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Short Communication

Considerations regarding the dominance of *Cylindrospermopsis raciborskii* under low light availability in a low phosphorus lake

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ABSTRACT

Although many studies have shown that the dispersion, increased abundance and dominance of cyanobacteria can be attributed to nutrient enrichment, we discuss features contributing to the dominance of *Cylindrospermopsis raciborskii* in a shallow, polymictic, subtropical coastal lake with low phosphorus and light limitation (Peri Lake). The presence and dominance of *C. raciborskii* in an environment with such characteristics emphasizes the idea that nutrients alone do not explain the high density of this cyanobacterium. Other features should be considered in explaining this species dominance, such as phosphorus storage and physiological flexibility, which seem to be key features to high densities in low phosphorus systems.

Keywords: Cyanobacteria, cyanotoxins, freshwater, nutrients, Peri Lake, phytoplankton, plasticity, subtropical

In recent years, many studies have shown that the dispersion and increased presence and dominance of Cyanobacteria in lakes can be attributed to nutrient enrichment, especially phosphorus in coastal areas (e.g. Padisák 1997; Heisler *et al.* 2008; Pearl & Huisman 2008; Carey *et al.* 2012; Dolman *et al.* 2012; Soares *et al.* 2013). Concomitantly, improvements have been done in order to understand why *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya & Subba-Raju has been so successful worldwide (Bonilla *et al.* 2011; Piccini *et al.* 2011). In the present short communication, we attempt to contribute to a better understanding and to the discussion about the features contributing to *C. raciborskii* dominance, especially in a low phosphorus (P) context in southern Brazil.

Peri Lake is a freshwater coastal lake within a conservation area of Subtropical Atlantic Rain Forest located in Santa Catarina Island, which is used as drinking-water supply. The lake has a surface area of 5.07 km^2, maximum depth of 11.0 m, and showed spatial homogeneity, both horizontally and vertically, concerning chlorophyll-a and nutrients (Hennemann & Petrucio 2011). The lake has been considered polymictic and light limited, according to Tonetta *et al.* (2013). However, recent findings from high-frequency measurements taken from the deepest part of the lake have shown that some short stratifications and de-stratifications occur on a daily basis, that the mixing zone is highly variable, and the euphotic zone is on average 4.0 m (D. Tonetta, unpubl. res.). Despite low concentration of dissolved inorganic nutrients (mean soluble reactive phosphorus: 2.5 μg.L^{-1}; ammonium: 15.0 μg.L^{-1}; nitrate: 6.1 μg.L^{-1}; and nitrite: 0.4 μg.L^{-1}), total nutrients indicate a mesotrophic condition (mean Total Nitrogen: 746 μg.L^{-1}; mean Total Phosphorus: 14.8 μg.L^{-1}) and a potential P limitation to phytoplankton growth (Reynolds 2006). A previous study in the lake showed that traditional trophic state indices do not represent conditions in Peri Lake appropriately (Hennemann & Petrucio 2011). According to the authors, the indices developed for temperate lakes indicate a mesotrophic condition concerning total P concentration, while indices adapted for warmer water bodies considered the lake oligotrophic. Additionally, the classification considering Secchi disk depth (water transparency) and chlorophyll-a concentration also differed significantly (from mesotrophic to hypertrophic), according to the index used (see Hennemann & Petrucio 2011 for an extended discussion about application of trophic state indices in the lake). The relative high chlorophyll-a concentration (17.7 μg.L^{-1}), mostly due to the high *C. raciborskii* density, reflects on low water transparency (Secchi depth ~ 1.0 m).

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Cylindrospermopsis raciborskii is a filamentous Cyanobacteria, which has been recorded worldwide and can promote damages to water quality as a result of toxin production (Padisák 1997, and references on Tab.1). This species presents a great ecological success that is attributed to many factors, as shown in Tab. 1.

In Peri Lake, this species has been recorded since 1994 (Laudares-Silva 1999; Grellmann 2006) and since 2009 has accounted for about 90% of phytoplankton total density, showing dominance throughout most of the year (Tonetta *et al.* 2013; Silveira 2013). Although nutrient concentration has not shown significant changes since 1994, the phytoplankton density has increased considerably. In 1996 and 1997, *C. raciborskii* varied between 3 and 41 × 10^3 ind.mL^{-1} (Laudares-Silva 1999). During 2004-2005, the densities were 40 to 116 × 10^3 ind.mL^{-1} (Grellmann 2006); and in 2009-2011, the density varied from 23 to 220 × 10^3 ind.mL^{-1} (Tonetta *et al.* 2013).

In a recent review by Soares *et al.* (2013), the authors highlighted the occurrence of Cyanobacteria in Brazil, especially the genera *Cylindrospermopsis* Seenayya & Subba-Raju, *Dolichospermum* (Ralfs ex Bornet & Flahault) P.Wacklin, L.Hoffmann & J.Komárek, and *Microcystis* Kützing ex Lemmermann, and the habitat preferences for these species. In this sense, *Dolichospermum* and *Microcystis* dominated mainly in warm-rainy periods, whereas *Cylindrospermopsis* was more common during colder-dry periods, in mixed systems, and with maximum P concentrations, as it is well known in the worldwide literature. It is well recognized that *Cylindrospermopsis* has been extending its distribution to colder regions (Vidal & Kruk 2008; Sinha *et al.* 2012), although always in systems with high nutrients concentration. Here we focus on trying to understand the features leading to *C. raciborskii* dominance in an environment with low P concentration, light limitation, constantly mixed, and showing *C. raciborskii* dominance even at low temperatures (Hennemann & Petrucio 2011; Tonetta *et al.* 2013).

Cyanobacteria can be dominant in low nutrient conditions due to the high affinity for P, which allows them to outcompete other phytoplankton species (Carey *et al.* 2012; Rigosi *et al.* 2014). However, reports of Cyanobacteria dominance or persistence under low phosphorus conditions are absent to our knowledge. Some studies have cited the presence but not the dominance of *C. raciborskii* in poor nutrient lakes. In Gomes *et al.* (2013), it was not possible to identify if *C. raciborskii* was constant or sporadic in low P Brazilian systems (Duas Bocas – ES; Funil, Juturnaíba, Imboassica – RJ), because the dataset was constructed with the occurrence of *C. raciborskii* at least sporadically. A recent publication has shown the ability of *C. raciborskii* to dominate under very low (7:1) and very high (122:1) N:P ratios, but in experimental conditions (Chislock *et al.* 2014). Thus, to our knowledge, Peri Lake is the only low P environment in which this species is dominant for prolonged periods.

In an attempt to explain *C. raciborskii* dominance, Soares *et al.* (2013) did not raise two important features: competition and P storage, possibly because their research found this species in eutrophic waters. In this sense, the ability of *C. raciborskii* to tolerate wide variations in nutrient availability and fix atmospheric nitrogen is well documented (Isvánovics *et al.* 2000; Moisander *et al.* 2012), as well the high ammonium and nitrate uptake affinity (Présing *et al.* 1996). Literature review shows that *C. raciborskii* can present physiological trade-offs in abilities to acquire and utilize resources, especially the advantage over bacteria and/or other phytoplankton to quickly assimilate P (Currie & Kalf 1984; Prinsep *et al.* 2001; Marinho *et al.* 2013), being considered an opportunistic species in its P-storage capacity (Isvánovics *et al.* 2000). Due to this ecophysiology flexibility there is evidence that *C. raciborskii* from several parts of the world have different genotypes (Dyble *et al.* 2002; Fathalli *et al.* 2011) and ecotypes that are able to growth in lakes of different trophic status (Piccini *et al.* 2011).

The lower light requirements of *C. raciborskii* (Wu *et al.* 2009; Gomes *et al.* 2013) make possible for this species to survive under conditions that are limiting to other Cyanobacteria (Jensen *et al.* 1994; Padisák 1997; Briand *et al.* 2002; Posselt *et al.* 2009). In addition, this species can live in deep and turbid systems, excluding other phytoplankton (Scheffer *et al.* 1997; Marinho *et al.* 2013).

Many other important eco-physiological traits have been related to *C. raciborskii* success, such as toxin production, grazing resistance and allelopathic effects (Leonard & Pearl 2005; Figueredo *et al.* 2007; Panosso & Lürling 2010 and references on Tab.1). Allelopathy was suggested by Figueredo *et al.* (2007), according to which *C. raciborskii* exudates showed strong inhibitory effects on photosynthetic activity of several phytoplankton species. Bittencourt-Oliveira *et al.* (2012) showed that *C. raciborskii* exhibited considerable phenotype plasticity, changing the morphology of the trichomes during the development of the cultures. In Peri Lake, Komárková *et al.* (1999) found an extreme morphology of *C. raciborskii* filaments, possibly related to the deficient nutrient condition. These filaments, when isolated and cultivated in laboratory conditions, change their morphology (R Laudares-Silva, unpubl. res.). All these characteristics make *C. raciborskii* an unusually competitor which may be favoring and contributing to its dominance in Peri Lake. In this sense, the presence of *C. raciborskii* in this system could be related to the physiological flexibility and phenotypic plasticity of the species.

The findings in Peri Lake point out to many possible factors driving *C. raciborskii* dominance. Tonetta *et al.* (2013) found density changes driven by changes in water temperature and nutrient availability. Furthermore, the authors suggested that some filamentous species could co-exist with *C. raciborskii* (e.g. *Limnothrix* sp. Meffert, *Planktolyngbya brevicellularis* G.Cronberg & Komárek, and *P. limnetica* (Lemmerm.) Komárk.-Legn. & Cronberg), each

Table 1. Features of *C. raciborskii* that corroborate its high ecological success.

Features	Authors
High affinity and P-storage £	Currie & Kalf 1984, Isvánovics *et al.* 2000
Presence of heterocytes ¥	Padisák 1997, Moisander *et al.* 2012
Tolerance to low light £	Wu *et al.* 2009, Gomes *et al.* 2013
Production of toxins ¥	Othani *et al.* 1992, Hawkins *et al.* 1997, Lagos *et al.* 1999, Molica *et al.* 2002
Grazing resistance ¥	Leonard & Pearl 2005, Soares *et al.* 2009, Panosso & Lürling 2010, Hong *et al.* 2013
Allelopathic effects £	Figueredo *et al.* 2007
Phenotypic plasticity £	Bonilla *et al.* 2011, Bittencourt-Oliveira *et al.* 2012
Tolerance to salinity £	Padisák 1997, Carneiro *et al.* 2013
Buoyancy regulation ¥	Padisák 1997
Akinetes ¥	Moore *et al.* 2004

¥ Shared traits by other Nostocales
£ Particular traits of *Cylindrospermopsis raciborskii*

of them having distinct niches or competing for the same resource (more details in Tonetta *et al.* 2013). On the other hand, the mixing in Peri Lake could act as a disturbance factor, which according to Baptista & Nixdorf (2014), could explain the occurrence of steady states at low disturbance levels in Peri Lake and consequently the dominance of *C. raciborskii*. Recently, Fuentes & Petrucio (2015) have suggested that physical conditions could directly influence phytoplankton growth; however, the authors did not present *C. raciborskii* data.

Finally, the literature review shows that the dominance of *C. raciborskii* around the world and in Brazilian ecosystems cannot be predicted from a single factor, especially when the factors are synergic. Thus, the comprehension of the characteristics that allow *C. raciborskii* to succeed in low P conditions is crucial for predicting future bloom-forming behavior in global changing scenarios, especially in the context of cyanotoxins and its allelopathic effects.

In this sense, nutrients itself do not explain the high densities of *C. raciborskii*, and physical conditions of the lake and species physiology should be considered as important factors driving the occurrence and dominance of this Cyanobacteria. Studies in Peri Lake have been shown that *C. raciborskii* can dominate even in low nutrient conditions and low light availability, what may have important consequences in management of eutrophic systems in which this is species is also dominant. More studies are necessary to better understand the factors that promote the dominance of this species, especially in low P systems.

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