LIMNOLOGY AROUND THE WORLD:
BRAZIL

Mitigation measures for controlling and managing cyanobacterial blooms in a tropical shallow urban pond in Southeast Brazil.

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Restoration of eutrophic waters is one of the main challenges of current limnology and one of the most severe environmental problems water resource managers face. The most noticeable effects of eutrophication in urban lakes worldwide are high turbidity associated with high densities of cyanobacteria, unpleasant odors, fish mortality, changes in food webs, and loss of biodiversity. These effects seriously impair the ability of urban lakes to provide essential ecosystem services (Hamilton *et al.*, 2014, Le Moal *et al.*, 2019).

Reducing eutrophication and the consequent blooms of cyanobacteria require integrated actions and strategic decisions (Lürling *et al.*, 2016). One of the most important actions is a system analysis that identifies the sources of nutrients, the primary sources of water for the system, and the dominant cyanobacterial species. Such analyses provide the insights needed to propose measures to decrease nutrient inputs, algal blooms, and, consequently, restore aquatic ecosystem services.

Cyanobacterial blooms in the pond at the Mariano Procopio Museum Park (Mapro), located in Juiz de Fora, Brazil, have been reported since early 2012, when visitors and park employees noticed changes in the color of the pond's water and dense green scum on its surface. A collaboration between the museum and the Federal University of Juiz de Fora (UFJF) was the basis for several management strategies concerning this emerging problem. Analysis of the pond's water quality in March 2012 showed high phosphorus and nitrogen concentrations, indicating intense eutrophication, with high densities of cyanobacteria (blooms). A working group formed by researchers from various educational and research institutions, in partnership with the UFJF, sought to identify the leading causes of eutrophication and cyanobacterial blooms and to test the effectiveness and applicability of geoengineering techniques to control these issues. The results of this study were published in Miranda (2017), Miranda *et al.*, (2017, 2021), and Josué *et al.*, (2019).

The Mapro Pond is a small artificial, shallow, and urban reservoir (1.1 ha surface area, 1.3 m maximum depth) created for scenic purposes in the Mariano Procópio Museum Park (Fig. 1). The pond is hypereutrophic (total phosphorus >200 mg L^{-1}), leading to regular and persistent algal blooms, mainly dominated by cyanobacteria, usually *Microcystis* spp. and sporadically *Raphidiopsis raciborskii* (formerly *Cylindrospermopsis raciborskii*). Mapro Pond is fed by rainwater, runoff from the drainage basin that covers most of the park, a perennial fountain connected to a pipe coming from an uphill water spring, and an electric well pump that pumps in groundwater and is controlled by the museum's administration. The administration also controls the single outflow to the Paraibuna River, the city's main waterway. The pond is home to some fish species, including *Cyprinus* sp. (herbivorous), *Prochilodus* sp. (detritivorous), and *Hoplias* sp. (carnivorous), turtles *(Phrynops hilarii)*, swans (*Cygnus* sp.), and ducks (*Anas platyrhynchos, Amazonetta brasiliensis*). Herons (Ardeidae) and doves (Columbidae) spend the night on an island in the middle of the pond.

Mapro Pond is representative of a common problem in Brazil, where the absence or mismanagement of water resources and poor sanitation in urban areas promote eutrophication. To identify the leading causes of eutrophication and to obtain the most promising

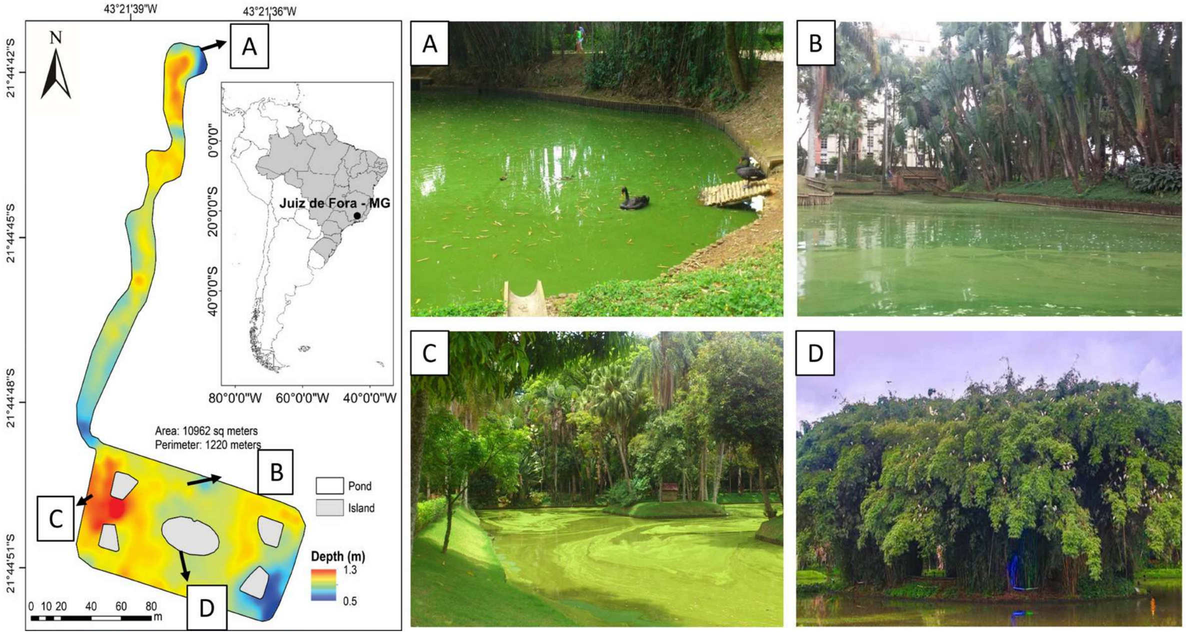

Fig. 1 Map and photos of Mapro Pond in the Mariano Procopio Museum Park in the Juiz de Fora municipality. A, B, and C: Bloom of cyanobacteria in the Mapro Pond. D: Birds on the central island of the Mapro Pond.

measures to improve the water quality of Mapro Pond, a three-stage research approach was implemented (Fig. 2): 1) **system analysis** to identify the primary sources of nutrients (P and N) and the dynamics of planktonic communities in the pond; 2) **laboratory experiments** to evaluate the efficiency of the combination of coagulants and ballasts for the removal of cyanobacterial biomass and P; and 3) **mesocosm experiments** in the pond, to test the control of eutrophication based on the results of stage 2. Stages 2 and 3 evaluated the applicability of geoengineering techniques as a fast, efficient, and low-cost alternative to dredging.

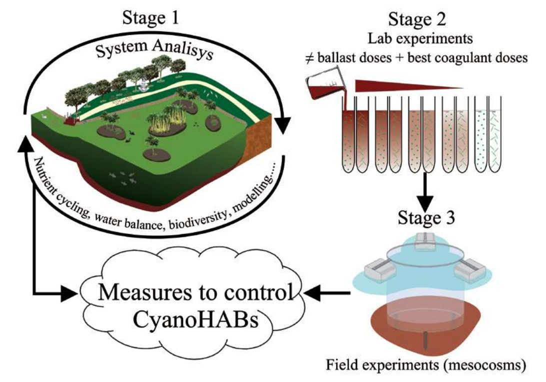

Fig. 2 Schematic diagram of the eutrophication mitigation alternative development to solve the problem of Cyanobacterial Harmful Algae Blooms (CyanoHABs) in the MAPRO Pond

System analysis

Mapro Pond was monitored monthly for two years (November 2012 to October 2014). In addition, hydrological and P balances were determined. The PClake model (Janse *et al*., 2010) estimated the critical P loading, defined by gradual changes in water quality, alternative states, or stable regimes (*e.g.,* a clear-water state dominated by submerged plants to a turbid-water state dominated by phytoplankton). More details about this approach can be found in Miranda *et al*., 2021.

Use of geoengineering techniques

Removing algae from the water column using a combination of coagulants and ballast, promoting flocculation and sedimentation (Floc & Sink), is a promising geoengineering technique to control cyanobacterial blooms (Lürling *et al*., 2016; 2020). This approach manipulates biogeochemical processes, using materials to achieve the desired chemical and/or ecological response. Given the peculiarities of each system, the first tests were carried out in the laboratory to evaluate the most efficient combination of coagulants and ballasts (Stage 2; Miranda *et al*., 2017). Experiments were then carried out in mesocosms to verify the efficiency of the *in situ* treatment (Miranda *et al*., in preparation, Stage 3).

Main results in the work stages

In Stage 1, we identified that cyanobacterial blooms in the Mapro Pond were dominated by *Microcystis* spp. and sporadically by *Raphidiopsis raciborskii*. The main variables responsible for phytoplankton dynamics were related to seasonality (dry and rainy season) which alters the availability of nutrients and light. The P balance study pointed out that the waterbirds were the most significant contributor of P to the pond (Fig. 3). Most of the P that enters the water column goes into the sediment, and part of this is released back into the water column (Miranda *et al*., 2021). Modeling results indicate that the critical P load for Mapro Pond to change from its current turbid-state to a clear-state is 8.6 mg P m^{-2} d^{-1}. Scenarios of increased water flow show that decreasing residence time from 79 to 35 days would increase this critical load to 14.6 mg P m^{-2} d^{-1} (Miranda *et al*., 2021).

In Stage 2, we observed that the best combination of coagulants and ballast for removing cyanobacterial biomass depends on the dominant species. For instance, the use of chitosan (CHI), an organic coagulant, was effective in removing the biomass of *M.aeruginosa*, however ineffective in removing the biomass of *R. raciborskii* from pond water and also had a harmful effect, promoting the release of saxitoxins (Miranda *et al*., 2017).

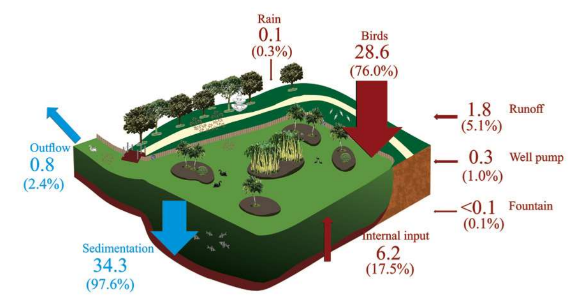

Fig. 3 Annual phosphorus balance of Mapro Pond in mg m^{-2} d^{-1} and percentage (%) considering input and output.

In Stage 3, after applying the Floc & Sink technique to the mesocosms, we observed an 85% reduction in chlorophyll-a over 24h (Fig. 4). However, this biomass reduction was not maintained for long due to the resurfacing of settle flocs from ongoing photosynthesis within the flocs and entrapment of oxygen. Resurfacing of settle flocs can effectively be avoided by applying an algaecide, such as hydrogen peroxide, before using the Floc & Sink technique. However, it can promote the release of toxins (Miranda *et al*., in preparation).

The use of local red soil as ballast is as efficient as lanthanum modified bentonite (LMB) in removing cyanobacterial biomass from the water column, thereby reducing the cost of system recovery.

Considerations

The eutrophication of Mapro Pond is a case of guanotrophy, with the primary P input to the pond through birds (76%). We found that the critical P-load for Mapro Pond is 8.6 mg P mg m^{-2} d^{-1}. Reductions in external and internal P loads must be considered along with residence time management to decrease cyanobacterial proliferation. The Floc & Sink technique is unsuitable in Mapro Pond unless preceded by an algaecide such as hydrogen peroxide and unless sediment resuspending fish are removed.

Managing the eutrophication and cyanobacterial blooms in Mapro Pond will depend on integrated actions to reduce external and internal P loading and cyanobacterial biomass. For example, the Floc & Sink technique should be considered alongside managing the pond's retention time to alleviate cyanobacterial blooms.

Removing cyanobacterial blooms from eutrophic systems can be a simple process using chemicals. However, the biggest challenge is keeping the water clear without bloom recurrence for an extended period. A long-lasting recovery will rely on integrated actions, and more than one strategy can be adopted. For this, tailored solutions are required, as each system is unique.

Recommendations to management in Mapro Pond

- Assessment of pond infrastructure and feasibility of channels to redirect rainwater, thus reducing particulate matter and P inputs.
- Increasing water flow and reducing backwater areas conducive to algae growth.
- Dredging the upper sediments to decrease internal P load.
- Removal of all fish that contribute to P resuspension: *Cyprinus* sp., *Prochilodus* sp., and *Hoplias* sp.
- Installation of a water level meter.
- Implementation of a monthly water monitoring program including physical and biological variables.
- Management of the resting bird population that is the main nutrient contributor to the pond.
- Abatement of cyanobacteria using hydrogen peroxide, which has algacide properties, before removing cyanobacterial biomass by geoengineering techniques (Floc & Sink) or removing cyanobacterial biomass.

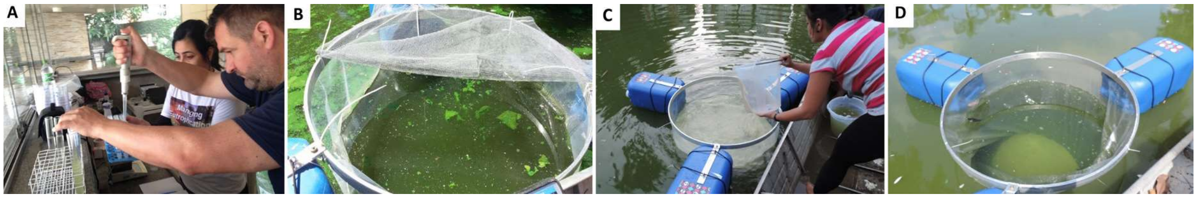

Fig. 4 Testing combinations of coagulant (bentonite modified with lanthanum, LMB) and red soil using mesocosms in Mapro Pond (Museu Mariano Procópio, Juiz de Fora, Brazil). A:Miquel Lürling and Marcela Miranda testing the coagulant dose. B: the control mesocosm. C: Marcela Miranda dosing LMB. Panel D: a treated mesocosm.

Partner institutions

Laboratory of Aquatic Ecology (LEA) of the Federal University of Juiz de Fora (UFJF)- Logistic support for data collection and limnological analysis of Mapro Pond.

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Fig. 5 Mesocosm working group at Mapro Pond (Museu Mariano Procópio, Juiz de Fora, Brazil, September 2016).

Collaborators

A network of collaborators contributed directly to the acquisition of data, laboratory analysis, and paper preparation.

Stage 1: Dr. Maria Carolina Soares - general coordination and idealization of Stage 1 (UFJF); Dr. Fábio Roland- logistical and intellectual support (UFJF); Gladson Marques - sampling and nutrient analysis (UFJF); Felipe Rust - fieldwork and carbon analysis (UFJF); Michaela Melo - cyanobacteria counts (UFJF); Rafael Paiva and Iollanda Josué - fieldwork and zooplankton counts (UFJF); Maíra Mucci - fieldwork, phytoplankton counts, and Intellectual support (UFJF); Mariana Mello - work by Campos and Intellectual support (UFJF/ WUR); Dra. Raquel Mendonça - academic support and sediment collection (UFJF); Dr. Simone Cardoso - academic support (UFJF); Dr. Roberto Junior and Roberto Marchesini - ciliate analysis (UFJF); Dr. Haroldo Lobo - benthic macroinvertebrate analysis (UFJF); Rodrigo Silva do Carmo – bird counts (CES); Frank van Oosterhout - ntellectual support (WUR).

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