



ARIANE GUIMARÃES

**PAPEL DO IMPACTO DO CLIMA NA DISTRIBUIÇÃO DE CIANOBACTÉRIAS
EM AMBIENTES AQUÁTICOS NEOTROPICAIS DE ÁGUA DOCE**

Anápolis
2021

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Tese de doutorado apresentado ao Programa de Pós-Graduação *Stricto Sensu* em Recursos Naturais do Cerrado, da Universidade Estadual de Goiás para obtenção do título de Doutora em Recursos Naturais do Cerrado.

Orientador: **Prof. Dr. Daniel Paiva Silva**

Anápolis
2021



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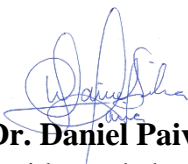
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Tese defendida no Programa de Pós-Graduação *Stricto Sensu* em Recursos Naturais do
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Para Maria, meu maior amor.

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“Tente uma, duas, três vezes e se possível tente a quarta, a quinta e quantas vezes for necessário. Só não desista nas primeiras tentativas, a persistência é amiga da conquista. Se você quer chegar aonde a maioria não chega, faça o que a maioria não faz”.

Bill Gates

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1 RESUMO

2 Os ambientes de água doce neotropicais estão entre os ecossistemas de maior
3 produtividade e fornecem vários produtos e serviços ecológicos para a humanidade. Nos
4 ambientes aquáticos de água doce neotropicais, as mudanças climáticas são uma ameaça
5 à segurança hídrica global, e os períodos hidrológicos extremos, como precipitação
6 extrema ou seca extrema, sem dúvida, reestruturarão as cadeias alimentares, gerando
7 novas comunidades compostas por novas combinações de espécies. Em corpos de água
8 doce, os eventos extremos nas mudanças climáticas podem intensificar o florescimento
9 de cianobactérias tóxicas (CyanoHABs). Em geral, as distribuições geográficas das
10 cianobactérias são pouco conhecidas e apresentam inúmeras lacunas de informação
11 (déficit Wallacean) muitas vezes relacionadas à falta de esforços de coleta. Nesta tese os
12 dados disponíveis sobre a distribuição geográfica das espécies de cianobactérias em
13 ambientes de água doce estão longe de estar completos e têm vieses geográficos óbvios.
14 Muitos dos registros de cianobactérias em ambientes aquáticos não eram acessíveis, o que
15 pode ter reduzido a capacidade de avaliar a distribuição das espécies. Os resultados aqui
16 apresentados podem fornecer informações relevantes sobre as lacunas de amostragem em
17 regiões que precisam de mais pesquisas para melhorar os dados de distribuição sobre a
18 ocorrência dessas espécies e apoiar as práticas de monitoramento dessas espécies. De
19 modo geral, nossos mapas apresentam dados disponíveis sobre as áreas com
20 adequabilidade para cianobactérias tóxicas e o nosso esforço amostral foi investido na
21 América do Sul. No capítulo 1, apresentamos um artigo de divulgação científica,
22 contendo informações e conceitos científicos sobre as cianobactérias e seus
23 florescimentos. No capítulo 2, descrevemos o número de publicações coletadas na
24 literatura científica que documentaram a ocorrência de florações de cianobactérias ao
25 longo dos anos, bem como as ordens responsáveis e os registros dos estados brasileiros
26 onde ocorreram. Além disso, usamos os dados de ocorrência obtidos nesta investigação
27 cienciométrica para estimar áreas climaticamente adequadas para a ocorrência de eventos
28 de floração cianobacteriana. No capítulo 3, usamos ferramentas de modelagem de nicho
29 ecológico a partir de registros de ocorrência coletados em bancos de dados disponíveis
30 para prever as áreas suscetíveis na América do Sul para o cenário presente e futuro do
31 Filo Cyanobacteria representado por: *Microcystis aeruginosa* (Kützing) Kützing 1846,
32 *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek 1988 e *Raphidiopsis*
33 *raciborskii* (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique e
34 Salerno 2018. Consideramos três métodos de modelagem diferentes: Modelo Linear
35 Generalizado (GLM); Modelo Gaussiano (GAU) e Entropia Máxima (MXS). Nos
36 resultados, as distribuições para o cenário atual foram consistentes com as distribuições
37 conhecidas e, para o cenário futuro, identificamos novas áreas de pesquisa. Concluímos
38 que as espécies modeladas respondem às mudanças ambientais atuais e futuras e que o
39 Filo devem ocorrer em áreas que atualmente não são detectadas em nossa análise ENM.

40 **Palavras-chave:** Cianobactéria, CyanoHABs, Modelos de nicho ecológico; Mudança
41 climática; Fitoplâncton; Ecossistemas de água doce.

42 **ABSTRACT**

43 Neotropical freshwater environments are among the most productive ecosystems and
44 provide many ecological products and services to humanity. In neotropical freshwater
45 aquatic environments, climate change is a threat to global water security, and extreme
46 hydrological periods such as extreme precipitation or extreme drought will undoubtedly
47 restructure food chains, generating new communities composed of new combinations of
48 species. In freshwater bodies, extreme events in climate change can intensify the bloom
49 of toxic cyanobacteria (CyanoHABs). In general, the geographic distributions of
50 cyanobacteria are poorly known and present numerous information gaps (Wallacean
51 deficit) often related to the lack of collection efforts. In this thesis the available data on
52 the geographic distribution of cyanobacterial species in freshwater environments are far
53 from complete and have obvious geographic biases. Many of the records of cyanobacteria
54 in aquatic environments were not accessible, which may have reduced the ability to assess
55 species distribution. The results presented here can provide relevant information about
56 sampling gaps in regions that need further research to improve distribution data on the
57 occurrence of these species and support monitoring practices for these species. In general,
58 our maps present available data on the areas with suitability for toxic cyanobacteria and
59 our sampling effort was invested in South America. In chapter 1, we present a scientific
60 dissemination article, containing information and scientific concepts about cyanobacteria
61 and their blossoms. In chapter 2, we describe the number of publications collected in the
62 scientific literature that documented the occurrence of cyanobacterial blooms over the
63 years, as well as the responsible orders and the records of the Brazilian states where they
64 occurred. In addition, we used the occurrence data obtained in this scientometric
65 investigation to estimate climatically suitable areas for the occurrence of cyanobacterial
66 flowering events. In chapter 3, we use ecological niche modeling tools from occurrence
67 records collected from available databases to predict the susceptible areas in South
68 America for the present and future scenario of the Phylum Cyanobacteria represented by:
69 *Microcystis aeruginosa* (Kützing) Kützing 1846, *Planktothrix agardhii* (Gomont)
70 Anagnostidis & Komárek 1988 and *Raphidiopsis raciborskii* (Woloszynska) Aguilera,
71 Berrendero Gómez, Kastovsky, Echenique and Salerno 2018. We consider three different
72 modeling methods: Generalized Linear Model (GLM); Gaussian Model (GAU) and
73 Maximum Entropy (MXS). In the results, the distributions for the current scenario were
74 consistent with the known distributions and, for the future scenario, we identified new
75 areas of research. We conclude that the modeled species respond to current and future
76 environmental changes and that the Phylum must occur in areas that are currently not
77 detected in our ENM analysis.

78 **Keywords:** Cyanobacteria, CyanoHABs; Ecological niche models; Climate change;
79 Phytoplankton; Freshwater ecosystems

80 INTRODUÇÃO

81 Os ambientes de água doce neotropicais incluem a América Central, as ilhas do
82 Caribe e quase toda a América do Sul (ANTONELLI; SANMARTÍN, 2011). Estão entre
83 os ecossistemas de maior produtividade (LEE; GARCIA-ULLOA; KOH, 2011) e
84 fornecem vários produtos e serviços ecológicos para a humanidade (LAURANCE;
85 SAYER; CASSMAN, 2014). Nos ambientes aquáticos neotropicais de água doce, as
86 mudanças climáticas são uma ameaça à segurança hídrica global (CHIA et al., 2018). Os
87 períodos hidrológicos extremos (BORTOLINI; TRAIN; RODRIGUES, 2016), como a
88 precipitação extrema (STOCKWELL et al., 2020) ou seca extrema (CROSSETTI et al.,
89 2019) irão, sem dúvida, reestruturar as cadeias alimentares (WELLS et al., 2020), gerando
90 novas comunidades compostas por novas combinações de espécies (PADISÁK;
91 NASELLI-FLORES, 2021). Em corpos de água doce, os eventos extremos na mudança
92 do clima pode aumentar a sensibilidade à invasão das assembléias fitoplanctônicas
93 (NASELLI-FLORES; PADISÁK, 2016; RIBEIRO; DUARTE; CROSSETTI, 2018).

94 As cianobactérias fazem parte das assembléias fitoplanctônicas, que por sua vez,
95 formam um grupo extremamente diverso de organismos (BORTOLINI et al., 2014). São
96 espécies que estão distribuídas em ambientes pelágicos de lagos de água doce, rios,
97 reservatórios, ambientes marinhos, bem como em superfícies iluminadas de rochas e
98 solos (SVIRČEV et al., 2019). Morfologicamente as cianobactérias podem ser
99 unicelulares, coloniais e filamentosas multicelulares, (KOMÁREK et al., 2014). Embora
100 sejam semelhantes estruturalmente às bactérias e funcionalmente às algas (uma vez que
101 realizam a fotossíntese utilizando a clorofila-a (pigmento fotossintético também das algas
102 e plantas), possuem estruturas que lhes diferenciam destes organismos, tais como a bainha
103 mucilagínosa, os vacúolos gasosos, os pigmentos acessórios, os acinetos, os heterocitos
104 (PADISÁK; VASAS; BORICS, 2016).

105 As cianobactérias podem produzir substâncias como o metilisoborneol (MIB) e a
106 geosmina, que conferem gosto e odor de terra à água (WATSON, 2003). Além disso, as
107 cianobactérias podem produzir florações (CyanoHABs). Diz-se, normalmente, que há
108 florações quando o número total de células de cianobactérias passa a ser maior que a
109 média normalmente encontrada naquele corpo d'água (HUISMAN et al., 2018), sendo
110 que o tipo de substância produzida em uma floração varia amplamente entre as diferentes
111 cepas da mesma espécie, já que as florações de cianobactérias geralmente consistem em

112 misturas de cepas tóxicas e não tóxicas (KURMAYER et al., 2004). Essas toxinas, em
113 contato com o ser humano – através, por exemplo, da ingestão da água ou de peixes
114 contaminados (ZANCHETT; OLIVEIRA-FILHO, 2013) podem provocar danos no
115 fígado e sintomas como diarreia, inflamações, problemas no cérebro e coceiras na pele
116 (MANTZOUKI et al., 2018). Dentre os metabólitos com propriedades tóxicas
117 produzidos, entre os mais conhecidos estão hepatotoxinas (microcistinas e nodularina),
118 neurotoxinas (anatoxinas, saxitoxinas e o aminoácido β -metilamino-L-alanina - BMAA),
119 citotoxinas (cilindrospermopsinas), dermatotoxinas (aplysiatoxins e lyngbyatoxins) e
120 lipopolissacarídeos extracelulares irritantes para a pele (BURATTI et al., 2017).

121 Outra questão de grande preocupação é que a floração limita a transferência da
122 produção primária para níveis tróficos mais elevados na cadeia alimentar (ULLAH et al.,
123 2018) e compromete a capacidade do zooplâncton de pastar cianobactérias coloniais e
124 filamentosas (FERRÃO-FILHO et al., 2019). Alguns metabólitos secundários produzidos
125 pelas cianobactérias podem ser tóxicos para o zooplâncton. No entanto, determinadas
126 espécies de zooplâncton desenvolveram adaptações à baixa qualidade nutricional das
127 cianobactérias ou apresentam tolerância contra as cianotoxinas (SADLER; VON ELERT,
128 2014). Ainda, organismos planctônicos que se alimentam de cianobactérias, como
129 *Daphnia*, são alvo de toxinas, ocorrendo frequentemente o aumento da taxa de
130 mortalidade, redução da fecundidade, taxa de alimentação, paralisia, alterações
131 comportamentais e bioquímicas (OMIDI; ESTERHUIZEN-LONDT; PFLUGMACHER,
132 2018), o que afeta a aptidão das populações de herbívoros (FERRÃO-FILHO;
133 KOZLOWSKY-SUZUKI, 2011).

134 Considerando que as cianobactérias têm sido uma preocupação mundial por serem
135 capazes de produzir diversos metabólitos com atividade biológica, o conhecimento sobre
136 o padrão de distribuição de cianobactérias neotropicais é indispensável, porém ainda é
137 inconsistente e fragmentado. Algumas espécies de cianobactérias são amplamente
138 distribuídas, mas a maior parte do grupo ocorre em ambientes restritos. Portanto, algumas
139 espécies apresentam ampla distribuição em diferentes regiões do mundo, mas sempre
140 ocorrem em um dado tipo de ambiente, refletindo suas preferências ecológicas e
141 adaptações a determinados habitats. Usualmente, as informações sobre as ocorrências de
142 cianobactérias não são aleatoriamente distribuídas no espaço geográfico. Em geral, as
143 distribuições geográficas dessas espécies apresentam inúmeras lacunas de informação

144 (déficit Wallaceano) frequentemente relacionadas com a falta de esforços de coleta
145 (WHITTAKER et al., 2005).

146 Ainda que o conhecimento das distribuições espaciais e temporais de espécies de
147 cianobactérias no ambiente em escalas local, regional e continental seja limitado
148 (NASELLI-FLORES; PADISÁK, 2016), é possível realizar estimativas para suprir a falta
149 de informação sobre a distribuição dessas espécies com base no seu nicho ecológico.
150 Nesta perspectiva, a determinação do padrão de distribuição de cianobactérias de
151 ambientes continentais neotropicais pode demandar novas ferramentas para avaliação de
152 impacto e propostas para conservação dos ambientes aquáticos neotropicais. Portanto, ao
153 responder o padrão de distribuição de espécies de cianobactérias neotropicais de
154 ambientes continentais pretende-se ainda entender se de fato essas espécies estão em todo
155 local diante das suas altas taxas de dispersão ou se apresentam padrões claros de
156 distribuição determinados pelo nicho ecológico das espécies.

157 No **Capítulo 1**, apresentamos um artigo de divulgação científica, onde
158 disponibilizamos informações e conceitos sobre cianobactérias e suas florações para o
159 público leigo e que desconhece ou pouco sabe sobre a temática. No **Capítulo 2**,
160 considerando que a ocorrência de florações de cianobactérias tóxicas é um problema
161 recorrente em vários reservatórios de água doce em muitos países e que esses eventos
162 tornem a água potável imprópria para consumo humano, há um grande interesse em
163 desenvolver a capacidade de prever a ocorrência de florações de cianobactérias em
164 ambientes de água doce. Assim, descrevemos o número de publicações coletadas na
165 literatura científica que documentaram a ocorrência de florações de cianobactérias ao
166 longo dos anos, bem como as ordens responsáveis e os registros dos estados brasileiros
167 onde ocorreram. Além disso, usamos os dados de ocorrência obtidos nesta investigação
168 cienciométrica para estimar áreas climaticamente adequadas para a ocorrência de eventos
169 de floração de cianobactérias. No **Capítulo 3**, usamos ferramentas de modelo de nicho
170 ecológico a partir de registros de ocorrência coletados em bancos de dados disponíveis
171 para prever as áreas suscetíveis para o cenário presente e futuro do Filo Cianobactéria em
172 ambientes de água doce Neotropicais. As espécies foram representadas por: *Microcystis*
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620 **CAPÍTULO 1¹**

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Por que a água está verde?

Figura 1. Ilustração de uma Floração de cianobactérias na Represa Billings, São Paulo, Brasil. Fonte: Guimarães, A.

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Em janeiro de 2021, pelo segundo verão consecutivo, a água que chegava nas torneiras dos moradores do Rio de Janeiro voltou a apresentar gosto e cheiro de terra. Os cientistas afirmam que um organismo de forma de vida simples conhecido por formar “tapetes verdes” em lagos e oceanos, chamado de cianobactéria é o grande vilão. Imagine uma bactéria que não possui um núcleo e, que surgiu há aproximadamente 3,5 bilhões de anos (HUISMAN et al., 2018). A cianobactéria pode até ser uma bactéria, mas é capaz de produzir seu próprio alimento e ser encontrada no solo, em desertos, córregos, lagos, lagoas, rios, reservatórios, geleiras e ainda ocorrer em união com fungos.

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As cianobactérias na evolução da vida em nosso planeta, foram as responsáveis pelo aparecimento do oxigênio em nossa atmosfera, liberado através da fotossíntese. O processo da fotossíntese é a forma como todas as plantas do mundo se alimentam, e aquele ipê amarelo na esquina da sua casa continua crescendo. Outra contribuição das

¹ O artigo de divulgação será publicado em forma de jornal no site do Centro de Educação Ambiental da Secretaria de Meio Ambiente e Recursos Hídricos do município de Ipameri-GO. O texto também será divulgado no grupo da página do facebook (Cyanobactéria Brasil).

634 cianobactérias é o surgimento das plantas, já que os cloroplastos, através dos quais
635 plantas sintetizam seu próprio alimento, são cianobactérias que se tornaram parte das
636 células vegetais. Mas, as cianobactérias também podem ser organismos tóxicos aos seres
637 vivos (RAI; RAI, 2018), e apesar de serem organismos essenciais, as cianobactérias
638 geralmente se multiplicam e crescem quando a água está quente, parada e rica em
639 nutrientes (“esses nutrientes funcionam como “fertilizantes”). O crescimento industrial e
640 urbano desordenado, o lançamento de esgotos sem tratamento (TAVARES; UZÊDA;
641 DOS SANTOS PIRES, 2019), a construção de hidrelétricas, o desmatamento, a
642 agropecuária, as queimadas, a erosão dos solos são responsáveis pelo aumento de
643 nutrientes (LAURANCE; SAYER; CASSMAN, 2014). Logo, as cianobactérias ocorrem
644 com maior frequência em locais onde os ambientes são eutrofizados, ou seja, em ambientes ricos
645 em nutrientes.

646 As cianobactérias formam florações. As florações são aglomerados espessos e
647 verdes nas margens dos rios e reservatórios e quando ocorrem, uma espuma pode flutuar
648 na superfície da água (SCHULIEN et al., 2017). Um grande problema é que a floração
649 produz substâncias como o metilisoborneol (MIB) e a geosmina, que conferem gosto e
650 odor de terra à água (WATSON, 2003), afetando de forma negativa a qualidade da água
651 e exigindo processos mais caros de tratamento para tornar a água própria para o nosso
652 consumo (GENUÁRIO et al., 2016). As cianobactérias também liberam toxinas nocivas.
653 Estas toxinas, podem ser perigosas para humanos e animais. Quando as toxinas estão em
654 contato com o ser humano, pela ingestão da água ou de peixes contaminados
655 (ZANCHETT; OLIVEIRA-FILHO, 2013), podem provocar danos no fígado e sintomas
656 como diarreia, inflamações, problemas no cérebro (MANTZOUKI et al., 2018).

657 Além disto, a floração é um sério problema para as estações de tratamento de água,
658 pois pode causar o entupimento e a perda dos filtros. No Brasil, há registros de florações
659 tóxicas em reservatórios de água, açudes, rios, lagos e lagoas de todas as cinco regiões do
660 país (GUIMARÃES et al., 2020), se em alguns estados ou mesmo municípios não
661 ocorreram até o momento relato de floração de cianobactérias, pode ser o reflexo da falta
662 de estudos e não uma melhor qualidade da água naquele local. Nas lagoas da Barra da
663 Tijuca, Jacarepaguá (Rio de Janeiro), no rio Amazonas no Brasil (VIEIRA et al., 2003,
664 2005), no lago Dianchi na China (SHENG et al., 2012) no lago Erie nos EUA/Canadá
665 (SCAVIA et al., 2019) e em reservatórios de abastecimento de água potável como em
666 Cingapura (TORTAJADA; WONG, 2018) e países do continente africano, são alguns

667 exemplos que mostram onde as florações de cianobactérias já são relatadas à várias
668 décadas. As florações de cianobactérias tóxicas existem há milhões de anos. A
669 mortalidade em massa pré-histórica envolvendo cervos, cavalos, elefantes, auroques e
670 leões das cavernas nos lagos do Pleistoceno e Eoceno (BRAUN; PFEIFFER, 2002), uma
671 seca severa há, aproximadamente, 4.000 anos atrás em áreas úmidas na ilha de Maurício
672 (que coincidiu com a mortalidade em massa de milhares de dodôs e tartarugas gigantes)
673 (DE BOER et al., 2015) e a perda de tropas do general Zhu Ge-Ling por envenenamento
674 durante a travessia de um rio na dinastia Han da China, cerca de 1.000 anos atrás
675 (CHORUS; BARTRAM, 1999) foram atribuídos às cianobactérias tóxicas e seus efeitos.
676 Outros casos envolvendo toxinas ocorreram em Caruaru (Pernambuco), Itaparica e na
677 África. Em Caruaru, no ano de 1996, ocorreu um surto de insuficiência hepática ocorrido
678 em pacientes renais crônicos submetidos a hemodiálise onde 76 pessoas vieram a óbito
679 (AZEVEDO et al., 2002). Em Itaparica no ano de 1993, 88 mortes foram confirmadas
680 por gastroenterite causadas por espécies do gênero *Microcystis*.

681 Mesmo com o conhecimento de que as cianobactérias causam problemas,
682 infelizmente, nos últimos anos em diversos locais do Brasil e do mundo, temos notado
683 um aumento expressivo de florações com a presença de toxinas e com substâncias
684 causadoras de gosto e odor. Para auxiliar na prevenção da formação de florações tóxicas,
685 a sociedade pode se organizar para defender e melhorar a qualidade das águas dos lagos,
686 rios e outras fontes, de forma a garantir água boa e em quantidade suficiente para o
687 consumo humano. Em cada região do País acontecem ações programadas por grupos de
688 pessoas que participam dos chamados Planos de Bacias Hidrográficas.

689 Essas ações representam o Governo e a Comunidade afetada. É através desse
690 plano de recursos hídricos de uma bacia hidrográfica que as ações podem se transformar
691 em realidade. Mas é preciso saber que é necessário dinheiro para realizar ações tão
692 importantes, como: a construção de redes de coleta e tratamento de esgotos,
693 reflorestamentos de margens de rios e de fontes de água, ou mesmo a análise da qualidade
694 da água. Esses recursos financeiros devem ser fornecidos pelas prefeituras, governos
695 estaduais, governo federal e pelas parcerias dos governos com empresas privadas
696 (parcerias público-privadas). Você acha que a responsabilidade de proteger o meio
697 ambiente é dever apenas instituições públicas e privadas? Claro que não. Somos todos
698 responsáveis por preservar o planeta e tudo depende de grandes e pequenas ações. Até a
699 conservação de uma pequena nascente de água ou o recolhimento e envio correto do lixo

700 da sua residência são atitudes que contribuem para a qualidade da água que abastece a
 701 nossa casa. Coletar e tratar os lixos e esgotos são ações esperadas tanto das pessoas como
 702 dos que administram os serviços públicos e privados. Todos nós temos o direito e dever
 703 de manter e defender o meio ambiente.

704 Comece usando apenas as quantidades recomendadas de fertilizantes em
 705 gramados e plantas, faça a manutenção adequada dos sistemas sépticos domésticos e
 706 mantenha uma proteção de vegetação natural ao redor de lagoas, lagos e nascentes para
 707 filtrar a água que entra. Também é muito importante diminuir o desperdício com a água
 708 em nosso dia a dia. É necessário que você compreenda que a água é um recurso que tem
 709 fim, e que pode se esgotar e gostaríamos de contar com a sua colaboração.

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Using distribution models to estimate blooms of phytosanitary cyanobacteria in Brazil

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Abstract: The multiple uses of aquatic ecosystems by humankind and the continuous interference of their activities have contributed to the emergence of potentially toxic cyanobacteria blooms. Here, we firstly created a database of occurrences of cyanobacteria blooms in Brazil through a systematic review of the scientific literature available in online platforms (e.g. Web of Science, Capes Thesis Catalogue). Secondly, we carried out ecological niche models with occurrence data obtained from these studies to predict climatically suitable areas for blooms. We select 21 bioclimatic variables input environmental data. We used five modeling methods for the current climate scenario: (1) Maxent; (2) Support Vector Machines; (3) Random Forest; (4) Maximum Likelihood e (5) Gaussian. We found that the number of publications about bloom events was higher in 2009 with a decline in the years 2012, 2013 and 2017. Furthermore, the years with the higher records of blooms in freshwater environments were 2005, 2011 e 2014. These events occurring mainly in public supply reservoirs and are mostly of the genera *Microcystis* Lemmermann, 1907, *Dolichospermum* (Ralfs ex Bornet & Flahault) P.Wacklin, L.Hoffmann & J.Komárek, 2009 and *Raphidiopsis* F.E.Fritsch & F.Rich, 1929. Modeling the potential distribution of blooms, we found sampling gaps that should be targeting for future researches, especially in the Amazon biome. Overall, the models did not predict highly suitable areas in the /north of Brazil, while other regions were relatively well distributed with a higher number of occurrence records in the Southeast region.

Keywords: freshwater ecosystems, species distribution models, bloom occurrence, cyanobacteria.

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1172 **Usando modelos de distribuição para estimar florações de cianobactérias**
 1173 **fitossanitárias no Brasil**

1174 **Resumo:** Os múltiplos usos dos ecossistemas aquáticos pela humanidade e a contínua interferência das
 1175 suas atividades têm contribuído para o surgimento de florações de cianobactérias potencialmente tóxicas.
 1176 Aqui, primeiramente criamos um banco de dados de ocorrências de floração de cianobactérias no Brasil
 1177 por meio de uma revisão sistemática da literatura científica disponível em plataformas on-line (por
 1178 exemplo, Web of Science, Catálogo de Teses da Capes). Em segundo lugar, realizamos modelos de nicho
 1179 ecológico com dados de ocorrência obtidos a partir desses estudos para prever áreas climaticamente
 1180 adequadas para as florações. Seleccionamos 21 variáveis bioclimáticas como dados ambientais de entrada.
 1181 Usamos cinco métodos de modelagem diferentes para no cenário climático atual: (1) Maxent; (2) Support
 1182 Vector Machines; (3) Random Forest; (4) Maximum Likelihood e (5) Gaussian. Encontramos que o número
 1183 de publicações sobre eventos de floração foi maior em 2009 com um declínio nos anos de 2012, 2013 e
 1184 2017. Além disso, os anos com os registros mais altos de florescimento em ambientes de água doce foram
 1185 2005, 2011 e 2014. Esses eventos ocorrem principalmente em reservatórios de abastecimento público e são
 1186 na sua maioria dos gêneros *Microcystis* Lemmermann, 1907, *Dolichospermum* (Ralfs ex Bornet &
 1187 Flahault) P.Wacklin, L.Hoffmann & J.Komárek, 2009 e *Raphidiopsis* F.E.Fritsch & F.Rich, 1929.
 1188 Modelando a distribuição potencial das florações, encontramos lacunas de amostragem que devem ser
 1189 direcionadas para futuras pesquisas, especialmente no bioma Amazônia. Em geral, os modelos não
 1190 previram áreas altamente adequadas no norte do Brasil, enquanto outras regiões estavam relativamente bem
 1191 distribuídas com um número maior de registros de ocorrência na região Sudeste.

1192 **Palavras-chave:** ecossistema de água doce; modelos de distribuição de espécie; ocorrência de floração;
 1193 cyanobacteria.

1194 **Introduction**

1195 Freshwater ecosystems sustain much of Earth's biodiversity, providing multiple products and
 1196 ecological services to humankind (LAURANCE; SAYER; CASSMAN, 2014). However, these ecosystems
 1197 are suffering from several kinds of human pressures, such as changes in use and land cover (HUISMAN et
 1198 al., 2018). Inadequate use of natural resources, as well as the different process of overexploitation,
 1199 pollution, eutrophication, dam construction and silting, has intensified over recent decades (HANNAH et
 1200 al., 2013), causing negative impacts on the environment and the health of human populations (GREEN et
 1201 al., 2015). Specifically, the broad degradation has generated a loss of species and habitats, threatening
 1202 several biological communities of rivers, lakes and flood plains (VITULE et al., 2017).

1203 Overgrowth of algae, especially cyanobacteria, is one of the problems in aquatic environments
 1204 (Walls et al., 2018). Results from the interaction of physical, chemical and biotic factors (Behrenfeld &
 1205 Boss, 2017), which is marked mainly by increased cyanobacterial density broadly geographically
 1206 distributed, and that respond rapidly to environmental changes in aquatic environments (PADISÁK;
 1207 VASAS; BORICS, 2016), such as light intensity, CO₂ accessibility, high pH and low N:P ratio
 1208 (GENUÁRIO et al., 2016). The growth of harmful cyanobacteria in high densities, known as water-blooms
 1209 or blooms (PAERL; OTTEN, 2013), produces a variety of cyanotoxins (KOSTEN et al., 2012) that may

1210 cause liver, digestive and neurological diseases when ingested by birds or mammals (MANTZOUKI et al.,
1211 2018). Furthermore, they directly affect water quality, producing taste and odor, increased turbidity,
1212 decreased submerged aquatic vegetation (MEREL et al., 2013), decreasing, and promoting the death of fish
1213 and benthic invertebrates (JOSUÉ et al., 2018). The problems tend to increase with the abundance,
1214 frequency, and extent of blooms (O'NEIL et al., 2012). Thus, it is of great importance to know what
1215 determines the occurrence of these events in aquatic environments (GLIBERT et al., 2008).

1216 Patterns that determine the spatial and temporal distributions of these organisms are environmental
1217 characteristics (HERNÁNDEZ-FARIÑAS et al., 2014), biological interactions and dispersal capacity of
1218 the species (SOBERÓN, 2007; SOBERÓN; PETERSON, 2005). These species act as "refined sensors of
1219 environmental properties" because they respond quickly to variations in the availability of environmental
1220 resources (MEKONNEN; HOEKSTRA, 2018). However, lack of knowledge about the global distribution
1221 and abundance of cyanobacteria restricts our ability to understand the mechanisms that determine its
1222 distribution (FLOMBAUM et al., 2013). In general, geographic distributions are poorly known and have
1223 numerous information gaps (MOREIRA; VASCONCELOS; ANTUNES, 2013). The Wallacean shortfall
1224 refers to inadequate knowledge about the species' geographic distribution (HORTAL et al., 2015;
1225 WHITTAKER et al., 2005b) and is a constraint particularly important to improve understanding about
1226 cyanobacterial blooms events (HORTAL et al., 2015). The predominance of studies close to traditional
1227 research centers (NEWBOLD, 2010) or uneven spatial distribution of infrastructure (OLIVEIRA et al.,
1228 2016) may also generate a geographic bias about known cyanobacterial bloom events (SASTRE; LOBO,
1229 2009).

1230 To reduce the Wallacean shortfall it is necessary to find the potential geographic gaps of these
1231 organisms and fill them in. In this context, scientometrics studies can contribute significantly to a general
1232 analysis of the patterns found. This research method allows us to measure the available data on species
1233 geographic distribution and to assess existing citations (CARNEIRO; NABOUT; BINI, 2008), revealing
1234 trends and gaps in scientific production (DEBACKERE et al., 2002). Additionally, scientometric analyzes
1235 can identify gaps in Cyanobacterial geographic distribution, helping to formulate new hypotheses about the
1236 mechanisms that determine these distributions. Thereby, it is possible to use Ecological Niche Models
1237 (hereafter ENMs) to fill these gaps (JENSEN; MOUSING; RICHARDSON, 2017). ENMs are statistical
1238 procedures that use species occurrence records to estimate suitable areas through environmental similarity
1239 between different sites (PETERSON, 2017). These models assume the premise that species' ecological

1240 niche is fully known and never changes over time, being completely dependent on the amount observed
1241 and the distribution pattern of the occurrence records (PETERSON, 2011). Therefore, it is possible to
1242 estimate new environmentally similar areas for species to occur. These models are widely used to (i) define
1243 potential distributions (FLOMBAUM et al., 2013); (ii) indicate suitable areas for future sampling
1244 (JENSEN; MOUSING; RICHARDSON, 2017); (iii) test biogeographic and evolutionary hypotheses
1245 (SILVA et al., 2014); (iv) suggest the establishment of conservation units (LOYOLA et al., 2008;
1246 NÓBREGA; DE MARCO, 2011); and (v) determine how species respond to climate change (BARTON et
1247 al., 2016; OLIVEIRA; CASSEMIRO; ESTADUAL, 2015).

1248 Assuming that the occurrence of toxic cyanobacterial blooms is a recurring problem in several
1249 freshwater reservoirs in many tropical countries and that these events make drinking water unfit for human
1250 consumption (MOWE et al., 2015), there is a strong interest in developing an ability to predict the
1251 occurrence of cyanobacterial blooms in freshwater environments. A major obstacle in attempting to reduce
1252 cyanobacterial growth events in freshwater ecosystems is a consequence of the lack of reliable data on the
1253 distribution of these species. From this perspective, we describe the number of publications collected in the
1254 scientific literature that documented the occurrence of cyanobacterial blooms over the years, as well as the
1255 responsible orders and the records of the Brazilian states where they occurred. Also, we used the occurrence
1256 data obtained in this scientometric investigation to estimate climatically suitable areas for the occurrence
1257 of cyanobacterial bloom events. For us, the pattern of the wide distribution of flowering events reflects the
1258 arrangement of their corresponding habitats, and the occurrence of these species is restricted to
1259 environments that correspond to specific adaptations of the species. As cyanobacterial bloom events are
1260 more common in lentic environments (e.g., reservoirs), we hypothesize that locations with higher intensity
1261 of use (e.g.: higher population density) and greater damming of rivers (e.g. reservoirs) will exhibit a higher
1262 frequency of blooms.

1263 **Material and methods**

1264 *Database of blooms events in freshwater environments*

1265 We created our database of cyanobacteria blooms occurrences in Brazil through a systematic
1266 review of the scientific literature available in the platforms Web of Science (WoS,
1267 <http://apps.isiknowledge.com>) maintained by Clarivate Analytics and Capes Thesis Catalogue
1268 (<http://catalogodeteses.capes.gov.br>), using the code of search: [("bloom*") AND ("Brasil" OR "Brazil")]

1269 AND ("cyanobacteria" OR "cyanophyceae")] and "florações" (in Portuguese). The WoS database has the
1270 advantage of providing data on publications over a broad time, presenting detailed and accurate scientific
1271 articles data, and is widely used in systematic review articles (FALAGAS et al., 2007). The Capes Thesis
1272 Catalogue stores many dissertations and thesis published in Brazil, facilitating the compilation of blooms
1273 events that occurred in the Brazilian territory.

1274 In both databases, we searched for articles and reviews that contained the search terms in the title,
1275 abstract and/or keywords (access date: May 22th, 2018). We established two criteria to select the occurrence
1276 records in the scientific articles: (1) cyanobacteria blooms classified according to the distribution of cells
1277 and individuals in the water column (accumulation of high concentrations of chlorophyll-a in the first
1278 centimeters of the water surface; accumulation of high concentrations of chlorophyll-a in water depth; and
1279 when the cells are dispersed in the water column); and (2) blooms according to the density of chlorophyll-
1280 a (minimum concentration of 10 $\mu\text{g/L}^{-1}$ of chlorophyll-a; and minimum density of 20.000 cells/mL of
1281 cyanobacteria) (DE LEÓN; CHALAR, 2003). In our search, we obtained 208 scientific articles in the WoS
1282 database, selected 98 studies after reading the abstracts and included 47 in our study. At the Capes Thesis
1283 Bank, we found 385 records. However, not all records were made available for reading. Thus, according to
1284 the established criteria, we were able to include only 18 studies in our database. We also included 10 studies
1285 cited in the bibliographic review of Freitas et al., (2012), in which they present a synthesis of blooms events
1286 in Brazil. Finally, we added two other scientific studies found in two Brazilian repositories (Universidade
1287 Nacional de Brasília e Universidade Federal de Goiás). Of the 77 papers found in the scientific literature,
1288 five papers were of the same area and the same species or were located in marine water environments,
1289 therefore they were not included.

1290 *Scientometric analysis*

1291 We compiled a list of 72 scientific studies that mention cyanobacterial blooms in freshwater
1292 environments in Brazil. The species names were updated following information from the On-line Database
1293 of Cyanobacterial Genera (CyanoDB.cz, <http://www.cyanodb.cz/>) (Komárek et al. 2014). We classified the
1294 occurrence records according to the distribution of the taxa at the collection sites. We corrected possible
1295 georeferencing errors considering several quality criteria (latitude and longitude exchange; occurrence
1296 records outside of the freshwater environments; and duplicate records) (GIOVANNI et al., 2012). When
1297 the latitude and longitude were incorrect, but there was information about the sampling and collecting site,

1298 we used Google Earth to get surrogate information. Each event record in a given location was considered
1299 as a sample. Bloom events that occurred in distinct months were considered as different records. To estimate
1300 the sampling effort in Brazil, we counted the number of bloom events in 1-degree cells.

1301 Then, we elaborated on a map demonstrating the total number of bloom events distributed in
1302 Brazil. Also, we produced bar charts evidencing the number of blooms events and the number of scientific
1303 studies published per year. To identify whether there is a relation between the number of blooms and the
1304 number of scientific studies, we performed a simple linear regression analysis between those variables. We
1305 verified the residues normality and used a transformation ($\log+1$) to meet that basic premise based on the
1306 protocol for data exploitation provided by (ZUUR; IENO; ELPHICK, 2010). To identify if there was a
1307 relationship between the number of flowering in freshwater environments and the population density, we
1308 performed a simple regression analysis between the variables using the premise mentioned above. For this,
1309 we consider the population density per municipality and the year for each point where the flowering event
1310 occurred. For the collection of the population estimation data, we consider the information provided by the
1311 IBGE (<https://cidades.ibge.gov.br/>). We combined the same geographic coordinates, and then our N which
1312 was 90 points, resulted in 59 records of reports of bloom in freshwater environments.

1313 *Environmental variables*

1314 To produce the ENMs, we used the environmental variables obtained from WorldClim 1.4
1315 (<http://worldclim.org/current>; Hijmans et al., 2005) and WorldClim 2.0 databases
1316 (<http://worldclim.org/version2>; Fick and Hijmans, 2017). We select all 19 bioclimatic variables from
1317 WorldClim 1.4, average altitude and solar radiation from WorldClim 2.0 as input environmental data. These
1318 variables have a spatial resolution of 5 arc-minutes (≈ 10 km of cell size). We considered the variables
1319 already reported in other studies. For example, the temperature variable is often considered the most
1320 important determinant of growth and metabolism in freshwater algae, including cyanobacteria, due in part
1321 to the fact that many of the enzymatic reactions involved in photosynthesis and respiration are temperature
1322 dependent. Solar radiation is justified because it is an essential resource for photosynthesis since these
1323 organisms are autotrophic (WALLS et al., 2018). We used altitude as a variable because it is highly related
1324 to weather variables (TEITTINEN et al., 2017). Finally, we chose the precipitation variable, in the rainy
1325 season the highest nutrient transport takes place for the aquatic ecosystems, being observed the increase in
1326 the density of cyanobacteria. Furthermore, climate variations can modify from the community structure in

1327 freshwater ecosystems. For instance, the cyanobacteria presence may be strongly influenced by physical
 1328 factors, such as the local climate conditions (KARADŽIĆ et al., 2013). The extreme precipitation in a
 1329 reservoir cause increased nutrients concentration and, then, altered the composition of the phytoplankton
 1330 community by cyanobacteria, evidencing the first bloom events after the suppression of other species
 1331 (SIMIĆ; DORDEVIĆ; MILOŠEVIĆ, 2017).

1332 To reduce the multicollinearity of the data, we performed the Principal Component Analysis
 1333 (PCA) (PEARSON, 1901). This method calculates the mean of all variables and subtracts from the
 1334 individual values. Then, the resulting values are divided by the standard deviation of each variable (z
 1335 transformation). Thus, the cells of all variables range from -1 to 1, with zero mean. Thereby, we produced
 1336 21 orthogonal principal components (independent) and selected the first seven, which accounted for 96.4%
 1337 of the variation of the original dataset (Table 1). This method allows the variables to have the same
 1338 importance in the ENM predictions (DORMANN et al., 2012). Consequently, it also avoids the overfitting
 1339 of the models, which can result in unreliable predictions (DE MARCO; NÓBREGA, 2018).

1340 **Table 1** Summary of the Principal Component Analysis performed from 21 environmental variables used
 1341 in the Ecological Niche Modeling. Principal Component axes (PC) were selected until the cumulative
 1342 explanation proportion reached 95% or more of the total variation of the original matrix. Loadings of PCs
 1343 for each variable are presented, as well as PC's eigenvalues, the proportion of explained variance of each
 1344 PC, and accumulated proportion of explained variance.

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Annual Mean Temperature (bio1)	-0.266	-0.240	-0.063	-0.015	-0.044	0.078	0.056
Mean Diurnal Range (bio2)	0.197	-0.206	0.026	0.456	-0.045	-0.052	0.539
Isothermality (bio3)	-0.225	0.018	0.370	0.030	0.064	0.263	0.382
Temperature Seasonality (bio4)	0.233	-0.053	-0.384	0.120	0.135	-0.130	0.107
Max Temperature of Warmest Month (bio5)	-0.157	-0.355	-0.262	0.112	0.038	-0.060	0.170
Min Temperature of Coldest Month (bio6)	-0.296	-0.111	0.049	-0.155	-0.001	0.104	0.016
Temperature Annual Range (bio7)	0.244	-0.138	-0.264	0.279	0.031	-0.175	0.152
Mean Temperature of Wettest Quarter (bio8)	-0.211	-0.290	-0.136	0.122	-0.107	0.157	0.037
Mean Temperature of Driest Quarter (bio9)	-0.270	-0.167	0.012	-0.117	0.078	-0.004	0.130
Mean Temperature Warmest Quarter (bio10)	-0.204	-0.304	-0.258	0.028	0.034	0.021	0.019
Mean Temperature of Coldest Quarter (bio11)	-0.286	-0.171	0.072	-0.057	-0.069	0.099	0.081
Annual Precipitation (bio12)	-0.268	0.190	-0.017	0.215	0.028	-0.183	0.034

Precipitation of Wettest Month (bio13)	-0.268	0.076	0.122	0.217	-0.014	-0.391	0.154
Precipitation of Driest Month (bio14)	-0.153	0.325	-0.233	0.188	0.147	0.307	0.088
Precipitation Seasonality (bio15)	0.057	-0.278	0.404	0.190	-0.056	-0.192	0.139
Precipitation of Wettest Quarter (bio16)	-0.269	0.087	0.116	0.212	-0.030	-0.395	0.105
Precipitation of Driest Quarter (bio17)	-0.163	0.324	-0.229	0.190	0.156	0.273	0.077
Precipitation of Warmest Quarter (bio18)	-0.165	0.174	-0.093	0.437	-0.539	0.162	0.270
Precipitation of Coldest Quarter (bio19)	-0.207	0.187	-0.016	0.035	0.583	-0.309	0.131
Radiation solar	0.047	-0.309	0.116	0.281	0.506	0.329	0.545
Altitude	0.178	0.091	0.399	0.335	0.105	0.217	0.123
Proportion explain by each PC %	0.490	0.205	0.115	0.062	0.038	0.034	0.020
Accumulated Proportion Explained by the PCs	0.490	0.695	0.811	0.872	0.910	0.944	0.964

1345 *Modeling procedures*

1346 We performed the ENMs only for orders of cyanobacteria that had a minimum of 10 occurrence
1347 points. For Phylum Cyanobacteria, we compiled a total of 109 occurrence records, where 47 belonged to
1348 Chroococcales, 44 to Nostocales, 12 to Oscillatoriales and 6 to Synechoccales. We also included a general
1349 model for Cyanophyta to represent the order Synechoccales in our study. To ensure independence in the
1350 dataset used to fit and evaluate the performance of the models, we chose to use geographic partitions in a
1351 grid format, similar to a checkerboard (MUSCARELLA et al., 2014). This partition subdivides the study
1352 area equally and in a spatially independent manner, alternating between training (to perform the model) and
1353 testing (to evaluate the model). We used five ENM algorithms to model the distribution of bloom events:
1354 (1) Maximum Entropy (MXE) (PHILLIPS; ANDERSON; SCHAPIRE, 2006); (2) Support Vector Machine
1355 (SVM) (GUO; KELLY; GRAHAM, 2005); (3) Random Forest (RDF) (BREIMAN, 2001); (4) Maximum
1356 Likelihood (MLK) (ROYLE et al., 2012) e Gaussian (GAU) (GOLDING; PURSE, 2016a).

1357 The MXE algorithm is a technique of machine-learning that estimates the nearest probability
1358 distribution of the uniform distribution under constraint whose expected values for each variable are in
1359 agreement with empirical values observed in the occurrence records (PHILLIPS; ANDERSON;
1360 SCHAPIRE, 2006). This technique constrains the possibilities of adjusting linear or quadratic functions,
1361 reducing the complexity of the models and producing better predictions in certain situations (PHILLIPS et
1362 al., 2017; PHILLIPS; DUDÍK; SCHAPIRE, 2004). The SVM algorithm is a set of methods of supervised
1363 learning belonging to the family of generalized linear classifiers. This algorithm reduces the probability of
1364 misclassifying in patterns not observed by the distribution of data probabilities (RANGEL; LOYOLA,

1365 2012). SVM creates hyperplanes to differentiate the occurrence records from absence sets (GUO; KELLY;
1366 GRAHAM, 2005). The RDF algorithm produces accurate predictions that do not overload data, fitting the
1367 models based on decision trees that use a subset of random predictors (BREIMAN, 2001). The MLK
1368 algorithm predicts the species occurrence probability in a given location by estimating a distribution of
1369 occurrence probability based on observed environmental conditions (ROYLE et al., 2012). The GAU
1370 algorithm predicts the species occurrence probability based on adjustments made by Bayesian inference
1371 (GOLDING; PURSE, 2016a).

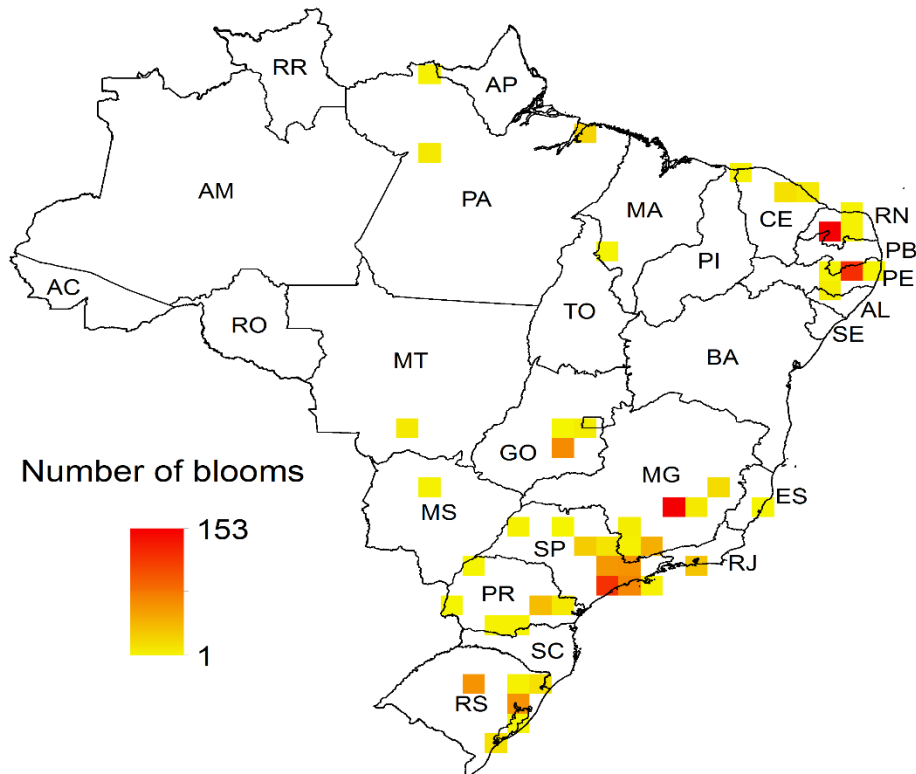
1372 We used a method to create pseudo-absence to meet some algorithms' requirements. Here, we
1373 used bioclimatic envelopes similar to the BioClim algorithm (BOOTH et al., 2014). This procedure
1374 constrains the occurrence points of the taxa in the geographical space using a bioclimatic envelope (LOBO;
1375 TOGNETTI, 2011; VANDERWAL et al., 2009). Then, the external area is considered as not suitable for
1376 the occurrence of species. In this area, pseudo-absences are created in a ratio of 1:1. We used a threshold
1377 that maximizes the sum of the sensitivity and specificity obtained from the Receiver Operating
1378 Characteristic (ROC) curve. This method is given by the graphical representation of True Positive Rate and
1379 True Negative Rate in several threshold settings. We measured the performance of the ENM algorithms by
1380 True Skill Statistics (TSS; Allouche et al., 2006). TSS is a threshold-dependent metric and ranges from -1
1381 to 1. Predicted distributions with negative values and close to zero are not considered better than random
1382 models. 'Acceptable' projections for potential species distributions generally reach TSS values close to 0.5.
1383 'Good' projections reach TSS values close to 0.7, while 'excellent' projections reach close to 0.9.

1384 We represented the final distributions using consensus maps to reduce the uncertainties associated
1385 with each algorithm (ARAÚJO; NEW, 2007). We made the consensus maps using the average of the
1386 models that presented TSS values above the average. The idea of the consensus models considers that
1387 different errors may affect the final result (e.g. sensitivity of the models, lack of true absences). For this
1388 reason, it has been argued in the literature that the use of consensus maps as final distribution models may
1389 reduce the number of errors (DINIZ FILHO et al., 2010).

1390 **Results**

1391 *Scientometric analysis*

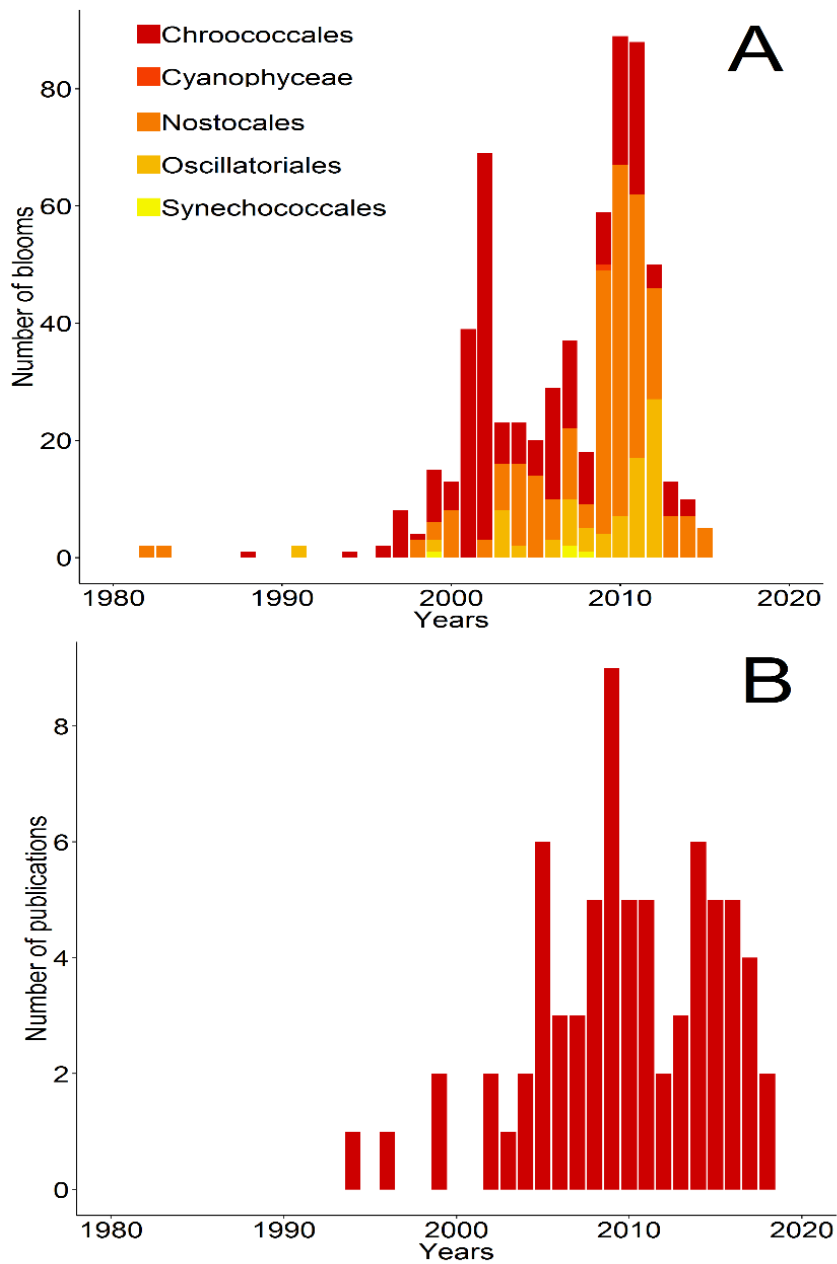
1392 We found 72 scientific studies in the literature that mention the occurrence of bloom events in
1393 freshwater environments in Brazil. We detected that the orders Chroococcales, Nostocales, Oscillatoriales,
1394 and Synechococcales were the most reported. Species of the orders Chroococcales and Nostocales,
1395 represented by the genera *Microcystis*, *Raphidiopsis*, and *Dolichospermum* (old *Anabaena*), occurred mainly
1396 in the states of São Paulo, Paraná, Rio Grande do Sul and Minas Gerais (Fig. 1). There were differences in
1397 the number of records distributed among Brazilian states. In some states we obtained a large number of
1398 blooms, while there were no records at all for others. The highest numbers of blooms found in the literature
1399 were obtained in the states of São Paulo, Minas Gerais, Pernambuco, and Rio Grande do Norte. On the
1400 other hand, we found the smallest amounts of bloom registered in the literature in the Amazon hydrographic
1401 basin. Mainly, bloom events were reported in sites of high human concentrations and with public supply
1402 reservoirs: Acarape do Meio Reservoir (Ceará), Armando Ribeiro Gonçalves Reservoir and Cruzeta
1403 Reservoir (Rio Grande do Norte), Carpina Reservoir (Pernambuco), Billings and Guarapiranga Reservoir
1404 (São Paulo), Utinga Reservoir (Belém do Pará) and Juturnaíba Reservoir (Rio de Janeiro).



1405 **Fig. 1** The number of events registered in the literature in freshwater environments. Each cell has a spatial
 1406 resolution of 1 decimal degree. The number of bloom events was counted in each cell considering the entire
 1407 time series for all occurrence records (evaluating the temporal consistency of the blooms). All records are
 1408 of freshwater environments. The maximum value for each cell is 153 bloom events. Note: the initials for
 1409 the twenty-six states and Federal District (in Portuguese, Distrito Federal) are, respectively: Acre-AC;
 1410 Alagoas-AL; Amapá-AP; Amazonas-AM; Bahia-BA; Ceará-CE; Distrito Federal-DF; Espírito Santo- ES;
 1411 Goiás-GO; Maranhão- MA; Mato Grosso- MT; Mato Grosso do Sul- MS; Minas Gerais-MG; Pará-PA;
 1412 Paraíba- PB; Paraná- PR; Pernambuco- PE; Piauí- PI; Roraima- RR; Rondônia- RO; Rio de Janeiro-RJ;
 1413 Rio Grande do Norte- RN; Rio Grande do Sul-RS; Santa Catarina-SC; São Paulo-SP; Sergipe-SE;
 1414 Tocantins-TO.

1415 We observed the first bloom events in 1982 ($n = 2$) and the highest number of bloom records in
 1416 2010 ($n = 89$) (Fig. 2A). On the other hand, the year with the highest number of studies reporting blooms
 1417 are 2009 ($n = 9$), 2005 and 2014 ($n = 6$), with the first study published in 1994 ($n = 1$) (Fig. 2B). We found
 1418 no relationship between the number of blooms and the number the scientific studies ($F = 3.231$; $R^2 = 0.076$;
 1419 $p = 0.083$). However, we must point out that since our database is composed of scientific studies and is not

1420 based on random sampling and probably does not have the same number of repetitions in each region, the
 1421 sampling effort is an important factor in the frequency of occurrence of bloom. Thus, although the statistical
 1422 relation has not been observed, it is difficult to consider that there is no relation between a number of blooms
 1423 events and the numbers of scientific studies. We observed a relationship between the number of blooms in
 1424 freshwater environments and population density (R^2 adjusted = 0.35; $p = <0.001$). Furthermore, we
 1425 observed that the years with the relationship number of blooms are not necessarily the years with the
 1426 relationship numbers of studies.



1427

1428 **Fig. 2** The number of occurrence records and number of publications (scientific studies) over the years. (A)
 1429 The total number of cyanobacterial blooms per year in freshwater ecosystems in Brazil. (B) The number of
 1430 scientific studies reporting blooming events in the Brazilian territory per year.

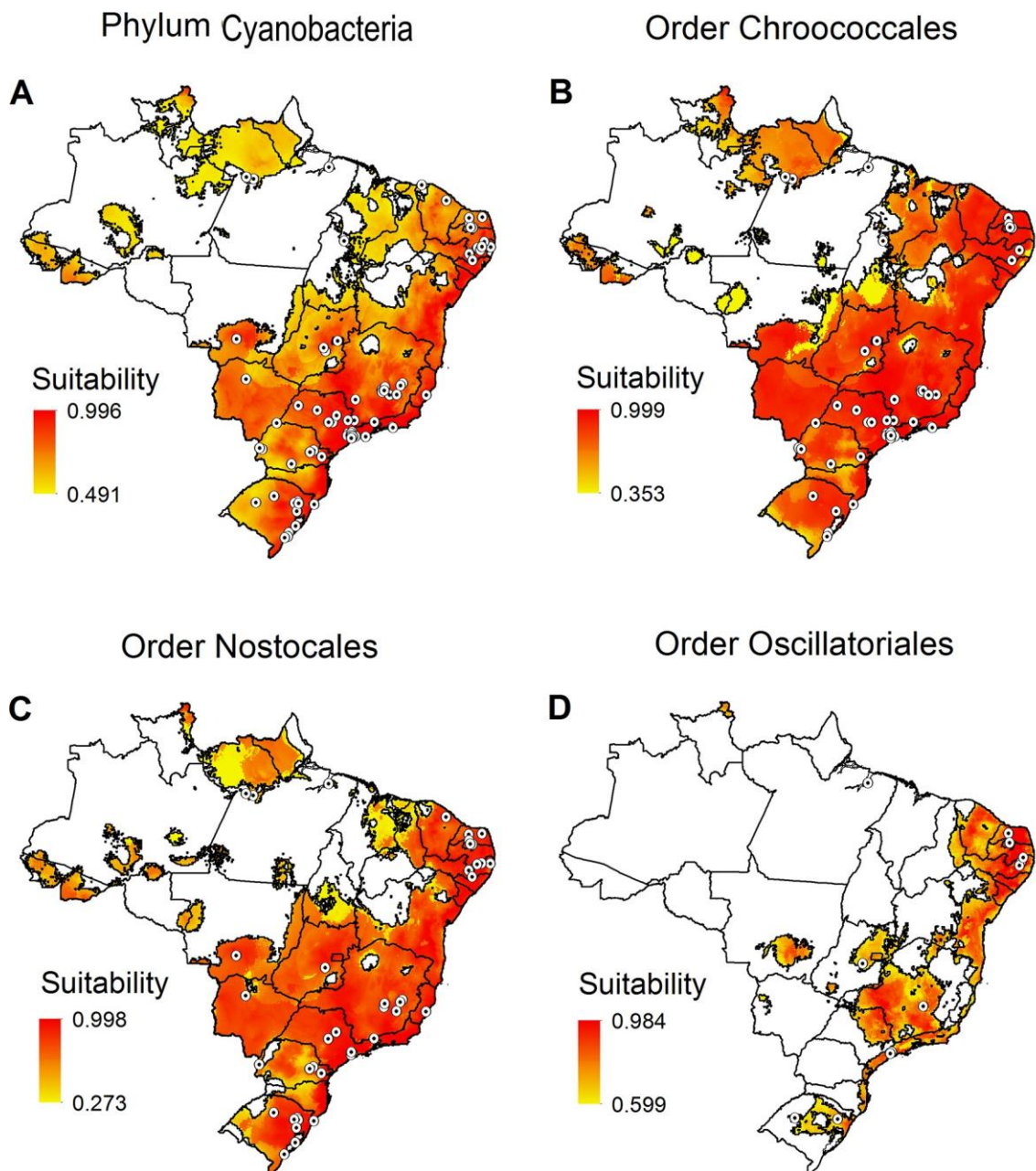
1431 *Cyanobacteria potential distributions*

1432 In general, TSS values obtained for the modeled taxa were considered acceptable (greater than
 1433 0.5) or excellent (greater than 0.7). TSS values for phylum Cyanobacteria (0.856) and the order
 1434 Chroococcales (0.882) were the highest. For the orders Nostocales (0.743) and Oscillatoriales (0.657) the
 1435 values indicate models with good adjustment (Table 2).

1436 **Table 2** TSS values for the evaluation of the distribution models of the Phylum Cyanobacteria and of the
 1437 orders Chroococcales, Nostocales and Oscillatoriales in different algorithms and for the ensemble map.

Taxonomic group	TSS					
	GAU	MLK	MXS	RDF	SVM	Ensemble
Phylum Cyanobacteria	0.769	0.595	0.828	0.725	0.798	0.856
OrderChroococcales	0.799	0.417	0.646	0.819	0.750	0.882
Order Nostocales	0.690	0.192	0.590	0.799	0.668	0.743
Order Oscillatoriales	0.343	0.271	0.586	0.486	0.243	0.657

1438 While the Phylum Cyanobacteria, the orders Chroococcales and Nostocales obtained wide
 1439 potential distributions range among the Northeast, South, Southeast and Midwest regions, the order
 1440 Oscillatoriales presented a restricted distribution between Northeast and Southeast regions (Fig. 3).
 1441 Altogether, no model designed suitable areas in the Northern region, so that the distribution of the taxa was
 1442 mainly concentrated in Southeastern Brazil. The prediction for the phylum Cyanobacteria showed that
 1443 52.5% of the Brazilian territory has highly suitable area for the occurrence of blooming events. The orders
 1444 Chroococcales, Nostocalles and Oscillatoriales showed high suitability in 55.5%, 49.9% and 17.3% of the
 1445 Brazilian territory.



1446

1447 **Fig. 3** Potential distributions for the groups of modeled Cyanobacterial in the Brazilian territory. (A)
 1448 Phylum Cyanobacteria; (B) order Chroococcales; (C) order Nostocales; and (D) Order Oscillatoriales. The
 1449 most suitable areas are represented colors closer to red, while the less suitable regions have colors closer to
 1450 yellow. The dark line spatially delimits the threshold obtained from the values that maximized the sum of
 1451 the sensitivity and specificity of the models, selecting only areas of high suitability.

1452 Discussion

1453 We observed that the number of publications on blooming events was higher in 2009, showing a
 1454 decline in 2012, 2013 and 2017. However, the blooms have been reported in publications with data since

1455 1982. Our results indicate the higher number of freshwater blooms in 2005, 2011 and 2014, and the vast
1456 majority of these records occurred in public supply reservoirs. We observed a relationship between the
1457 number of blooms in freshwater environments and population density (R^2 adjusted = 0.35; $p = <0.001$).
1458 Furthermore, we observed that the years with the relationship number of blooms are not necessarily the
1459 years with the relationship numbers of studies. For instance, 2009 presented the highest number of scientific
1460 studies and a median number of bloom events. Then, we also observed that species of potentially toxic
1461 genera, such as *Microcystis*, *Raphidiopsis*, and *Dolichospermum* have a wide geographic distribution.

1462 The increase in publications during the years 2005, 2009 and 2014 indicates an increase in the
1463 number of researchers in this field of study, as well as its scientific and technological progress, considering
1464 that the number of publications is one of the most used measures to quantify the scientific production
1465 (DEBACKERE et al., 2002). Between the years of 2010 and 2018, the publications did not exceed the
1466 number of five studies, demonstrating a small number of scientific studies mentioning the bloom
1467 occurrences. The lack of studies on the occurrence of cyanobacterial bloom events, as well as the
1468 concentration of records sampled in large cities and close to researches centers, were the main observed
1469 biases. The amount of published research over the years may indicate gaps to be filled in later studies since
1470 cyanobacteria are potentially toxin-producing organisms lethal to aquatic biota and humans. Our findings
1471 indicate that the occurrences are located where there is a greater human population density and in public
1472 supply reservoirs with historic of persistent blooms. What may justify the greatest number of events
1473 recorded in supply reservoirs is the existence of criteria related to the growth of cyanobacteria that are set
1474 out in the Ministry of Health Ordinance N°. 2.914, dated December 12, 2011, and which, in turn, revoked
1475 the Ministry of Health Ordinance N°. 518 of March 25, 2004. The federal law evidences the need to monitor
1476 cyanobacteria in all sources of public supply, thus contributing to the largest number of publications in
1477 supply reservoirs.

1478 Since bloom events occur mainly in large urban centers favors the accumulation of pollutants and
1479 the accelerated growth of the phytoplankton community, causing a considerable increase in biomass
1480 (BEHRENFELD; BOSS, 2018). This biomass has negative consequences on the efficiency and cost of
1481 water treatment, which can generate a loss of the resources destined to the public supply due to the economic
1482 unviability related to the water treatment (LORENZI et al., 2018). The blooms were mostly of the genus
1483 *Microcystis*, which in turn provide great shading for the other phytoplankton species, hindering their

1484 development, reducing the competition rate and eventually reducing the richness and diversity of organisms
1485 (CIRES et al., 2013). Also, morphological adaptations and the presence of gas vesicles allow buoyancy
1486 (VAN GREMBERGHE et al., 2011) and access to active photosynthetic radiation that facilitates its success
1487 in aquatic ecosystems (PADISÁK, 1997). Yet, the dense mucilage in cyanobacteria (REYNOLDS, 2007)
1488 ensures the increase in tolerance to high luminous intensities due to the acclimation by an increase in the
1489 production of photoprotective pigments (PAERL; OTTEN, 2013). In contrast, species of the genus
1490 *Cylindrospermopsis* can to adapt to low luminous intensity, being able to coexist with 'floating' genera,
1491 such as *Dolichospermum* and *Microcystis*, forming blooms in greater depths (PAERL; HUISMAN, 2008).
1492 Also, the genera *Cylindrospermopsis* presents success in dispersal attributed, in large part, to its ability to
1493 tolerate journeys along with river courses (MOREIRA; FATHALLI; VASCONCELOS, 2015; RICK;
1494 NOEL; RICK, 2007). In the genera *Dolichospermum* and *Microcystis*, the wind is an important dispersing
1495 agent for phytoplankton (CHRISOSTOMOU et al., 2009), as well as the animals that can also transport
1496 their vegetative forms on their body surface (PADISÁK; VASAS; BORICS, 2016). Cyanobacteria occur
1497 at environmentally suitable sites, where adequate dispersion rates are paramount for tracking changes in
1498 environmental conditions between localities (HEINO; VIRKKALA; TOIVONEN, 2009). Cyanobacterial
1499 dominance is associated with high temperatures, and the close relationship between temperature and the
1500 dominance in water bodies is evident (COTTINGHAM et al., 2015).

1501 The use of ENMs can estimate environmentally suitable areas where the knowledge about
1502 cyanobacterial geographic distribution is incomplete (SILVA et al., 2013); guiding future field surveys
1503 (JENSEN; MOUSING; RICHARDSON, 2017). In an attempt to reduce the lack of knowledge about the
1504 geographic distribution of cyanobacteria responsible for bloom events, also known as Wallacean shortfall
1505 (CARDOSO et al., 2011; WHITTAKER et al., 2005b), the data compilation from specialized literature,
1506 becomes an effective tool to mitigate such a problem. However, it is necessary not only to record the
1507 collection biases but also to identify the priority areas for inventories to overcome this problem (SOUSA-
1508 BAENA; GARCIA; PETERSON, 2014).

1509 Our ensemble distribution maps revealed that the northern portion of Brazil does not have high
1510 suitability for bloom events, being that the blooms are distributed in greater number of occurrences in the
1511 Southeast region. This result is the same for all four models. The suitability observed in this region may be
1512 a reflection of the lack of information about bloom events due to the low human concentration. Another
1513 explanation for the low occurrence in the North is that in these environments there is still a large proportion

1514 of the rivers preserved and not converted into reservoirs. Lentic environments are more amenable to
1515 flowering than lotic. Also, these species that were more reported are more successful in reservoirs
1516 (KOMÁREK et al., 2014). Incomplete data of geographic distribution are common in biological datasets
1517 from tropical regions (BALLESTEROS-MEJIA et al., 2013; KAMINO et al., 2012; SOBERÓN, 2007);
1518 with the Amazon region being generally sub-sampled (FREITAS et al., 2012). The distribution data are
1519 overlapped to regions with high human density (LETTERS; JAN, 2013) and the spatial patterns that we
1520 observed reflect the activities of the Brazilian researchers in reservoirs that show the historical persistence
1521 of blooms (LORENZI et al., 2018). Sampling bias is quite common for several biological groups and can
1522 have a strong effect on ENMs results (KRAMER-SCHADT et al., 2013).

1523 Although the sampling bias demonstrated here is one of the main reasons that may explain the
1524 fragmentary distributional patterns we observed, less appreciated factors may also explain this pattern, such
1525 as: (1) material sampled extensively in a given area, causing an accumulation of many data to be processed
1526 (HORTAL et al., 2015); (2) Financial and/or human insufficient resources for the identification and curation
1527 of species (FONTAINE; PERRARD; BOUCHET, 2012); and (3) social and logistical variables (e.g.,
1528 accessibility, number of inhabitants of a region, economy) (WHITTAKER et al., 2005b). Even more
1529 subjective factors, such as the researcher's preference for certain organisms or regions, may leave
1530 incomplete the distribution and occurrence scenarios for cyanobacteria (FICETOLA et al., 2014).

1531 Our results indicate that the available data on the geographic distribution for cyanobacterial
1532 blooms in freshwater environments are far from complete and have obvious geographical biases. However,
1533 it is much more comprehensive than the information available in the literature, as also reported in Freitas
1534 et al. (2012). We are aware that many of the cyanobacterial bloom events in water environments were not
1535 accessible, which may have reduced our ability to assess bloom events in Brazil. In our study, we mapped
1536 the available biological data about cyanobacteria responsible for the bloom events and the sample effort
1537 invested in the Brazilian territory. Our results can provide useful information on current sampling gaps that
1538 need further research to improve distribution data on the occurrence of bloom events in public supply
1539 reservoirs and support the monitoring practices of these events.

1540 Monitoring practices and risk assessments in water bodies include a proactive approach,
1541 encompassing inspection and monitoring programs with specific preventive actions (HUISMAN et al.,
1542 2018). However, although the enrichment of freshwater environments by nutrients is considered a major
1543 problem of pollution worldwide (GLIBERT et al., 2008), it is also one of the most important factors

1544 contributing to the increase in the number of bloom events (GLIBERT et al., 2008). In Brazil,
1545 eutrophication is still on the rise because of the increasing human population in many regions, which
1546 increases energy demands, increases the use of nitrogen fertilizers (N) and phosphorus (P) for agriculture,
1547 and increases the production of meat and animal waste. Nevertheless, we have noticed that the monitoring
1548 programs developed in Brazil are divided into four types of policies: prevention, restoration, improvement
1549 and no action (CARON et al., 2010). In other countries (e.g. the United States of America), advances are
1550 being made to detect bloom events and, in some cases, predict the occurrence and potentially reduce
1551 impacts. The rapid detection ability of phytosanitary cyanobacteria has progressed greatly from classical
1552 microscopic methods for detection involving specific molecules and genomes, which can be detected with
1553 a fluorescent signal (reviewed by Sellner et al., 2003). In addition, uses of remote images, packets and
1554 arrays that can detect and provide real-time information about species, as well as physical and chemical
1555 parameters have been enhanced (LOPES et al., 2016; MISHRA; MISHRA, 2014; STUMPF; TYLER,
1556 1988). In Brazil, such advances and techniques are still far from being widely used, which may
1557 underestimate the actual bloom's occurrence in the country, affecting the data available on bloom events
1558 (SELLNER; DOUCETTE; KIRKPATRICK, 2003).

1559 Thus, we hope that this study will stimulate new cyanobacterial samplings and increase efforts to
1560 understand and predict algal blooms to reduce its occurrence or impacts in the future. The most effective
1561 way is to reduce the entry of nutrients into aquatic environments since blooms are a widespread problem
1562 affecting estuaries, coasts and freshwaters around the world with effects on ecosystems, human health, and
1563 economies.

1564 **Conclusions**

1565 Using a scientometric analysis and ENMs, we demonstrate that many of the bloom events of
1566 phytosanitary cyanobacteria reported in the Brazilian literature are of the toxic genera *Microcystis*,
1567 *Raphidiopsis*, and *Dolichospermum*. These genera are broadly distributed in Brazil and respond quickly to
1568 current environmental changes and should certainly occur in areas that were not currently detected in our
1569 scientometric and ENMs analyzes. Thus, we believe that there are still several sampling gaps to be filled to
1570 effectively unravel the geographic distribution of cyanobacterial that cause blooms in freshwater
1571 environments and, consequently, diminish the effect of the Wallacean shortfall in this group. For instance,
1572 the northern portion of Brazil, which still has low suitability for bloom events compared to the occurrences

1573 in other Brazilian regions with a large concentration of human centers and population, needs to be better
1574 sampled, especially, in large urban centers. The cyanobacteria overgrowth has been highlighted because of
1575 possible problems in aquatic ecosystems, and by ecological and sanitary interest.

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1582 **Author Contributions**

1583 a) Substantial contribution to the design and design of the work;

1584 Ariane Guimarães, Fernanda Melo Carneiro, Pablo Henrique, Daniel Paiva Silva;

1585 b) Contribution to data acquisition

1586 Ariane Guimarães, Fernanda Melo Carneiro

1587 c) Contribution in the analysis and interpretation of data

1588 Pablo Henrique, Daniel Paiva Silva, Ariane Guimarães

1589 d) Contribution in the writing of the work

1590 Ariane Guimarães

1591 e) Contribution in critical review adding intellectual content

1592 Daniel Paiva Silva

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1970 **CAPÍTULO 3³**1971 **Role of the climate in the distribution of toxic cyanobacteria in Neotropical**
1972 **freshwater aquatic environments**1973 Ariane Guimarães¹, Pablo Henrique da Silva², Facundo Alvarez³, Daniel Paiva Silva⁴1974 ¹ Postgraduate Program in Cerrado Natural Resources, State University of Goiás, Anápolis, Goiás, Brazil.1975 arianeifgoiano@gmail.com; ORCID: 0000-0001-9276-3686;1976 ² Postgraduate Program in Cerrado Natural Resources, State University of Goiás, Anápolis, Goiás, Brazil.1977 phecosilva@gmail.com; ORCID: 0000-0001-5800-9268;1978 ³ Postgraduate program in Ecology and Conservation. New Xavantina Câmpus. State University of Mato1979 Grosso, Brazil. facualva87@gmail.com. ORCID: <https://orcid.org/0000-0002-7095-9570>.1980 ⁴Department of Biological Science, Goiano Federal Institute – Câmpus Urutaí, Brazil. daniel.paivasilva@gmail.com.

1981 ORCID: 0000-0002-2457-6245;

1982 Corresponding author: arianeifgoiano@gmail.com;

1983 **Abstract:** Neotropical freshwater environments are among the most productive ecosystems and
 1984 provide many ecological products and services to humanity. In neotropical freshwater aquatic
 1985 environments, climate change is a threat to global water security, and extreme hydrological
 1986 periods such as extreme precipitation or extreme drought will undoubtedly restructure food
 1987 chains, generating new communities composed of new combinations of species. In freshwater
 1988 bodies, extreme events in climate change can intensify the bloom of toxic cyanobacteria
 1989 (Cyanobacteria). Modeling the distribution potential of Cyanobacteria in freshwater environments
 1990 can serve as a new tool for impact assessment and conservation proposals for Neotropical aquatic
 1991 environments. We used ecological niche tools (ENMs) from occurrence records collected from
 1992 available databases to predict the susceptible areas for the present and future scenario of the
 1993 cyanobacteria phylum (*Microcystis aeruginosa* (Kützing) Kützing, *Raphidiopsis raciborskii*
 1994 (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique and Salerno 2018, and
 1995 *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek 1988). We considered three different
 1996 modeling methods: generalized linear models (GLM), Gaussian model (GAU), and maximum
 1997 entropy (MXS). In the results of the ENMs, the distributions for the current scenario were
 1998 consistent with the known distributions, and, for the future scenario, we identified new areas of
 1999 research. We concluded that the modeled species respond to current and future environmental
 2000 changes and should occur in the regions where the species are currently not detected in our ENM
 2001 analyses.

³ O manuscrito foi submetido ao *Jornal Limnologia* (2020: 2.093 © Clarivate Analytics Journal Citation Reports 2021).

A *Limnologia* publica artigos revisados por pares abordando aspectos biológicos, físicos e químicos de ecossistemas de água doce e habitats adjacentes.

2002 **Keywords:** CyanoHabs; Ecological Niche Model; Freshwater ecosystems; Microcystis
2003 aeruginosa; Planktothrix agardhii Raphidiopsis raciborskii; Toxins.

2004 **1. Introduction**

2005 The proliferation and persistence of toxic cyanobacteria (CyanoHABs) in
2006 freshwater ecosystems have increased significantly lately (WELLS et al., 2020).
2007 Additionally, in scenarios of temperature increases, the flowering of cyanobacteria is
2008 stimulated, with the abundance peaks of many (but not all) cyanobacteria species
2009 occurring at relatively high temperatures, often above 25°C (HUISMAN et al., 2018).
2010 Therefore, climate change is a strong catalyst for expanding cyanoHABs proliferation
2011 (PAERL; HUISMAN, 2009). In the future, climate change (CC) will undoubtedly
2012 restructure food chains, generating new communities made up of new species
2013 combinations (PADISÁK; NASELLI-FLORES, 2021). CC concerns events related to
2014 climate or meteorology (KASPRZAK et al., 2017) as extreme hydrological periods
2015 (BORTOLINI; TRAIN; RODRIGUES, 2016), extreme precipitation (STOCKWELL et
2016 al., 2020), or severe drought (CROSSETTI et al., 2019).

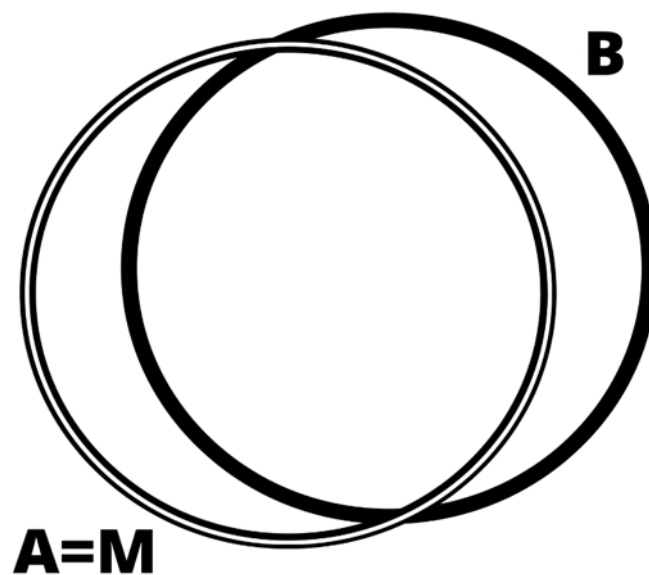
2017 In freshwater bodies, abrupt changes are related to the composition of
2018 phytoplankton but without dramatic changes in the number of species or community
2019 composition, although such extreme events may increase sensitivity to the invasion of
2020 phytoplankton assemblages (CROSSETTI et al., 2019; PADISÁK; VASAS; BORICS,
2021 2016). CC raises the temperature, consequently the water evaporation, and decreases the
2022 dilution of nutrient inputs in rivers and lakes (CHARLTON et al., 2018). The increase in
2023 water temperature can especially favor the blooming of cyanobacteria, which can
2024 negatively impact the functioning and services of the ecosystem. Therefore, climate
2025 change is a strong catalyst for expanding cyanoHABs proliferation (CONLEY et al.,
2026 2009).

2027 The cyanoHABs are characterized by the formation of thick clusters on the
2028 margins of water bodies (MILLER et al., 2017) and loss of water clarity that suppresses
2029 macrophyte growth and impacts invertebrate fish and habitats (PAERL; OTTEN, 2013).
2030 CyanoHABs are often formed by both toxin producers and non-producer cyanobacteria
2031 species. Independently of the kind of strain, compounds like geosmin (GSM) and 2-
2032 metilisoborneol (2-MIB) produced and conferred unpleasant taste and odor to the water
2033 (WATSON, 2003). Furthermore, these organisms produce a variety of cyanotoxins that
2034 cause liver, digestive and neurological diseases in humans (AZEVEDO et al., 2002) and
2035 animals (FERRÃO-FILHO; KOZLOWSKY-SUZUKI, 2011), besides compromising the
2036 quality of the water supply and increase their treatment costs (GENUÁRIO et al., 2016).
2037 These potential results of cyanobacterial growth also imply increased surveillance
2038 responsibilities to authorities responsible for producing water consumed by humans
2039 (HAMILTON et al., 2013). Therefore, there is an urgent need to identify suitable areas
2040 for cyanobacteria species to reduce water quality problems.

2041 A significant obstacle in reducing the cyanobacterial growth in freshwater
2042 ecosystems is, to some extent, a consequence of the lack of reliable data on the
2043 distribution of those species at the geographical space, called the Wallacean shortfall
2044 (HORTAL et al., 2015). This gap may constrain a profound understanding of the actual
2045 distribution of potentially toxic cyanobacteria (OLIVEIRA et al., 2016). In general, the
2046 geographic distributions of these species are poorly known and present numerous
2047 information gaps (Wallacean deficit) often related to the lack of collection efforts.
2048 (WHITTAKER et al., 2005).

2049 The distribution of a species is represented by the intersection of environmental
2050 conditions suitable for its survival (A), fundamental biological interactions to maintain
2051 their main ecological functions (B), and the ability to disperse to occupy the regions

2052 suitable for its persistence over time (M). Based on this, it is possible to assume that the
 2053 areas where the set of environmental conditions and ecological functions are preserved
 2054 represent the fundamental niche of a species, but mobility will define precisely the
 2055 realized niche of the species. For cyanobacteria, the accessible region is very extensive,
 2056 with practically no geographical limitation for their occurrence. Still, they necessarily
 2057 need some dispersal agent (e.g., river, air, animals, man) and travel conditions that meet
 2058 the transport tolerance of the species (PADISÁK; VASAS; BORICS, 2016). Therefore,
 2059 given the lack of restriction for dispersion, it is possible to conclude that the effect of
 2060 mobility is very low or even non-existent and, therefore, the set of environmental
 2061 conditions can be very representative for the geographic distribution of these organisms
 2062 (Figure. 1).



2063 **Figure 1.** Diagram of BAM according to SOBERÓN (2007). It represents the biotic (B), abiotic
 2064 (A), and mobility (M) conditions related to the life of a cyanobacterium. (M) concerns areas that
 2065 are physically accessible, (A) represents the entire region with environmental conditions (abiotic
 2066 factors) favorable to the establishment, survival, and reproduction of individuals who are
 2067 established by the fundamental niche. (B) represents the geographic space where the species can
 2068 occur, given the restrictions imposed by biotic interactions. (M) represents the entire region
 2069 accessible to the species according to its dispersal capacity.

2070 The classic concept of ecological niche established by Hutchinson (1957)
2071 (HUTCHINSON, 1957) is defined as an n-dimensional space of physical and biological
2072 requirements that would allow the survival and reproduction of a species and, at the same
2073 time, limit its abundance and distribution. However, this concept has changed over time
2074 to establish a more robust view of what defines the presence or absence of a species in a
2075 given location. One of the elements that most contributed to a concise explanation of the
2076 actual distribution of a species is the mobility, very well-argued from the BAM diagram
2077 (biotic, abiotic, and mobility) (SOBERÓN, 2007; SOBERÓN; PETERSON, 2005). The
2078 concept of niche in this work was thought of in the view of Grinnell (GRINNELL, 1917),
2079 where the Grinnellian niche is defined by abiotic or scenopoetic environmental variables
2080 and large-scale environmental conditions (SOBERÓN, 2007). It fits best to larger scales,
2081 where distribution areas are typically defined. When it comes to the large-scale
2082 distribution of species, the Grinnellian niche components are the most significant
2083 explanatory/predictive power (ARAÚJO; GUI SAN, 2006).

2084 Ecological niche models (ENMs) relate species occurrence records to a set of
2085 environmental predictors to determine suitable environments for cyanobacterial survival
2086 (GUI SAN; EDWARDS; HASTIE, 2002). In ENMs, it is assumed that the ecological
2087 niche of the species is fully known and is conserved over time, being dependent on the
2088 pattern of distribution of occurrence records (PETERSON, 2011). Based on this, we can
2089 estimate environmentally suitable areas for the occurrence of a particular species
2090 (PETERSON, 2017). These models are widely used to (i) define potential distributions
2091 (FLOMBAUM et al., 2013); (ii) indicate suitable areas for further sampling efforts
2092 (JENSEN; MOUSING; RICHARDSON, 2017); (iii) estimate suitable areas for the
2093 occurrence of cyanobacterial bloom events (GUIMARÃES et al., 2020), for example.

2094 In this study, our goal was to test the hypothesis that climate change will influence
2095 the size of areas suitable for cyanobacterial species when incorporated into niche models.
2096 Assuming that CC is responsible for broader geographic distributions of cyanobacteria
2097 species, with changing rain patterns (e.g., higher frequency of high-intensity rain events
2098 and more extended drought periods), cyanobacteria may expand geographically due to
2099 more extended and more stable stratification periods. Also, the higher expected frequency
2100 of extreme rain events would lead to the enrichment of nutrients and, consequently, a
2101 competitive advantage for cyanobacteria. Thus, we would observe changes in the size of
2102 the potential distribution for the future.

2103 **2 Material and Methods**

2104 2.1 Target species

2105 We applied this approach in three cyanobacteria, *Microcystis aeruginosa*
2106 (Kützing) Kützing (order Chroococcales), *Planktothrix agardhii* (Gomont) Anagnostidis
2107 & Komárek 1988 (order Oscillatoriales) and *Raphidiopsis raciborskii* (Woloszynska)
2108 Aguilera, Berrendero Gómez, Kastovsky, Echenique, and Salerno 2018 (order
2109 Nostocales). The cyanobacterium *M. aeruginosa* (order Chroococcales) produces the
2110 toxin Microcystin-LR and is an uncomfortable species, as it forms large blooms on the
2111 water surface and predominantly dominates the ecosystem through the formation of
2112 colonies in temperate and tropical water bodies worldwide (HUISMAN et al., 2018).
2113 Such blooms create a shading that hinders the development of other species, reducing
2114 competition and decreasing diversity (MONCHAMP et al., 2018). The morphological
2115 adaptations and presence of aerotypes (gas vesicles) allow for buoyancy (MOREIRA;
2116 VASCONCELOS; ANTUNES, 2013), and access to photosynthetic radiation of this
2117 species facilitates its success in freshwater ecosystems (HARKE et al., 2016a). These
2118 species cause a wide range of toxic effects that can cause severe liver damage, alter the

2119 redox system and cause cellular inflammation after acute or severe exposure (HARKE et
2120 al., 2016b) and damage to other tissues in mammals (JACOBY et al., 2000). Such
2121 substances are also responsible for the deaths of various birds, mammals, including sheep,
2122 dogs, and cattle (HANNON et al., 2010). Further, microcystins can be harmful to aquatic
2123 animals (FERRÃO-FILHO; KOZLOWSKY-SUZUKI, 2011).

2124 The cyanobacterium *P. agardhii* is a filamentous species that also produces
2125 microcystin and occurs in eutrophic shallow lakes. (PADISÁK; VASAS; BORICS,
2126 2016). Blooms of *M. aeruginosa* and *P. agardhii* are a significant problem in countries
2127 with inadequate water treatment, as microcystin production causes several severe toxic
2128 effects to the liver and other mammalian tissues (MATSUDA et al., 2006). The
2129 cyanobacterium *R. raciborskii* is an invasive, very toxic species that forms blooms and
2130 affects water quality and public health by producing different types of toxins such as
2131 cylindrospermopsin and saxitoxin (PONIEDZIAŁEK; RZYMSKI; KOKOCIŃSKI,
2132 2012). Such toxins affect multiple organs and tissues in mammals and inhibit protein
2133 synthesis in animals and plants. Saxitoxin is also one of the most potent paralyzing toxins
2134 (PST) found in freshwater ecosystems. (BURFORD et al., 2016). There are reports that
2135 drinking water contaminated with saxitoxins (STX) by humans infected with the Zika
2136 Virus results in fetal malformation and more severe microcephaly cases (PEDROSA et
2137 al., 2020).

2138 2.2 Occurrence records

2139 To estimate suitable areas in neotropical environments in South America, we used
2140 occurrence records (Figure 3A) of three widely distributed cyanobacterial species. We
2141 carried out the search on a global scale in the Global Biological Information Facility
2142 (GBIF; <http://www.gbif.org>) on June 15th, 2020. We obtained 789 records for *R.*
2143 *raciborskii*, 8.207 records for *P. agardhii*, and 1.089 records for *M. aeruginosa*. Overall,

2144 we fixed possible tradeoffs between longitude and latitude, removed records that did not
2145 contain geographic coordinates and duplicates. We did not consider occurrences in
2146 marine environments. Together, we obtained 69 records for *R. raciborskii*, 1,352 records
2147 for *P. agardhii*, and 330 records for *M. aeruginosa*. We chose to use occurrence records
2148 on a global scale, as the cyanobacteria species are globally distributed, and therefore,
2149 using data only for Brazil would leave the model incomplete. In such conditions, we
2150 would not be capturing the complete realized niche of the species, biasing the model.

2151 We also include cyanobacteria in our database blooms occurrences in Brazil
2152 through a systematic review of the scientific literature available in the platforms Web of
2153 Science (WoS, <http://apps.isiknowledge.com>) maintained by Clarivate Analytics using
2154 the code of search: [(“bloom*”) AND (“Brasil” OR “Brazil”) AND (“cyanobacteria” OR
2155 “cyanophyceae”)]. We searched both databases for articles and reviews that contained the
2156 search terms in the title, abstract, or keywords (access date: on June 15th, 2020). In our
2157 search, we obtained 208 scientific articles in the WoS database, selected 98 studies after
2158 reading the abstracts, and included 47 in our study.

2159 2.3 Environmental variables

2160 We selected environmental variables that maximized the set of primary conditions
2161 to understand the ecological niche of cyanobacteria. We used the environmental variables
2162 taken from WorldClim Version 1.4 (HIJMANS et al., 2005), considering the resolution
2163 of 10 arc-min (~ 18.5 km at the Equator) (Figure 3B). We chose this resolution because
2164 cyanobacteria are species with high rates of dispersion. Thus, larger cells could show a
2165 more significant effect of climate on the distribution of the species.

2166 We selected 19 bioclimatic variables, and for future models, we considered the
2167 climate variables available for the 17 Global Atmosphere-Ocean Circulation Models
2168 (AOGCMs): ACCESS1-0, BCC-CSM1-1, CCSM4, CNRMCM5, GFDL124 CM3,

2169 GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-
2170 CM5A125 LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR,
2171 MRICGCM3, NorESM1- 126 M. The representative carbon pathway scenario that we
2172 used was carbon concentration (“Representative Carbon Pathway” - RCP) 8.5, which
2173 corresponds to the most pessimistic scenario, in which it forecasts warming of
2174 approximately 4° C throughout the 21st century (IPCC, 2013; Chou *et al.*, 2014).

2175 Once climate variables are correlated with local aquatic variables, such variables
2176 can be considered for the large-scale representation of the aquatic processes (ALVAREZ
2177 *et al.*, 2020). Climate variations in large geographical scales can modify community
2178 structures in freshwater ecosystems (DOMISCH; AMATULLI; JETZ, 2015). For
2179 example, extreme precipitation contributes to increased nutrient concentration and
2180 biomass, and abundance values of the cyanobacterial community (SIMIĆ; DORDEVIĆ;
2181 MILOŠEVIĆ, 2017). The temperature variable directly influences competition between
2182 phytoplankton species, potentially intensifying cyanobacterial proliferation (MESQUITA
2183 *et al.*, 2019). The direct effects are related to its growth, which affects the metabolic
2184 processes related to photosynthesis and biosynthesis (MOSS, 2011). Other effects can be
2185 observed, such as stratifying the water column and reducing and increasing vertical
2186 mixing sediment nutrient flow (JÖHNK *et al.*, 2008).

2187 We standardized the variables to have their mean zero and their variances |1|.
2188 Next, we performed principal component analysis (PCA) to reduce the number of
2189 predictor variables and produce new orthogonal principal components (PCs) to be used
2190 as new environmental variables to predict the distribution in the species (Figure 3B). The
2191 selected orthogonal components accounted for 95% of the gross climate variation before
2192 the PCA analysis. For each scenario, we used the 19 bioclimatic variables of each
2193 scenario, which were later standardized. We then projected the PCA linear coefficients

2194 of the current scenario in each of the future scenarios to ensure future scenarios on the
2195 current scenario. Finally, we performed a PCA for each of the 17 scenarios and selected
2196 the main orthogonal components responsible for 95% of the original raw climate
2197 variation.

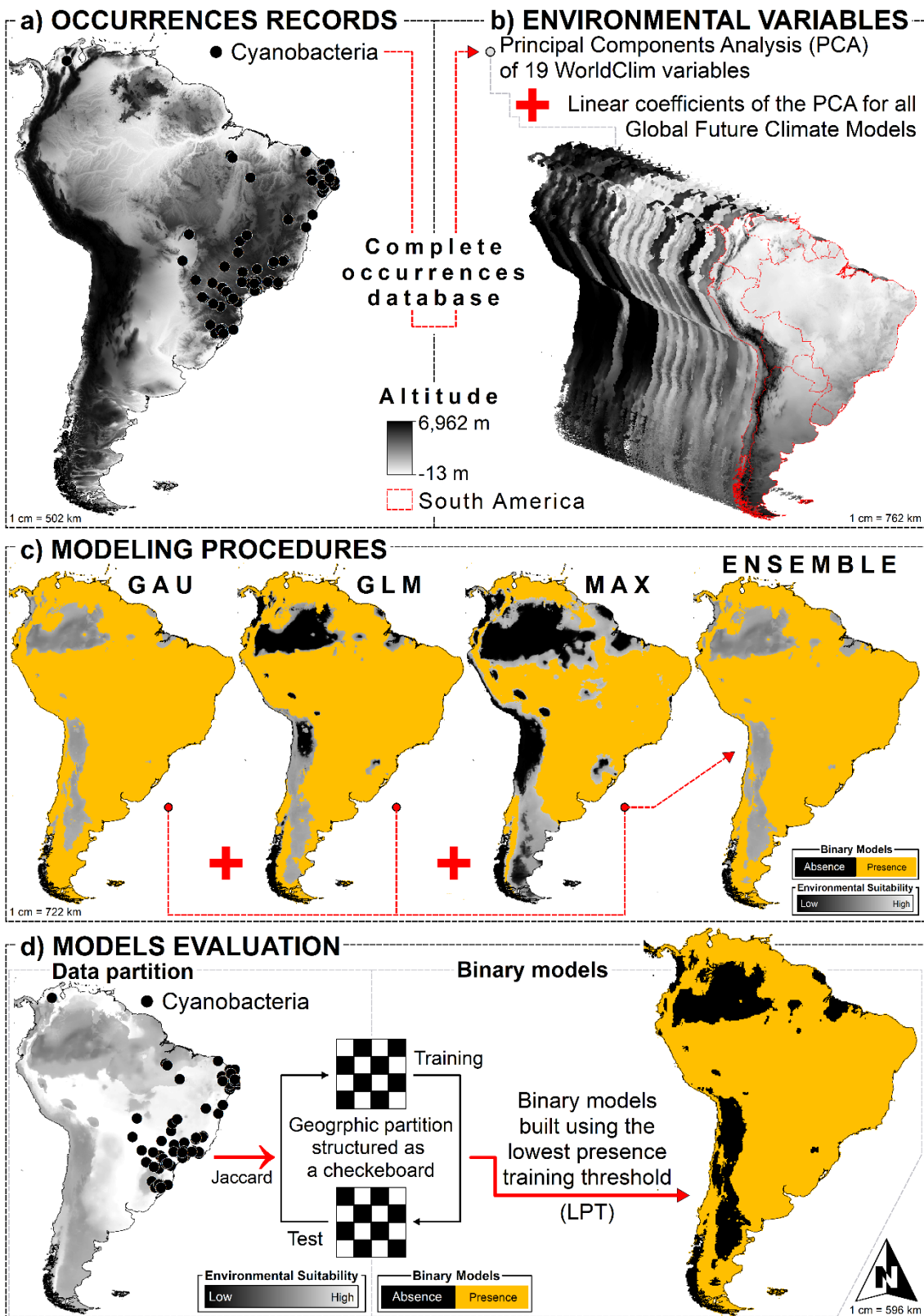
2198 2.4 Modeling procedures and model evaluation

2199 The algorithms we used in this predictive modeling are classified into three
2200 categories according to their model fit method: (i) based only on actual presences, (ii)
2201 presences and background, and (iii) presences and absences. Here, we use algorithms
2202 belonging to the three groups to avoid mistaken adjustments conditioned by the range of
2203 species distribution or the number of occurrence records. The entire modeling procedure
2204 was performed in R software version 4.0.3, using the ENMTML Package (ANDRADE;
2205 VELAZCO; DE MARCO JÚNIOR, 2020). We chose to use a checkerboard partition to
2206 guarantee independence between the data set used (MUSCARELLA et al., 2014) and
2207 used a method to create pseudo-absence to meet some algorithms requirements (Figure
2208 3D). Here, we used bioclimatic envelopes similar to the BioClim algorithm (BOOTH et
2209 al., 2014). This procedure constraints the occurrence points of the taxa in the geographical
2210 space using a bioclimatic envelope (LOBO; TOGNELLI, 2011; VANDERWAL et al.,
2211 2009). Then, the external area is considered unsuitable for the occurrence of species. In
2212 this area, pseudo-absences are created in a ratio of 1:1.

2213 We considered three different modeling methods for distribution modeling:
2214 Generalized Linear Model (GLM); (GUISAN; EDWARDS; HASTIE, 2002), Gaussian
2215 Model (GAU; (VANHATALO; VENERANTA; HUDD, 2012) and the Entropia Máxima
2216 (MAX) (PHILLIPS; ANDERSON; SCHAPIRE, 2006; PHILLIPS; DUDÍK, 2008). The
2217 GLM algorithm is a statistical method. MAX is a machine learning method, while the

2218 GAU method predicts the probability of occurrence of a species based on Bayesian
2219 inference adjustments (GOLDING; PURSE, 2016).

2220 We focused the evaluation metrics on three components of the confusion matrix:
2221 true positives, false positives, and false negatives. In particular, we sought to maximize
2222 true positives and minimize false positives and false negatives relative to true positives.
2223 The Jaccard metric (the metric is based on how well predictions match observations based
2224 only on observed presences) measures the similarity between predictions and
2225 observations. A value of 1 indicates that the forecasts perfectly match the observations
2226 without any false positives or false negatives, while a value of 0 indicates that none of the
2227 forecasts corresponded to the observation. The lower the similarity value, the greater the
2228 number of false positives and false negatives concerning the number of true ones
2229 (LEROY et al., 2018). The predictions are assumed as acceptable to reach values close to
2230 0.7, while “excellent” projections reach values closer to 0.9.



2231

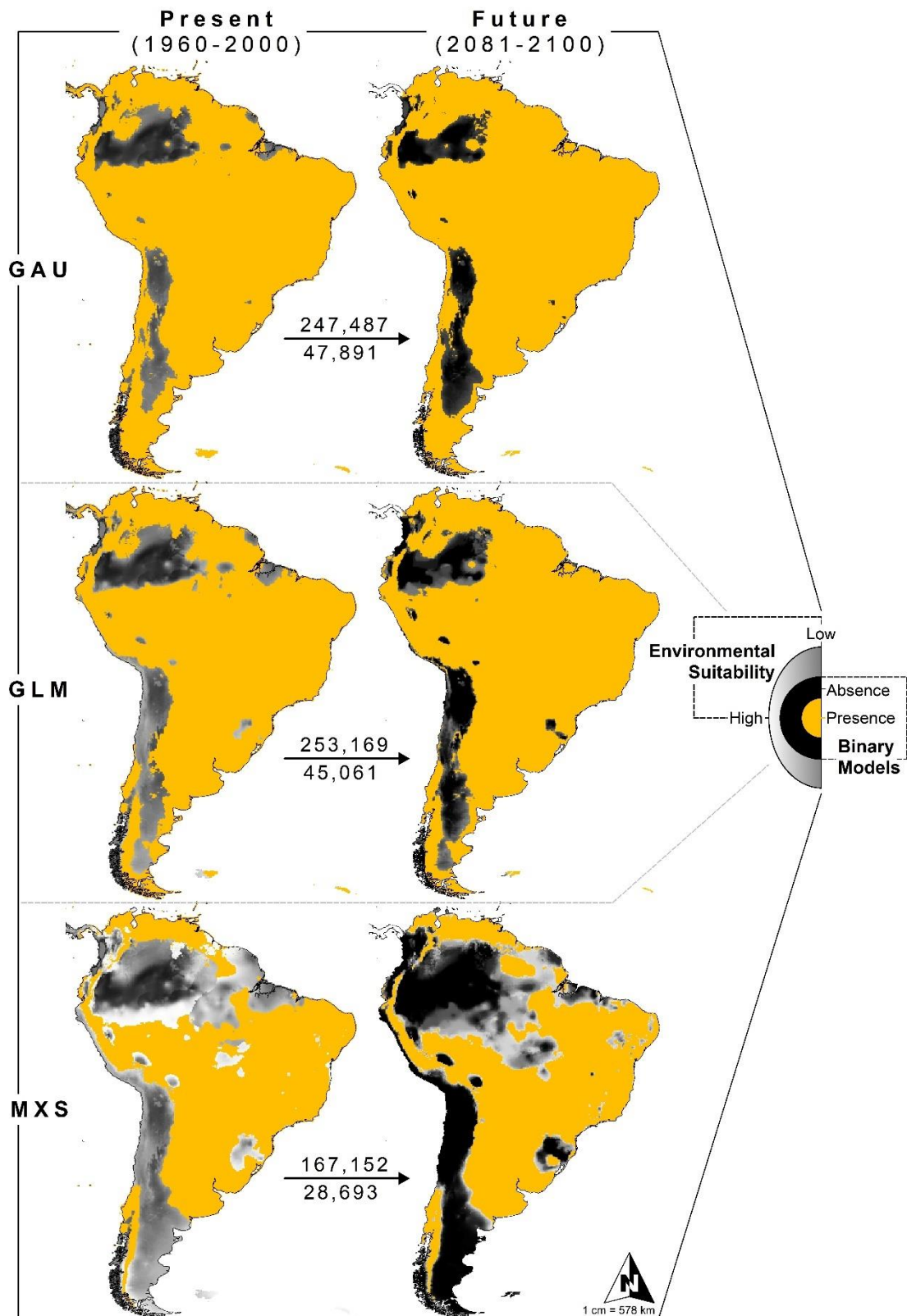
2232 **Figure 3.** Flowchart depicting the cyanobacteria distribution modeling procedures showing the
 2233 four main steps required to model the potential species distribution: occurrence records A;
 2234 Environmental variables B- Modeling procedures C; Evaluation of model D. The flowchart
 2235 summarizes the procedures performed for the modeling of cyanobacteria. The processes that were
 2236 used were used to make the models in the present and future scenarios.

2237 2.5 Ensemble

2238 To ensure a high quality of the models, we represent the final distributions using
2239 consensus maps to reduce the uncertainties associated with each algorithm (ARAÚJO;
2240 NEW, 2007). We made the consensus maps using the mean of the models that presented
2241 Jaccard values above the mean. The mean was 0.945, which means that the GLM method
2242 was not used in the *ensemble*. The idea of consensus models considers that different errors
2243 can affect the final result (e.g., the sensitivity of models, lack of true absences). For this
2244 reason, it has been argued in the literature that the use of consensus maps as final
2245 distribution models can reduce the number of errors (DINIZ-FILHO et al., 2010). This
2246 method produces ecological niche models from the most accurate algorithms, resulting in
2247 potentially more realistic predictions.

2248 **3 Results**

2249 The predicted potential distribution for the group (Phylum Cyanobacteria) of
2250 cyanobacteria was not similar in the climate scenarios considered (present and future
2251 scenarios). We observed differences in the size of the potential distribution for the group
2252 when using the different algorithms to model (Figure 4). We observed that the areas with
2253 suitability for the group in the MXS method scenarios were smaller than the other
2254 algorithms used. The evaluation values of the models obtained by the Jaccard method
2255 were MSX (0.988), GAU (0.984), GLM (0.861), *Ensemble* (0.991). Such values were
2256 high and indicated models with excellent fit.

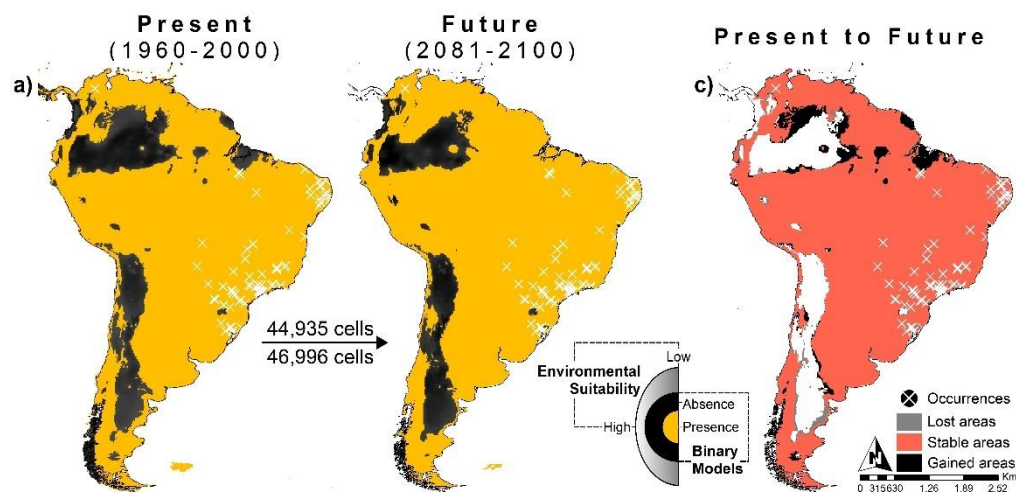


2257

2258 **Figure 4.** Ecological niche modeling was used to estimate the potential distributions for
 2259 two cyanobacteria and, consequently, for monitoring. These models represent three
 2260 modeling methods [Generalized Linear Model (GLM), Gaussian (GAU), and Maximum
 2261 Entropy (MAX)] for potentially toxic cyanobacteria (*R. raciborskii* and *M. aeruginosa*).

Analyzing the projection of suitable areas for the present and future scenarios (Figure 3A and 3B), we observe that for South America, there is a broad geographic distribution of suitable areas, which corresponds to an area of 17,840,000 km² with suitability for the occurrence of toxic cyanobacteria. In Argentina, Bolivia, Paraguay, Uruguay, and practically all Brazilian regions, there was high suitability for the occurrence of the group of toxic cyanobacteria in both projected scenarios. We also observed that for the current scenario (14,385,469 km²), the suitability was lower in the northern portion of Brazil, comprising the Amazon Basin. Nonetheless, in the projection for the future scenario (15,088,370 km²) (Figure 3B), we observed an increase in suitable areas, with an increase of 702,901 km² of areas with suitability for the occurrence of cyanobacteria.

Furthermore, from the current scenario to the future (Figure 3C), we observed an increase in favorable areas, especially in the northern South American region, with advances in aquatic environments within the Amazon Basin. Also, a loss of areas with suitability in the lower region of Chile. In general, there was an increase of suitable regions in climate change projections. Furthermore, when we looked at the maximum adequacy values, our modeling results indicated concern.



2262 **Figure 5.** Ecological niche modeling used to estimate the potential distributions for
2263 cyanobacteria. These models represent three modeling methods [Generalized Linear
2264 Model (GLM), Gaussian (GAU), and Maximum Entropy (MAX)] for potentially toxic
2265 cyanobacteria.

2266 **4 Discussion**

2267 Here, we showed the current and future potential distribution of a group of
2268 cyanobacteria. Estimating the potential distribution of species is one of the main
2269 objectives of macroecology, especially when sampling biases can affect knowledge about
2270 how the environment and variables affect this distribution. Our niche models predicted
2271 potential distribution areas for cyanobacterial species based on their environmental
2272 requirements. We chose to make a single model joining the occurrences of the three
2273 species because cyanobacteria have similar environmental preferences, so there would be
2274 no significant differences if we made models for each species individually. Therefore, to
2275 reveal the potential distribution and area suitability of cyanobacteria, we consider that the
2276 distribution patterns of these organisms depend on environmental filters (PADISÁK;
2277 VASAS; BORICS, 2016).

2278 Although the prediction that changes in climate will contribute to the increase in
2279 temperature and precipitation patterns, the evidence that the higher temperature will favor
2280 the occurrence of cyanobacterial blooming and the impact of altered rain patterns is
2281 largely under-researched and, therefore, even less understood (REICHWALDT;
2282 GHADOUANI, 2012). Overall, we can expect the two extremes, greater frequency of
2283 storms and prolonged droughts. The frequency of extreme rain events will change
2284 precipitation limits, and heavy rains will occur more frequently (CHANGING; OF, 2003).
2285 However, total precipitation is forecasted to change slowly (GROISMAN et al., 2005).
2286 Consequently, changes in rainfall patterns will lead to favorable conditions for the growth
2287 of cyanobacteria due to a more significant entry of nutrients into water bodies during

2288 heavy rains (BUDAI; CLEMENT, 2007), combined with potentially longer periods of
2289 high evaporation and stratification (BOUVY et al., 2003). Such conditions can contribute
2290 to intensifying the eutrophication process and prolonged periods of heating without
2291 mixing the water column (CHARLTON et al., 2018). Primarily, precipitation episodes
2292 produce changes in physicochemical conditions (e.g., temperature, nutrients, light,
2293 conductivity). These changes, in turn, depend on the particularities of the precipitation
2294 event, the hydrology of the basin, the use of the soil in the catchment area, and the trophic
2295 state of the aquatic system (NÖGES et al., 2011). In the absence of nutrient limitations,
2296 higher concentrations of nutrients in eutrophic systems lead to higher biomass loading
2297 and production capacities, which favors the occurrence of potentially toxic cyanobacterial
2298 biomass due to its greater affinity for nutrients compared to other phytoplankton
2299 (HUISMAN et al., 2018).

2300 On the other hand, the frequent occurrence of heavy rain events can also lead to a
2301 temporary halt in the proliferation of cyanobacteria due to discharge and de-stratification,
2302 and significant storm events have a long-term adverse effect on cyanobacteria
2303 proliferation (XIAO et al., 2017). We notice that cyanobacteria are sensitive to
2304 temperature, and it is known that environmental variables play a role at the beginning of
2305 the formation of the resulting colonies of *M. aeruginosa* (HUISMAN et al., 2018).

2306 The lack of suitability observed in some regions may reflect incomplete data from
2307 regional distribution or concentration in high human density centers (WHITTAKER et
2308 al., 2005b). This problem is quite common for many groups and can seriously affect the
2309 ENM results (KRAMER-SCHADT et al., 2013). Thus, the estimated occurrence of the
2310 species of cyanobacteria produced may not yet fully reflect the distribution capacity in
2311 Brazilian freshwater environments. Our results show that the most significant concern
2312 areas are distributed in locations with high human density and public supply reservoirs.

2313 The lack of suitability observed in some regions may reflect incomplete regional
2314 distribution or concentration data in areas high-populated by humans. Thus, the estimated
2315 occurrence of the cyanobacteria may not yet fully reflect the distribution capacity in
2316 América of Sul freshwater environments.

2317 Problems of cyanobacteria growth in freshwater environments for man arise due
2318 to direct contact during their recreational time in contaminated water bodies, through poor
2319 treatment of drinking water reservoirs, by bioaccumulation of microcystins and other
2320 cyanotoxins in biological matrices, or through the consumption of irrigated vegetables
2321 and contaminated fish (as a result of these risks, maximum daily intake of $0.04 \mu\text{g kg}^{-1}$
2322 body weight of microcystin-LR (MC-LR) from fish and other food products is
2323 recommended) (CHIA et al., 2021). Cyanobacterial toxins can also enter the human body
2324 by inhalation or absorption through the skin (ZANCHETT; OLIVEIRA-FILHO, 2013).
2325 In Brazil, two intoxication events in human beings caused by cyanobacteria are described.
2326 In 1988, an epidemiological correlation was found between cyanobacterial blooms in the
2327 Itaparica Reservoir (Bahia, Brazil) and the death of 88 people and 2000 people had
2328 gastroenteritis symptoms due to intoxication (TEIXEIRA et al., 1993). In 1996,
2329 microcystin, a toxin released by *M. aeruginosain* in the water supply from the Caruaru
2330 Hemodialysis Center in Pernambuco, Brazil, was confirmed. Out of 116 intoxicated
2331 people, 76 patients died after treatment at this institution (AZEVEDO et al., 2002).

2332 Overall, compared to the current scenario, we observed that the distributions of
2333 the two species were similar. Our consensus distribution maps revealed that species are
2334 distributed in more significant numbers of occurrences in the Southeast region and
2335 smaller proportions in the northern region of the country, comprising the Amazon basin.
2336 Our findings indicate that areas of suitability for the current scenario are higher human
2337 density, and the supply reservoirs have persistent blooming histories. Regarding the

2338 future scenario, our projection results indicate an increase in the areas with the potential
2339 distribution of the two species.

2340 Therefore, the monitoring of toxic cyanobacteria and cyanotoxins is essential to
2341 identify potential risk sites. Usually, monitoring programs collect samples in the field and
2342 analyze them in the laboratory, requiring both time, sophisticated equipment, and
2343 specialized staff, limiting the collection points and frequency. Consequently,
2344 conventional monitoring programs are limited to providing a generic assessment of the
2345 ecological quality of the studied sites and are insufficient for providing monitored bloom
2346 development warning systems throughout the monitored water body (HUNTER et al.,
2347 2010). It is well known that the rapid detection capability of potentially toxic
2348 cyanobacteria can be accomplished through the ability to detect both remote images and
2349 packages and arrays that can detect and provide real-time information (STUMPF et al.,
2350 2016). In countries such as the United States, rapid advances are being made to detect
2351 events and, in some cases, to predict their occurrence and potentially reduce their impacts
2352 (SELLNER; DOUCETTE; KIRKPATRICK, 2003). In Brazil, such advances and
2353 techniques are still far from being widespread, which may underestimate the current
2354 occurrence rates of bloom events in the country, affecting the availability of event data.

2355 In an attempt to reduce ignorance about the geographical distribution of
2356 potentially toxic cyanobacteria, also known as a Wallacean deficit (WHITTAKER et al.,
2357 2005b), it is necessary not only to record collection biases but also to identify priority
2358 areas to overcome this problem (SOUSA-BAENA; GARCIA; PETERSON, 2014). Given
2359 this, we also propose the use of suitable habitat extension maps (concern areas maps).
2360 This approach is practical for monitoring planning because it combines readily available
2361 data from databases for many species in regions with insufficient data (LIST et al., 2010).
2362 Thus, we hope that this work will stimulate further sampling of the potential distribution

2363 of cyanobacteria and increased efforts to understand and predict their blooms, reducing
2364 their occurrence and impacts.

2365 The suitable areas that we observe for the species are distributed in the central-
2366 southeast portion of South America. For most species with distribution in low latitudes
2367 (temperate climate), the temperature is considered the main barrier for expanding to
2368 latitudes. Considering the occurrence data of *R. raciborskii* at low temperatures, its
2369 occurrence is possible at temperatures below 12° C. This winter survival ensures that it
2370 reestablishes a population when conditions become favorable again, which allows the
2371 species to expand and thrive in new environments (DOKULIL, 2016). This ensures a
2372 competitive advantage, allowing them to colonize waters in temperate or cooler regions
2373 of the globe. (VÁRKONYI et al., 2000). To ensure the successful dispersal of
2374 cyanobacteria, traveling along river courses has been the most evident form of dispersal,
2375 as the risk of desiccation can be controlled. The successful dispersal of *R. raciborskii* is
2376 primarily attributed to its ability to tolerate travel in river courses. (PADISÁK, 1997).

2377 For *M. aeruginosa*, which forms colonies surrounded by mucilage, colony
2378 formation is essential for its success in freshwater ecosystems. (BULLERJAHN et al.,
2379 2016). The wind is a crucial dispersing agent (CHRISOSTOMOU et al., 2009) and
2380 animals that can also carry their vegetative forms on the body surface (PADISÁK;
2381 VASAS; BORICS, 2016). Environmental variables play a role in the early formation of
2382 your colonies and influence the size and morphology of the resulting colonies (XIAO et
2383 al., 2017). The species *P. agardhii* is a widespread cyanobacterium that changes in time
2384 scale from days to weeks due to changes in cloudiness or wind-induced sediment
2385 resuspension in shallow and turbid lakes. Changes in light conditions affect microcystin
2386 production, and thus *P. agardhii* is more toxic during periods of sunny weather when
2387 recreational activities in lakes are more attractive. (TONK et al., 2005).

2388 **5 Conclusions**

2389 Our results indicate that the available data on the geographic distribution of
2390 cyanobacterial species in freshwater environments is far from complete and has obvious
2391 geographic biases. We know that many of the records of cyanobacteria in aquatic
2392 environments were not accessible, which may have reduced our ability to assess species
2393 distribution. In our study, we mapped the available data on toxic cyanobacteria, and our
2394 sampling effort was invested on a world scale and our models for the neotropical
2395 environments of South America. Our results can provide relevant information about
2396 sampling gaps in regions that need more research to improve distribution data on the
2397 occurrence of these species and support monitoring and management practices for these
2398 species.

2399 The toxic species are widely distributed, respond rapidly to current environmental
2400 changes, and should undoubtedly occur in areas not detected in our ENMs analysis. We
2401 know that cyanobacteria multiply in the environment and can be concentrated in certain
2402 lakes and reservoirs by wind action. The formation and dispersion of blooms can change
2403 in days or even hours, making it difficult to assess the associated hazards. Then, planning
2404 a monitoring program should consider the objective to be achieved and the characteristics
2405 of the evaluated water body. Furthermore, monitoring programs may also include
2406 identifying susceptible areas and information and education for the population. Our
2407 monitoring planning approach, which combines data available from the database, can
2408 stimulate new sampling methods of the potential distribution of cyanobacteria and reduce
2409 the impacts of toxins in the supply areas.

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2858 CONCLUSÕES GERAIS

2859 No geral, as distribuições geográficas das cianobactérias são pouco conhecidas e
2860 apresentam inúmeras lacunas de informação (déficit Wallaceano) frequentemente
2861 relacionadas com a falta de esforços de coleta. Na tese, os registros disponíveis sobre a
2862 distribuição geográfica das espécies de cianobactérias em ambientes de água doce estão
2863 longe de estar completos. Sabemos que muitos dos registros de cianobactérias em
2864 ambientes aquáticos não eram acessíveis, o que pode ter reduzido a capacidade de avaliar
2865 a distribuição potencial das espécies de cianobactérias. Nós, demonstramos que muitos
2866 dos eventos de floração de cianobactérias fitossanitárias relatados na literatura brasileira
2867 são dos gêneros tóxicos *Microcystis*, *Raphidiopsis* e *Dolichospermum*. Esses gêneros
2868 estão amplamente distribuídos no Brasil e respondem rapidamente às mudanças
2869 ambientais atuais e certamente devem ocorrer em áreas que não foram detectadas
2870 atualmente em nossas análises cienciométricas e ENMs.

2871 Aqui, os dados disponíveis sobre as cianobactérias tóxicas e o esforço amostral
2872 foi investido em escala mundial. Para produzirmos os modelos para a América do Sul,
2873 optamos por usar registros de ocorrência em escala global, pois as espécies de
2874 cianobactérias estão globalmente distribuídas e, portanto, usar dados apenas para o Brasil
2875 deixaria o modelo incompleto. Nessas condições, não estaríamos capturando todo o nicho
2876 realizado da espécie, enviesando o modelo. Na América do Sul existem evidências que
2877 destacam um grande esforço amostral na região da Mata Atlântica, enquanto na região da
2878 Floresta Amazônica poucas regiões são de fato amostradas. A porção norte do Brasil, que
2879 ainda apresenta baixa aptidão para eventos de floração em comparação com as
2880 ocorrências em outras regiões brasileiras com grande concentração de centros urbanos e
2881 população, precisa ser amostrada com maior precisão. De fato, os resultados aqui
2882 apresentados podem fornecer informações relevantes sobre as lacunas de amostragem em
2883 regiões que precisam de mais pesquisas para melhorar os dados de distribuição sobre a
2884 ocorrência dessas espécies e apoiar as práticas de monitoramento dessas espécies. O
2885 estudo é inovador, pois na literatura especializada não há nenhum trabalho publicado
2886 envolvendo a modelagem de nicho e cianobactérias em ambientes de água doce
2887 Neotropical. Dessa forma, o estudo poderá fornecer embasamento teórico para futuras
2888 medidas de monitoramento, podendo esta abordagem ser aplicada não somente na região
2889 neotropical, mas em qualquer outra área de estudo.