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A Latin American network of microbial observatories for monitoring aquatic ecosystems

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Abstract. Freshwater environments and coastal marine areas provide key ecosystem services to society and serve as habitats for biodiversity. However, they face major challenges from human activities and climate factors, leading to global degradation. The effect of these agents depends on geographic location and climate, among other factors. To comprehensively understand the effect of these factors, continuous, standardized and long-term information is crucial. In particular, the aquatic microbiome plays a fundamental role in the cycling of matter and has been shown to act as a robust indicator of ecological status. Long-term monitoring of microbial assemblages can provide valuable insights into the characteristics and the changes water bodies undergo, delivering early warnings of critical impacts. Thus, the Latin American Aquatic Microbial Observatory Network (AMO*Lat*) was set up during the inaugural meeting of the Latin American Collaborative Network on Microbial Aquatic Ecology (µSudAqua) in 2017. Observatory sites were carefully chosen, considering their accessibility and local relevance to each research group, ensuring the ongoing consistency of sampling efforts. This work aims to provide a historical overview of the network's formation, highlighting key debates and definitions that took place during 2017-2023. Furthermore, it includes an initial characterization of the observatory sites and explores the possibilities that they offer to understand the structure and function of aquatic ecosystems in Latin America. The network presently encompasses 13 observatories, spanning a broad latitudinal range, numerous ecoregions and diverse aquatic ecosystems, displaying different environmental and anthropic impacts. Participating groups enhanced interactions, created a Protocol Book and showcased initial results through various communication efforts. Ultimately, establishing a regional network of aquatic observatories becomes mandatory for providing essential reference points to assess the response of microorganisms to global change in both the short and long term within Latin America.

[Keywords: aquatic ecosystems, biomonitoring, microorganisms, research consortium]

Resumen. Red latinoamericana de observatorios microbianos para el monitoreo de sistemas acuáticos. Los cuerpos de agua dulce y las zonas marinas costeras brindan servicios ecosistémicos clave para la sociedad y son reservorios de la biodiversidad. Sin embargo, presentan amenazas importantes derivadas de los impactos antropogénicos y los factores climáticos, llevándolos a su deterioro a nivel mundial. El impacto de estos agentes depende de la ubicación geográfica y del clima, entre otros factores. Para comprender exhaustivamente sus efectos, es crucial disponer de información continua, estandarizada y a largo plazo. En particular, el microbioma acuático desempeña un papel fundamental en el ciclo de la materia, pudiendo ser un indicador robusto del estado ecológico. El monitoreo a largo plazo puede revelar información valiosa sobre las características y los cambios en las masas de agua. Durante la reunión inaugural de la Red Colaborativa en Ecología Acuática Microbiana de América Latina (µSudAqua) en 2017 se estableció la Red de Observatorios Microbianos Acuáticos de América Latina (AMO*Lat*). Los sitios-observatorios se eligieron teniendo en cuenta su accesibilidad y relevancia local, y asegurando la continuidad de los muestreos. Este trabajo tiene como objetivo proporcionar una visión histórica de la formación de la red, destacando los debates que tuvieron lugar entre 2017 y 2023. Además, incluye una caracterización de los sitios-observatorios, explorando las posibilidades que ofrecen para comprender la estructura y función de los ecosistemas acuáticos en América Latina. La red actualmente incluye 13 observatorios y abarca un amplio rango latitudinal, numerosas ecorregiones y ecosistemas acuáticos, con diferentes impactos ambientales y antrópicos. Los grupos participantes fortalecieron sus interacciones, elaboraron un Libro de Protocolos; además, se realizaron comunicaciones con los primeros resultados. El establecimiento de una red regional de observatorios acuáticos resulta indispensable para proporcionar puntos de referencia esenciales para evaluar la respuesta de los microorganismos al cambio global a corto y largo plazo en Latinoamérica.

[Palabras clave: ecosistemas acuáticos, bio-monitoreo, microorganismos, consorcio de investigación]

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INTRODUCTION

Aquatic systems play essential roles in regulating global climate, sustaining the hydrological cycle and providing key functions to humanity and biodiversity. The American continent contains a substantial proportion of the Earth's marine and freshwater ecosystems, where several regions stand out as hotspots of biodiversity (Wilkie et al. 1995; Benzaquén 2017). Particularly, Central and South America have a complex geological history and great habitat heterogeneity (Antonelli 2022). The region is affected by changes in temperature and rainfall, demographic growth and the consequent increase in anthropic activities. These threats pose serious impacts on biodiversity and ecosystem functions. Despite their vast extent, only a few areas are preserved. In South America, just 6% of the world's wetlands have been designated as protected sites (Xu et al. 2019). Therefore, understanding how regional ecosystems respond to different drivers is an urgent priority.

Within aquatic ecosystems, microbial assemblages stand out as robust indicators of ecological and health status (Sagova-Mareckova et al. 2021). Microorganisms are essential for nutrient processing and biogeochemical cycling, as their interactions determine the amount of primary production available to higher trophic levels (Fermani et al. 2013). Indeed, microbiomes drive a broad range of ecosystem services in aquatic environments (Azam et al. 2022). The ecological services they provide to the Earth underline the importance of clarifying their ecological patterns, to guide effective conservation strategies and ensure the preservation of these vital components.

Biogeographic patterns of microbial communities have shown complex variations across space or time, influenced by both local and regional factors. However, most studies are confined to the Northern Hemisphere (Veach et al. 2021). In Latin America, although there are efforts to assess the responses of microbial assemblages to multiple stressors (nutrient enrichment, organic matter, turbidity, etc.) (e.g., Berman et al. 2020; Mateus-Barros et al. 2021; Modenutti et al. 2023), these remain scarce in the context of global meta-analysis (Sala et al. 2000). Environmental differences across the continent raise the question of how different stressors might affect the microbial community. To understand the effects of diverse factors, it is important to have continuous, standardized and long-term information on abiotic and biotic variables at an adequate sampling frequency. Large-scale assessments of microbiome variations can be achieved when sampling is carefully coordinated. Thus, several observatories have been established around the world (Buttigieg et al. 2018), with Latin America being a significantly underrepresented region on the global scale.

Given the key role of microorganisms in aquatic ecosystems and the regional information gap, the Latin American collaborative Network on Microbial Aquatic Ecology (µSudAqua) was created in 2017 (microsudaqua.netlify.app/en/). This network connects researchers and students in aquatic microbial ecology to foster collaboration, build a scientific community and support long-term partnerships (Figure 1A). Within this network, different working groups have been established. Because observatories are valuable tools to access systematized information about ecosystems, the Latin American Aquatic Microbial Observatories (AMO*Lat*) was founded. AMO*Lat* Network allows carrying out long-term monitoring of microbial assemblages, providing valuable information on the status of aquatic systems in this region across temporal, local and/or regional scale. Therefore, the objective of this work is to provide a historical overview of the observatories' network formation and key issues that shaped its establishment, as well as the unique features that have allowed the network to be sustained over the last 7 years. Additionally, we present a preliminary overview of the observatory sites, exploring the concrete possibilities they offer to understand the structure and function of aquatic ecosystems in Latin America, their ecological health and the factors that threaten them.

Materials and Methods

AMOLat network formation

Qualitative analysis was conducted on the primary documents from 2017 to 2023. It included materials such as the formation call, founding declaration, site status survey, group meeting reports and publications to date. Based on these sources, the information was synthesized into a historical analysis of its formation, categorized into three main stages and identifying the main debates and challenges that emerged during the period. Finally, an online survey with open- and closed-ended questions was sent to the leaders of each AMO*Lat* observatory to investigate the interactions between network nodes.

AMOLat observatory characterization

A general characterization was based on four criteria. Ecoregions were identified according to Metz et al. (2022). The environment was classified into three types (inland, estuarine and marine-coast). In turn, inland waters were categorized into lakes (natural: shallow lakes; artificial: reservoir), streams/rivers and wetlands (i.e., wetland, pond and marsh) (Benzaquén 2017). The main anthropogenic impact of each observatory was classified into: climate change and local anthropogenic disturbances. Quantitative analysis of physicochemical and biological variables was carried out to characterize current sites. For this, water temperature, light attenuation coefficient (K_d), bacterial abundance and chlorophyll-*a* (Chl-*a*) concentration were measured following methods defined by the AMO*Lat* Network (Supplementary Material 1).

Results

Setting-up (2017-2018)

According to the foundational document (Latin American Microbial Observatory Network 2017), during the first µSudAqua Network (Uruguay 2017)(Figure 1B), we aimed to 1) assess how anthropogenic influences and climatic factors impact the microbial community dynamics in this region; 2) standardize collection methods, and 3) create a web platform displaying temporal microbial dynamics for broader audiences. Observatories-sites were proposed during this first meeting, encompassing several ecosystems from many countries. Sites were selected based on existing ongoing projects, accessibility and a long-term vision for their establishment (Table 1). The design of the monitoring was based on standardized methodology and periodic, synchronized sampling routines.

Key topics of discussion were the selection of the variables that best capture the behavior and characteristics of aquatic environments and also to find simple, fast and accessible methods for research groups, while identifying the local and central capabilities of the network. Table 2 summarizes the criteria for characterizing the study locations, biological communities and observatory capacities. The standardized methodology was compiled in an open-access Protocol Book (Latin American Microbial Observatory Network 2024).

Observatory beginnings (2019-2020)

Sampling started synchronously in April 2019 on a bimonthly frequency. The initial sampling design covered diverse environments and types of impacts; however, due to the difficulties of carrying out long-term sampling, some sites were unable to continue. Samplings were suspended during the COVID-19 pandemic and resumed synchronously in June 2022. New sites were added to AMO*Lat* (Table 2), while others were permanently discontinued after the pandemic, mainly due to limited personnel, financial resources and accessibility (e.g., Gómez Lake and Beagle Channel, Argentina) (personal communication).

Table 1. Current observatories-sites (Abr.=abbreviation).
Tabla 1. Sitios-observatorios actuales (Abr.=abreviatura).

Site	Site name	Abr.	Geographical coordinates	Country	Ecoregion	Environment	Main impact	
1	Bahía San Antonio	BSA	40°46′ S - 64°54′ W	Argentina	North Patagonian Gulfs/Beaches and marshes of the Patagonian coast	Atlantic Ocean, Marine coast	Anthropogenic local disturbances	Land water discharge from septic systems and industrial activities
2	Las Grutas	LG	40°48′ S - 65°05′ W	Argentina	North Patagonian Gulfs/Beaches and marshes of the Patagonian coast	Atlantic Ocean, Marine coast	Anthropogenic local disturbances	Maritime activities and tourism
3	Golfo Nuevo	GN	42°47′ S - 64°57′ W	Argentina	North Patagonian Gulfs/Beaches and marshes of the Patagonian coast	Atlantic Ocean, Marine coast	Climate change	Invasive species
4	Laguna de Rocha	SAMO	34°37′ S - 54°17′ W	Uruguay	Uruguayan savanna/ Pampa	Atlantic Ocean, Marine coast	Anthropogenic local disturbances	Land water discharge from adjacent coastal lagoon supplying nutrients, fertilizers and pesticides, maritime activities, tourism
5	Río Negro	RN	41°02′ S - 62°49′ W	Argentina	Beaches and marshes of the Buenos Aires coastlines	Atlantic Ocean, Estuary	Anthropogenic local disturbances	Urban effluents (stormwater, treated and untreated sewage) and agricultural drainage
6	Golfo Nicoya	CR	9°48′ N - 84°48′ W	Costa Rica	North Pacific	Pacific Ocean, Estuary	Anthropogenic local disturbances and climate change	Urban effluents, fisheries, red tides
7	BroaMO	BroaMO	22°11′ S - 47°53′ W	Brazil	Atlantic Forest/ Cerrado	Freshwater, reservoir	Anthropogenic local disturbances	Recreation, livestock, sewage
8	Chascomús	CH	35°36′ S - 58°02′ W	Argentina	Southern Flat, Humid Pampa sub-region	Freshwater, shallow lake	Anthropogenic local disturbances and climate change	Livestock, agriculture, fertilizers and pesticides, recreation, tourism, sewage waste, eutrophication, temperature increase
9	El Trébol	TR	41°4′ S - 71°29′ W	Argentina	Patagonia wetland, extra-Andean sub-region	Freshwater, shallow lake	Anthropogenic local disturbances	Urban effluents
10	Río Luján	LJ	34°34′ S - 59°7′ W	Argentina	Sub-region rivers, estuaries, and lagoons of the Paraná River/ wetlands of the Paraná River Delta	Freshwater, urban river	Anthropogenic local disturbances and climate change	Livestock and agriculture, industrial plants, sewage treatment, urbanization
11	San Francisco	SF	34°48′ S - 58°21′ W	Argentina	Pampa	Freshwater, urban river	Anthropogenic local disturbances	Wastewater pollution, urbanization
12	Negro	NE	41°12′ S - 71°50′ W	Argentina	Patagonia wetland	Freshwater, glacial-fed river	Climate change	Rising temperatures, melting glaciers
13	Blanco	BL	41°12′ S - 71°49′ W	Argentina	Patagonia wetland	Freshwater, glacial-fed river	Climate change	Rising temperatures, melting glaciers

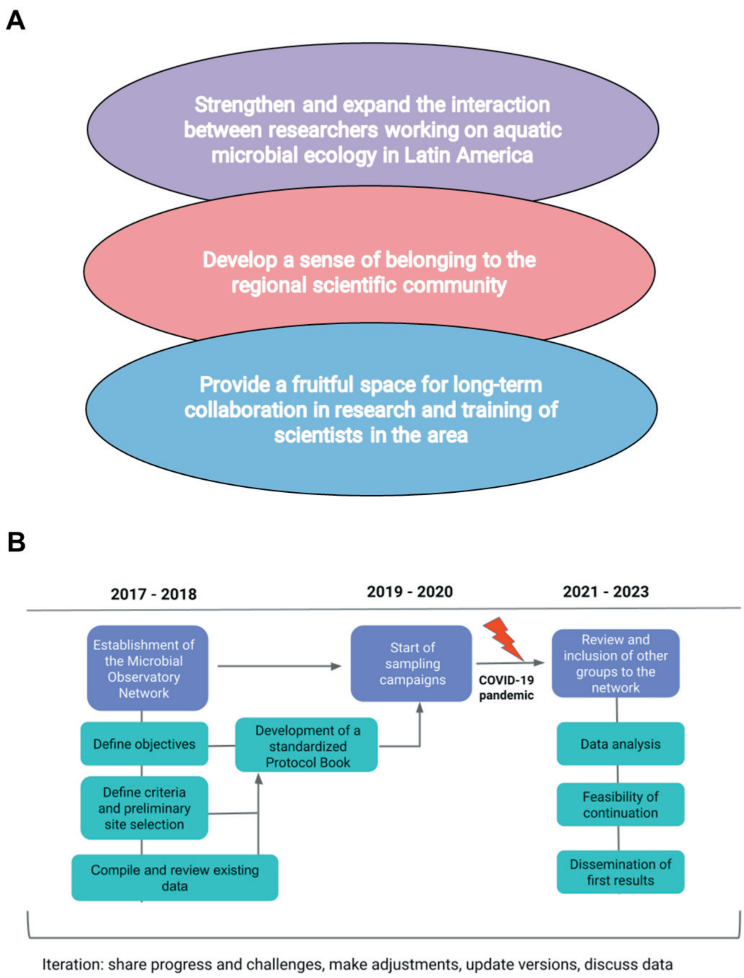

Figure 1. A) Foundational principles of µSudAqua Network. B) Summary of key stages in developing the AMO*Lat* Network.

Figura 1. A) Principios fundacionales de la Red µSudAqua. B) Resumen de las principales etapas para el desarrollo de la Red AMO*Lat*.

AMOLat network consolidation (2019-2023)

Through various meetings (Argentina 2019; virtual 2020, 2021; Brazil 2022), progress and challenges were shared, and the feasibility of common protocols was discussed. Due to different ecological characteristics, some procedures could not be standardized, leading to case-by-case analyses. For cytometric analyses, site-specific fixatives were used to maximize sample quality, with analyses centralized in specialized institutes. For metagenomics, sample optimization included manual protocols and commercial DNA extraction kits (Latin American Microbial Observatory Network 2024).

Current observatory network

Currently, 13 observatories are operational (Figure 2A). Argentina has 10 observatories, mainly in the Pampean and Patagonian regions. Uruguay, Brazil and Costa Rica each host one site each. These locations encompass diverse aquatic ecosystems including 4 marine coasts, 4 rivers/streams, 2 estuaries, 2 shallow lakes and 1 reservoir (Table 1).

These observatories are interconnected in various ways and have enhanced their connections and skills (Figure 2B, Table 3). AMO*Lat* observatory leaders highlight that participation significantly boosts opportunities for discussing results and new projects (100%), with 91% gaining access to new techniques or improved methods and 36% getting access to equipment. Outside network meetings, interactions among observatory members were frequent, focusing on technical training (80% of observatories), sample processing (60%), co-authorship of publications unrelated to the network (60%) and research or training stays for postgraduate students (50%). Among all observatories, Chascomús (CH) is the most connected with 10 links and

Table 2. Methodology and AMO*Lat* capacities.
Tabla 2. Metodología y capacidades de AMO*Lat*.

General information			Abiotic variables*							Biological variables**				
Site	Abr	Starting date***	Depth	Cond	Transp.	DO	Temp, pH	Nut	DOC	Chl-*a*	Flow cyt.	Env. DNA	phyto/ periphyton	Observations
1	BSA	March 2022	✓	✓	✓	✓	✓	✓	x	✓	x	✓	✓	CH Cytometer DOC analysis in TR
2	LG	March 2022	✓	✓	✓	✓	✓	✓	x	✓	x	✓	✓	CH Cytometer DOC analysis in TR
3	GN	August 2021	✓	✓	✓	✓	✓	✓	x	✓	x	✓	✓	CH Cytometer DOC analysis in TR
4	SAMO	April 2019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
5	RN	August 2022	✓	✓	✓	✓	✓	✓	x	✓	x	✓	✓	CH Cytometer DOC analysis in TR
6	CR	April 2019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
7	BroaMO	April 2019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
8	CH	April 2019	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	DOC analysis in LJ
9	TR	April 2019	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	CH Cytometer
10	LJ	January 2022	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	CH Cytometer
11	SF	April 2019	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	outside AMO*Lat* DOC analysis
12	NE	April 2019	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	outside AMO*Lat* Cytometer
13	BL	April 2019	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	outside AMO*Lat* Cytometer

X lack capacity. *Cond.: conductivity. Transp.: Secchi disk, total suspended solids, turbidity, light availability (UV+PAR). DO: dissolved oxygen. Temp: water temperature. Nut.: nutrients. DOC: dissolved organic carbon. Chl-*a*: chlorophyll *a* concentration. **Flow cyt.: flow cytometry. Env. DNA: environmental DNA (extraction). Phyto/periphyton: phytoplankton/ periphyton sample collection.

Table 3. Survey of enhanced skills and observatory interactions*.
Tabla 3. Encuesta de habilidades mejoradas e interacciones entre observatorios.

Question	Answer: observatories (%)
Question: How has participation in the AMO*Lat* Network improved your opportunities of…?	
…discussion of results or projects	100%
…application of new techniques	90.90%
…accessibility to missing equipment	36.40%
None	0%
Others	Protocol harmonization
	Research training
Question: Has your observatory developed or improved connections with members of other observatories outside AMO*Lat* meetings?	
Yes	90.90%
No	9.10%
Question: … in what way was that link?	
Training related to technical or methodological aspects	80%
Processing of samples of the network	60%
Co-authorship of scientific work in publications or conferences	60%
Research or training stays	50%
Joint grant application	30%
Participation in projects not conducted by the network	20%
Others	Collaboration in postgraduate courses

*Responses based on the total number of observatories (N = 13)

connections with every network member (Figure 2B), which is due to its background in long-term monitoring and its experience in flow cytometry (Quiroga et al. 2021). The Bahía San Antonio (BSA) observatory is the second most collaborative site (6), and is part of a subgroup of geographically close nodes in the Patagonian region. These results demonstrate the capacity of the network to facilitate the establishment of new monitoring

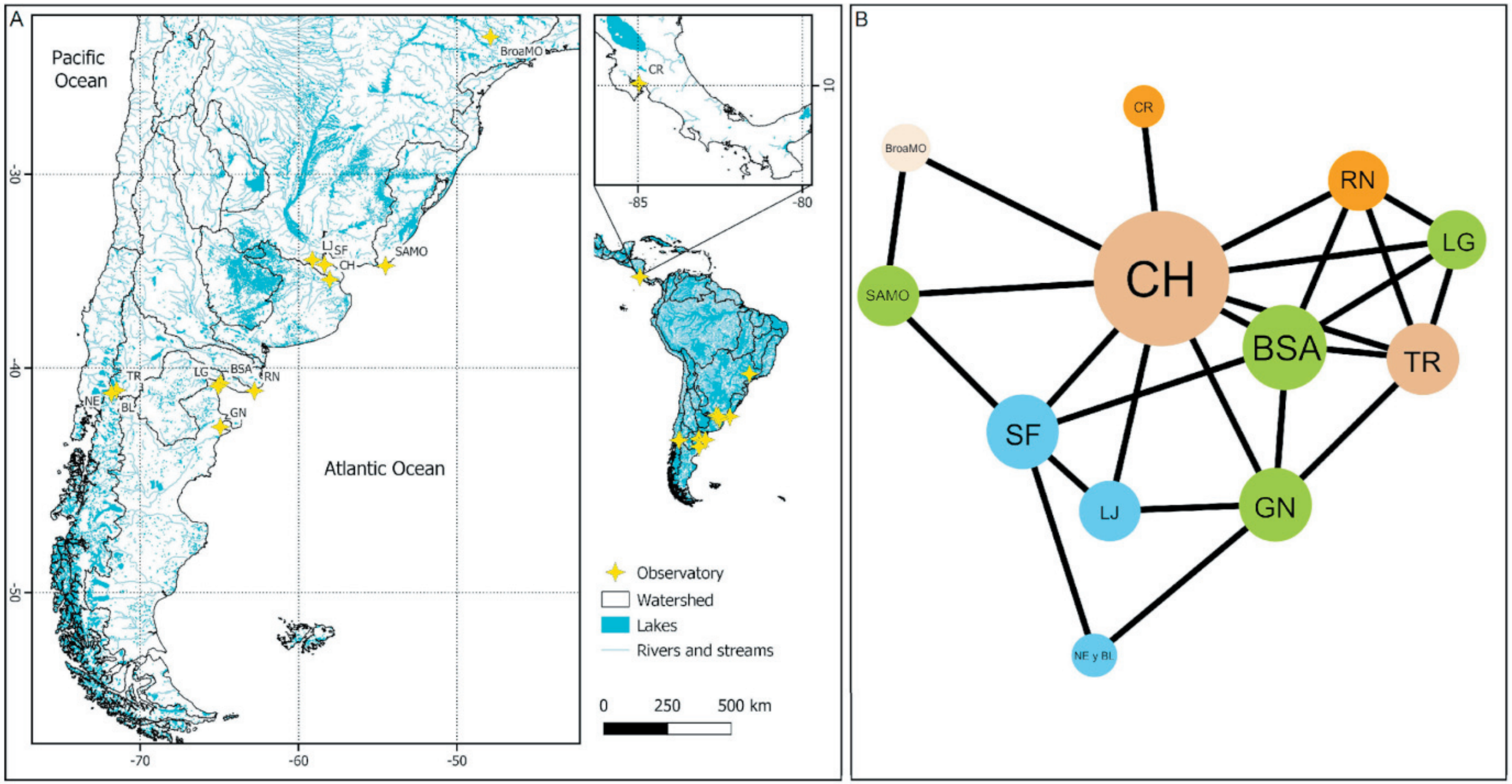

Figure 2. A) Map of the main Latin American continental basins and distribution of current observatory sites. See abbreviations in Table 1. B) Member's observatories interactions (see color code in Figure 3).

Figura 2. A) Mapa de las principales cuencas continentales latinoamericanas y distribución de los observatorios actuales. Ver abreviaturas en la Tabla 1. B) Interacciones de los miembros de los observatorios (ver código de colores en la Figura 3).

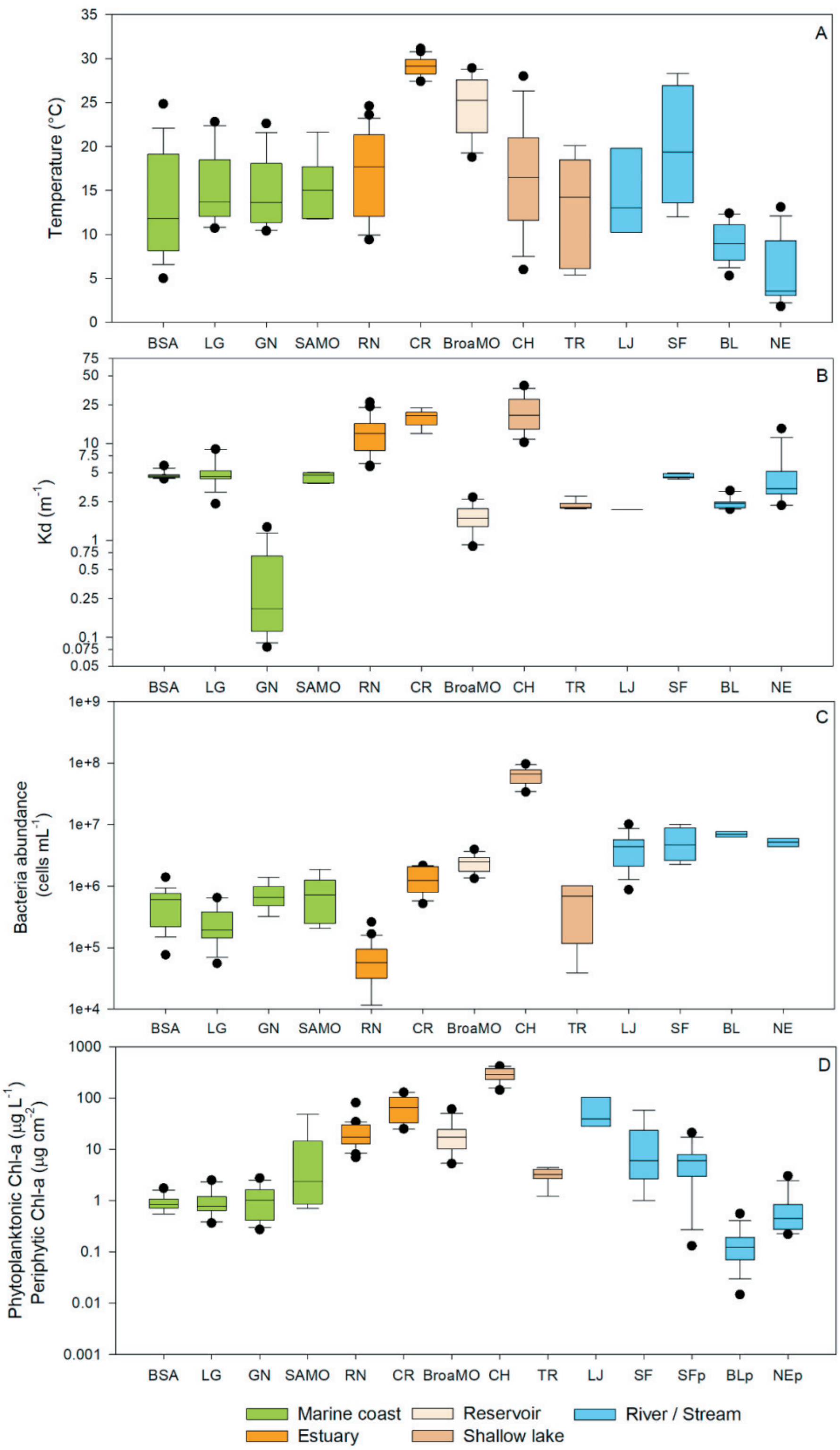

Figure 3. Physicochemical and biological characterization of each site. A) Water temperature. B) Light extinction coefficient (K_d). C) Bacteria abundance. D) Phytoplanktonic and periphytic chlorophyll-*a*. 'p' label in sites abbreviature means periphytic Chl-*a*. See abbreviations in Table 1.

Figura 3. Caracterización fisicoquímica, y biológica de cada sitio. A) Temperatura del agua. B) Coeficiente de extinción de la luz (K_d). C) Abundancia de bacterias. D) Clorofila-*a* fitoplanctónica y perifítica. La etiqueta p en la abreviatura de los sitios significa clorofila-*a* perifítica. Ver abreviaturas en la Tabla 1.

sites. A detailed description of the evolution of some landmark observatories can be found in Supplementary Material 2.

So far, the information available from these 13 sites provides insights into the diversity of aquatic environments in Latin America and on some of the major anthropogenic and climatic disturbances (Table 1, Figure 3). Average water temperatures recorded in the observatories span from 30 °C in Costa Rica to 4°C in the glacier-fed streams of Patagonia (Figure 3A). Similarly, a broad spectrum of underwater light climates can be observed through the K_d ranging from very transparent, such as the marine environment of Patagonia (GN), to very turbid environments caused by sediment resuspension (RN, CR, NE) and organic matter concentration (CH) (Figure 3B). These contrasting physicochemical characteristics among sites also imply significant variations in bacterial abundance (Figure 3C) and primary producer's communities (Figure 3D), which both vary spanning almost three orders of magnitude. The broad variability in these key parameters in the diverse set of heterogeneous aquatic ecosystems allowed us to analyze the impact of anthropogenic activities such as urbanization, agriculture, maritime activities and climate change.

Finally, the challenges identified by the observatory leaders include expanding the network's geographical scope, securing joint funding for improved operations (e.g., setting up a real-time website), strengthening collaborations and material exchanges, and initiating joint data analysis to increase the effectiveness of the network.

Discussion

The establishment of a regional network of observatories is essential to provide the baseline and starting point for assessing both short-term and long-term ecological dynamics of microbial communities. Most long-term microbial studies have been or are being conducted in the Northern Hemisphere (e.g., BATS-Sargasso Sea, BBMO-Blanes Bay or WCO-Western English Channel) (Veach et al. 2021), where the stability in scientific policies, consistent funding, technological access and research group density facilitate the initiative. Despite this, in our region long-term microbial dynamic studies have been conducted in different systems (Molina et al. 2020; Quiroga et al. 2021; Menezes et al. 2023). However, to the best of our knowledge, a continent-wide approach has not yet been reported. The creation of this microbial observatory network is significantly expanding pre-existent local initiatives with the inclusion of several new observatories and by fostering a collaborative space where technological and/or economic limitations can be overcome.

Currently, the network covers a wide latitudinal range and diverse ecosystems, which are experiencing different forces of change, both from human-induced changes and from natural processes (e.g., Efron et al. 2014; Saad et al. 2019; Griffero et al. 2019), such as shifts in land use (e.g., Gómez-Ramírez et al. 2019; Berman et al. 2020) and local responses to global climate change (e.g., Lozada et al. 2022; Modenutti et al. 2023). These factors, combined with the environmental relevance of microbial communities, highlight their crucial role in monitoring various phenomena associated with global change through a microbial lens. We anticipate that long-term monitoring will offer valuable insights for managing aquatic ecosystems and understanding their role in global change, while also enabling the exploration of questions from both regional and global perspectives.

This pioneering collaboration among regional research groups provides a favorable framework for strengthening microbial ecology in our region. Scientific partnerships within collaborative networks improve coordination, the co-development of methods and the access to shared high-cost equipment, which is crucial for developing countries. All sites are involved in collaborative projects, dissemination themes, exchange of ideas and active participation of researchers. The consortium aims to pursue innovative international funding, ensure the sustainability of the network and achieve collective and individual goals. In addition, we acknowledge that more Latin American environments need to be represented. The μSudAqua Network welcomes research groups adhering to our working philosophy and protocols, to join efforts for carrying out long-term research spanning the immense diversity of biomes and aquatic systems, as well as countries, cultures and resources in our continent.

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