium *Microcystis aeruginosa*; *Microcystis* did not support growth of *Brachionus*, but even killed them within the 2 days experimental period (74). *Asplanchna girodi* was sensitive to toxins of *Anabaena flos-aquae* and *L. majuscula* (82). More, the toxin-producing *Anabaena flos-aquae* has been shown
to decrease lifespan, fecundity, and population growth rate of the rotifers *Brachionus calyciflorus* and *Synchaeta pectinata* (33). Usually, MCs are released into water after demise of cells and dissolved MCs during the collapse of heavy blooms can come in contact with a wide range of aquatic organisms including rotifers and have adverse effects on them by increasing mortality (81). Notably is that when different species coexist in the ecosystem react different to the toxins (64).

For example the impact of *M. aeruginosa* in the diet had a more adverse effect on *B. calyciflorus* than on *B. havanaensis*, (64) but the same strain manage to kill the cladocerans *Ceriodaphnia dubia* and *Moina macrocopa* in previous study (75).

Important to be mentioned is that rotifer density and water temperature were negatively correlated (83). Depending of the ecosystem type (either temperate or tropical) rotifers react different: some species could survive if they are exposed to *Cylindrospermopsis*, but can be profoundly affected if they are exposed to *Microcystis* for example (41). However, when analysed at the population level, rotifers and cladocerans showed a weak positive response to microcystin. For rotifers, negative relationships were observed for *Brachionus calyciflorus*, *Conochilus* sp., *Hexarthra* sp. with respect to the different orders, calanoid copepods showed a positive response to microcystin (41).

Rotifers consumed half of what a cladocerans consumed in term of food; that could be an explanation why rotifers resist longer in the nature if the ecosystem experience a toxic bloom (76). Also in the same study was reveal that cladocerans filtrate rate is growing if the food quality is lower, so again another motive why they survival rate is less: they manage to eat more *Microcystis* cells in comparison with rotifers in the same time interval.

**Protists**

Sometimes a higher density of zooplankton , mostly protists and rotifers showed the worse trophic state of the ecosystem (52). This suggests that whilst toxin production is likely to be linked with defense against protozoan grazing in some species (33). It has already been confirmed that toxins produced by *M. aeruginosa* did not change significantly the protozoan’s mobility, morphology or viability in contrast, microcystins produced by *Gloeotrichia echinulara* was lethal for *Paramecium caudatum*, while extracts of *L. majuscula* acted very fast to provoke the lysis of the protozoan *Tetrahymena pyriformis* (82). Other study demonstrated that *Microcystis aeruginosa* was unable to produce MC in response to direct and indirect exposure to a protozoan grazer, this suggest that toxin production could be linked with defense against protozoan grazing only for some species (33).

A study conducted on the ciliate *Nassula* sp. isolated from a water body with no history of toxic blooms and fed with a toxic strain of *Planktothrix agardhii* for 8 months showed that this species can survive feeding exclusively on toxic cyanobacteria over an extended period of time, despite increasing MC concentrations (84). Conversely, a number of protozoan grazers are known to actively feed and grow on toxic cyanobacteria and in some cases *Microcystis aeruginosa* was unable to produce MC in response to direct and indirect exposure to a protozoan grazer (33). The toxins are probably
accumulated in the ciliates and only fractions of MC remain in the water. Therefore, in water frequently can be found a small cyanotoxin concentration in comparison with the amount found in zooplankton tissues\(^{(85)}\). For these reasons, this group of protist is seen as a potentially biotic agent to reduce toxins levels in freshwaters bodies that usually develop cyanobacterial blooms. However, the ability to synthesize microcystin does not seem to offer to toxic Microcystis populations a significant defense against grazing by co-occurring zooplankton communities\(^{(86)}\).

### 2.2.3. Other zooplankton

Unlike with rotifers, the presence of cladocerans can trigger the MC production in Microcystis sp. More exactly, in the presence of high zooplankton abundance (Daphnia pulex and Brachionus calyciflorus), at low cell density of Microcystis sp. the MC concentration was significantly higher as compared to controls\(^{(87)}\). Therefore, cladocerans react different in comparison with other zooplankton groups, for example Keratella cochlearis was superior in competition with Daphnia pulex under toxic Microcystis\(^{(88)}\). One must consider that that natural mesozooplankton were better grazers of both toxic and non-toxic strains of Microcystis than their cultured counterparts\(^{(86)}\).

A study designed to test the development of tolerance in several zooplankton species to MC in a range of temperatures showed that the ability to utilize Microcystis improved at 30°C in species like Moina macrocopa, Daphnia carinata and Hexarthra mira, but significantly decreased in case of rotifers\(^{(89)}\). It was also shown that low concentrations of edible algae favors small-sized cladocerans, while high concentrations favor large-sized cladocerans, such as Daphnia, but the presence of cyanobacteria can affect the dominance status of large-bodied daphnid especially. Some cladocerans can coexist well with Microcystis sp. in nature but colony size affects cladoceran population and their interactions\(^{(88)}\).

There are also strong intraspecific differences in the tolerance of different Daphnia clones to toxic/non-toxic cyanobacteria, and therefore the dynamics of the daphnid populations vary significantly in the presence of these microalgae in their diet\(^{(90)}\).

Zooplankton groups may act as vector of the toxin uptake in the aquatic food web\(^{(91)}\) and it seems that toxins are bioaccumulated in the ciliates and in the water remain mostly fractions of microcystins (referring to their chemical structure)\(^{(84)}\). Therefore, in water frequently can be found a small cyanotoxin concentration in comparison with the amount found in zooplankton tissues\(^{(85)}\).

### 2.2.4. Macrophytes and algae

It is well known that one of the more serious impacts of eutrophication on aquatic ecosystems is the disappearance of submerged macrophytes and the shift to a phytoplankton-dominated state\(^{(92)}\). When aquatic plants cover the wetland by 60% of the water surface, the equilibrium of the ecosystem was maintain and the proportion of the cyanobacteria was
maintain below 25%, almost the same with other algae groups namely Chlorophyta (36.8%) and Bacillariophyta (31.0%) (52).

Experiments provides evidence that resource competition can occur between benthic and water column primary producers (93) and studies have shown that macrophytes can successfully suppress the growth of algae through releasing allelochemicals in nature and in experimental systems (94). However, there is a lack of studies to integrate laboratory and field observations with respect to establishing allelopathic effects of macrophytes (32) There are good hints for allelopathic mode of action of cyanobacterial secondary metabolites within a lake phytoplankton community but not much is known on the mechanisms of interactions between cyanobacteria and algae, and how both sides contribute to phytoplankton dynamics during the year (92).

Some carophytes germinated less in the presence of MC in the sediment, and they also had lower chlorophyll concentrations. Different species have displayed variable sensitivity to the presence of MC in the water (95). MC-LR affects macrophyte Ceratophyllum demersum (lost of pigmentation, loss of leaves) (96). High concentrations of exudates and extracts of M. aeruginosa can allelopathically inhibit both seed germination and the early growth and photosynthesis of Potamogeton malaianus seedlings (97). A reduced growth in the presence of M. aeruginosa was observed for Lemna minor and for submerged plant Ceratophyllum demersum and also a significant decrease of chlorophyll a and b as well as total carotenoids (92). MC-LR has also been shown to exert inhibitory effects on aquatic plants, such as Ceratophyllum demersum, with the toxin inhibiting growth, morphology, and photosynthesis at environmentally relevant concentrations (5 μgL⁻¹) (33) or 90% inhibition of photosynthesis E. canadensis (92).

There is one study that shows that a golden algae have a great potential to biodegrading microcystin-LR (MC-LR) (98). They reported that the alga Poterioochromonas sp was able to degrade MC-LR in cells of M. aeruginosa while digesting the whole cells; degradation process was determined to be carried out inside the algae cell. As well, another study showed that Ochromonas sp., a mixotrophic chrysophyte, was able to feed on all four cyanobacterial strains tested, including the very toxic single-celled strain PCC 7806 (63).

Notably is that symbiosis between diatoms and cyanobacterial colonies may also occur in natural water ecosystems (99). Cyanobacterial toxin production can be regulated by complex growth phase dependent and environmental parameters and suppressed by the presence of extracellular products of a eukaryotic green alga like Chlamydomonas reinhardtii (100).

However, Microcystin-LR extracted from Microcystis aeruginosa had a negative effect on the growth of several green algae (33).

3. Conclusions
In conclusion, since we cannot discuss about one or few direct factors that trigger the cyanobacteria mass development, target genes involved in cyanotoxin production and toxin production and release into environment, we formulate in this short review chapter five possible scenarios of cyanobacteria behavior in any freshwater ecosystem, especially shallow lakes (Fig. 1-5).

**Scenarios 1 (Fig. 1).** Interpretation/explanation: in this ideal case, in our lake ecosystem, there are also fish, zooplankton (especially daphnia), phytoplankton, bacterioplankton and aquatic plants, an ideal freshwater ecosystem. Cyanobacteria from here don’t need to release toxins to any of other trophic compartment because: (i) there exists enough zooplankton that will eat microalgae, so those are not a stress factors for our cyanobacteria; (ii) there exists enough fish that will eat the zooplankton so that is not a stress factor for our cyano community; (iii) there are enough plants that will keep under control an algal bloom so that our zooplankton and fish could survive, but not that many that could disturb our cyanobacteria community. Conclusion: this represents the ideal picture of a typical lake ecosystem and a scenario were cyanobacteria could live in “no stress.” Lake type: oligo-mesotrophic

**Figure 1.** First scenario of cyanobacteria behavior into a freshwater ecosystem: no toxin release

**Scenarios 2 (Fig. 2).** Interpretation/explanation: in second case, in our lake ecosystem we have also fish, zooplankton, (especially daphnia), bacterioplankton and aquatic plants but less phytoplankton, because we have a cyanobacteria blooming. Cyanobacteria from here don’t need to release toxins to any of other trophic compartment because:(i) exists enough zooplankton that will eat cyano (because those are the main food source), but will not survive enough to become a stress factor for our cyano population; (ii) there is enough fish that will eat plants and the zooplankton so that will be kept under control limit and not eat very much cyano; (iii) there are some plants that will keep under control an massive algal bloom so that our zooplankton and fish could survive, but not that many that could disturb our...
cyanobacteria community. Conclusion: this represents the picture of a small cyanobacteria blooming but were the environmental changes are not that dramatic like in hipereutrofic lake for example, so our cyano have only “low stress”.

Lake type: meso-eutrophic.

**Figure 2.** Second scenario of cyanobacteria behavior into a freshwater ecosystem: no toxin release

*Scenarios 3 (Fig. 3).* Interpretation/explanation: in this ideal case, in our lake ecosystem there are also fish, phytoplankton, bacterioplankton and aquatic plants, but no cladocerans for example. Cyanobacteria from here don’t need to release toxins to any of other trophic compartment because: (i) there is enough fish that will eat other microalgae and zooplankton so that not represent as much an stress factor for our cyano community; (ii) there are enough plants that will keep under control an algal bloom by others microalgae so that our zooplankton and fish could survive, but not that many that could disturb our cyanobacteria community. Conclusion: this represents the ideal picture of a typical lake ecosystem and a scenario were cyanobacteria could live in “medium stress”. Lake type: meso-eutrophic.

**Figure 3.** Third scenario of cyanobacteria behavior into a freshwater ecosystem: no toxin release
**Scenarios 4** (Fig. 4). Interpretation/explanation: in this ideal case, in our lake ecosystem are also fish, zooplankton, bacterioplankton and aquatic plants, but no other microalgae, because we have a cyano bloom. Cyanobacteria from here began to release toxins to any of other trophic compartment because: (i) exists enough zooplankton that will eat them, because don’t have others microalgae, so those are a stress factors for our cyanobacteria; (ii) don’t exist enough fish that will eat the zooplankton and keep them under control; (iii) there are some plants that are struggling to survive so they release alelopathic compounds against cyanobacteria, so this is another stress factor. Conclusion: *this represent the picture for instability of a typical lake ecosystem, if one important group is missing and a scenario were cyanobacteria live in “high stress” and became toxic*. Lake type: eu-hypertrophic.

**Figure 4.** Fourth scenario of cyanobacteria behavior into a freshwater ecosystem: toxin release

**Scenarios 5** (Fig. 5). Interpretation/explanation: in this ideal case, in our lake ecosystem there are also fish, zooplankton, phytoplankton, bacterioplankton and aquatic plants, but the diversity is low regarding species. We don’t have a cyano bloom. Cyanobacteria from here began to release toxins to any of other trophic compartment because: (i) there exists too much zooplankton that will eat microalgae, but also cyanobacteria so those are a stress factors for our cyanobacteria; (ii) it doesn’t exist enough fish that will eat the zooplankton so that is a stress factor for our cyanobacteria community; (iii) there are enough plants that will keep under control an algal bloom so that the release alelopathic substance and stress our cyanobacteria community. Conclusion: *this represents the ideal picture for instability of a typical lake ecosystem and a scenario were cyanobacteria live in “high stress” and became toxic*. Lake type: eu-hypertrophic.
Figure 5. Five scenario of cyanobacteria behavior into a freshwater ecosystem: toxin release

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